A Study on the Strength and Fatigue Properties of Seven-Wire Strands in Hangers under Lateral Bending

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Received: 30 January 2020; Accepted: 20 March 2020; Published: 22 March 2020

Abstract: Hangers are important tensile members in half-through arch bridges and through arch bridges (HTABs and TABs). The floating deck structures of HTABs and TABs will commonly produce longitudinal deformation and rotate under the effect of temperature and the temperature gradient, which will cause bending deformation at anchorages of fixed-end hangers. This bending deformation can generate adverse bending stress for hangers and decrease the strength and fatigue properties of the seven-wire strands in the hangers. Firstly, theoretical derivation and finite element analysis are conducted to study the bending stress of hangers that is caused by bending deformation. We find that bending stress of hangers is mainly generated by lateral bending caused by the difference in longitudinal displacement at both ends of the hangers under the effect of temperature. Subsequently, the ultimate tensile strength of the seven-wire strands under lateral bending is obtained by FEM and an experimental study. The ultimate tensile strength of the seven-wire strands could decrease by 23.3% when lateral bending is considered. Moreover, the relationship between the fatigue properties of the seven-wire strands and lateral bending is obtained based on observing the ultimate tensile strength under lateral bending. Lateral bending significantly influences the fatigue properties of the seven-wire strands. When the lateral bending angle reaches about 50 mrad, the fatigue resistance of the seven-wire strands drop by almost 40%. The considerable decrease in the strength and fatigue properties of the seven-wire strands indicates that lateral bending has a significant adverse influence on hangers that consist of seven-wire strands. Finally, it is advised to use the tied arch structure for HTABs and TABs to mitigate the adverse influence of lateral bending on hangers.

Keywords: hangers; lateral bending; seven-wire strands; strength; fatigue properties

1. Introduction

In half-through and through arch bridges (HTABs and TABs), bridge decks are connected to arch ribs by hangers. Hangers transfer loads from the bridge decks to the arch ribs and they are arranged evenly along the longitudinal directions of bridges to transmit the load on the bridge decks to the arch ribs uniformly. HTABs and TABs have long been considered to be safe and reliable structural patterns. However, in the past few decades, many HTABs and TABs with floating deck structures have failed due to the sudden failure of their hangers [1–3], such as Nanmen Bridge (2001) (as shown in Figure 1a), Peacock River Bridge (2011), Gongguan Bridge (2011), and Nanfang’ao Bridge (2019). It is clear that corrosion and fatigue are the main factors that lead to the fracture of tension-resisting elements in hangers and further cause the sudden failures of bridge hangers [4–7]. In recent years, some scholars have suggested that, besides corrosion and fatigue, the bending deformation of both
end-fixed hangers might be an important factor in the sudden failure of hangers [8–10]. The bending stress that is caused by the bending deformation (as shown in Figure 1b) of hangers could accelerate the corrosion rates of the tension-resisting elements in hangers and, therefore, shorten the lives of hangers significantly [11–13]. However, bending stress is difficult to correctly measure in hangers using sensors and few numerical studies have been conducted on bending stress. Therefore, it remains difficult to further study the effect of bending on the corrosion and fatigue of hangers. Besides bending stress, the strength and fatigue properties of tension-resisting elements under bending are poorly understood; these elements may be greatly weakened by bending deformation, but only a few scholars have studied this topic. The neglect of the decrease on properties of tension-resisting elements in hangers might lead the safety of hangers is overrated under bending.

![Fractured hanger](image1)

![Bending zone](image2)

**Figure 1.** (a) Fracture of hangers of half-through and through arch bridges (HTABs and TABs); (b) Hangers under lateral bending.

According the above literature review, it is of great necessity to conduct a detailed study on the bending stress of hangers and the strength and fatigue properties of tension-resisting elements in hangers under bending deformation. In this paper, the types of hangers, the boundary conditions, and arch bridge structures are first discussed. We propose that end-fixed hangers consisting of parallel seven-wire strands (or hangers could be simplified as both end-fixed hangers) have sufficient bending stiffness to bear the bending moment. Moreover, it is found that HTABs and TABs with floating deck structures can cause a significant lateral bending to hangers. Therefore, the bending stress of HTAB and TAB hangers with floating deck structures and the strength and fatigue properties of seven-wire strands are studied.

Firstly, the two possible factors of the bending of hangers, the longitudinal deformation of the deck, and the rotation of deck are discussed. The floating deck structure is only connected to the arch ribs by hangers and bearings at both ends allow for the deck to produce longitudinal deformation and rotation. In this case, the bridge deck can produce significant deformation along the longitudinal direction of the bridge under the effect of temperature and rotate under the effect of the temperature gradient [14]. The deformation of arch ribs would be restricted at skewbacks and there would be difference in longitudinal displacements between the arch and deck. The different displacements at both ends of hangers and the rotation of the bridge deck will cause bending deformation of hangers.

Subsequently, the theoretical formulations for the bending angles and maximum bending stress of hangers caused by the effects of temperature and the temperature gradient are developed. The finite element method (FEM) then verifies the accuracy of the formulas for bending angles and the maximum bending stress of the hangers. Based on an analysis of the hangers of a real TAB with a floating deck structure, we find that the bending of hangers is mainly caused by the difference in longitudinal displacement between the arch and the deck under the effect of temperature. Thus, the following study is conducted under the consideration of lateral bending of hangers that is caused by the difference in
longitudinal displacement between the arch and the deck. Based on an analysis of the mechanical model of hangers, it is concluded that, besides the maximum bending stress $\sigma_b$ in hangers, the ultimate tensile strength $\sigma_u$ of the seven-wire strand under lateral bending is also the primary influential factor of the safety of hangers when hangers have lateral bending deformation. The influence of lateral bending deformation on the ultimate tensile strength of the seven-wire strands is obtained, according to finite element analysis and tests on the seven-wire strands. It is found that the ultimate tensile strength of the seven-wire strands under lateral bending decreases significantly. Thus, a method for checking the strength of the seven-wire strands in hangers under lateral bending is proposed. In addition, the S–N curve of the seven-wire strands under lateral bending can also be obtained based on the ultimate tensile strength under lateral bending. The fatigue properties of seven-wire strands will be weakened with an increase in lateral bending $\theta$ according to the S–N curve of the seven-wire strands under lateral bending. When the lateral bending $\theta$ is over 40 mrad, the fatigue properties of seven-wire strands will fall dramatically.

In conclusion, lateral bending can exert a significant adverse influence on the seven-wire strands in hangers, so it is advised to take several measures to mitigate this adverse influence, such as using a tied arch structure as much as possible, replacing the fixed connections with hinged connections for short hangers, and using a jointless bridge structure. Using a tied arch structure for HTABs and TABs might have fewer side effects when compared with using the other methods above, so using a tied arch structure is more strongly recommended.

2. Discussion on the Types and Boundary Conditions of Hangers, as Well as Arch Bridge Structures

The bending stiffness and boundary conditions of a component are the primary influential factors that determine its mechanical behaviors when suffering a bending moment. Further investigations into the bending of hangers can only be meaningful when the hangers of arch bridges have sufficient stiffness to bear the bending moment and do not release the bending moment at both ends. Therefore, it is necessary to determine what type of hangers and connections can bear the bending moment. Besides the types and boundaries of the hangers, the bridge deck structures also affect the extent of the bending of hangers. Thus, it is necessary to clarify the types of hangers, the boundary conditions, and the bridge deck structure that can allow hangers to produce significant bending deformation.

2.1. Type of Hangers

The hangers of arch bridges are mostly made of structural ropes or a bundle of parallel seven-wire strands [15,16]. According to [15], the mechanical properties of hangers consisting of structural ropes are quite different could not be regarded as a whole. When a section of hangers is subject to bending action, the structural ropes of the same cross-section can cause slippage, which will lead to a large decrease in the bending stiffness of the hangers. Therefore, the effect of bending on hangers that consist of structural ropes is not significant. Hangers consisting of seven-wire strands are further investigated in this paper. Firstly, it is of great necessity to analyze the bending stiffness of hangers consist of seven-wire strands. Presently, there have been few numerical methods used to directly calculate the bending stiffness of hangers that consist of seven-wire strands. The structures of hangers consisting of parallel seven-wire strands are analyzed in order to calculate the bending stiffness as accurately as possible. Generally, hangers are made of coated parallel strands, inter PE pipes, a compression wrapping layer, and an outer PE pipe from inside to outside (as shown in Figure 2). The inner coating, outer coating, inter PE pipe, compression wrapping layer, and outer PE pipe can all work to protect the seven-wire strands from corrosion. Besides playing a part in corrosion protection, the compression wrapping layer and outer PE pipe have another function to make seven-wire strands bundle together tightly. The compression wrapping layer is used to bundle the seven-wire strands. The outer PE pipe is formed by thermoplastic extrusion and it applies a large bond force to the seven-wire strands in hangers. Under the joint action of the compression wrapping layer and the outer PE pipe, there is huge
contact stress among the strands. This significant contact stress can generate a frictional bond among parallel strands when the parallel strands in the hangers are bent. According to [15], the frictional bonds among parallel strands can allow for the cross-section of the hangers to maintain their integrity in the process of bending; thus, the bending theory of beams could be suitable for hangers. A hanger that consists of seven-wire strands should have sufficient bending stiffness to bear the bending moment, so this type of hanger will be studied further, based on the above analysis.

2.2. Boundary Conditions of the Hanger and Bridge Deck Structure

For the boundary conditions of hangers the hangers to be investigated should be able to suffer the bending moment based on the analysis above; both end-fixed hangers must meet this requirement and the hangers hinged at both ends are not considered. Further, if one end of the hangers is the hinge connection and the other end is the fixed connection, there would be a bending moment at the end with a fixed connection. In this case, the bending moment at the end with the fixed connection is nowhere near as significant as that of both end-fixed hangers, so hangers with only a fixed connection at one end are not considered. However, there is an exception (as shown in Figure 3). In this case, the upper ends of the hangers are hinged on the arch rib, but the hangers can be simplified as both end-fixed [17].

In a simplified model of the boundary conditions for these kinds of hangers, the dampers are simplified as rigid links that are based on the great rigidity of dampers. The displacement of the top
head of the hanger is restricted by the spherical bearings, and the rotation is restricted by rigid links, so hangers can be assumed to be fixed at both ends.

For a bridge deck structure, the bridge decks of the TABs and HTABs can be subcategorized into many categories. A floating deck structure is one of the most common deck structures of TABs and HTABs. A floating deck structure is only connected to the arch rib by hangers and it is not connected to the arch rib at the skewbacks of bridges (as shown in Figure 4). Therefore, the floating deck structure of TABs and HTABs can produce significant longitudinal deformation and rotate without the limitations of the arch rib, which further leads hangers to produce obvious bending deformation [14]. In addition, the studies in [1–3] indicate that most accidents involving a failure of hangers are on TAB and HTAB with floating deck structures. HTABs and TABs with floating deck structures were constructed in large quantities in the past decades in China and are still in construction in many areas, according to [18], so the hangers of TABs and HTABs with floating deck structures are studied in this paper.

![Unconnected](image)

**Figure 4.** Skewback of HTABs and TABs with a floating deck structure.

In summary, both end-fixed hangers consisting of the parallel seven-wire strands (or hangers could be simplified as both end-fixed hangers) of HTABs and TABs with floating deck structures can significantly bend, so bending can affect the seven-wire strands in hangers. Thus, both end-fixed hangers consisting of parallel seven-wire strands of HTABs and TABs with floating deck structures are covered by this study and its conclusions.

### 3. Study on the Main Bending Form of Hangers

#### 3.1. Theoretical Formulation for the Bending Angle and Maximum Bending Stress of Hangers

The theoretical formulation for the lateral bending angles and maximum bending stress of hangers is conducted here. Presently, bearings that allow for bridge decks to have longitudinal deformation of their bridges and rotate (such as rubber bearings) are widely used in HTABs and TABs with floating deck structures [13]. Under the effect of temperature and the temperature gradient, bridge decks can produce longitudinal deformation and rotate. The longitudinal deformation of bridges is related to the temperature changes of the whole bridge, and the rotation of bridge decks is related to the temperature gradient throughout the bridge sections.

Based on the analysis above, the lateral bending angle of hangers consists of two parts. One is the bending angle ($\theta_1$) that is caused by the longitudinal deformation of the bridge decks (as shown in Figures 5 and 6), and the other part is the bending angle ($\theta_2$) that is caused by the rotation of the bridge decks [19] (shown in Figure 7). We theoretically deduce the formulas to describe the bending
angle caused by the longitudinal deformation of bridge decks and the bending angle caused by the rotation of the bridge decks, according to the analysis above.

Firstly, the bending angle that is caused by the longitudinal deformation of bridge decks is discussed. The displacement of the lower anchorage zone of the \( i \)-th hanger on the right side of the bridge center is

\[
\Delta L_i = \alpha \Delta t L_i
\]

where \( L_i \) is the distance between the bridge center and the \( i \)-th hanger; \( \Delta t \) is the change in the temperature of the whole bridge deck; and, \( \alpha \) is the thermal expansion coefficient of the bridge deck [20].

**Figure 5.** Lateral bending angles caused by the longitudinal deformation of bridge decks.

Subsequently, the lateral bending angle \( \theta_2 \) of the hangers that is caused by the rotation of the bridge decks is further studied (as shown in Figure 7).

**Figure 6.** Lateral bending deformation of the hangers under the longitudinal deformation of bridge decks.

Firstly, the bending angle that is caused by the longitudinal deformation of bridge decks is discussed.

The displacement of the lower anchorage zone of the \( i \)-th hanger on the right side of the bridge center is

\[
\theta_1 = \frac{\Delta L_i}{H_i}
\]

where \( H_i \) is the length of the \( i \)-th hanger.

It is assumed that the temperature at the top of the bridge decks is \( T_1 \), and the temperature at the bottom of the bridge decks is \( T_2 \). According to Figure 8, the following can be obtained:

\[
T_1 - T_2 = \alpha \cdot \frac{\pi d x}{h} \Delta \theta
\]
Figure 6. Lateral bending deformation of the hangers under the longitudinal deformation of bridge decks.

Subsequently, the lateral bending angle $\theta_2$ of the hangers that is caused by the rotation of the bridge decks is further studied (as shown in Figure 7).

Figure 7. Bending angles caused by the rotation of the bridge decks.

It is assumed that the temperature at the top of the bridge decks is $T_1$, and the temperature at the bottom of the bridge decks is $T_2$. According to Figure 8, the following can be obtained:

$$ \theta_1 = \frac{\Delta L_i}{H_i} $$

(2)

where $H_i$ is the length of the $i$-th hanger.

Subsequently, the lateral bending angle $\theta_2$ of the hangers that is caused by the rotation of the bridge decks is further studied (as shown in Figure 7).

It is assumed that the temperature at the top of the bridge decks is $T_1$, and the temperature at the bottom of the bridge decks is $T_2$. According to Figure 8, the following can be obtained:

$$ d\theta_2 = \frac{\alpha(T_1 - T_2)dx}{h} $$

(3)

where $h$ is the height of the bridge deck.

Figure 8. Rotation angle of the bridge decks.
After integrating the above equation, the rotation angle of the bridge decks is

\[ \theta_2 = \frac{\alpha (T_1 - T_2)}{2h} \]  

(4)

where \( L \) is the distance \( L_i \) between the \( i \)-th hanger and the center line of the bridge. The rotation angle \( \theta_2 \) is the bending angle of the \( i \)-th hanger that is caused by the rotation of the bridge decks.

Thus, the total bending angle of the hangers is

\[ \theta = \theta_1 + \theta_2. \]  

(5)

The maximum bending stress is further studied based on the formula for the bending angle of the hangers derived above.

According to the analysis in Section 2.1, the bending stiffness of the hanger that consists of seven-wire strands and can be calculated by the bending theory of beams, so the bending stiffness of the \( i \)-th hanger is

\[ K_i = E_i I_i \]  

(6)

where \( E_i, I_i \) are, respectively, the Young’s modulus and the moment of inertia of the \( i \)-th hanger. According to [15], the Young’s modulus of the hangers that consist of seven-wire strands is mainly determined by the seven-wire strands and can be the same as that of the seven-wire strands. The moment of inertia of the hangers can be considered as the moment of inertia for all the seven-wire strands in the hangers, because the PE pipe and compression wrapping layer do not have significant bending stiffness and can be ignored in the process of calculating the bending stiffness of hangers. The study in [21] provides a method for calculating the moment of inertia for the seven-wire strands in hangers. This method uses the number of seven-wire strands in hangers, the radius of the seven-wire strands, and the transverse strain of the seven-wire strands to calculate the moment of inertia for the seven-wire strands in the hangers with good accuracy. Therefore, the moment of inertia of the \( i \)-th hanger can be calculated, as follows, according to the above method:

\[ I_i = C_n r^4 (1 + \varepsilon')^4 \]  

(7)

where \( r \) is the radius of the seven-wire strands; \( C_n \) is the coefficient of the moment of inertia of the cross-section; and, \( \varepsilon' \) is the transverse strain of the seven-wire strands in the hangers. \( C_n \) and \( \varepsilon' \) can be calculated by the following formulas:

\[ C_n = \frac{\pi}{2} (27.5 + 208.5n + 523.5n^2 + 630n^3 + 315n^4) \]  

(8)

\[ \varepsilon' = \frac{-vT_i}{EA} \]  

(9)

where \( n \) is the number of the seven-wire strands in the hangers; \( v \) is the Poisson’s ratio of the seven-wire strands; \( T_i \) is the tension force of the \( i \)-th hanger; and, \( A \) is the sum of the section area of all seven-wire strands in the hangers.

According to the slope-deflection equations [22,23], the bending moment at the end of the \( i \)-th hanger caused by the bending angles \( \theta_1 \) and \( \theta_2 \) are, respectively,

\[ M_{i\theta_1} = \Delta L_i \cdot \left( \frac{E_i I_i}{H_i^2} + T_i \right) = \theta_1 \cdot \left( \frac{E_i I_i}{H_i^2} + H_i \cdot T_i \right) \]  

(10)

\[ M_{i\theta_2} = 4\theta_2 \cdot \frac{E_i I_i}{H_i} \]  

(11)
where $T_i$ is the tension force of the $i$-th hanger. The maximum bending stress that the seven-wire strand bears in $i$-th hanger caused by $\theta_1$ is

$$\sigma_{b\theta_1} = \frac{y_{\text{max}} M_{i\theta_1}}{I_i} = \frac{y_{\text{max}}}{I_i} \cdot \theta_1 \cdot \left(6 \cdot \frac{E_i I_j}{H_i} + H_i \cdot T_i\right)$$

(12)

where $y_{\text{max}}$ is the distance from the center of the hanger to the outermost steel strand (as shown in Figure 9).

![Cross-section of seven-wire strands in the hangers.](image)

Figure 9. Cross-section of seven-wire strands in the hangers.

In the same way, the maximum bending stress that the seven-wire strand bears in $i$-th hanger caused by $\theta_2$ is

$$\sigma_{b\theta_2} = \frac{y_{\text{max}} M_{i\theta_2}}{I_i} = 4y_{\text{max}} \cdot \theta_2 \cdot \frac{E_i}{H_i}.$$ 

(13)

The maximum bending stress that the seven-wire strand bears in $i$-th hanger caused by $\theta_1$ and $\theta_2$ is:

$$\sigma_i = \frac{y_{\text{max}} (M_{i\theta_1} + M_{i\theta_2})}{I_i} = \frac{y_{\text{max}}}{I_i} \left[ \theta_1 \cdot \left(6 \cdot \frac{E_i I_j}{H_i} + H_i \cdot T_i\right) + 4\theta_2 \cdot \frac{E_i I_j}{H_i} \right]$$

(14)

where $y_{\text{max}}$ is the distance between the seven-wire strand at the outer edge of the hangers between the centers of the hangers. The theoretical deduction above is based on the assumption that the hangers are simplified as beams and the curvature of hangers is not considered. In fact, the stiffness of hangers would decrease with the increase of length, so the theoretical deduction above would be more precise when applied for short hangers [24].

Thus far, the formulas for the bending angle and maximum bending stress of the hangers are obtained. The finite modeling method (FEM) in next section further verified the accuracy of these formulas.

### 3.2. Validation of the Theoretical Formulations by FEM and Defining the Main Form of the Bending of Hangers

In this section, the FEM is used to verify the accuracy of the above theoretical formulation. Figure 10 shows a finite element model of a TAB with a floating deck structure in Southeast China [23]. The main span of the bridge is 105 m. There are 12 pairs of hangers for the bridge, and all of the hangers are fixed at both ends. Each hanger is made of 19 $\Phi 15.2$ seven-wire strands. The radius of the seven-wire strands in the hangers is 7.6 mm [25]. The distance between the seven-wire strand at the outer edge of the hangers between the centers of the hangers ($y_{\text{max}}$) is 91 mm. The modulus of elasticity of the hangers is $1.95 \times 10^5$ MPa, according to [25]. The length and tension force of the hangers can be obtained by design data. The joining temperature of the bridge is about 5 °C. In the finite element analysis of the bridge, the hangers are simulated as both end-fixed beam elements. The temperature and temperature gradient of the bridge are obtained using the data that were measured in bridge monitoring. Ambient temperature sensors are installed on the bridge, and the top plate and bottom plate of the bridge deck are equipped with temperature sensors. The temperature of the bridge is
assumed to be the ambient temperature. The ambient temperature fluctuates between −15 °C and 40 °C, so the temperature of whole bridge is set between −15 °C and 40 °C, according to the measured data. The temperature gradient is obtained via the data that were measured from the temperature sensors at the top plate and bottom plate of the bridge deck. It is assumed that the temperature gradient is linear between the top plate and bottom plate of the bridge deck, so the temperature gradient can be obtained by using the temperatures of the top plate and bottom plate of the bridge deck. Thus, when different ambient temperatures are applied on the bridge, the temperature gradient that corresponds to the ambient temperature can be obtained, according to the temperatures at the top plate and bottom plate of the bridge deck at the same time.

Figure 10. Finite element model of a TAB.

The above discussion provides a method for applying the temperature and temperature gradient to the bridge in FEM. The bending angles and maximum bending stress in the hangers under the effect of temperature can be obtained by the results of the finite element analysis, as described above. Formulas (2), (4), (5), and (12)–(14) are used to calculate the bending angles and maximum bending stress of the hangers, and then the results are compared with the results of the finite element analysis to verify the accuracy of the above theoretical formulation. Figure 11a shows the bending angle according to the calculations and the bending angles according to the FEM of the hangers. Figure 11b shows the maximum bending stress according to the calculations and the maximum bending stress according to the FEM of the hangers. The bending angle and maximum bending stress of the hangers are also given, respectively, under the effect of temperature and the effect of the temperature gradient. Figure 11a,b show the data of the shortest hanger of the bridge to verify the accuracy of the formulas when considering that the range of the bending angle and the maximum bending stress of the shortest hanger are the largest among all the hangers.

It can be concluded that the results of the calculations using the formulas are close to those of FEM, which verifies that the formulas are basically accurate.

Besides verifying the accuracy of the theoretical formulations, it can be obtained from Figure 11a,b that the bending angle and maximum bending stress of hangers are mainly caused by the lateral bending of hangers under the effect of temperature. The bending of hangers caused by the rotation of the bridge deck under the effect of temperature gradient is far smaller than the lateral bending that is caused by different displacements at both ends of the hangers under the effect of temperature. The difference between Formulas (12) and (13) also supports the above results. Formula (12) includes the tension force T of the hangers, which is not present in Formula (13). The value of the tension force T of hangers is relatively large and it is the primary influential parameter that determines bending stress. Thus, the bending stress that is caused by rotation of the bridge deck is small when lacking the influence of the tension force of the hangers.
4.1. Stress Characteristics of Parallel Seven-Wire Strands in Hangers under Lateral Bending

The main form of the bending of hangers is the lateral bending deformation that is caused by temperature, according to the analysis of the previous section. Figure 12 shows the stress state of hangers under lateral bending.

![Figure 12: Stress state of hangers considering lateral bending deformation.](image)

When hangers experience lateral bending deformation, the tensile stress is not uniformly distributed on the cross-sections of the hangers. The maximum bending stress $\sigma_b$ on the cross-section of the hangers caused by bending moments is located at the outer edge of the hangers [22]. The seven-wire strand that is located at the outer edge of the hangers will bear the maximum bending stress...
and it is under the most unfavorable loading conditions in all parallel seven-wire strands, as shown in Figure 13. When the seven-wire strand under the most unfavorable loading conditions bears tensile stress (when it contains the bending stress that is caused by lateral bending deformation) that exceeds its own ultimate tensile strength $\sigma_u$, the strand will break, and the hangers will not have the adequate strength to bear loads.

**Figure 13.** Mechanical model of the parallel seven-wire strands in the hangers considering lateral bending deformation.

Overall, the maximum bending stress $\sigma_b$ of hangers and the ultimate tensile strength $\sigma_u$ of the seven-wire strands are the primary influential factors underlying the safety of hangers when hangers experience lateral bending deformation. The maximum bending stress $\sigma_b$ has been previously investigated in detail. Thus, a study on the ultimate tensile strength of seven-wire strands under lateral bending deformation is conducted here.

### 4.2. Ultimate Tensile Strength of the Seven-Wire Strands under Lateral Bending

Generally, the ultimate tensile strength of the seven-wire strands is obtained via the breaking force in the tensile test, so the finite element analysis method is used to simulate the fracture of the seven-wire strands under lateral bending. Firstly, a solid element simulated the middle (king) wire of the seven-wire strand. Subsequently, the axes of the six wires of the outer layer are set around the middle wire as the helices. The solid element is also used to simulate the six wires of the outer layer. The material of the model is structural steel. According to [25], the lay length of the seven-wire strands should be 12–16 times the diameter, so a lay length of 14 times the diameter was used to model. The frictional coefficient between the wires is assumed to be 0.2 [26,27]. Figure 14 shows the model of the seven-wire strand in ANSYS [28].

The damage model [29,30] of the material adopts the ductile fracture criterion. The damage initiation (Equation (15)) and evolution standard (Equation (16)) of the seven-wire strands is obtained according to [31]:

$$\omega_D = \int \frac{d\varepsilon_{pl}^D}{\varepsilon_{pl}^D(\eta, \varepsilon_{pl}^D)} = 1 \quad (15)$$

$$\varepsilon_{pl}^D = \varepsilon_{pl}^D(\eta) \quad (16)$$

where $\varepsilon_{pl}^D$ is the equivalent plastic strain and $\eta$ is the stress triaxiality [32]. The $\eta$ is defined, as Equation (17):
Thus far, we have built a finite element model of seven-wire strands. Next, we set different lateral bending angles for the model. The steps are as follows. Firstly, the fixed support is set for one end of the seven-wire strand and it is assumed that this end is connected to the arch rib in the hangers. Subsequently, the other end of the seven-wire strand is assumed to connect to the bridge deck. Displacement perpendicular to axis of the strand is applied to this end. Setting the value of the displacement at the end can control the lateral bending angle of the seven-wire strands. Thus, six lateral bending angles (5 mrad, 10 mrad, 15 mrad, 20 mrad, 25 mrad, and 30 mrad) are applied to the model of the seven-wire strands by setting six different displacements perpendicular to axis of strands at the end of model. The lateral bending angle of the hangers of the Pingnan Third Bridge, which is the longest arch bridge under construction in the world [33], could reach about 30 mrad. At most, the lateral bending angle of the seven-wire strands is set to 30 mrad. After setting the lateral bending angles for the finite element model, the seven-wire strand is tensioned along the axial direction until it breaks (as shown in Figure 15). The above process is conducted at different lateral bending angles of the seven-wire strand. The breaking tensile forces of the seven-wire strands at different lateral angles are recorded. The ultimate tensile strengths of the seven-wire strands at different lateral bending angles (shown in Table 1) can be obtained by the tensile breaking force and cross-sectional area of the model.

\[
\eta = \frac{(\sigma_1 + \sigma_2 + \sigma_3) / 3}{\sqrt[3]{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}}
\]

(17)

Figure 14. Finite element model of a seven-wire strand.

Figure 15. Fracture of the seven-wire strands simulated by a finite element simulation.
Table 1. The ultimate tensile strengths of the seven-wire strands at different lateral bending angles by finite element analysis.

| Lateral Bending Angles $\theta$ (mrad) | Ultimate Tensile Strength $\sigma_u$ (MPa) |
|---------------------------------------|------------------------------------------|
| 0                                     | 1805.6                                   |
| 5                                     | 1732.1                                   |
| 10                                    | 1665.7                                   |
| 15                                    | 1584.2                                   |
| 20                                    | 1499.3                                   |
| 25                                    | 1442.8                                   |
| 30                                    | 1399.2                                   |

4.3. Experimental Study on the Ultimate Tensile Strength of the Seven-Wire Strands under Lateral Bending

A tensile test of the seven-wire strands under lateral bending was implemented to confirm the accuracy of the results of the finite element analysis. In this test, the lateral bending angle was set for the seven-wire strands by setting the places for the anchorage opening on the anchor plates at both ends. Normally, the anchorage openings on the anchor plates at opposite ends of the seven-wire strand share one axis, which can help the anchored seven-wire strands to remain straight under tension. When the anchorage openings on the anchor plates at opposite ends of the seven-wire strand have different axes, the seven-wire strand will bend (as shown in Figure 16). Thus, four pairs of anchorage openings (as shown in Figure 17a) were set on two anchor plates (due to the limitations of the area of the anchor plate, four anchorage openings at most can be set on an anchor plate). When the seven-wire strand is anchored through different pairs of anchorage openings, the lateral bending angle is set at different values (as shown in Figure 18). In order to maintain consistency with the finite element analysis in the previous section, the lateral bending angles are set, as follows: 0 mrad, 10 mrad, 20 mrad, and 30 mrad. The anchor plate is then attached to the reaction frame, and a single strand is tensioned on the reaction frame each time. The length of tested seven-wire strands is 1.14 m and the length of tested strands cannot reach to the length of real hangers due to the limitation on the size of the reaction frame, so the tests here are scale model tests and the effect that is caused by the scale of components is not considered [34]. According to [35,36], the order of applying loads to cables does not influence the finally stress state of cables so we can set the angles for seven-wire strands before applying tensile stress in the test.

The tensile tests were repeated three times at each lateral bending angle. The seven-wire strands were tensioned to break (shown in Figure 17b), and Table 2 records the breaking forces.

Figure 16. Lateral bending of the seven-wire strands in the test.
Figure 16. Lateral bending of the seven-wire strands in the test.

Figure 17. (a) Modified anchor plate; and, (b) failure cross-section of the seven-wire strand.

Figure 18. Seven-wire strands and reaction frame in the tensile test.

Table 2. Ultimate tensile strengths of the seven-wire strands at different lateral bending angles in the tests.

| Lateral Bending Angle $\theta$ (mrad) | Ultimate Tensile Strength of the Seven-Wire Strands $\sigma_u$ (MPa) |
|--------------------------------------|---------------------------------------------------------------|
|                                      | Results of Tests                                              | Average Value |
| 0                                    | 1978.5, 1957.1, 1928.5, 1821.4                                 | 1954.7        |
| 10                                   | 1814.2, 1792.8, 1621.1                                         | 1809.5        |
| 20                                   | 1621.1, 1607.1, 1471.4                                         | 1616.4        |
| 30                                   | 1435.7, 1428.5                                                 | 1445.2        |

It can be seen that the results of the finite element analysis and the results of the test are similar with an increase in the lateral bending angles based on a comparison between the results of the finite element analysis and the tests (as shown in Figure 19a). The error is 8.9% when the lateral bending angle is 0 mrad, and the error is 3.1% when the lateral bending angle is 30 mrad. The error of the ultimate tensile strength between the results of the finite element analysis and the results of the tests is controlled by 10%, which indicates the validity of the finite element method (FEM). The ultimate tensile
strength of the seven-wire strands at different lateral bending angles, as obtained by the finite element analysis, is chosen to conduct further studies, since the production lot decides the performance of each seven-wire strand in the test at random. The fitting curve (as shown in Figure 19b) of the ultimate tensile strength of the seven-wire strands at different lateral bending angles is

\[ y = -14.03x + 1800 \]  

(18)

where \( y \) is the ultimate tensile strength \( \sigma_y \) of the seven-wire strands under lateral bending, and the unit is MPa; \( x \) is the lateral bending angle \( \theta \) of the seven-wire strands, and unit is mrad.

\[ Lateral bending angle (\text{mrad}) \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \]

\[ 0 \quad 500 \quad 1000 \quad 1500 \quad 2000 \quad 2500 \]

(a)

\[ Lateral bending angle (\text{mrad}) \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \]

\[ 0 \quad 500 \quad 1000 \quad 1500 \quad 2000 \quad 2500 \]

(b)

\[ \text{Ultimate tensile strength of seven-wire strands (MPa)} \]

\[ \text{Results of finite element analysis} \]

\[ \text{Results of tests} \]

\[ \text{Curve fitting of finite element analysis results} \]

\[ y = -14.03x + 1800 \]

\[ \text{Curve fitting of test results} \]

\[ y = -17.22x + 1964 \]

Figure 19. (a) The ultimate tensile strength of seven-wire strands versus lateral bending angle; and, (b) the curve fitting of ultimate tensile strength—lateral bending angle.

It can be calculated using formula (18) that the ultimate tensile strength of the seven-wire strands in the hangers decreases by 23.3% when the lateral bending angle is 30 mrad. Such a drastic reduction of strength in the seven-wire strands indicates that the adverse influence of lateral bending cannot be ignored and it necessitates a method for assessing the safety of seven-wire strands in hangers under lateral bending.

5. Strength Check and Fatigue Properties of Seven-Wire Strands in Hangers under Lateral Bending

5.1. Strength Check of Seven-Wire Strands in Hangers under Lateral Bending

The strength of seven-wire strands in hangers cannot be checked through the test directly due to the limitations of the tonnage of the testing machine, so the only way to check the strength of seven-wire strands in hangers using the technical codes [37] is to compare the tensile stress of the cross-section with the reduced ultimate tensile strength of the seven-wire strands, as shown in Equation (19):

\[ \sigma \leq F f_{tpk} \]  

(19)

where \( \sigma \) is the tensile stress on the cross-section of the hanger and \( F \) is the factor of safety based on the allowable stress design method. \( f_{tpk} \) is the ultimate tensile strength of the tension-resisting elements in the hangers [25]. When the tension-resisting elements in the hangers are parallel seven-wire strands, \( f_{tpk} \) is the ultimate tensile strength of the seven-wire strands.

When considering the influence of lateral bending, the tensile stress \( \sigma \) in formula (19) should contain the maximum bending stress \( \sigma_b \), and the ultimate tensile strength \( f_{tpk} \) of the seven-wire strands.
can be modified by Formula (12). The suggested assessment method for the strength of the hangers of HTABs and TABS with a floating deck structure under lateral bending is:

\[ \sigma + \sigma_b \leq F(-14.03x + 1800) \]  \hspace{1cm} (20)

where \( \sigma_b \) is the maximum bending stress caused by lateral bending and can be obtained by Formula (12); \( x \) is the lateral bending angle and it can be obtained by Formula (2).

5.2. The Fatigue Properties of Seven-Wire Strands under Lateral Bending

Based on the previous analysis, it is known that the ultimate tensile strength of seven-wire strands is weakened when the seven-wire strands experience lateral bending deformation. The fatigue properties of seven-wire strands may be weakened by a decrease in the ultimate tensile strength, according to [38]. The fatigue properties of seven-wire strands are one of the main influential factors for the fatigue life of hangers. Therefore, an investigation of the properties of seven-wire strands under lateral bending is conducted. The S-N curve is a typical method to reflect the fatigue properties of materials, so we decide to study the S-N curve of seven-wire strands under lateral bending [39–41].

The S–N curve of the seven-wire strands with 1860 MPa ultimate tensile strength under 1050 MPa mean stress is [42]:

\[ \log_{10} N = 13.84 - 3.5 \log S_a \]  \hspace{1cm} (21)

where \( N \) is the number of cycles to failure and \( S_a \) is the cyclic stress amplitude (\( S_a = \frac{S_{\text{max}} - S_{\text{min}}}{2} \)). When the ultimate tensile strength of the seven-wire strands is assumed as the function of the lateral bending angle, the S–N curve of the seven-wire strand under lateral bending can be deduced based on Equation (21).

For Equation (21), when \( N = 2 \times 10^6 \) or \( 2 \times 10^7 \), the corresponding value of \( S_a \) is described as endurance limit \( \sigma_a \). When the stress amplitude \( S_a \) is lower than \( \sigma_a \), \( N \) is bigger than \( 2 \times 10^6 \) or \( 2 \times 10^7 \) and the number of cycles to failure is regarded as infinity. In this paper, we take \( 2 \times 10^6 \) as the value of \( N \) to obtain the endurance limit \( \sigma_a \) of seven-wire strands. Thus, when \( N = 2 \times 10^6 \), \( \sigma_a \) is 143 MPa. According the Goodman equation [43] (Equation (22)), when \( S_m \) is the mean stress whose value is 1050 MPa; \( \sigma_a \) is 143 MPa; \( S_u \) is 1860 MPa, the following can be obtained: \( \sigma_{-1} = 328 \) MPa.

\[ \sigma_a = \sigma_{-1}(1 - \frac{S_m}{S_u}) \]  \hspace{1cm} (22)

Furthermore, the \( \sigma_a \) under \( N = 2 \times 10^6 \) and \( S_m = 1050 \) MPa is obtained:

\[ \sigma_a = 328(1 - \frac{S_m}{S_u}) \]  \hspace{1cm} (23)

According to the ideal S–N curve, the slope of the S–N curve of materials with different ultimate tensile strengths is constant, and the intercept of the S–N curve is:

\[ b = \log 2 \times 10^6 + 3.5 \log S_a. \]  \hspace{1cm} (24)

The S–N curve of the seven-wire strands under the mean stress \( S_m = 1050 \) MPa is

\[ \log N = b - 3.5 \log S_a \]  \hspace{1cm} (25)

where \( b \) is

\[ b = \log 2 \times 10^6 + 3.5 \log(328(1 - \frac{1050}{S_u})) = 15.1 + 3.5 \log(1 - \frac{1050}{S_u}). \]  \hspace{1cm} (26)
The function of the ultimate tensile strength of the seven-wire strands under lateral bending is \( y = -14.03x + 1800 \). The S–N curve of the seven-wire strands under lateral bending can be obtained by Equations (25) and (26):

\[
\log N = 15.1 + 3.5 \log \left( \frac{1}{S_a} - \frac{1050}{S_a(-14.03\theta + 1800)} \right)
\]

(27)

where \( N \) is the number of loading cycles to failure for the seven-wire strands under lateral bending; \( S_a \) is the stress amplitude; \( S_m \) is the mean stress; and, \( \theta \) is the lateral bending angle of the seven-wire strands.

When a value is specified for stress amplitude \( S_a \), Equation (27) can be plotted to show the influence of lateral bending \( \theta \) on the number of loading cycles to failure for the seven-wire strands (N). Therefore, a suitable value 2 MPa is specified for stress amplitude \( S_a \) (according to [44,45], the modes of monitoring data for the stress amplitude of hangers of many arch bridges are close to 2 MPa). The value 2 MPa for stress amplitude \( S_a \) is only used to provide the necessary parameter for Equation (22) and it does not represent the actual stress amplitude.

Figure 20 shows the curve of the relationship between lateral bending \( \theta \) and the number of loading cycles to failure of the seven-wire strands (N). It can be seen that the fatigue properties of the seven-wire strands are gradually weakened when the lateral bending \( \theta \) is smaller than 20 mrad. However, the sliding speed becomes increasingly faster between 20 mrad and 40 mrad. After 40 mrad, the fatigue properties of the seven-wire strands dramatically decrease. When the lateral bending angle reaches about 50 mrad, the fatigue properties of the seven-wire strands drop by almost 40%. It is apparent that lateral bending can decrease the fatigue properties of the seven-wire strands significantly. Therefore, it is necessary to take lateral bending into account for the fatigue strength analysis of both end-fixed hangers that consist of seven-wire strands of HTABs and TABs with a floating deck structure.

![Curve of the relationship between θ and N](image)

**Figure 20.** The fatigue properties of the seven-wire strands versus the lateral bending angle.

5.3. *Advice to Mitigate the Adverse Influence of Lateral Bending on the Seven-Wire Strands in Hangers*

The strength of the seven-wire strands in the hangers can be checked by Equation (20), above, for the constructed HTABs and TABs with a floating deck structure. For HTABs and TABs that will be constructed in the future, it is necessary to take corresponding measures during design to decrease the adverse influence of lateral bending on the seven-wire strands in the hangers. The lateral bending that is caused by the different displacements at both ends of the hangers is the main bending form of hangers based on the conclusions in this paper. Therefore, the most desirable method is to eliminate the relative displacement between the arch ribs and bridge decks. Based on the above analysis, some measures could be taken to mitigate the adverse influence of lateral bending on hangers.

(1) The tied arch structure can be used for TABs to mitigate the adverse influence of lateral bending of hangers effectively when the tied arch structure meets the requirements of the topography. The bridge deck of the tie arch structure is straightly connected to the arch rib at both ends of
the arch rib; therefore, the arch rib can restrict the longitudinal deformation of the bridge deck. The extent of lateral bending could be significantly decreased in this way.

(2) Hinged connections could be used for short hangers that are closed to the abutment instead of fixed connections. The shorter length and larger longitudinal deformation of the lower end of the short hangers when compared with those of the long hangers makes lateral bending more apparent with short hanger. Therefore, when fixed connections are used in the hangers for HTABs and TABs with floating deck structures, fixed connections could be replaced by hinged connections for short hangers. This method might make the hangers require more devices for their connections and slightly increase the cost of constructing bridges.

(3) A jointless bridge structure should be used [46]. A jointless bridge does not have expansion joints, and the abutment is directly connected to the superstructure of the bridge, which could decrease the deformation of the bridge decks [47,48]. When compared with a tied arch structure, the abutments of jointless bridges would suffer lateral forces from the decks, which require a stronger design for lateral abutment loads. Therefore, this method is suitable when the bridges have good rigid foundations.

Tied arch structures can effectively mitigate lateral bending and may produce fewer side effects than the other two methods. From the result of the analysis, using tied arch structures is more strongly recommended than other methods.

6. Conclusions

(1) We conclude that end-fixed hangers consisting of parallel seven-wire strands of HTABs and TABs with a floating deck structure can produce significant bending deformation based on the investigations of types of hangers, boundary conditions, and arch bridge structures. The bending deformation of hangers can exert an adverse influence on the strength of the hangers.

(2) We propose that lateral bending causes the uneven loading of the parallel seven-wire strands in hangers based on the study of the mechanical model of hangers under lateral bending deformation. The seven-wire strand that is located at the outer edge of the hangers will bear the maximum bending stress and it can be regarded as under the most unfavorable loading conditions in all the parallel seven-wire strands. The properties of the seven-wire strands under the most unfavorable loading conditions and the maximum bending stress that they bear decide the safety of the hangers.

(3) FEM developed and verified the theoretical formulation for the lateral bending angle and maximum bending stress in hangers. According to the results of the calculations using the formulas and FEM, the bending of hangers is mainly caused by the different displacements along the longitudinal direction of the bridge at both ends of the hangers and the bending that is caused by the rotation of the bridge deck can be ignored. Moreover, FEM and tests obtained the ultimate tensile strength of the seven-wire strands under lateral bending. The S–N curve that could reflect the fatigue properties of seven-wire stands under lateral bending is also obtained based on the ultimate tensile strength of the seven-wire strands under lateral bending. It was found that the ultimate tensile strength and fatigue properties of the seven-wire strands significantly decrease when lateral bending is considered. Therefore, the adverse influence of lateral bending on hangers cannot be ignored, and a method for checking the strength of seven-wire strands in hangers considering lateral bending is proposed.

(4) Several measures are proposed for mitigating the adverse influence of lateral bending on hangers, such as using tied arch structures as much as possible, replacing fixed connections with hinged connections for short hangers, and using a jointless bridge structure. Synthetically speaking, using tied arch structures might produce fewer side effects is more strongly recommended than using other methods.
Author Contributions: N.D. designed the experiments and funded the paper. Y.Z. conducted the experiments, analyzed the data, and wrote the paper. T.Y. audited the content. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (grant no. 51868006), the scientific research foundation of Guangxi university (XTZ150324); the key R & D project of Guangxi Science and Technology Program (grant no. AB17292018); the cultivation program jointly funded by Guangxi natural science foundation of China (2018GXNSFAA138067); and the High-level innovation team and outstanding scholar plan of Guangxi high colleges.

Conflicts of Interest: The authors declare no conflict of interest.

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