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Characteristics Comparison and Case Study of Traditional Anti-Slip Saddles and Innovative Rolling Saddles in Highway Long-Span Bridges

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Abstract: The cable saddle structure is the main support component for long-span bridges to transmit cable force, which is of great significance for the structural force system. Nowadays, the main cable saddle structures used in long-span bridges are mainly traditional anti-slip saddles and innovative rolling saddles. To clarify the characteristics of the saddles in long-span bridges, the design principles, mechanical properties, and casting process of these two types of saddle structures were researched. A rolling saddle in a bridge project was taken as an example and its mechanical situation in the roller area was investigated. The results showed that the stress concentration phenomenon is prone to occurring in the rolling saddle because of the line contact in the contact area and the rolling saddle is mainly subjected to vertical force. Thus, attention should be paid to the von Mises stress in the contact area between the saddle base and the roller shaft, the lower surfaces of both ends of the roller shaft, and the top surface of the tower, to avoid material damage. Furthermore, the casting process of the anti-slip saddle structure is mature, but also faced with problems due to the welding of thick plates, and urgently needs to be improved and upgraded. The rolling saddle is used with the all-welded casting process, but its technology is relatively immature and the requirements for the roller shaft material performance are strict. The research results can provide a reference for the selection and design of the saddle structure in long-span bridges.

Keywords: anti-skid saddle; rolling saddle; structural design; mechanical properties; fabrication technology

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Citation: Wan, J.; Liu, G.; Qian, Z. Characteristics Comparison and Case Study of Traditional Anti-Slip Saddles and Innovative Rolling Saddles in Highway Long-Span Bridges. *Appl. Sci.* **2024**, *14*, 5290. https://doi.org/10.3390/app14125290

Academic Editor: Kang Su Kim

Received: 23 May 2024
Revised: 12 June 2024
Accepted: 14 June 2024
Published: 19 June 2024

1. Introduction

Large-span bridges have been widely adopted because of their great crossing ability [1–3]. The saddle structure is an important part of a large-span suspension bridge as it helps to realize the large span and crossing function [4,5]. It is used as the main support component for the suspension cable or diagonal cable to pass through the top of the tower and transfer the cable force. It plays an important role in reasonably reducing the maximum bending moment at the bottom of the tower, effectively adjusting the load-carrying capacity of the tower and the scale of the foundation, as well as equalizing the cable force of the main cable [6]. At present, the main saddle structure used in large-span bridges can be divided into an anti-slip saddle and a rolling saddle. The anti-slip saddle is generally set up as an anti-slip device in the saddle balance system, to avoid the slip phenomenon in a suspension cable or cable-stayed cable during the bridge operation process [7]. The rolling saddle is optimized and designed based on the anti-slip saddle structure. A row of rollers is set below the saddle base, which changes the original form of friction from sliding friction to rolling friction, and leads to the automatic equalization of the cable system [8].

To date, many researchers have carried out several in-depth studies and research on the anti-slip function of the cable saddle [9–12]. Ye et al. [13] proposed a combination of horizontal and vertical friction plates in the saddle groove and investigated the anti-slip problem between the saddle and the main cable in the main tower saddle of the Wenzhou Oujiang Beikou Bridge in China. Chang et al. [14] set polytetrafluoroethylene (PTFE) slip plates on the lower part of the tower saddle body on both sides of the Jinan Phoenix Yellow River Bridge and the top fixed joint of the cable tower to reduce the top thrust friction resistance. They were also lubricated to adapt to the relative positional difference generated in the construction process. In the test study of the friction coefficient between the main cable and the cable saddle, the field bridge test values of the friction coefficient of the George Washington and Forth Road bridges in America are 0.3 [15]. The test result of the Delaware River bridge is between 0.19 and 0.21. The test value of the Kanmon bridge in Japan is between 0.15 and 0.21. The test value of the Honshu–Shikoku bridge is between 0.16 and 0.44 [16]. Researchers at Southwest Jiaotong University tested the friction coefficients between different numbers of strand bundles and test saddles through model tests, and the friction coefficients of ordinary saddles and those setting vertical friction plates were found to be 0.473 and 0.552, respectively [17].

For research into a new rolling saddle, Teng et al. [18] analyzed its internal force in Wanxin Bridge, and the results showed that the wall thickness of the saddle should not be too large, and especially the radius of the inner tangent circle of the saddle groove part should not be too large. In the outdoor test simulation of the main bridge of the Jinshajiang River Bridge over Tiger Leaping Valley, it is confirmed that in the case of unbalanced cable force, the saddle can be rolled using the roller shaft to achieve the adjustment of the two ends of the cable force [19]. The cable force system tends to be balanced through the bias load test of the saddle structure. To ensure the anti-slip safety of the main cable in the main saddle of a long-span suspension bridge, contact and slip behaviors of the main cable of a long-span suspension bridge were investigated [20].

From the above research, it can be seen that there are differences between the slip-resistant saddle structure and rolling saddle structure in many aspects, which has an important impact on the structural force system and service performance of large-span bridges. In order to clarify the characteristics of different saddle structures for long-span bridges, this paper analyzes the anti-slip saddle from the three aspects of design principles, mechanical characteristics, and the casting process, so as to provide references for the selection and design of saddle structures for highway long-span bridges.

2. Design Principles

2.1. Anti-Slip Saddle

Taking a large-span main bridge anti-slip cable saddle as an example, the saddle adopts a cast-welded structure, the center tower saddle is directly connected to the top of the tower, and the PTFE anti-slip plate is set under the tower saddle body, as shown in Figure 1.

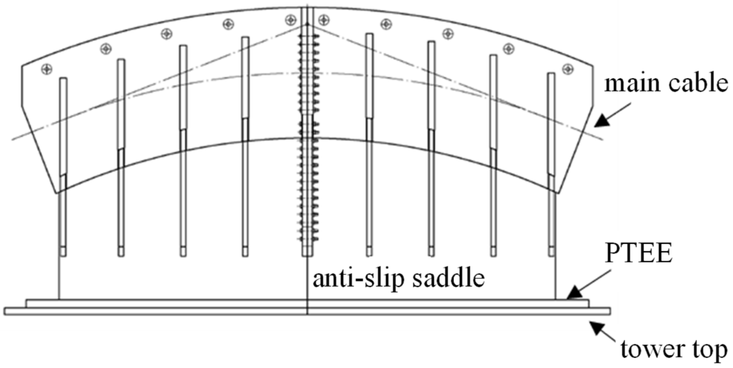

Figure 1. Structural design sketch of an anti-slip saddle in the center tower of a bridge.

For the anti-slip device in the anti-slip saddle, three technical solutions are proposed in the design of this bridge. Among them, the radial direction of the horizontal friction plate can freely transfer the pressure and constrain it along the bridge. The shear pin transfers the friction between the main cable strand and the friction plate directly to the side wall of the saddle groove, while the force between the lower part of the saddle groove and the side wall is the same as that of the ordinary cable saddle. The lateral friction force of the strand can also be used to improve the anti-slip characteristics of the saddle by replacing the ordinary spacer of the saddle with a vertical friction plate. As the height of the strand increases, the friction created by the lateral pressure on the sidewalls of the saddle groove rises gradually, which can be used to minimize the slipping phenomenon of the strand. In the above two cases, the horizontal friction plate can easily cause the strand to generate a stratified slip phenomenon. Thus, the vertical friction plate can be added on the basis of the original horizontal friction plate. The space for setting up the friction plate can be obtained by varying the vertical and lateral positions of the strand, so as to improve the anti-slip performance of the saddle.

2.2. Rolling Saddle

Examples of the application of rolling saddles in China are mainly found in the Dongming Yellow River Bridge Rehabilitation Project. As the core technology of the new steel wire cable suspension system in this project, the architectural design of the rolling saddle must comply with the following conditions: (1) Safe and reliable overall structural design; (2) The rollers of the saddle must have good mechanical properties, including smaller friction and larger surface hardness.

A rolling saddle is mainly composed of a saddle cover, the saddle body, a roller shaft assembly, a saddle bottom plate, a cable, and other basic structures, as shown in Figure 2. Its sliding part is composed of the lower and upper planes of the saddle body, a sliding plate, and the roller shaft assembly. The axial pressure of the cable is transmitted to the base of the saddle through the base plate of the saddle, which mainly consists of the base plate, limit plate, and a block at both ends. The limit plate and block are used to control the sliding of the rolling saddle in the direction of the bridge and realize the automatic equalization of the cable force. However, because of the installation of roller components, rolling failure and other problems are prone to occur, resulting in the insufficient stability of structural performance.

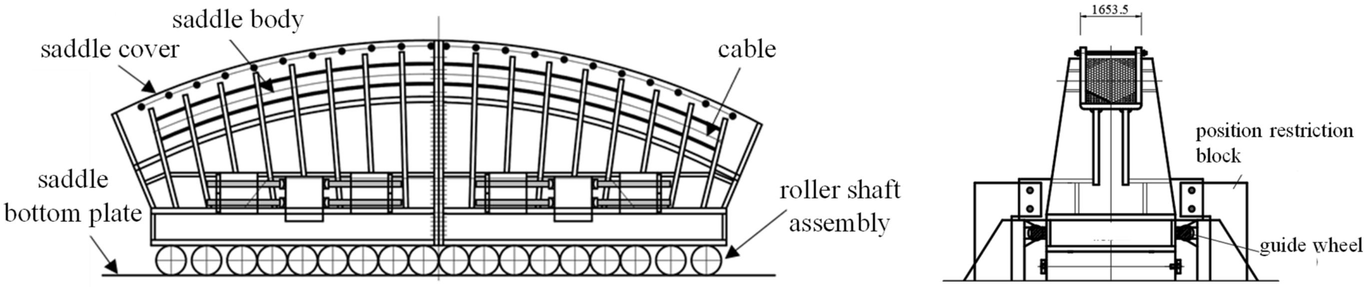

Figure 2. Structural design of a rolling saddle in the center tower of a bridge.

3. Mechanical Characteristics

3.1. Anti-Slip Saddle

The cable saddle transmits the cable force at the tower. Due to the curved shape, the saddle is subjected to contact stresses from the cable and transmitted to the tower. The inside of the saddle groove is also subjected to friction in contact with the cable, as shown in Figure 3. Gradually, the unbalanced horizontal force at the top of the tower increases, material loss and structural wear inside the saddle occurs, and the tie rope slips. The cable saddle is not rigidly connected to the cable tower, but is lubricated by a PTFE slip sheet to accommodate the slip phenomenon. A face contact is formed between the saddle and the top of the towers, and there is no significant stress concentration in the contact zone.

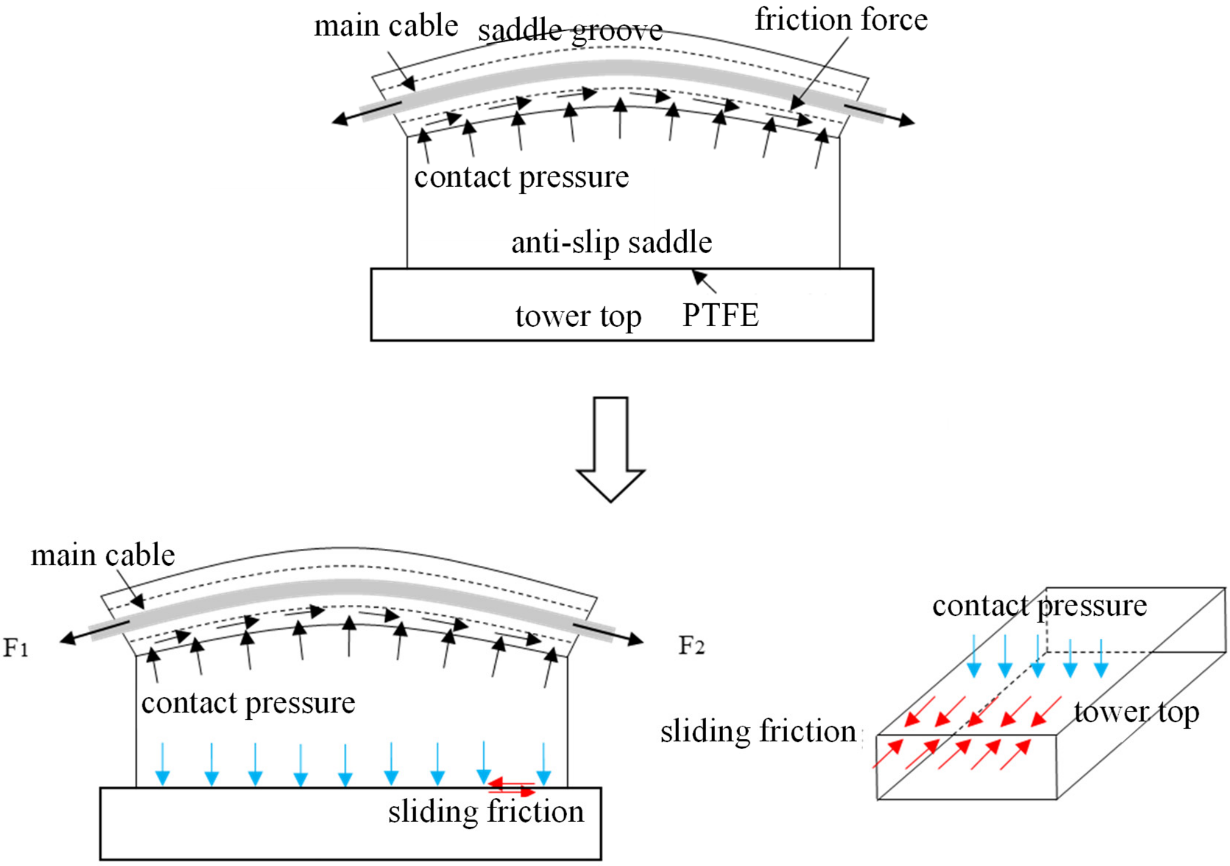

Figure 3. Schematic diagram of main cable axial force transfer in an anti-slip saddle.

3.2. Rolling Saddle

Unlike an anti-slip saddle, a rolling saddle is in contact with the top of the towers through roller shafts, as shown in Figure 4. The contact pressure between the saddle and the main cable is transferred to the bottom of the saddle and to the top of the tower via the roller shaft. The friction between the roller shaft and the bottom of the saddle and the top of the tower is rolling friction. Thus, the saddle only provides vertical forces, and the adverse effects due to the rise and fall in the overall temperature can be eliminated by lateral rolling. The roller shaft and the upper and lower plates form a line contact, and there is a significant stress concentration in the contact area, which results in a relatively large structural deformation and material yielding.

It can be seen that with the increase of the unbalanced force of the cable saddle, especially in high-tower suspension bridges, the bending moment in the tower body and bottom will consequently increase, which would further jeopardize the safety of the bridge. The rolling saddle, as a self-balancing system, adopts a smaller friction coefficient of the multi-row rollers and changes the original sliding friction into rolling friction. Thus, the self-balancing in the two sides of the main cable horizontal force and saddle rolling friction force can be achieved even under the temperature, vehicle load, and other common load. It can prolong the service life of the saddle and maintain the stability of the cable-stayed tower. However, the stresses in the upper and lower contact areas of the roller shaft are more concentrated, which makes it prone to problems such as roller shaft failure and reduces the stability of the self-balancing system structure.

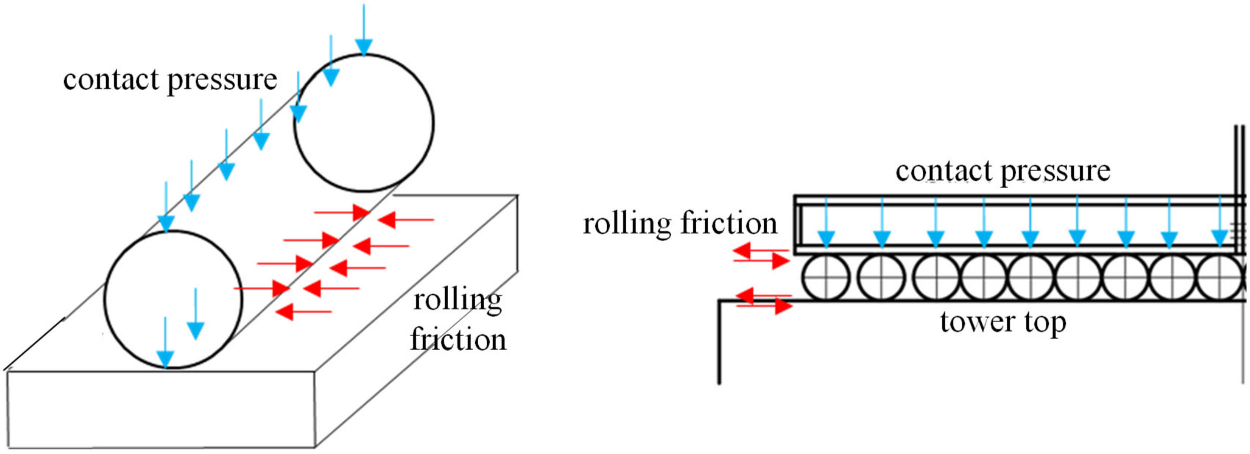

Figure 4. Schematic diagram of contact force on a roller shaft.

4. Casting Process

4.1. Anti-Slip Saddle

A saddle is characterized by its complex structure, large volume, and heavy weight. The most common types can be divided into cast and welded, all-cast, all-welded and combined saddles [21–23]. A large saddle often utilizes a cast and welded structure design. It fully absorbs the advantages of all-cast and all-welded saddles. It has many engineering examples and its process is relatively mature. As a large structural device, the upper part of a cast and welded saddle often uses steel casting. The lower part often uses a number of thick welding steel plates. The number of welds is larger, which also causes welding difficulties in the main saddle. The main difficulties are as follows: (1) the saddle head and seat steel plate after welding is prone to producing cold cracks; (2) small casting spacing is prone to welding operation difficulties; (3) thick plate welding causes increases structural rigidity and the stress concentration phenomenon, and laminar tearing is more likely after welding.

4.2. Rolling Saddle

Taking the Zhanggao River Crossing South Channel Bridge as an example, its bridge cable force and the number of rope strands are large. The larger lattice and cavity size of the saddle body provide a convenient welding condition. The mechanical and physical properties of the castings are excellent, but some problems occur after molding, such as loose organization, coarse crystals, and internal porosity. A thick casting plate leads to larger molding quality and weakened mechanical properties. Therefore, from the point of view of engineering quantity, construction, and structural performance, an all-welded cable saddle design is adopted in the Zhanggao River Crossing South Channel Bridge.

Since there is a line contact between the roller shafts and upper and lower plates, it is prone to causing stress concentration in the contact area. Thus, the contact material should be equipped with a significant ability to withstand large contact stress. In the structure design of the rolling cable saddle of the Dongming Yellow River Bridge in China, the overall casting of the saddle body adopts ZG270-480H carbon steel. The bottom surface is inlaid with a 40Cr alloy structural steel sliding plate. The measurement of tempering treatment combined with surface high-frequency quenching is adopted to improve its mechanical properties.

It can be seen that the roller shaft is in line contact with the saddle bottom surface and tower top surface. Stress concentration is generated in the contact area, which requires high pressure-bearing properties of the roller shaft material. A thick and large cast plate leads to larger molding quality and weak mechanical properties. Thus, the rolling saddle uses the all-welded saddle design, but faces process difficulties due to immature technology.

5. Case Study

Taking the rolling saddle of the Zhanggao River Crossing South Channel Bridge as an example, its mechanical situation in the roller area was investigated. Its different components are constructed, including a cable trough, saddle ribs, saddle base and rollers, as displayed in Figure 5. The length and diameter of the roller are 3500 mm and 800 mm, respectively. The length, width, and thickness are 18,000 mm, 4600 mm, and 1000 mm, respectively. The width of the saddle rib is 120 mm. In this paper, the computational analysis of the part of the saddle, the roller and the top surface of the tower was carried out. The middle longitudinal ribs were symmetrically restrained, and the upper and lower surfaces of the roller were in linear contact with the bottom surface of the saddle and the top surface of the tower, respectively. Under vertical pressure, fixed constraints in all directions were set between the saddle and the grill, fixed constraints in the transverse and longitudinal directions were set on both sides of the upper part of the saddle, transverse fixed constraints were set on the base of the saddle and the rollers, and full fixed constraints were set on the top surface part of the cable tower.

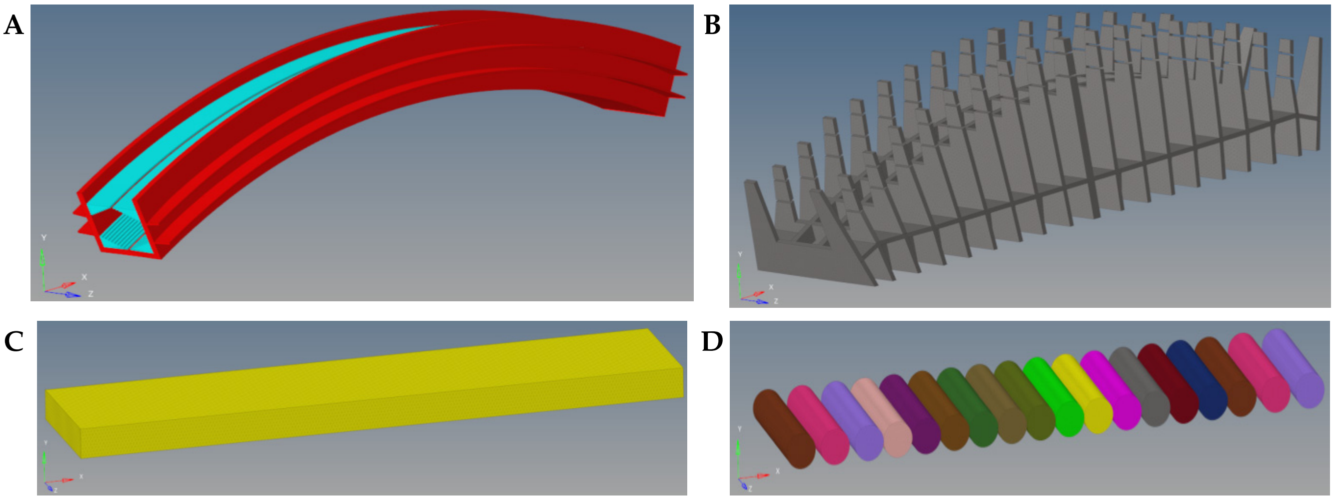

Figure 5. Different components of the typical rolling saddle: (**A**) cable trough; (**B**) saddle ribs; (**C**) saddle base; (**D**) rollers.

The loading method chosen was the direct face force method. The rib plates are L_1, L_2, . . ., L_9, L_{10} from the left, where L_{10} is the center rib plate, and the rib plates are loaded symmetrically. Table 1 shows the centripetal pressure of each column of cable strands.

Table 1. Centripetal pressure of each column of cable strands.

Rib Plate	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}
Centripetal pressure (MPa)	23.67	26.35	29.04	31.74	34.45	37.17	39.90	42.64	45.40	48.16

The whole model rolling saddle and cable tower is established and its Mises stress is calculated, as shown in Figure 6. Because the stress situation around the rollers is the main focus, the Mises stress in both sides of the rollers are further investigated. Its distribution is exhibited in Figure 7. The stress of each roller along the transverse direction is extracted, as shown in Figures 8 and 9.

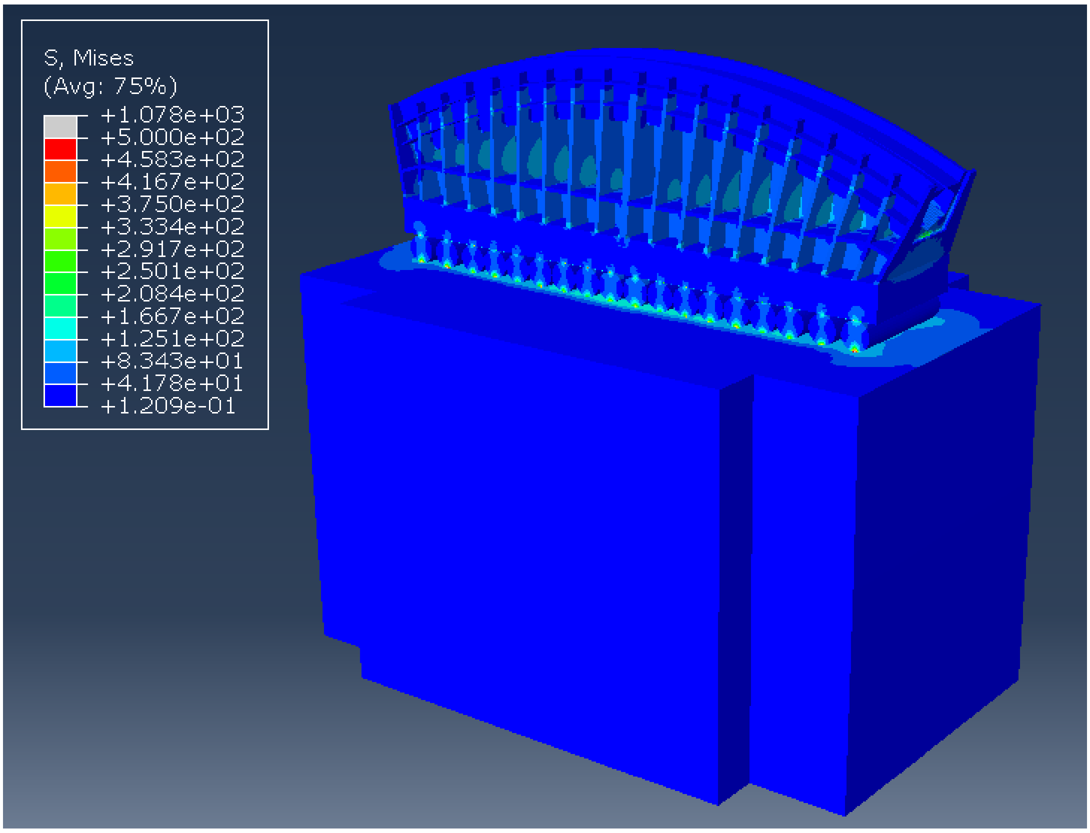

Figure 6. Whole model rolling saddle and cable tower and its von Mises stress distribution.

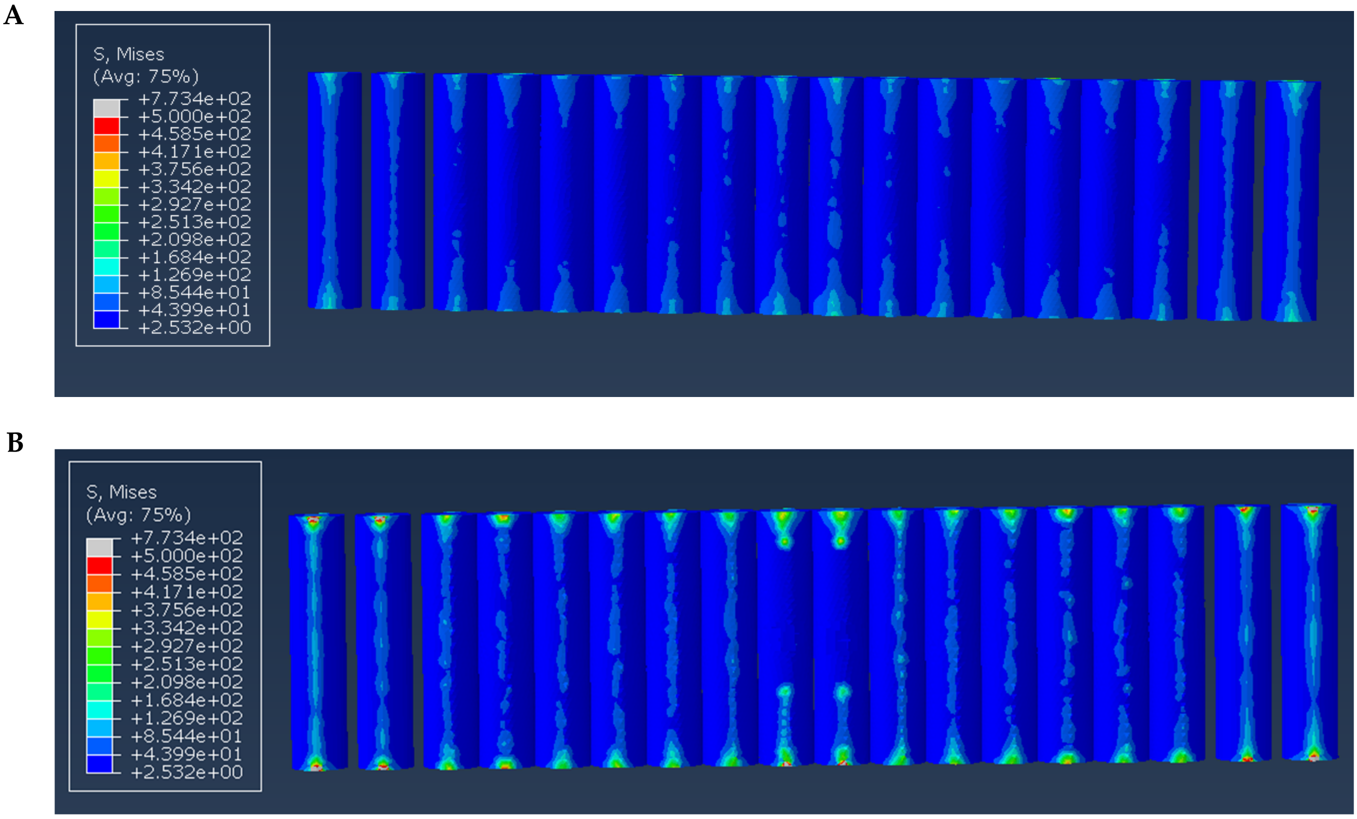

Figure 7. Mises stress in the surface of the rollers: (**A**) upper surface; (**B**) lower surface.

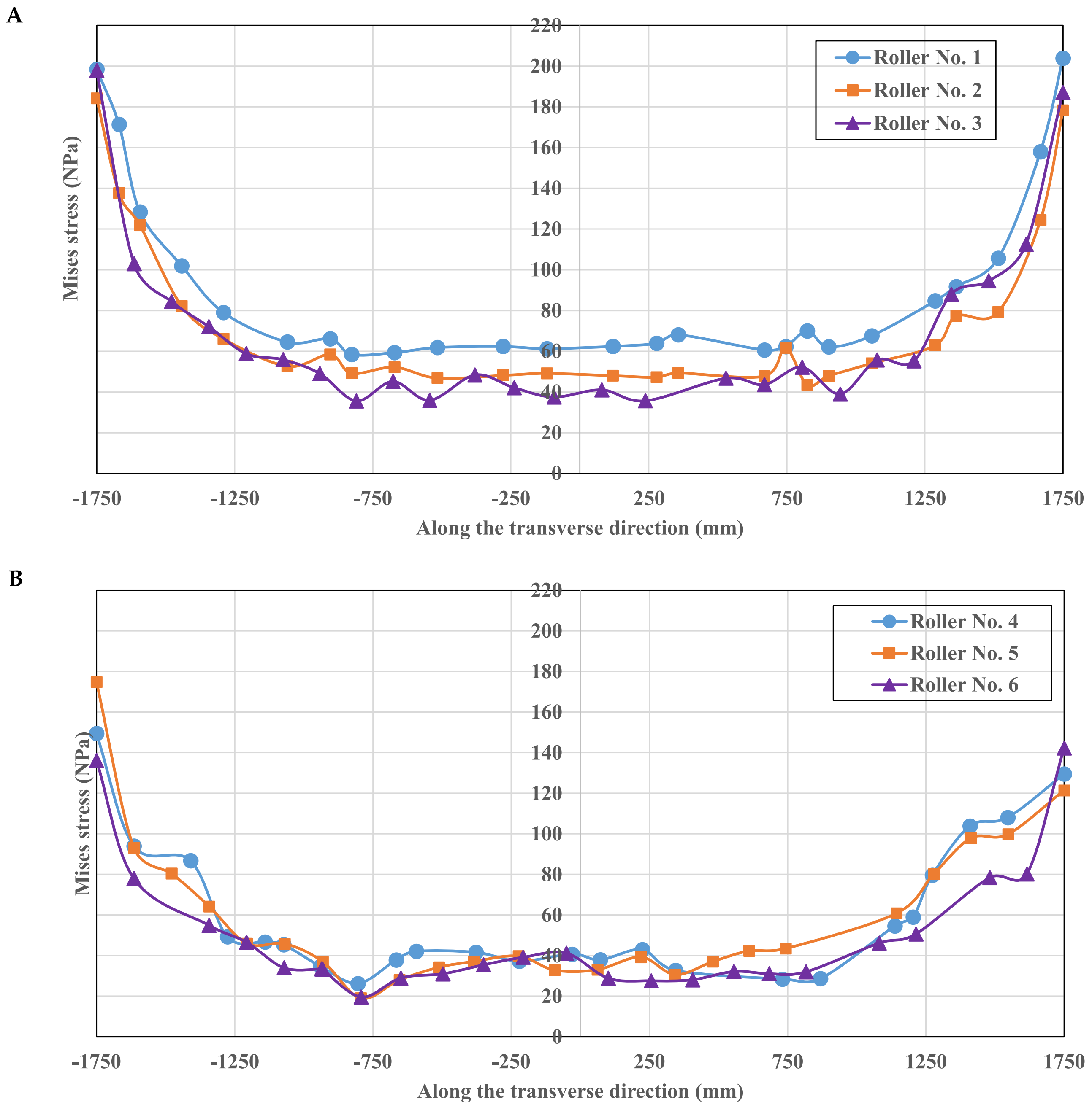

Figure 8. *Cont.*

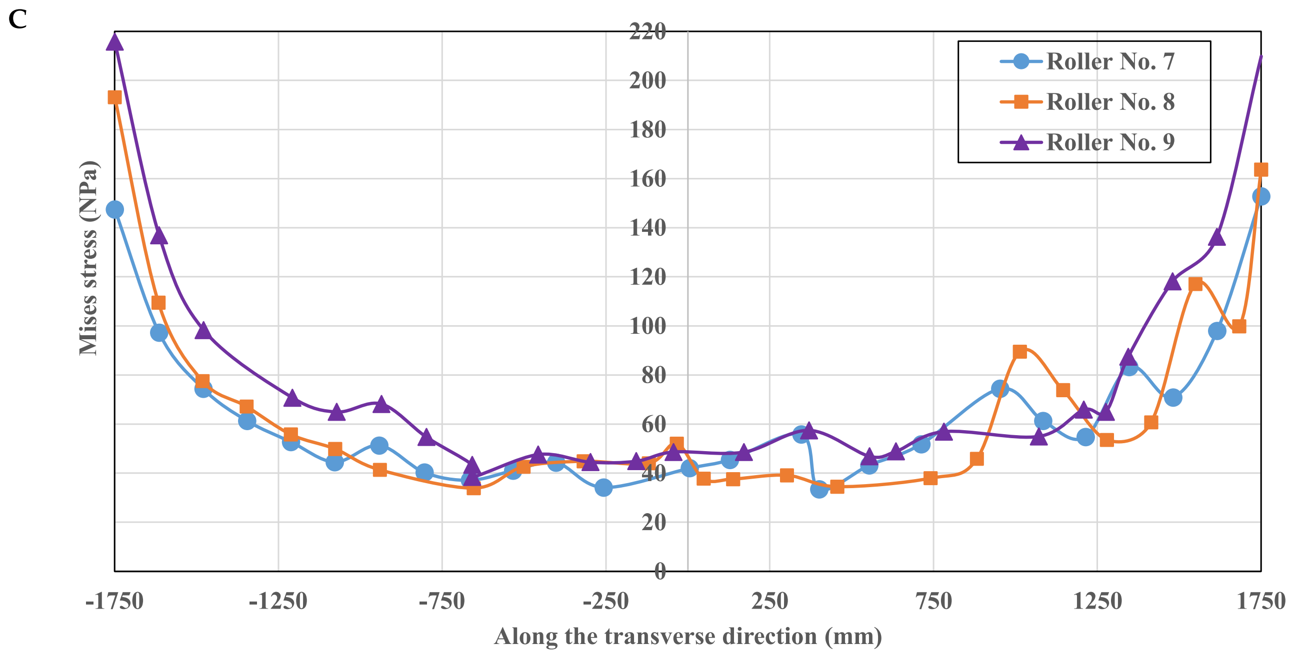

Figure 8. Mises stress distribution in the upper surface of the rollers: (**A**) Roller 1~3; (**B**) Roller 4~6; (**C**) Roller 7~9.

It can be seen that the maximum von Mises stress mainly occurs in the contact area of the base of the rope saddle and the roller shaft, which is 1078 MPa. The maximum von Mises stress in the upper structure of the rope saddle is 232 MPa, which occurs at the bottom of the saddle groove. For the Q345 steel, yield damage does not generally occur. The maximum von Mises stress of the roller shaft is 773 MPa, which appears at the ends of the lower surface of the roller shaft. The maximum von Mises stress on the top surface of the tower is 885 MPa, which occurs at both ends of the contact area with the roller shaft. Attention should be paid to the Von Mises stress in the contact area between the saddle base and the roller shaft, the lower surfaces of both ends of the roller shaft, and the top surface of the tower, to avoid material damage.

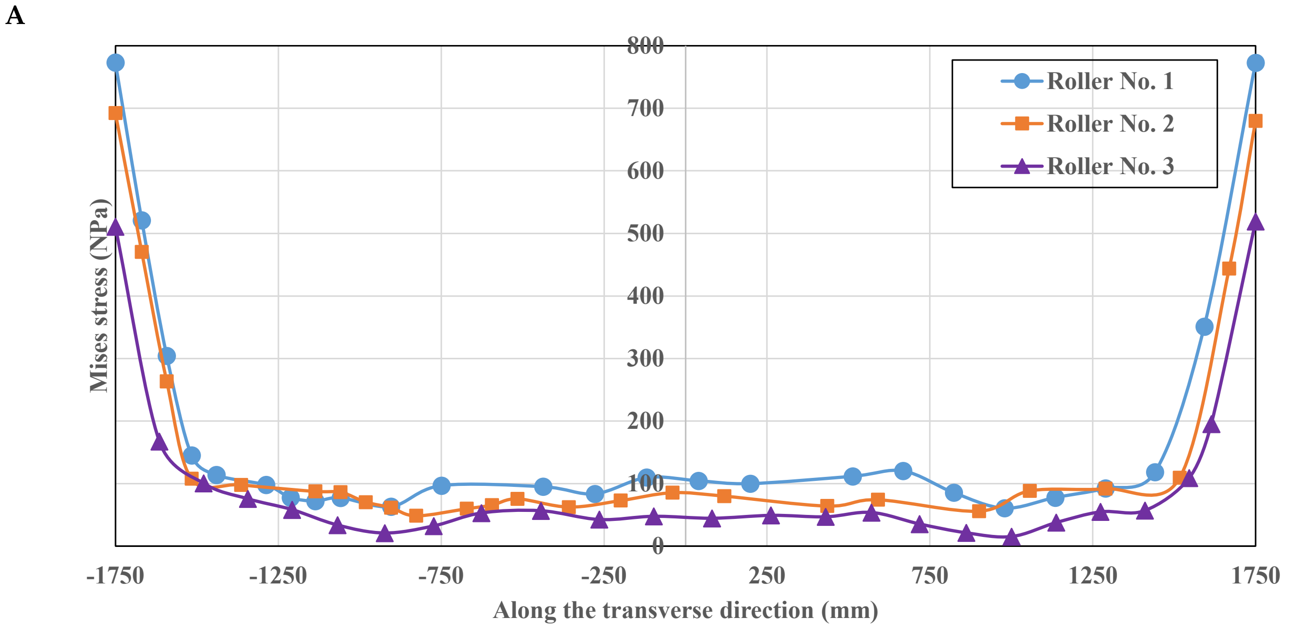

Figure 9. *Cont.*

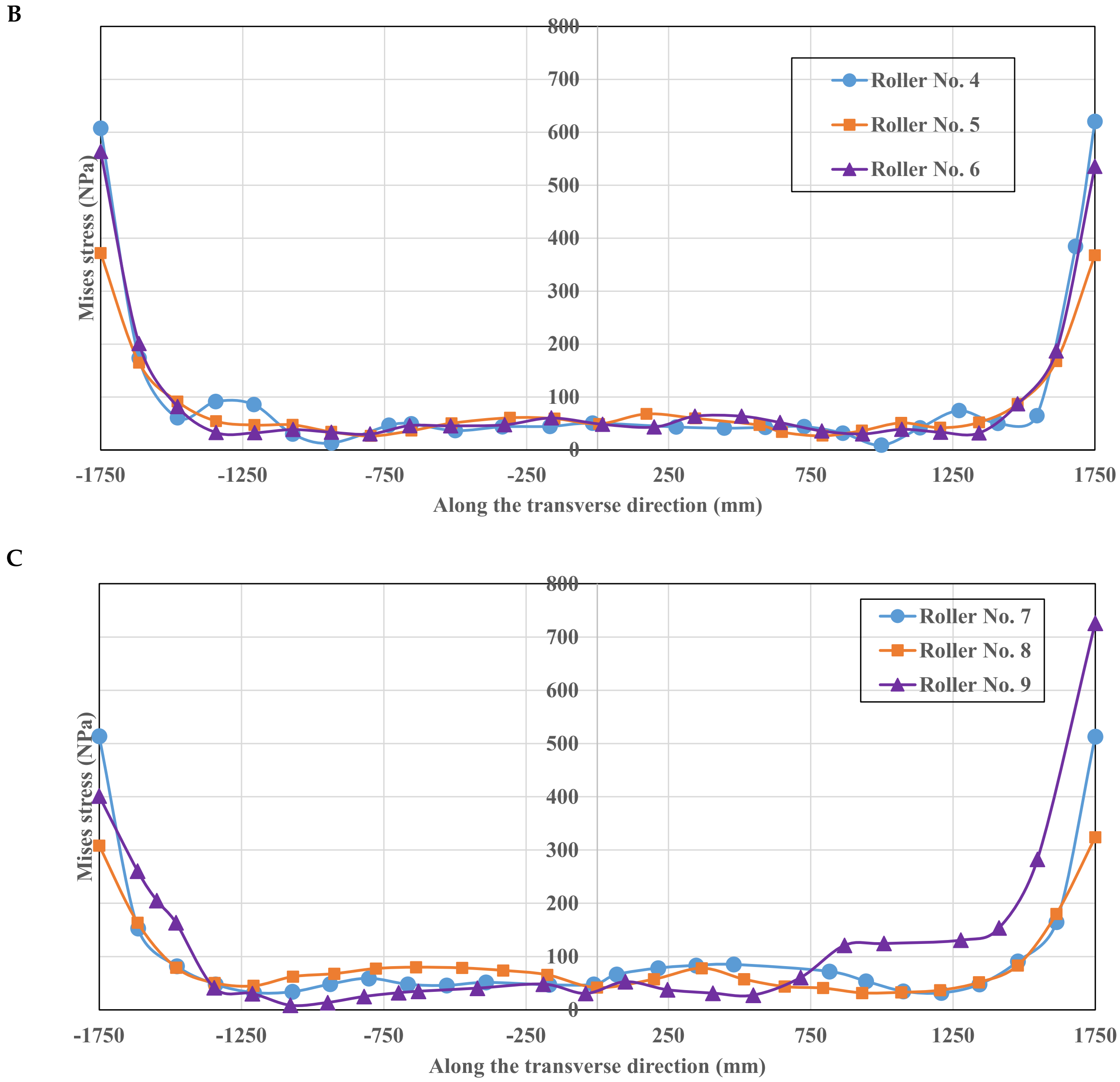

Figure 9. Von Mises stress distribution in the lower surface of the rollers: (**A**) Roller 1~3; (**B**) Roller 4~6; (**C**) Roller 7~9.

6. Characteristics Comparison

Through the above analysis of the anti-slip saddle and rolling saddle in the three aspects of structural design, mechanical characteristics, and the casting process, a comparison of their characteristics is summarized in Table 2.

Table 2. Comparison between an anti-slip saddle and a rolling saddle.

Content		Anti-Slip Saddle	Rolling Saddle
Structural design	Base design	PTFE, bonded connection	Roller contact
	Anti-skid measures	Horizontal and vertical friction plate	Self-equilibrating system

Table 2. *Cont.*

Content		Anti-Slip Saddle	Rolling Saddle
Mechanical characteristics	Contact type	Face contact	Line contact
	Friction type	Sliding friction	Rolling friction
	Stress condition	Welding stress, unbalanced force	Higher vertical forces, stress concentrations
Casting process	Structural fabrication	Cast-welded, mature process	All-welded, complex process
Used materials	Material Selection	Thick steel plates with high welding performance	Highly pressure-bearing contact surface materials

7. Conclusions

In this paper, the anti-slip saddle structure and rolling saddle structure in large-span bridges are studied in three aspects, including design principles, mechanical properties, and the casting process. The main conclusions are as follows:

(1) Based on the analysis of design principles and mechanical characteristics, it can be concluded that the anti-slip saddle increases the unbalanced horizontal force in the tower top, leading to saddle material loss and structural wear. The slip phenomenon is prone to occurring in the cable. The original sliding friction is changed into rolling friction. The two sides of the main cable horizontal force and the saddle rolling friction force are designed to be self-balancing, but the stability of the structural performance is insufficient.

(2) A rolling saddle in a bridge project was taken as an example and its mechanical situation in the roller area was investigated. The maximum von Mises stress mainly occurs in the contact area of the base of the rope saddle and the roller shaft. The maximum von Mises stress in the upper structure of the rope saddle occurs at the bottom of the saddle groove and that of the roller shaft appears at the ends of the lower surface of the roller shaft.

(3) The stress concentration phenomenon is prone to occurring in the rolling saddle because of the line contact in the contact area, and the rolling saddle is mainly subjected to vertical force, which is also consistent with the analysis of general mechanical characteristics. Thus, attention should be paid to the von Mises stress in the contact area between the saddle base and the roller shaft, the lower surfaces of both ends of the roller shaft, and the top surface of the tower, to avoid material damage.

(4) Combined with the analysis of stress distribution and the saddle casting process, it is obvious that the casting process of the anti-slip saddle structure is mature, but also faced with problems due to the welding of thick plates, and urgently needs to be improved and upgraded. The rolling saddle is used with the all-welded casting process but its technology is relatively immature and the requirements for the roller shaft material performance are strict.

Author Contributions: Conceptualization, J.W. and G.L.; methodology, J.W. and G.L.; validation, J.W. and G.L.; formal analysis, J.W. and G.L.; investigation, J.W. and G.L.; resources, Z.Q.; data curation, J.W. and G.L.; writing—original draft preparation, J.W. and G.L.; writing—review and editing, J.W. and G.L.; supervision, Z.Q.; project administration, Z.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Jun Wan was employed by the China Energy Engineering Group Zhejiang Electric Power Design Institute Company Limited. The remaining author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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