Relationship of Friction and Load Between Wires of Seven-Wire Galvanized Steel Strand

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Abstract. The contact parameters of materials have great influence on the results in structural dynamic analysis, but the friction relation between wires has not been solved, which often causes the simulation error. To improve the accuracy of the finite element simulation, this paper study the friction and load relationship between wires of galvanized steel strand, testing material friction coefficient and drawing load of single wire for different length, obtains the force-displacement curve of core wires. The results show the friction coefficient between wires of galvanized steel strand is from 0.42 to 0.52, the friction force and the length of the wires present a linear proportional relationship; The maximum static friction of core strands is independent of drawing velocity.

1. Introduction

With the extensive applications of steel strand, the security and reliability are becoming more and more concerned. The relationship between friction and load of steel strands has not been solved effectively. As an important parameter in finite element simulation, especially in dynamics study, the influence of contact condition on the analysis results is still unknown.

Many paper based on the finite element simulation often neglected or simplified in the contact information. The model of cable was established as a whole component but not separating wires, analysis with a model like this would ignore the force and touch within wires [1]. A meticulous model was established to study the stress and deformation distribution of independent steel wire rope, and comparing with experimental data, they find that the ignorance of friction can generate about 7% error [2]. The breakage response of a prestressing steel strand was studied, the friction coefficient in the model is set from 0.1 to infinite, which reduce the accuracy of simulation [3]. The influence of friction in high pressure contact on the relative displacement of wires in steel strand is very important, there is a clear displacement of wire after being impacted, the wires will produce huge contact load and the friction affects the mutual displacement between strands, ignore the friction between wires would lead to a huge analysis error [4]. The friction coefficient of the wire is different from the surface treatment and environment, the frictional forces between a stainless steel bracket and five different wire alloys under dry and wet (artificial saliva) conditions, it’s showed that the friction in the wet condition was less than that in dry condition due to the lubricating effect of artificial saliva[5]. The use of lubricants can further reduce friction and the friction coefficient affected by external environment cannot be simply valued.
2. Theoretical analysis of friction coefficient

The classical friction theory considers the material friction coefficient to be a fixed value, but a large number of experiments show that the friction coefficient is affected by many factors, such as slip rate and pressure, the friction coefficient of the same material varies in different environments and conditions [6,7]. The dry friction and wear behavior of high carbon steel changes at different temperatures [8]. It is pointed out that the variation law of friction coefficient was related to the surface state, the transformation of wear form and other factors.

Different with the classical friction theory, the friction adhesion theory indicates that when two surfaces of the same material are in contact with each other, the stress of some contact points is very large and plastic deformation occurred under certain loads, these points will be firmly adhered to form a surface, which called adhesion. When one surface slides against another, shear between the adhesive points occurred and the forces that cut these connections are defined as the friction. The plastic deformation will occur when the stress at the contact point reaches the yield limit under compression, the stress at the contact point will not change, but it can bear the increased load by enlarging the contact area. It is proved that the shear strength is related to both the sliding speed and the lubrication state and is very close to the shear strength limit of the softer material in the friction pair. The shear of adhesion points usually occurs inside the softer material, and the friction coefficient is calculated as Equation 1:

\[ \mu = \frac{\tau_b}{\sigma_s} \]  

where \( \tau_b \) is the shear strength limit of soft materials and \( \sigma_s \) is the yield strength limit of the softer material in the friction pair.

There is a corresponding relationship between the yield strength limit and shear strength limit of metal materials.

\[ \tau_b = \sqrt{3} \frac{f}{3} \]  

\[ f = \frac{\sigma_s}{\gamma_s} \]  

where \( f \) is the tensile strength of material, \( f \) is the shear strength of material and \( \gamma_s \) is the partial coefficient of material, steel strand value is 1.2.

The maximum yield stress \( \sigma_s \) is 1835 Mpa. The shear strength can be obtained by equation 2 and 3, \( \tau_b = 882 \) Mpa, the wires of steel strand have the same material, so the friction coefficient satisfies:

\[ \mu = \frac{\tau_b}{\sigma_s} = \frac{882 \times 10^6}{1835 \times 10^6} = 0.48 \]

Considering that the shear strength of the adhesive point on the contact surface is related to both the velocity and the contact pressure, the friction coefficient of the adhesive point will fluctuate.

3. Structure and contact load

The steel strand composes of a core and six external wires. The external wires twisted together with the same direction[9,10]. The parameters are shown in Table 1.

| Geometric Parameters | Mechanical property |
|---------------------|---------------------|
| diameter \( d \) (mm) | strength grade (Mpa) |
| Monofilament diameter \( d_0 \) (mm) | Modulus of elasticity (Gpa) |
| Twist distance \( l_0 \) (mm) | Poisson ratio |
| Twisting angle \( \alpha \) (° ) | Elongation (%) |

The structure of steel strand is shown in Figure. 1,
The friction between the core and external wires is different due to its configuration. The core wire only affected by the circumferential forces $p_i (i = 1, 2, \ldots, 6)$ from the external wires, which are equal in value and all point to the center of the core wire. The external wires are affected by the reaction force $p_c$ of the core wire and the force of adjacent external wires $p_o$. The forces between wires are shown in Figure 2.

The force acting on the core wires distributes along the longitudinal direction linearly. By the basic equation.

$$ F = \mu \cdot N_o \quad (4) $$

where $F$ is the maximum static friction force of the strand slip; $\mu$ is the coefficient of friction of steel strand; $N$ is the joint force of the external wires to the force of the core wire.

$$ N = \sum^6_{i=1} N_i \quad (5) $$

$$ N_i = p_i \cdot (l - l_o) \quad (6) $$

where $N_i$ is longitudinal friction force of external wires on core wire; $p_i$ is the line load of the external wire to the core wire; $l$ is the length of the test piece; $i$ is number of external wires.

When the length of the steel strand is less than the twist distance, the external wires have no winding tension on the core wire. The equation for the maximum friction of the core wire drawing:

$$ F = \mu \cdot \sum^6_{i=1}[p_i \cdot (l - l_o)] \quad (7) $$

For the tension load value of the external wires to core wire is small, the strain of the wires can be ignored, and the external wires should maintain uniform contact with the adjacent external wires. The external wire can be regarded as in the vertical tension. The drawing process considers two cases: the wires are drawn separate from one side, or they keep in touch with both sides and have pressure. When the external wire is drawn, the dividing force is produced along the tangent direction of the core wire, as shown in Figure 3.

$$ F_0 = T \cdot \sin \alpha \quad (8) $$

where $F_0$ is drawing load.

When the external wire and adjacent external wires maintain contact throughout, the maximum static friction of external wires drawing is linear with its length.
Decomposing load $T$, The resultant force of the wires is always unchanged by the force acting on the core and adjacent external wires, and is affected by the central filament force. The force from core wire satisfies formula:

$$N_c = N_i = \mu \cdot p_c \cdot (l - l_0)$$  \hspace{1cm} (10)

where $N_c$ is Friction of core wire on external wire, interacting forces and counteracting forces with $N_i$; $p_c$—The linear load of the core wire on the external wire, interacting forces and counteracting forces with $p_i$.

The force of adjacent external wire:

$$N_o = \mu p_o (l - l_0)$$  \hspace{1cm} (11)

Decomposition of tensile strands along the longitudinal direction can get the formula 12 based on force balance:

$$T \cdot \cos \alpha = 2N_o + N_c$$  \hspace{1cm} (12)

When the wire is separated, $N_o < T \cdot \sin \alpha$, equation 12 changes into:

$$T \cdot \cos \alpha = T \cdot \sin \alpha + N_c + N_o$$  \hspace{1cm} (13)

Whether the drawn external wire would separates from the adjacent wire, it need to be calculated and verified.

4. **Experimental research**

4.1. **Experiment scheme**

The drawing load will change at the moment the strand sliding when the wire of steel strand being pulled, the changing point of the drawing load is the maximum static friction, and then transforms into sliding friction. The contact load of wires is linear load, and the ends of steel strand are free, the load decreases from the middle to the ends gradually. While the stiffness of the steel strand is large and we can assume that all wires are in uniform contact. This means the linear load uniformly distributed along length, so the contact load of wires can be calculated based on measured static friction coefficient, and the static friction coefficient can be obtained by experimental method.

4.1.1 **Experiment scheme of friction coefficient measurement**

The surface of wires will wear when it slides, besides, sliding friction is affected by many external factors; the sliding friction measured produces larger fluctuations. The load of the first slip between the wires can be regarded as the effective anti-sliding load; it is related to static friction. The effect of speed and wear on friction coefficient do not need to consider in static friction. Therefore, the maximum static friction coefficient was designed. The test device is shown in Figure. 4.

![Figure 4. Schematic diagram of friction coefficient determination](image)

The material of the plate is 82B high carbon steel, it has superior mechanical properties[11]. The surface of the specimen makes hot galvanizing treatment and the process is same as galvanized steel strand. Placing the slide on different positions of galvanized plate, raise the side of the plate continuously, and record the slipping angle of slider. Changing the quality of the slider to change the contact force during friction. The experiment uses different bottom plates to avoid wear and the influence of processing technology on measurement data.
4.1.2 Experiment scheme of drawing
It is difficult to measure the contact load of wires directly, considering the longitudinal sliding load of wires only related to the maximum static friction, so can obtain the slip load of the steel strand through the tensile test. The maximum pulls out test load of steel strand is equal to the largest static friction, through the maximum static friction coefficient measured, the structural load between wires can be studied according to the friction relation[12].

The drawing experiment instrument adopts hydraulic drawing machine and matching data acquisition equipment, the two ends of the drawing machine are clamped fixed ends. In order to obtain structural load of steel strand, when wires are drawn, it need to be fixed without apply external loading. Otherwise, it will affect the determination of tectonic load. Clamping the ends of wires directly will increase the load between wires, which impact the experiment results. To reduce the influence of external loads on the measurement of the structural load of steel strand, customized equipment according to the structure of steel strand. The force of steel strand when drawing is shown in Figure 5.

![Figure 5. Schematic drawing of steel strand drawing](image)

4.2. Experiment results
Equivalent static friction coefficient of galvanized steel strand is equivalent, using galvanized steel with the same coating as steel strand, both the slider and the bottom plate are zinc plated[15], the slider slides freely along the slope, the static friction coefficient is between 0.42 and 0.52.

4.2.1 Drawing load of wire
The force-displacement curves of the core wire under different drawing rates are shown in Figure 6 to 8.

![Figure 6. Curves with rate of 10mm/min](image)
![Figure 7. Curves with rate of 20mm/min](image)
![Figure 8. Curves of with rate of 30mm/min](image)

Figure 9. Maximum drawing load under different velocity
The drawing process of core wire can be divided into three stages according to the time history curve of force-displacement. In the first stage, there is no slip occurs during the drawing of core wire,
and the force increases rapidly. When the friction reaches the maximum value, the wire begins to slip and the load value changes abruptly. In the second stage, the wire slides uniformly, and the axial force decreases continuously and tends to be stable. At this stage, the contact point of the wire is worn. In the third stage, the drawing force of steel strand is in a gentle stage, the force tends to be unchanged and the slip of wires is uniform. In this stage, the contact surface of core wire and external wire are worn out, the circumferential extrusion of external wires to core wire reduce, and therefore, the friction effect is reduced. Under the low-speed static drawing, the drawing rate has no obvious effect on the maximum static friction of wire slip, and the deviation comes from the production process of wire and the sample processing.

### 4.2.2 Analysis of experiment data

The maximum load of the core wires drawing is shown in Table 2.

| Length (cm) | Drawing velocity (mm·min⁻¹) | Average value (N) |
|-------------|-----------------------------|-------------------|
| 10          | 106.19                      |                   |
| 25          | 20                          | 108.64            |
| 30          | 118.15                      |                   |
| 10          | 142.40                      |                   |
| 30          | 164.04                      |                   |

Averaging the static friction value of all wires and the fitting line is shown in Figure 9. According to the load values fitted by Figure 13, the friction coefficient $\mu$ is 0.42-0.52 based on the measurement and theoretical calculation value. The maximum frictional forces of single wire is 0.42 N/m and the minimum value is 0.36 N/m.

$l_0 = 21.73\text{cm}$, compared with the theoretical value 22cm, the error is 1.5%. When the wire is short, the maximum static friction force of core wires in unit length Between $4.14\text{kN/m} \sim 6.00\text{kN/m}$. When $l < 0.22m$, $N_0 = 0$, there is no inter extrusion between wires. The maximum axial force in the drawing process of steel strand is smaller than 1kN, its strain is $4.8 \times 10^{-9}$, which can be neglected.

### 5. Conclusion

The drawing experiment is carried out to understand the effect of friction on wire slip between steel strand and internal load situation, the steel strand with different length was drawn under different velocity, comparing the results with theoretical calculation and the following conclusions are drawn: The maximum static friction coefficient of steel strand is a fluctuation value, which is related to material processing conditions and technology. The friction coefficient is between 0.42 and 0.52, and the theoretical calculation value 0.48 is within the range of measurement value.

The anti-slip load of core wire of steel strand is linear with the length. The linear load of friction between core wire and external wire is between 0.36 kN/m $\sim 0.42$kN/m; The maximum static friction
is not related to the drawing rate.

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