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ANALYSIS OF CONTACT FRICTION BEHAVIOR IN THE BENDING PROCESS OF SEMI-PARALLEL STEEL WIRE CABLE

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ABSTRACT

In the bending process of semi-parallel steel wire cable, with the increase of the lateral displacement of the bending, the interaction between the steel wires in the cable is remarkable and the mechanical behavior is complicated. In order to study the mechanical behavior of the contact friction between the inner steel wires in the process of cable bending, this paper uses the 37-φ7 semi-parallel steel wire as the research object and uses the ANSYS to set up the finite element model of the cable bending, and verifies the correctness of the refined finite element model by bending test data. Based on the refined finite element model of the test data verification, the variation rule of the contact friction between the inner steel wires in the semi-parallel steel wire of different boundary conditions in the bending process is studied, and the axial sliding behavior of the steel wires in the cable bending process is analyzed. The results show that the bending and mechanical properties of the semi-parallel steel wire cable can be calculated more accurately by considering the refined finite element model of the contact friction, and the amount of deformation between the steel wires during the bending process of the semi-parallel steel wire cable can be calculated. The contact pressure and the contact friction stress are non-linear with the increase of the lateral displacement of the bending, and there is a maximum value for the contact friction stress for the pre-tension semi-parallel wire cable, and the maximum position of the axial accumulated slip amount between the steel wires is located at the bending cable section of the calculated span of 1/4 or 3/4 times.

KEYWORDS

Semi-parallel steel wire cable, Refined finite element analysis (RFEA) model, Extrusion deformation, Contact pressure, Contact friction stress, Axial cumulative slip

INTRODUCTION

During the operation of cable-supported bridges, different degrees of local bending problems can be found for the cables of cable-stayed bridges, arch bridges and the suspension cables of suspension bridges [1]. Semi-parallel steel wire cable, as a common cable structure for cable-supported bridges, is the key force-transmitting and force-bearing component of this type of bridge. When it is locally bent, the contact friction mechanical behaviour between internal steel wires is complex. Finite element numerical simulation is commonly used in research on the interaction between the inner wires of a cable. Jiang [2] established a refined three-dimensional solid model of a simple seven-wire steel strand under pure bending. For the overall mechanical behaviour of the strand, the moment–curvature curve is consistent with the theoretical model in literature. The finite element model can accurately predict the continuous nonlinear plastic behaviour of the strand. Zhang [3] established a solid finite element model with two boundary conditions to study the bending stiffness of steel strands by taking the internal friction between steel wires into consideration. The results showed that ignoring the contact between the wires will reduce the bending stiffness of the strand leads due to the rotation of the cross section of the wires; the bending stiffness increased with increasing tension and decreasing curvature. Wu [4] and Chen [5] conducted a static bending test on semi-parallel steel wire cable under three boundary conditions. The unstressed cable was similar to an elastic-plastic steel beam. The load–displacement curve under bending was of elastic–plasticity. The welded end cable ensured the integrity of the cable, but the reinforcement effect was weak and limited. The pretension can improve the bending stiffness of the cable, which increased with increasing pretension level but decreased with increasing cable size. A simplified evaluation method for effective bending stiffness was proposed. Yu [6] simplified the extrusion and frictional slip between steel wires as spring action in three directions and established a semi-refined finite element model of beam–beam spring combination to evaluate the bending mechanical properties of wire cables. The model calculation was consistent with the bending test data but had huge errors. The semi-refined model was not accurate enough for the bending calculation and simulation of semi-parallel wire cables. Zeng [7] established a balanced equation and obtained variations in the wire slip with the section angle based on the layered slip model of cable strands and wires; the equation considered the influence of slip on the inertia moment of the section and used equal shear force between the wires and the ultimate friction force. However, the effect of friction between adjacent layers of steel wires on axial force was ignored in the theoretical model. Liang [8] established a simplified numerical model of the cable considering the friction between wires. Through the analytical solution of Costello theory and the verification of experimental data, scholars analysed the bending mechanical properties of the cable and determined the influence of broken wire on the dynamic response of the cable. The model can track the slip between the wires and be applied to dynamic analysis. Zhang [9-10] established a theoretical mechanical model for the bending of parallel steel wire cables considering the contact friction between layers through laminated beam theory and studied the change law of the bending stiffness of the steel wire cables. Data from the theoretical model were consistent with the experimental results obtained through experimental verification. Lalonde S [11] proposed a method for simulating multi-layer helical steel wire cables based on 3D finite element beam–beam contact model. In this model, a multi-level friction coefficient model that can better represent the bond and slip regions was proposed, and the concept of friction orthogonality was introduced. The axial direction was controlled by the inter-wire adhesion, while the orthogonal direction was related to the inter-wire adhesion and deformation contribution. The above research mainly focused on the bending mechanical properties and bending stiffness of the cable. The changing laws of extrusion deformation, contact pressure and contact friction stress between steel wires during the bending of semi-parallel steel wire cables remain unclear. In this paper, the changing law of extrusion deformation, contact pressure and contact friction stress between steel wires inside the cable structure during the bending of semi-parallel steel wire cables was studied under the action of vertical load at mid-span based on the refined finite element model of semi-parallel steel wire cable verified by experimental data. The axial slip behaviour between the wires during the bending process was also analysed.

REFINED FINITE ELEMENT ANALYSIS (RFEA)METHODS

Establishment and experimental verification of the finite element model of semi-parallel wire cable bending

Basic assumptions

Before establishing the refined finite element model of the semi-parallel wire cable, the following basic assumptions are made:

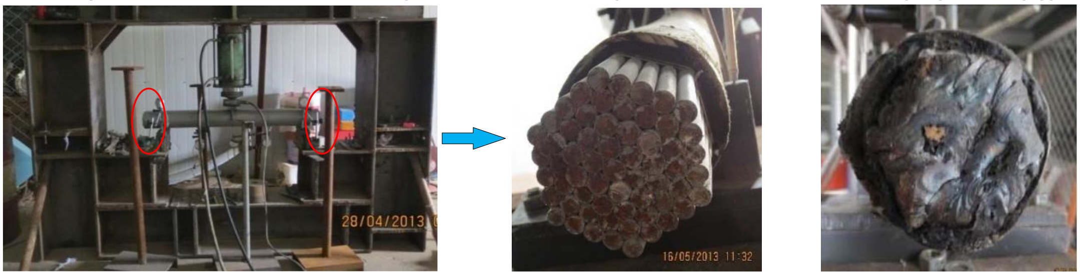
(1) The contact friction between the wrapping tape and the steel wire, the sheath and the wrapping tape is not taken into consideration; the gripping force of the sheath on the inner steel wire is simplified as a radially uniform load applied to the outermost steel wire of the wire cable.

(2) During the bending deformation process of the steel wire cable, each steel wire is allowed to be moved with each other; the contact part between the steel wires is simulated by the surface-to-surface contact element; the same friction coefficient is applied for all the steel wires of the same cable.

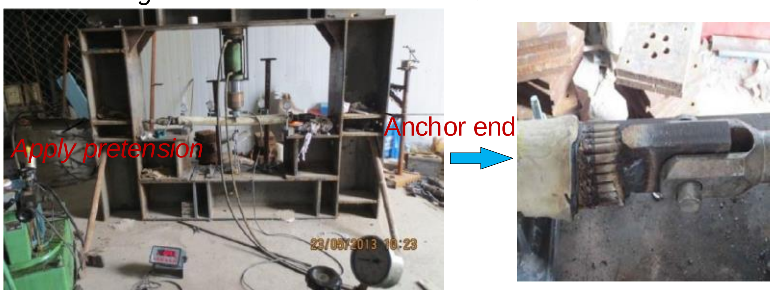
(3) The plastic development of the steel wire is not taken into consideration in the bending model; all the steel wires are assumed to be made of the same material, and the inner steel wire is always in the elastic stage during the bending process of the wire cable.

Establishment of refined finite element model

Based on the bending test of the semi-parallel steel wire cable in literature [4] (Figure 1), the three-dimensional finite element full contact model of the semi-parallel steel wire cable is established by finite element software ANSYS considering the three boundary conditions of the cable:①Free at both ends: The steel wire at both ends of the cable is allowed for sliding(Figure 1(a));②Weld at both ends: the cable end wire does not allow sliding and maintain a flat section(Figure 1(b));③Applying different pretensions at both ends(The pretension force was 50kN and 100kN):the cable is anchored at one end and prestressed after welding the articulated joints at the other end(Figure 1(c)).



Cable bending test（Free end or weld end） （a）*Free end* （b）*weld end*



Cable bending test（Apply pretension） （c）*Pretension cable end*

Fig. 1 –Bending test of semi-parallel steel wire cable [4]

Semi-parallel wire cable is formed by parallel steel wire concentric same direction for left mild twist, twist angle between 2°to 4°, the cable section is positive hexagonal or missing hexagonal closely arranged, and then tied with fiber polyester wrap belt, and finally in the outer layer directly crowded wrapped single layer or double layer high density polyethylene sheath (HDPE Sheath) cover as a protective layer. According to the structural characteristics of the semi-parallel wire cable, twist angle is 3°, the order from bottom to top (generating points, lines, surfaces and bodies in turn) is adopted. The wire surface is divided into meshes, and the surface is rotated at a certain angle to stretch into a cube to establish a geometric model of the cable. The steel wire adopts the SOLID186 element. The target element of the contact surface between the steel wires adopts the TARGE170 element. The contact element adopts the CONTA174 element.

The physical parameters of the main components of the steel wire cable in the finite element model are as follows:

① HDPE Sheath: the elastic modulus of the material is 150 MPa, and the density is 0.942 kilograms per cubic meter. The gripping force q of the sheath to the steel wire is calculated according to the formula $q=2\pi E\beta\Delta th/m$ in literature [12], where E is the elastic modulus of the sheath, β is the thermal expansion coefficient of the sheath, generally 0.00012~0.00013/℃ [13], where 0.00012/℃is taken. In the sheath making process, the upper limit of the melt temperature of HDPE sheath extrusion is generally set at 230℃, and it is generally controlled at about 200℃. HDPE sheath needs to be cooled in cooling water with temperature below 20℃. Therefore, the temperature change Δt in the production process of the sleeve is about 180℃ [14-17], where h is the wall thickness of the sheath, and m is the number of wires in the outermost layer of the wire cable. For a 37φ7 semi-parallel steel wire cable, the sheath thickness h is 8 mm and the number m of the outermost steel wires of the steel wire cable is 18. Therefore, the grip force allocated to each steel wire is calculated as q=9.04 kN/m.

② High-strength galvanised steel wire: the elastic modulus of the material is 200000 MPa, the density is 7850 kilograms per cubic meter, and the Poisson's ratio v is 0.3.

③ The friction coefficient between steel wire μ is taken according to the boundary conditions at both ends of the cable. Through cross-over wire vibration and sliding experiments, the friction coefficient between cable wire is 0.3~0.4[18]. By studying the influence of the interface contact force of the transverse contact steel strand, Gnanavel obtains the dry friction without sliding action between steel wires, and the friction coefficient μ can be 0.5[19]. The μ of free and welded at both ends is taken as 0.3. The pre-tension force applied at both ends μ is taken as 0.5. The space finite element model of 37φ7 semi-parallel steel wire cable and the representative contact point number of the cross-section contact surface are shown in Figure 2.

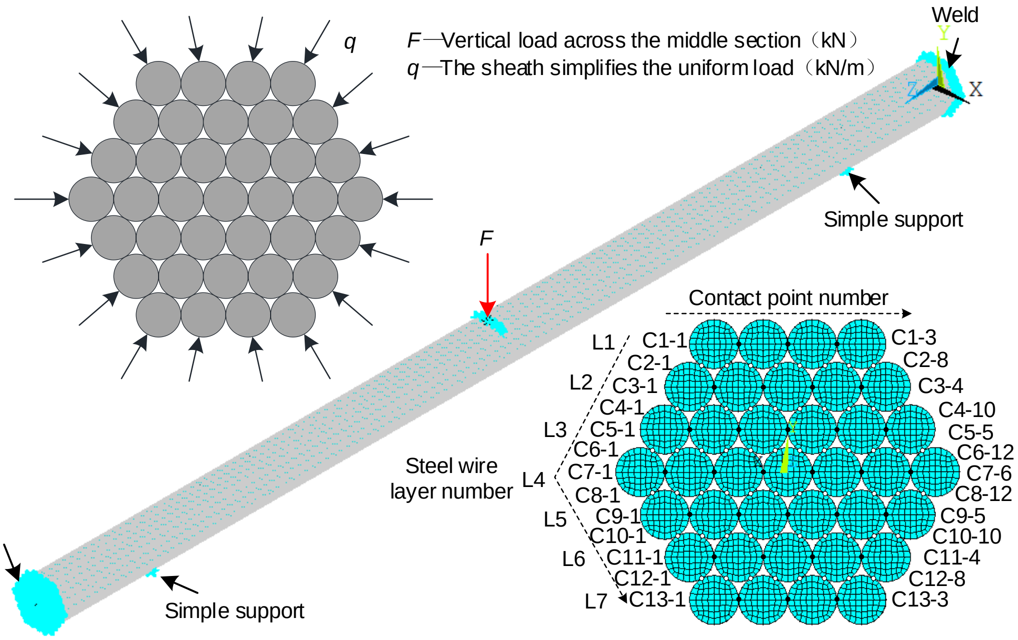


Fig. 2 – Finite element model and contact point number of 37φ7 semi-parallel steel wire cable（weld end）

Bending calculation and test verification of refined finite element model

A 37φ7 semi-parallel steel cable is taken as an example to verify the correctness of the refined finite element model. The correctness of the calculation of the bending refined finite element model is verified by comparison and analysis of the calculation results of the semi-refined finite element model in the bending test and literature [4] with the calculation results of the refined finite element model in this paper. The results of the lateral load–lateral displacement curve of the 37φ7 semi-parallel steel cable during mid-span bending under the boundary conditions of free ends, welded ends and different pretensions applied to both ends are shown in Figure 3.

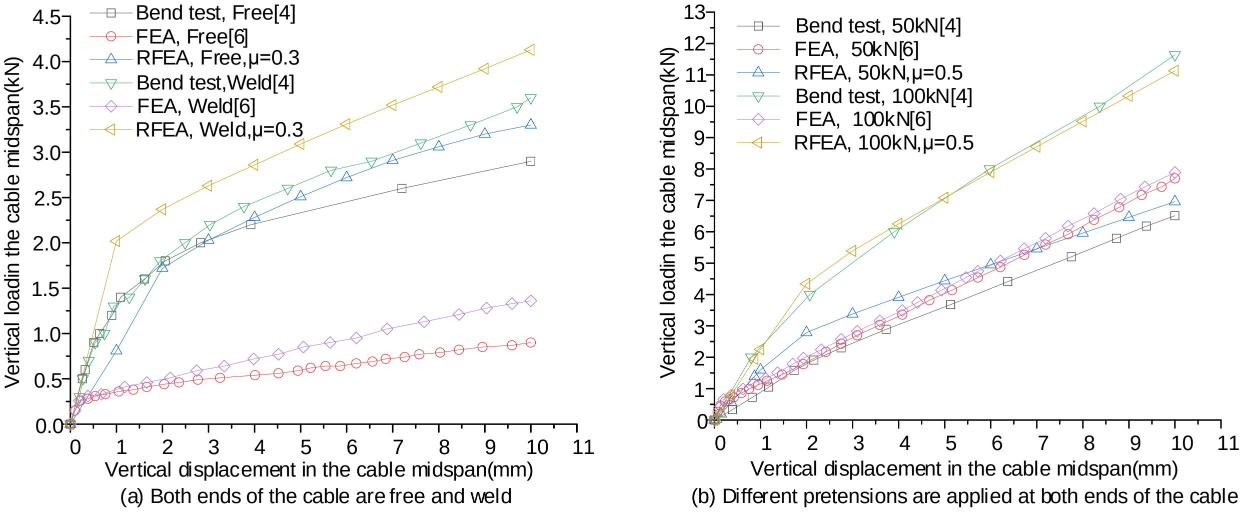


Fig. 3- Comparison of lateral load-displacement curves in mid-span bending of 37φ7 semi-parallel steel wire cables

As shown in Figure 3, the lateral load–displacement curve in mid-span bending calculated by the refined finite element model is consistent with the change trend of the bending test data, indicating that the laws are basically the same. However, the semi-fine finite element calculation value of the beam-beam-spring combination used in literature [6] is small and has huge error and poor simulation accuracy. For the pre-tension cable, the lateral bearing capacity of the cable is not significantly increased with increasing pre-tension and mid-span lateral displacement, which is not consistent with the test results. Reference [6] believes that the reason for the large difference in the calculation results is due to the wrapping effect of the cable sheath on the wire bundle in addition to the measurement error, thereby increasing the inertia moment of the cable section. Part of the lateral force will be shared during the bending process. However, the simulation calculation results of the refined finite element model show that the contact friction between the wires poses a great influence on the lateral force during the bending of the semi-parallel wire cable. The calculation results of the refined finite element model are closer to the experimental data. For the pre-tensioned semi-parallel wire cable, the calculation results are basically consistent with the experimental data, which verifies the correctness of the refined finite element model.

Mechanical behaviour analysis of contact friction between steel wires during bending of semi-parallel steel wire cables

For the 37φ7 semi-parallel wire cable, the boundary conditions as of free ends, welded ends and initial tension of 50kN and 100kN at both ends are mainly considered. The lateral displacement of the cable under mid-span bending is 10 mm. The changing law of the extrusion deformation, contact pressure and contact friction stress of the contact points on the contact surface between the steel wire layers of the mid-span section during the bending of the cable is obtained through the calculation of the refined finite element model of the cable. The rules for the maximum extrusion deformation, contact pressure and contact friction stress of the contact point on the contact surface are analysed. Finally, the axial slip behaviour between the wires during the bending process is analysed.

Contact extrusion deformation between steel wires

For different boundary conditions of 37φ7 semi-parallel steel wire cables, the change in the contact extrusion deformation of the indirect contact in the same or adjacent steel wires in the mid-span section of the cable is different. When the lateral displacement applied in the midspan is 0–10 mm, the maximum extrusion deformation of the contact point in the adjacent steel wire layers in the midspan section of the cable is obtained by calculating the refined finite element cable model at

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contact Point C2-1 between steel wire layers L1 and L2. The maximum extrusion deformation of the contacts of the same steel wires in the same layer is located at the contact point C11-4 of the steel wire layer L11. Figure 3 shows the changes in the contact extrusion deformation at the contact points C2-1 and C11-4 under different boundary conditions during cable bending.

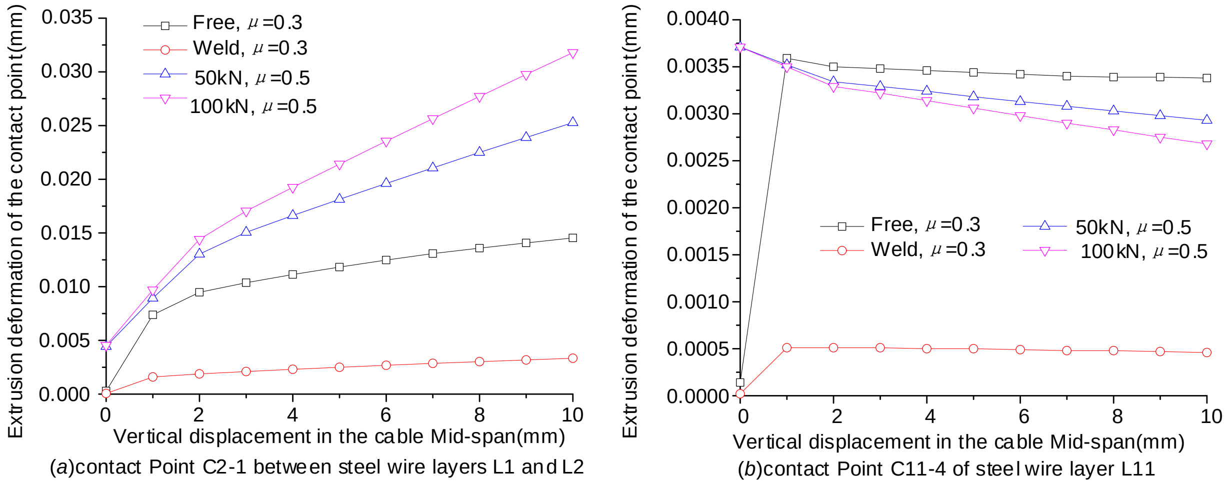

Fig. 4 –Extrusion deformation change of indirect contact of adjacent or the same steel wire layer

During the bending process of the 37φ7 semi-parallel steel wire cables, Figure 4(a) shows that for the extrusion deformation of the contact in adjacent steel wire layers, the maximum extrusion deformation of the contact point C2-1 in the mid-span section tends to nonlinearly increase with increasing lateral displacement. The extrusion deformation produced by the contact point of the pretension cable during the bending process is significantly higher than that of the free and welded boundary cables at both ends. For the extrusion deformation of the contacts in the same steel wire layers, Figure 4 (b) shows that for the free and welded cables at both ends, the extrusion deformation increases rapidly at the contact point C11-4 in the initial bending stage. When the lateral displacement is greater than 1 mm, the extrusion deformation at the contact point C11-4 slightly decreases with increasing lateral displacement and tends to be gentle; for the pre-tension cable, huge extrusion deformation can be found at the contact point C11-4 before it is bent due to the pre-applied tension. With increasing lateral displacement applied at the mid-span, the extrusion deformation at the contact point C11-4 decreases, and the greater initial pre-tension leads to the more extrusion deformation decrease of the contact point.

Contact extrusion stress between steel wires

For cables with different boundary conditions, the variations in the contact extrusion pressure of the indirect contact of the same and adjacent steel wires in the mid-span section of the semi-parallel steel wire cable are different. When the lateral displacement applied in the midspan is 0–10 mm, the maximum extrusion stress of the contact point of the adjacent steel wire layers in the midspan section of the cable is obtained through the calculation of the refined finite element cable model at contact point C2-1 between the steel wire layers L1 and L2. The maximum extrusion stress of the contacts in the same steel wires is located at the contact point C3-4 of the steel wire layer L3. Figure 5 shows the variations in the extrusion stress of indirect contacts in adjacent or the same steel wire layer under different boundary conditions during cable bending.

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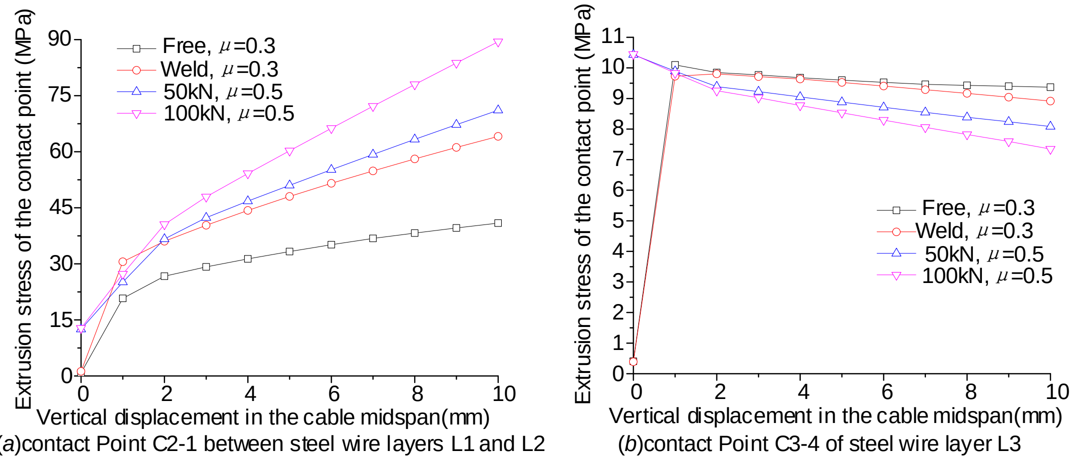
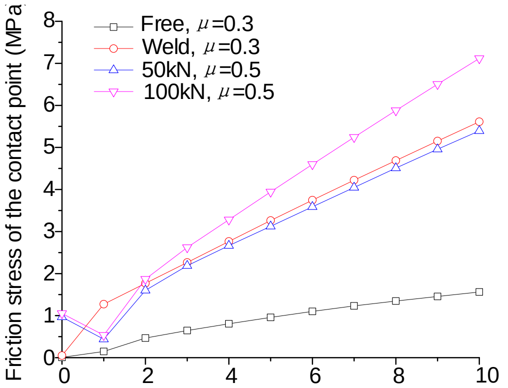


Fig. 5 -Variations in the extrusion stress of indirect contacts in adjacent or the same steel wire layer

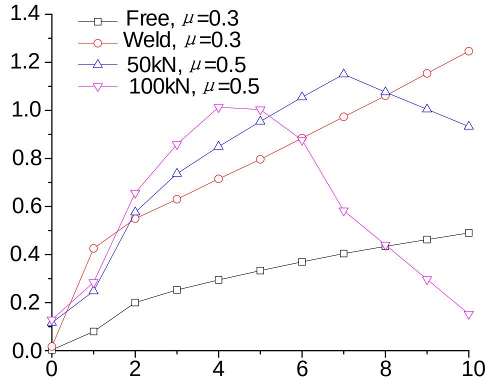
During the bending process of the 37φ7 semi-parallel steel wire cables, Figure 5(a) shows that for the extrusion stress of the contact in adjacent steel wire layers, the maximum extrusion stress of the contact point C2-1 in the mid-span section tends to nonlinearly increase with increasing lateral displacement. The extrusion stress produced by the contact point in the pretension cable during bending is significantly higher than that in the free and welded boundary cables at both ends. For the extrusion stress of the contacts in the same steel wire layers, Figure 5 (b) shows that for the free and welded cables at both ends, the extrusion stress increases rapidly at the contact point C3-4 in the initial bending stage. When the lateral displacement is greater than 1 mm, the extrusion stress at the contact point C3-4 slightly decreases with increasing lateral displacement and tends to be gentle. For the pre-tension cable, a huge extrusion stress can be found at the contact point C11-4 before it is bent due to the pre-applied tension at both ends of the bending cables. With increasing lateral displacement applied at the mid-span, the extrusion stress at the contact point C3-4 is nonlinearly decreased, and the greater initial pre-tension leads to the more extrusion stress decrease of the contact point C3-4, similar to the variation law of contact deformation of contacts in adjacent steel wires.

Contact friction stress between steel wires

For cables under different boundary conditions, the change in the contact friction stress at the contact point in the adjacent or the same steel wires at the mid-span of the semi-parallel steel wire cable is different. When the lateral displacement applied in the midspan is 0–10 mm, the maximum extrusion deformation of the contact point of the adjacent steel wire layers in the midspan section of the cable is obtained through the calculation of the refined finite element cable model at contact point C2-1 between the steel wire layers L1 and L2. The maximum extrusion deformation of the contacts in the same steel wires is located at the contact point C3-4 of the steel wire layer L3. Figure 6 shows the contact friction stress of indirect contacts in adjacent or the same steel wire layer under different boundary conditions during cable bending.



(a)contact Point C2-1 between steel wire layers L1 and L2



(b)contact Point C3-4 of steel wire layer L3

Fig. 6-Variations in the contact friction stress of indirect contacts in adjacent or the same steel wire layer

During the bending of the 37φ7 semi-parallel steel wire cables, Figure 6(a) shows that for the contact friction stress of the contact in adjacent steel wire layers, the maximum contact friction stress of the contact point C2-1 in the mid-span section tends to nonlinearly increase with increasing lateral displacement for cables with free ends and welded boundary conditions. The contact friction stress produced by the contact point in the cable with two ends welded during the bending process is significantly higher than that in the free cables at both ends. For the cable with the boundary condition of 50kN and 100kN pretension force, the maximum contact friction stress of the contact point C2-1 decreases firstly and then increases with increasing lateral displacement. When the lateral displacement is 1 mm, the maximum contact friction stress value of the contact point C2-1 is the smallest. The contact friction stress generated at the contact point during the bending of the cable with a pre-tension of 100kN is significantly higher than that of the free and welded boundary cables at both ends. For the contact friction stress of the contacts in the same steel wire layers, Figure 6 (b) shows that for the free and welded cables at both ends, the extrusion deformation increases rapidly at the contact point C3-4 in the initial bending stage. When the lateral displacement is greater than 2 mm, the contact friction stress at the contact point C3-4 nonlinearly increases with increasing lateral displacement. For the pre-tension cable, a huge contact friction stress can be found at the contact point C3-4 before it is bent due to the pre-applied tension at both ends of the cables. With increasing lateral displacement applied at the mid-span, the contact friction stress at the contact point C3-4 nonlinearly increases. The friction stress has a maximum value. For cables with a pretension of 50kN and 100kN, the mid-span lateral displacement values corresponding to the maximum frictional stress are 7 and 4 mm, respectively. During the bending of the cable, the larger initial pre-tension force applied leads to the smaller critical value of the mid-span lateral displacement corresponding to the decreasing trend of the contact friction stress at the contact point C3-4 of the mid-span section.

Analysis of axial slip behaviour between steel wires

According to the refined finite element model of the 37φ7 semi-parallel steel wire cable, the maximum cumulative amount of the indirect contact between the steel wires during the bending process is calculated, and the most unfavourable position of the cable is determined. The maximum lateral displacement applied at the mid-span of the semi-parallel steel cable is 10 mm, and the cross-sectional position of the maximum cumulative slip of the steel wire cable during the bending process of the 37φ7 semi-parallel steel cable is calculated (Figure 7).

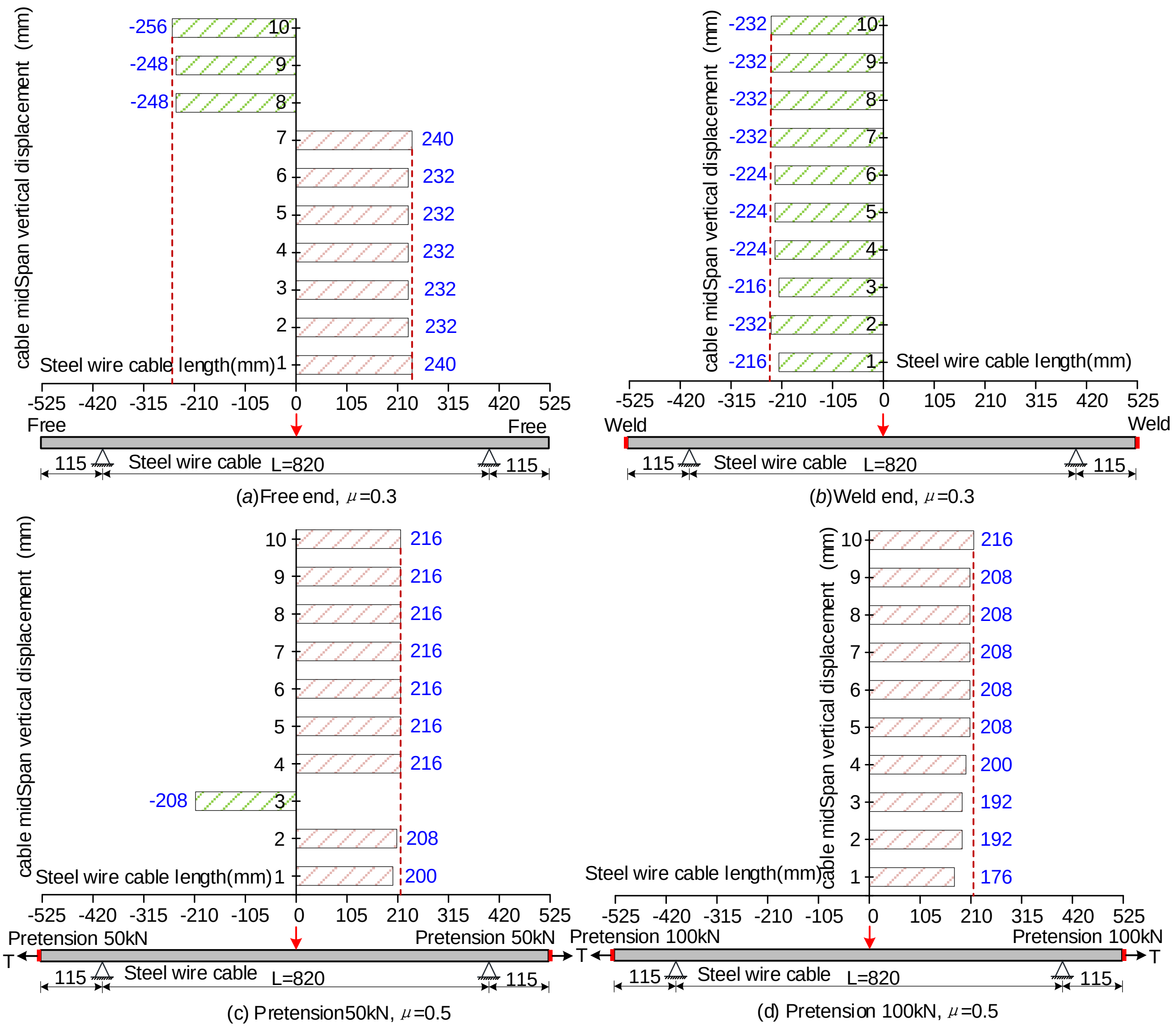


Fig.7-Section position of maximum cumulative slip of 37φ7 semi-parallel steel wire cable during bending

As shown in Figure 7, for 37φ7 semi-parallel steel wire cables with different boundary conditions, the position of the maximum cumulative slip between the steel wires varies with increasing mid-span bending degree of the cables. The maximum slip is mainly located in the bending cable segment near 1/4L or 3/4L (L is the calculated span of the cable).

CONCLUSION

(1) The refined solid finite element model of the semi-parallel steel wire cable taking the contact friction into consideration is more accurate for calculating the bending mechanical properties of the cable than the semi-refined finite element model in literature. For the pre-tension cable, the calculation results of the refined finite element model are basically close to the experimental data.

(2) With increasing mid-span lateral displacement of the cable, the contact deformation and contact extrusion stress of the indirect contact in the adjacent or the same steel wire cables under the three boundary conditions. The contact friction stress of the cables with free ends and welded boundary tends to nonlinearly increase, while the contact friction stress of the pretension cable tend to first decrease and then increase.

(3) Under the condition of cables with both free ends and welded boundary, the contact deformation and contact extrusion stress of the indirect contacts in the same steel wire layers are

first rapidly increased and then slightly increased; it then tends to be stable with increasing cable midspan lateral displacement. The frictional stress at the contact point is increased nonlinearly with increasing mid-span lateral displacement. Under different pretension boundary conditions, the contact deformation and contact extrusion stress of the contacts in the same steel wire layers tend to nonlinearly decrease with increasing mid-span lateral displacement. The frictional stress of the contact points is increased firstly and then decreased, and a maximum frictional stress can be found during bending.

(4) For 37φ7 semi-parallel steel wire cables with different boundary conditions, the position of the maximum cumulative slip between the steel wires is variable with increasing mid-span bending degree of the cables. The maximum cumulative slip between the wires is in the bending cable segment near 1/4L or 3/4L (L is the calculated span of the cable).

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