Scientific Research

Analysis of Local Compressive Behaviour of Concrete Mount Under Cambered Cast Iron Cable Saddle

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Abstract: The cable saddle on top of pylon not only helps the main cable pass through the summit of design form, but also transmits the enormous force to the pylon. An imbedded cast iron cable saddle is going to be adopted for a single pylon and two span cable stayed bridge. A cast in situ concrete foundation, which is called a concrete mount in this context, bears the imbedded cable saddle underneath. Due to the cambered shape of the bottom face of this imbedded cable saddle, the local compressive stress distribution on the contact part with the concrete mount may not be uniform. The finite element method is used to investigate the feature of the local compressive behaviour for the concrete mount. According to the results, the reduction factor for nonuniform local compression is approximately 0.73. This cable saddle structure could meet the local compression bearing capacity via theoretical verification, and indirect reinforcement under local compressive pressure is recommended to keep the structure in good condition for the serviceability limit state.

Keywords: local compressive behaviour; embedded cast iron cable saddle; non-uniform local compression; finite element method

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1. Introduction

The main cable saddle is a specific structural member installed on top of pylons for suspension bridges. It not only helps the main cable pass through the peak of the design cable form but also transmits the enormous vertical force to the pylons. In order to reduce the bending stress of the main cable curved on the cable saddle, the radius of the groove cast in the cable saddle is usually in the range from 8 to 12 times the main cable's diameter. Moreover, the cable saddle structure should guarantee that bundles of wires are fixed in it, where there is enough friction between the main cable and cable saddle.

For suspension bridges with two or more pylons, the cable saddles are usually offset to the side span a certain distance before the girder segments are lifted. This approach has advantage of cutting down the bending moment at the root of pylons, which is generated by the unbalanced cable forces on both sides of the cable saddles during construction. Then, the cable saddles will be propelled step by step toward the main span direction in accordance with the girder segments lifted and installed. These cable saddles eventually arrive at the center of the top section of pylons just when the girders are totally installed in right place under the main cable. In this research, the background involves a single pylon suspension bridge that is a symmetric hybrid of suspension and cable stayed structure. However, compared with the common suspension bridges just mentioned, the bending moment in pylon is not influenced by the unbalanced forces of the main cable; thus, the cable saddle no longer needs to be offset.

With respect to saving material and keeping the structure simple, an imbedded cast iron cable saddle is proposed in this paper. Compared with the common cable saddle structure, the amount of material for the alternative can be reduced by approximately 40%. It should be noted that the imbedded cable saddle is not an original innovation this time, and the Hardanger Bridge in Norway has adopted a similar approach to address the structural connection. It is apparent that the vertical force from the main cable on the cable saddle is transmitted to the top of the pylon via the imbedded cable saddle. Thus, the concrete surface at the bottom of the imbedded cable saddle is subjected to huge local compression. In terms of the local compressive pressure of concrete members, there have been a number of studies focusing on this aspect. Venckevicius proposed a method algorithm that was derived from numerous experimental data. According to this research, the local compressive strength was influenced by the material strength, relative member height and magnitude of the local pressure [1]. Wang et al. adopted a solid finite element model taking into account nonlinear material to simulate a concrete square column loaded at the center of the section. The local compression area ratio had an effect on the longitudinal stress of the specimen, and a strut-and-tie model proposed by the researchers was in line with the stress distribution in the specimen [2-3]. Miao and Zheng conducted an experimental study on 30 concrete pull-out specimens to evaluate the effect of bond stress on the local bearing capacity. There was an increase in the local bearing capacity of the concrete corresponding with an increase in the concrete strength and the load area [4]. Chen carried out a series of local compression experiments on 27 specimens strengthened by double-layer ring steel bars. There were three kinds of typical failure modes occurred. The local bearing capacity of the specimens improved significantly with decreasing height [5]. Cai investigated the local compressive behaviour of three concrete column joint zone specimens. The results showed obvious differences among specimens of various heights [6]. The bearing capacity of the specimen decreased with increasing height, and this result is consistent with a previous study. Xiao discussed the feasibility of double layer ring reinforcement for a pile cap subjected to local load, which was verified by a series of finite element models that had better tensile performance and higher local bearing capacity [7]. In addition, there are theoretical methods for the design process in different national specifications to verify the bearing capacity of local compression [8-10].

However, due to the specific arched shape of the cable saddle structure, the contact part between the cable saddle and concrete mount is fairly cambered. Therefore, the local compressive pressure on the concrete mount may not be uniform. This issue has received relatively less attention from researchers. This issue will be investigated in this paper to ensure that the imbedded cable saddle is able to work reasonably. Firstly, the mechanical analysis model for the action between the cable saddle and concrete mount is simplified as a plain strain problem, and the nonlinear contact state between the cast iron and concrete is also taken into account in the 2D plain strain finite element model. The stress distribution of the concrete mount is studied with different sections of the cable saddle. Secondly, the nonuniform local pressure on the curved surface is studied by a solid finite element, and then the factor for nonuniform local compression is proposed. The maximum design distribution area Ac1 proposed by Chinese research is used to verify the local bearing capacity safety. Finally, the contribution of the indirect reinforcement in the concrete mount under the cable saddle is discussed.

2. Background of the project

The imbedded cable saddle will be adopted by a hybrid suspension and cable-stayed bridge. The span of this bridge is 638+638 m, which has a single pylon (Figure 1). There are 20 pairs of steel cables and 23 pairs of hangers to support the main girder. It has been mentioned that the cable saddle on the top of the pylon does not need to be propelled for bending moment control in the pylon, so the imbedded cable saddle is designed and proposed for this project.

The structural appearance of the imbedded cable saddle recommended in this project is shown in Figure 2, which is 8 m long and made of cast iron ZG270-500 based upon the Chinese specifications [10], of which the yield strength is 200 MPa.

The cast in situ concrete mount bears the imbedded cable saddle underneath, as illustrated in Figure 3. The height of the cable saddle's section is 978 mm, and its bottom edge is 1400 mm wide. The imbedded cable saddle goes into the trapezoidal concrete mount at a depth of 778 mm. There is a small angle of 1.2° tilted between the symmetric axis of the cable saddle and the center line at the concrete mount bottom side. The concrete C55 is used to cast the concrete mount, of which the design axial compressive strength is 24.4 MPa and the elastic modulus is 3.55×104MPa [11].

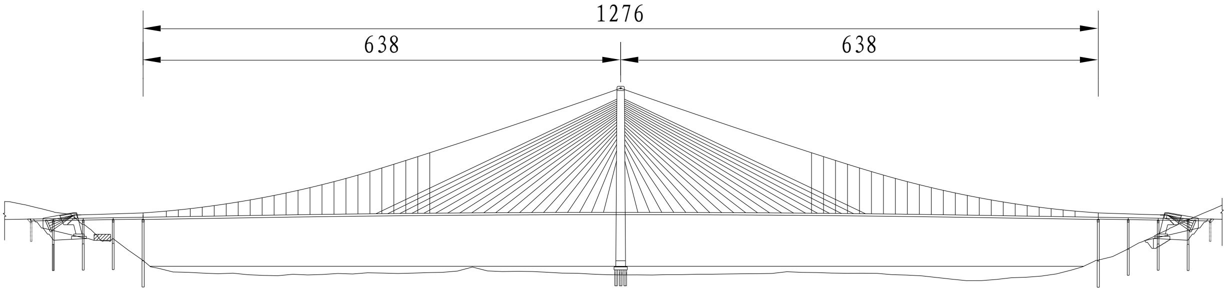

Figure 1. The elevation of the hybrid suspension and cable-stayed bridge

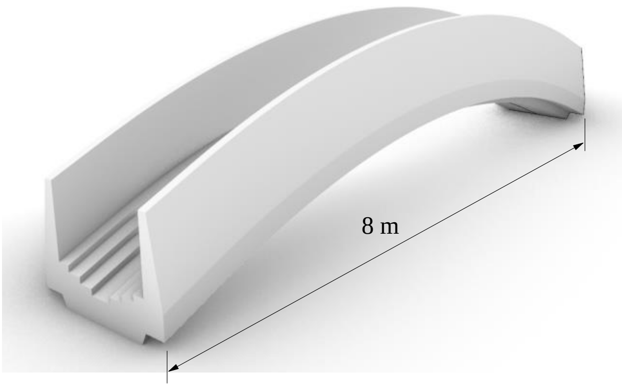

Figure 2. The imbedded cable saddle

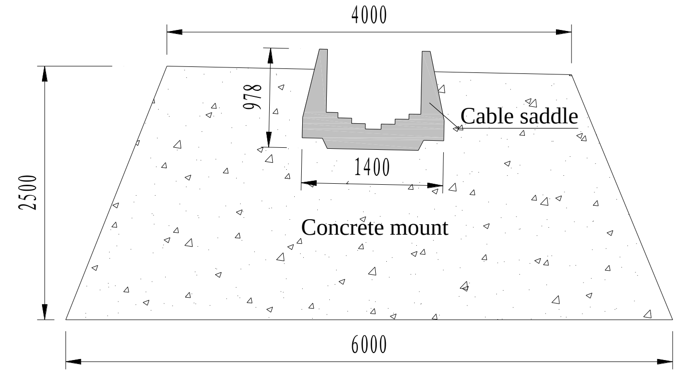

Figure 3. The recommended section of the imbedded cable saddle in the concrete mount

3. Influence of cable saddle structure forms on stress distribution in concrete mount

In order to study the influence of cable saddle shapes on the concrete mount, a series of sections for the cable saddle were used to investigate the stress distribution in the concrete mount, as shown in Figure 4. Actually, section A is the one adopted by the Hardanger Bridge. This cable saddle section has a couple of steps at the bottom. This step-like shape may increase the friction area with the concrete, but it is found that it is easy to cause stress concentration at the edge and right angle area of the cable saddle, which is prone to crack in the concrete, so the step-like shape is avoided in the recommended section.

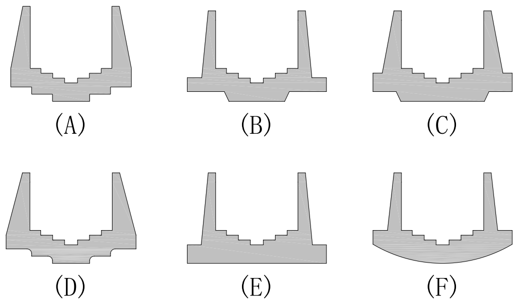

Figure 4. The silhouettes of the optional imbedded cable saddle sections

With respect to a number of parameter analyses in case studies, a clear and efficient approach must be selected. Assuming that the deformation along the cable saddle direction under the action of radial force can be neglected, so a 2D finite element (FE) plane strain model could be established for the cable saddle imbedded in the concrete, as illustrated in Figure 5. In order to take into account of the friction between the cable saddle and concrete, contact elements are added into the FE model along the contact parts. Based on the definition of the Coulomb friction, the friction force is equal to the value that pressure on the contact surface multiplies the friction coefficient, which is 0.4 in this study.

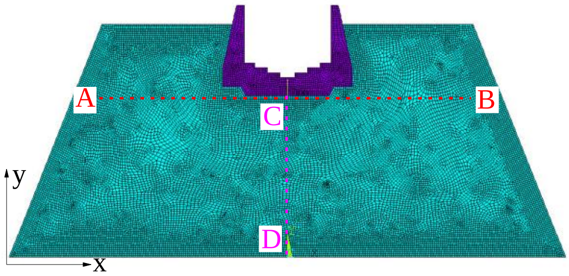

Figure 5. The plain strain FE model for the imbedded cable saddle in the concrete mount

The cable radial force in the groove of cable saddle is converted into pressure, which is applied on the FE element. In order to investigate the stress variation in the concerned part of the concrete mount, two paths Point A to B and Point C to D are located and used to obtain the stress values from the plain strain FE model. The vertical stress σ_y along the Path A to B and, correspondingly, the horizontal stress σ_x along the Path C to D are obtained. The stress distribution results are plotted in coordinates (Figure 6), and the abscissa is the length of two paths. The stress value with different sections is relatively close to the stress results, which indicates that the section shape has much less influence on the local compressive behaviour of the concrete mount.

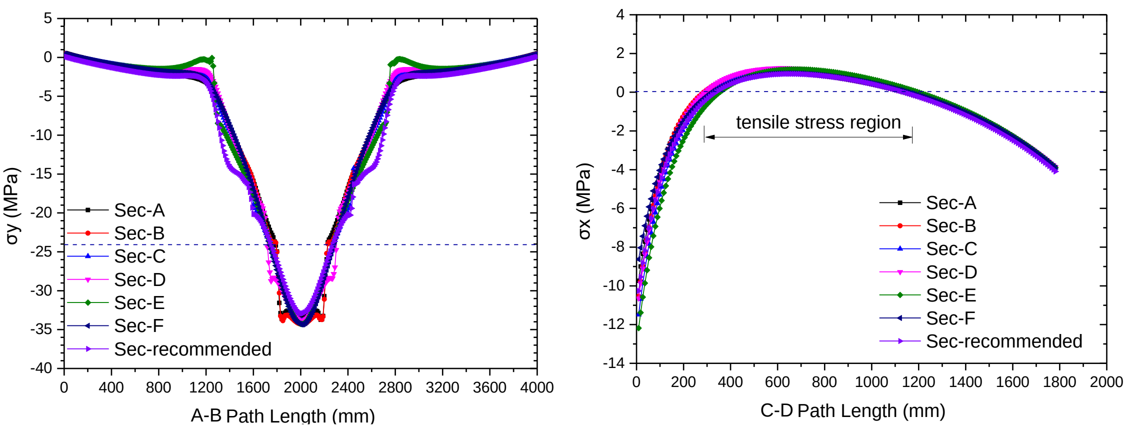

Figure 6. Stress distribution in the concrete mount

The vertical stress σ_y right under the bottom of cable saddle reaches the peak value around 34.5 MPa, which is much greater than the design value of the concrete compressive strength 24.4 MPa, and the width of stress distributions exceeding the design value limit is about 500mm. Nevertheless, this overlimit region could still bear the local compression because of its confined compressive state. This phenomenon has been confirmed and taken into account by Baushinger's empirical ratio factor:

$$m = \sqrt{A_{c1}/A_{c0}} \tag{1}$$

where A_{c0} is the load area, and A_{c1} will be discussed later. The confined stress state is also proved by horizontal stress distribution σ_x in Figure 6. It can be seen that the stress distribution from point C down 300 mm is compressive, and then it becomes tensile stress from 250 mm down to 1200 mm. Therefore, the maximum compression part may not be definitely unfavorable position, in addition to the confined effect from surrounding concrete, the friction at the bottom of cable saddle on concrete may also constrain the contact part.

4. Theoretical verification for non-uniform local pressure on the concrete mount

Although the concrete under the cable saddle may have higher strength due to surrounding confined effect, the local compressive area is an arched strip surface, and the load transmitted from the bottom of the cable saddle to the compressive surface is likely to be non-uniform compression, which is ambiguous for designers, so a relatively reliable theoretical method is going to be discussed here. According to the European concrete design specification Eurocode 2 [9], the concentrated resistance force is determined as follows (see Figure 7):

$$F_{Rdu} = A_{c0} \cdot f_{cd}\sqrt{A_{c1}/A_{c0}} \leq 3.0 \cdot A_{c0} \cdot f_{cd} \tag{2}$$

Where the f_{cd} is design value of the concrete compressive strength, A_{c1} is the maximum design distribution area with a similar shape to A_{c0}. In addition, the value of F_{Rdu} should be reduced if the load is not uniformly distributed on the area A_{c0}.

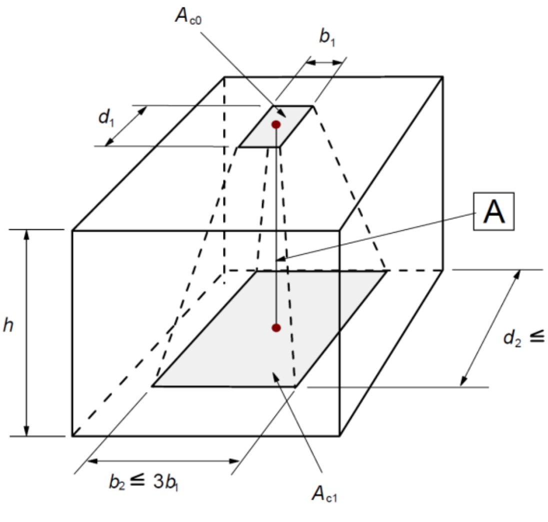

Figure 7. Design distribution for partially loaded areas in Eurocode 2

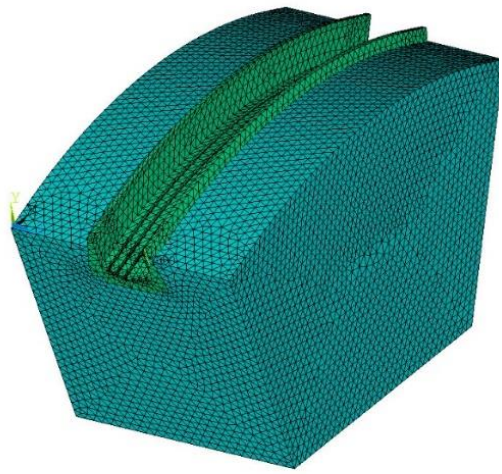

Figure 8. The solid element FE model for the imbedded cable saddle in the concrete mount

There are two questions for this verification method, it is not clear that to what extent the reduction factor for non-uniform local pressure should be, and Ac1 is conditional as there is no precise explanation to pinpoint it. In order to determine the reduction factor for the non-uniform pressure in the hogging strip, a solid element FE model, as shown in Figure 8, is established and used to investigate the stress distribution of the arched contact part under the imbedded cable saddle.

The cable saddle and concrete mount are both modeled by solid elements, and the mesh size is 100 mm. The material properties are consistent with the previous 2D finite element model, and the linear elastic constitutive model is adopted. The bottom area of the concrete mount area is constrained in XYZ degrees. The contact elements are also used to simulate the contact effect between the cable saddle and the concrete mount. The penalty stiffness method is adopted for the contact algorithm, with contact gaps closed and penetration reduced.

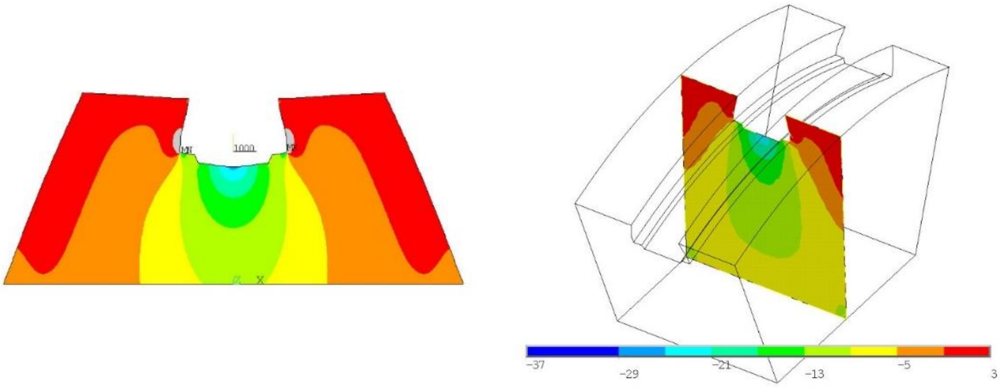

Figure 9. Comparison of the vertical stress distribution σ_y between the 2D and 3D FE models

Compared with the results of the plain strain FE model under the same pressure in the saddle groove, the vertical stress distribution σ_y in the symmetric area of the concrete mount is sliced and fetched, as shown in Figure 9. The contours of the stress distributions between the two kinds of FE model approaches could have a relatively good agreement. The stress distribution σ_y under the cable saddle in the solid FE model is shown in Figure 10, and the maximum stress value is approximately 25.2 MPa, which is much less than the result of the 2D strain plane model. For common recognition, the 3D solid FE model can reflect the performance of research objects. However, the results of the FE model are susceptible to the boundary condition and input data. The cable force in 3D model is idealized to be uniform hogging pressure, and the contact part of the concrete and steel is assumed to perfectly interact without gaps. Given the design redundancy of the local compression, the 2D strain plain model may be more suitable in terms of theoretical verification. Therefore, the reduction factor for nonuniform local compression could be $25.2/34.5 = 0.73$. Actually, in reference to AASHTO specification for bearing design, for the case of nonuniform bearing compression, the reduction factor is recommended to be 0.75 [8]. Thus, the result could be relatively reasonable.

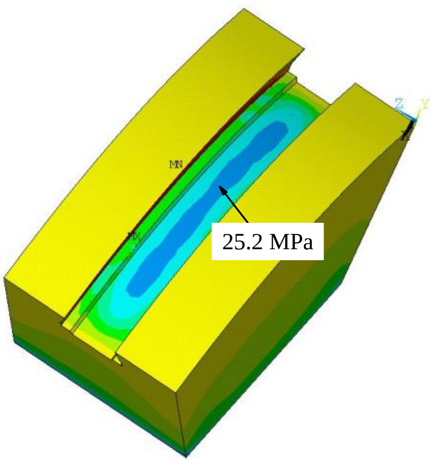

Figure 10. Stress distribution in the concrete mount solid FE model

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In regard to A_{c1} in Figure 7, the Chinese specification proposes an approach for strip local pressure, as depicted in Figure 11. In accordance with the results from laboratory tests, the practical modified ratio $m = \sqrt{A_{c1}/A_{c0}}$ is close to 1.73 [12]. The principle for this approach is that Ac1 and Ac0 should be concentric and symmetric.

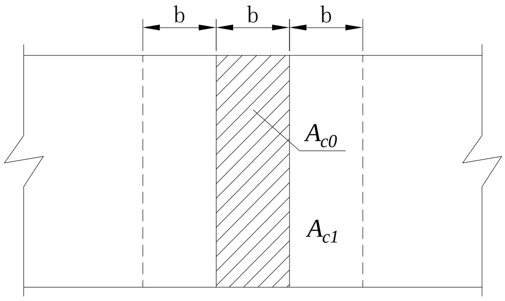

Figure 11. Definition of Ac1 in Chinese specification

The radial local pressure on the arched surface can be regarded in a similar way in Equation 2, but A_{c0} is calculated based upon the vertical mapping area, which is $1.4 \times 8 = 11.2\ m^2$. Based on the parameters obtained above, the concentrated resistance force can be calculated as:

$$24400 \times 11.2 \times 1.73 \times 0.73 = 3.45 \times 10^5\ kN$$

The maximum cable force could reach 2.85E5 kN, and the angle of the main cable tangent line and horizontal axis is 19.533°; thus, the vertical local load is equal to 1.91E5 kN, which is less than the theoretical concentrated resistance force.

5. Discussion on the indirect reinforcement under the local compressive pressure

Even though the theoretical local compression bearing capacity is much larger than the designed vertical force, structural measures are still needed to keep the structure in good condition for the serviceability limit state. According to the traditional theory of local compression failure, with the increase of load, cracks further develop and may lead to splitting, and a small wedge under the local pressure caused by shear failure may be formed, as shown in Figure 12.

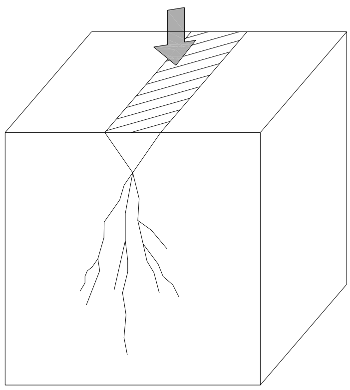

Figure 12. Failure mode caused by the strip local pressure

Previous local compression tests have concluded that under strip local pressure, cracks gradually occur inside or on the surface of specimens, which then leads to their splitting [13-14]. According to the stress distribution results in Figure 6, the tensile stress region is approximately 1000 mm deep immediately under the confined concrete part, and this region may crack at the beginning. In order to improve the splitting bearing capacity of the concrete mount, 5 layers of Φ12 mm indirect reinforcement are applied under the imbedded cable saddle. This effect does not mention any information in Eurocode 2 about assessing the contribution of the indirect reinforcement.

In addition to the lateral constraint provided by the indirect reinforcement in the wedge part, the indirect reinforcement under the concrete wedge can effectively control cracks development at inside of concrete members. A method algorithm for improving the local compression bearing capacity of indirect reinforcement is recommended as follows [12]:

$$F_{R-re} = \rho_v \cdot f_y(nA_{s1} + A_{cor}) \tag{3}$$

where ρ_v is the volume reinforcement ratio of indirect reinforcement, f_y is the design yield strength of reinforcement, nA_{s1} is the number of reinforcements in a layer and the area of a single reinforcement, and A_{cor} is the area of the wedge along the central axis. However, indirect reinforcement should be set up properly, which may affect the construction quality of the structure. The improvement of its bearing capacity F_{R-re} should be less than 0.8 times the concentrated resistance force F_{Rdu} for plain concrete.

6. Conclusions

The imbedded cable saddle is designed and used for a single pylon hybrid cable stayed bridge. The local compressive behaviour of the concrete mount under the cable saddle is investigated by a series of case studies in this paper. The local compression of this cambered cast iron cable saddle structure could meet the local bearing capacity via analysis of numerical FE models and theoretical verification, which could provide a reference case for similar types of structures. These conclusions can be drawn:

(1). The different section shapes have less impact on the local compressive distribution of the concrete mount. The stress concentration could be found at the edge and right angle area of the cable saddle, which is prone to crack in the concrete mount, so a complex or sharp angle shape should be avoided as much as possible.

(2). Due to the confined effect from the surrounding concrete, the maximum compression part in the concrete may not be unfavorable, and the friction at the bottom of the cable saddle on the concrete may also constrain the concrete.

(3). In order to improve the design redundancy, the reduction factor for nonuniform local compression could be 0.73 in this project, and the theoretical local compression bearing capacity in this case is larger than the designed vertical force.

(4). It is recommended to apply indirect reinforcement under local compressive pressure. Despite contributing to the local bearing capacity, it can also effectively control crack development inside concrete members.

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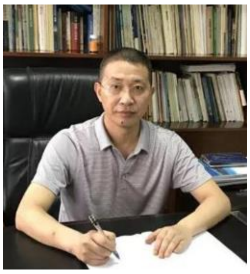

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