Research Article

Analysis of Strength Factors of Steel Cord Conveyor Belt Splices Based on the FEM

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1.Introduction

As a continuously moving transport facility, the conveyor has been widely used in fields such as mining, coal, port, electric power, chemical industry, metallurgy, architecture, and food [1, 2]. Figure 1 shows the structure of a conveyor belt and three application fields of the conveyors. A conveyor belt is an important element of the conveyor. Its properties greatly affect the functions of the conveyor system. Especially, the strength of the conveyor belt largely determines the carrying capacity, and it also has a great impact on operational safety. Therefore, the strength of the conveyor belt has always been the focus of researchers and users.

In order to increase the strength of the conveyor belt, the steel cords are arranged inside the rubber. First and foremost, the weakest region in the conveyor belt is the splice [3]. The belt broken accidents would occur due to decrease in splice strength. In previous studies and publications, researchers were more focused on the conveyor construction and conveyor belt splice strength detection. But for the strength factors of the steel cord conveyor belt splice, they paid insufficient attention, although the strength significantly affects the whole transport facility and even the whole system on the durability and reliability [4].

There have been various methods for detecting splice strength. In 1979, Harrison first proposed a nondestructive testing method for a steel rope of a conveyor belt based on the principle of electromagnetic induction and developed a CBM steel core conveyor belt steel rope detection device [5]. Based on this principle, similar devices have been developed by German DMT Company and American Goodyear Company [6]. In 2005, German Phoenix Conveyor Belt System Co., Ltd., designed a steel cord conveyor belt detection system using X-ray detection technology [7]. Our team developed a nondestructive testing system for the steel cord conveyor belt based on X-ray, which realized accurate
and reliable detection of splice twitch and steel cord breakage [8]. In 2013, Fedorko et al. proposed an experimental method based on CT technology for measuring the internal structure and dynamic characteristic parameters of the steel cord conveyor belt [9]. In 2015, Mazurkiewicz put forward a method of joint elongation monitoring based on fuzzy logic, which can realize the prediction and early warning of joint elongation by using the data acquired by using the electromagnetic induction sensor [10]. The above nondestructive testing technologies are increasingly mature and have been used in actual production. However, for the strength determination of the conveyor belt splice, all of these methods have the defects of poor accuracy and reliability.

In 2018, Bajda and Hardygòra analyzed the influence of the natural ageing time on the strength parameters of steel cord conveyor belts using the universal stretching machine. The tests included adhesion of the steel cords to the belt’s core rubber and the tensile strength of both the carry and the pulley covers [11]. But the strength performance analysis of the conveyor belt splice is not covered in this paper.

For the FEM (finite element method) as an effective numerical analysis method, more and more attention is being paid in many simulation studies. Quite a lot of researchers are using FEM for the study of conveyor belts [12, 13]. In 2014, Taraba modelled the influence of the dynamic force of the steel cord conveyor belt which under the stress and strain conditions [14]. In 2017, Du et al. simulated the steel cord stress and fatigue life of the steel cord conveyor belt. A valuable conclusion has been obtained, which fully reflects the feasibility of finite element analysis [15]. In 2018, our group has studied the steel cord pitch of the conveyor belt splice. It is concluded that the steel cord spacing has a certain influence on the splice strength. If the spacing is too large or too small, the strength of the conveyor splice will be reduced. This provided a theoretical basis for the selection of the overlap spacing of our splice steel cord [16–18].

In order to study the other factors those influence the strength of the conveyor belt and analyze the trends in the effects of each factor on the strength, in this paper, we will simulate and analyze the dynamic properties of the conveyor belt by using Abaqus. Four factors including the steel cord length, diameter, rubber thickness, and the number of steel cord will be mainly studied.

2. Finite Element Model Introduction

2.1. Finite Element Model Material. In the simulation of the conveyor the belt splice, the materialization of the model can be divided into two main parts: steel cord and rubber.

For the selection of the parameters of the steel cord material, we mainly refer to the correlation coefficient of the ST630 conveyor belt and the series of properties of the steel. We set the density \( \rho = 7.85 \times 10^{-9} \text{ Ton/mm}^3 \), Poisson’s ratio \( \mu = 0.29 \), and elastic modulus \( E = 210 \text{ GPa} \) [16].

Rubber is a polymer material, and its properties are complex. Its properties are usually rather varied and depend on its composition and the contents of special ingredients. The rubber used to make the conveyor belt is often not made of a rubber material. There are some other materials to change the hardness and strength of the conveyor belt rubber [19]. We set the rubber in the simulation model according to the parameters of the ST630 supplied by the conveyor belt manufacturer. In the many comparisons between simulation and experiment, we found the Mooney–Rivlin model is the best fit [16]. And we obtained the general strain energy function as follows:

\[
W = \sum_{i+j=1}^N C_{ij} (I_1 - 3)^i (I_2 - 3)^j + \frac{1}{2N} I_3 (I_3 - 1)^2, \tag{1}
\]

where \( C_{ij} \) are the material constants, \( I_1, I_2, \) and \( I_3 \) are the invariants of the left Cauchy–Green strain tensor, and \( N \) is the natural number.

Binomial third-order expansion is

\[
W = C_{01} (I_1 - 3) + C_{02} (I_2 - 3) + \frac{1}{D} (I - 1)^2, \tag{2}
\]

where \( C_{01} \) and \( C_{02} \) are the material constants and the strain gradient tensor \( F \) determinants \( J \), and \( D \) is the material constant related to the bulk modulus [16].

2.2. Failure Unit. In the actual conveyor joint, there is an adhesive layer between the rope and the rubber. The adhesive layer is also critical to the strength of the conveyor splice. In the finite element simulation, we placed a failure layer between the steel cord and the rubber to simulate the adhesive layer in the conveyor belt splice. From Figure 2, we can see the steel cord unit, rubber unit, and failure unit.

3. Numerical Simulation and Experimental Investigations

3.1. Finite Element Model and Experimental Samples. Figures 3(a)–3(d) are finite element models of single steel cord conveyor belt splices with lengths of 50.0, 70.0, 80.0, and 100.0 mm, respectively.

Figures 4(a)–4(d) are the splice samples of experimental single steel cord conveyor belt splices with lengths of 50.0, 70.0, 80.0, and 100.0 mm correspondingly. The coefficient of uniformity of the rubber and steel cord is the standard of the steel cord conveyor belt of ST630.

3.2. Change of Adhesive Layer in Simulation and Experiment. When the pullout force reaches the maximum value, the steel cord is completely debonded from the rubber. The steel cord and the rubber are in a slip state and separated. As shown in Figure 5(a), it is a steel cord and rubber separated in the simulation. When the pullout force reaches the maximum, the unit fails and is deleted. The force between the steel cord and the rubber is almost zero. As shown in Figure 5(b), in the experiment, the pullout force was maximized and the steel cord was separated from the rubber. By comparing the adhesion layer between the simulation and the experiment, we can find that the changes between the two are relatively close.
3.3 Simulation and Experimental Results. In the simulation, a forced displacement is applied to the steel cord. When the displacement between the steel cord and the rubber changes, the magnitude and variation trends of the pullout force are obtained. In the experiment, we used a universal stretching machine to clamp the ends of the experimental sample. A forced displacement is applied over a section to stretch the sample so that the steel cord draws a different displacement from the rubber. The computer will record the magnitude and trend of the extraction force at different displacements.

In general, both in the simulation and experiment, the displacement between the steel cord and the rubber is changed to obtain the magnitude and variation of the extraction force.

Figure 6(a) shows the varieties of pullout force with time in the numerical simulation, and Figure 6(b) shows the experimental result. We can see that when the length of the steel cord is the same, the trend of the simulation and experimental pullout force is very close.

Table 1 shows the simulation and experimental data of the pullout force. We can know that when the length of steel cord is same, simulation and experimental extraction force results are very similar. So the simulation can be considered successful.

4. Analysis of Conveyor Belt Strength Factors

Different conveyor belt finite element models have been established by using Abaqus/CAE, to study the strength changes of steel cords under different factors. In addition to the above different steel cord length studies, simulations were also done for different steel cord diameters, rubber thickness, and steel cord numbers, and they are varied to study the effect on the strength of the steel cord conveyor belt.

4.1 Steel Cord Conveyor Belt Length. In the above simulation experiment, the relationship between the length and strength of steel cord conveyor belts is obtained and is shown in Figure 7.

When the length of the steel cord increases from 50.0 mm to 100.0 mm, the pullout force increases linearly, and the approximate satisfaction of the relation is as follows:

$$F = 4349 + 74.4 \times \nabla l \quad (\nabla l \geq 0),$$

(3)

where $F$ is the pullout force and the unit is N and $\nabla l$ is the increments of steel cord length and the unit is mm.

4.2 Steel Cord Diameter. The effect of steel cord diameter from 2.0 mm to 4.5 mm has been studied numerically and the following conclusions are drawn. The finite element models of steel cord diameter of 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 mm are shown in Figure 8.

Numerical simulation results are shown in Figure 9. It shows the effect of the different steel cord diameters for the pullout force. When the diameter of the steel cord increases from 2.0 mm to 3.5 mm, the pullout force increases linearly, and the approximate satisfaction of the relation is as follows:

$$F = 2298 + 1943 \times \nabla d \quad (0 \leq \nabla d \leq 1.5),$$

(4)
where $F$ is the pullout force and the unit is N and $\nabla d$ is the increment of steel cord diameter and the unit is mm.

When the diameter of the steel cord increases from 3.5 mm to 4.5 mm, the pullout force is increasing, but it has become slow. However, the effect of different steel cord diameters on the strength of conveyor belts is enormous. It is important to guide us to produce the conveyor belt with the required strength.
4.3. Rubber Thickness. For studying the effect of rubber thickness on the pullout force, the rubber thickness was considered to be 4.0, 5.0, 5.5, 6.0, 6.5, and 7.0 mm, and the finite element models of the steel cord conveyor belt with the strength specification of ST630 are shown in Figure 10. All the numerical simulation results are shown in Figure 11.

When the rubber thickness is increased from 4.0 mm to 5.0 mm, the pullout force increased 671 N. It can be said that the change is more obvious. However, when the rubber thickness is increased from 5.0 mm to 7.0 mm, the change of the pullout force is quite slow. It can almost be considered that the force no longer increases. In general, the contribution of rubber to strength of the steel cord conveyor belt is very small compared to the steel cord. It is not feasible to change the strength of the conveyor belt by changing the rubber thickness.

4.4. Steel Cord Number. In the above simulations, all of them are single steel cord. In order to further study the strength of the steel cord conveyor belt, we built multiple steel cords. We established a model of steel cord conveyor belts with

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**Table 1: Simulation and experimental data.**

| Length of steel cord (mm) | Numerical value (N) | Experimental value (N) | Relative error (%) |
|--------------------------|---------------------|------------------------|--------------------|
| 50.0                     | 4669                | 4422                   | 5.59               |
| 70.0                     | 5484                | 5664                   | 3.18               |
| 80.0                     | 6384                | 6807                   | 6.74               |
| 100.0                    | 8067                | 8652                   | 6.76               |

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*Figure 6: Simulation and experimental results. (a) Numerical results. (b) Experimental results.*

*Figure 7: The change in pullout force with different lengths.*
different numbers of steel cords and simulated. As shown in Figure 12, there are two and four steel cord conveyor belt models. Simulations were performed on 50.0 mm long models of the single steel cord. The numerical and experimental pullout force with time for different steel cord numbers is obtained in Figures 13(a) and 13(b), respectively.

When the number of steel cord is increased from one to four, the pullout force also increases. However, compared to

Figure 8: Finite element model of different steel cord diameters. (a) 2.0 mm, (b) 2.5 mm, (c) 3.0 mm, (d) 3.5 mm, (e) 4.0 mm, and (f) 4.5 mm.

Figure 9: The change in pullout force with different steel cord diameters.
one and two steel cords, when the number of steel cord is increased, the pullout force is determined to be less than the same length of the single steel cord. The simulation and the experiment have the same conclusion. When we simulated two steel cord models, the force exerted by the two steel cords is reversed, the same as the actual experiment. In the process of pulling out the steel cord, the rubber damage between the two steel cords is quite serious. This leads to reducing the pullout force of the steel cord. In the study of multiple steel cords, the simulation results are in good agreement with the experimental results.

For four steel cords, there are two steel cords on each side. Comparing one and four steel cords is actually a comparison of the pullout force between one steel cord and two steel cords on one side. From the experimental results and simulation results, we can clearly see that increasing the number of steel cords does increase the pullout force of the conveyor belt. However, even if the steel cords are doubled, the increase in pullout force is less than doubled pullout force. In other words, the increase in the number of steel cords does not mean that the tension will increase by the same multiple, and the rate of increase in pullout force is less

Figure 10: Finite element model of different rubber thickness. (a) 4.0 mm, (b) 5.0 mm, (c) 5.5 mm, (d) 6.0 mm, (e) 6.5 mm, and (f) 7.0 mm.

Figure 11: The change in pullout force with different rubber thickness.

| Rubber thickness (mm) | Pullout force (N) |
|-----------------------|-------------------|
| 3.5                   | 3600              |
| 4.0                   | 3800              |
| 4.5                   | 4000              |
| 5.0                   | 4200              |
| 5.5                   | 4400              |
| 6.0                   | 4600              |
| 6.5                   |                   |
| 7.0                   |                   |
than the rate of increase in the number of steel cords. Therefore, we can say that, in practical applications, it is not economical to constantly increase the strength of the conveyor belt by increasing the number of steel cords.

5. Conclusion

There are many factors affecting the strength of the steel cord conveyor belt, such as steel cord length, diameter, rubber thickness, and the number of steel cord. This paper analyses the strength factors of the steel cord conveyor belt based on the FEM. Firstly, we verified the reliability of numerical simulation by comparing experiment and simulation. Then, we simulated the model with different steel cord diameters, rubber thickness, and different number of steel cords, to study the effect on the pullout force of the steel cord conveyor belt. The conveyor belt length, steel cord diameter, rubber thickness, and steel cord number at normal impact were found to have different influences. In the four factors, the effect of rubber thickness is the least noticeable. The diameter of the steel cord and conveyor belt length impact on the steel cord conveyor belt is approximately linear. For the different number of steel cords, the increase in the number of steel cords does not mean that the tension will increase by the same multiple, and the rate of increase in pullout force is less than the rate of increase in the number of steel cords. The conclusions obtained above provide values for splice strength, which can tell us the influence of different factors and guide us to make conveyor belts of different strengths. In this way, wasting resources can be avoided as well.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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