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Finite element simulation and experimental verification of steel cord extraction of steel cord conveyor belt splice

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Abstract. The splice is the weakest part of the entire steel cord conveyor belt. And it occurs steel cord twitch fault frequently. If this fault cannot be dealt with timely and accurately, broken belt accidents would be occurred that affecting the safety of production seriously. In this paper, we investigate the steel cord pullout of the steel cord conveyor belt splice by using ABAQUS software. We selected the strength of steel cord conveyor belt ST630, the same as experiment sample in type specification. The finite element model consists of rubber, steel cord and failure unit. And the failure unit is used to simulate the bonding relationship between the steel cord and the rubber. Mooney-Rivlin hyper-elastic model for rubber was employed in the numerical simulations. The pullout force of length 50.0 mm single steel cord,on both sides of a single steel cord and on both sides of the double steel cords each impacted at steel cord conveyor belt splice were numerically computer and typical results obtained have been validated by experimental result. It shows that the relative error between simulation results and experimental results is within 10% and can be considered that the simulation model is reliable. A new method is provided for studying the steel cord twitch fault of the steel cord conveyor belt splice.

1. Introduction

Conveyor belts are the key components of the belt conveyor traction and carrying, which account for more than 40% of the total cost of the belt conveyor [1]. The steel cord twitch fault is the main reason for broken belt and it is needed to be prevented and controlled. According to the statistics, 93.75% broken belt occurred at the splice [2,3]. As the steel cord twitch fault cannot be timely and accurate detection and treatment, broken belt accidents occur frequently, seriously affect the safety of production. Our team earlier developed a non-destructive detecting system for X-ray steel cord conveyor belts. However, it still needs to do a more in-depth study in the quantitative analysis of steel cord twitch. Especially, it is not clear in quantitative relationship between steel core twitch and splice strength. Due to the lack of quantitative theoretical analysis of steel cord twitch, after detecting the steel cord twitch fault, the users of the steel cord conveyor belts only by experience and connector lap margin, select the local processing, redo the connector or replace a section or the entire conveyor belt. The over correction will affect the production and cause a huge waste of resources [4,5].

Finite element simulation technology is an important numerical simulation technology in

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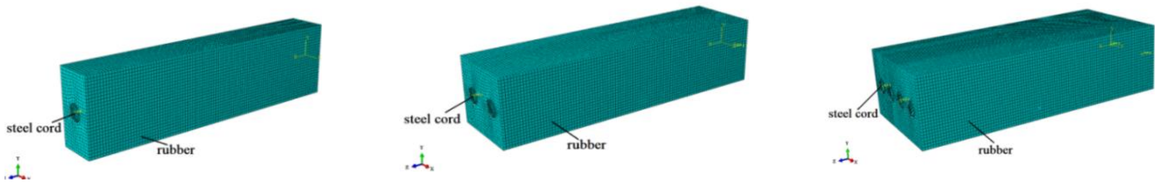
engineering application. It has been used in the steel cord conveyor belt splice analysis for many years. Conveyor Dynamics Inc. of the United States (CDI) developed a 3-dimensional finite element model of steel cord and isotropic hyper elastic nonlinear rubber. The numerical simulation was carried out by ANSYS software, and the formula for selecting these parameters is also given to guide the design of splice [6]. Adamas uses rubber as an incompressible material and analyzes the splice using finite element simulation techniques under nonlinear large deformation conditions, the simulation results obtained and the experimental results are similar [7]. In 2012, Mazurkiewicz investigated a finite element method that was used to simulate the behavior of a rubber conveyor splice, analyzed the influence of the rubber layer thickness on the strength of the splice, and evaluated the possibility of making predictions the fatigue and the strength of splice, and it is valuable of guiding the structural design of splice by using this model. However, the method and model are aimed at ordinary rubber conveyor belt, not the steel cord conveyor belt [8]. In 2016, Li Yuan *et al* studied finite element analysis method of Aramid fiber rubber belt splice strength, and established the finger splice finite element model. The influence of the width of the finger root, the thickness of the glue and the enhance layer placement direction on the strength of the splice were analyzed [9]. In 2017, Du Wenzheng *et al* found a method of steel cord stress analysis and a study of fatigue life. And the Von-Mises equivalent stress at the contact between the core cord and the inner steel cord is the maximum and the fatigue life is the minimum [10]. The above results show the feasibility and effectiveness of finite element simulation in the analysis of steel core twitch at the steel cord conveyor splice. However, the quantitative relationship between steel core twitch and splice strength based on this technology needs to be further studied.

In this paper, we investigate the steel cord pullout of the steel cord conveyor belt by using ABAQUS software. The pullout force of length 50.0 mm single steel cord, on both sides of a single steel cord and on both sides of the double steel cords each impacted at steel cord conveyor belt were numerically computer. Numerical simulations have been performed on ABAQUS / Explicit finite element code and typical results obtained have been validated by experimental result. Close correlation of typical experimental and numerical results validated the numerical procedure and the model.

2. Constitutive model

2.1. Finite element model establishment

The establishment of the model in the simulation and experiment are selected strength specifications for the ST630 steel cord conveyor belt. When establishing the model of the conveyor belt steel, the steel is simplified and replaced by a cylinder which in order to reduce the difficulty of modeling. The geometric model of the steel cord conveyor belt with length of 50.0 mm single steel cord, on both sides of a single steel cord and on both sides of the double steel cords was made in ABAQUS/CAE shown in figures 1(a)-1(c).



(a) Single steel cord (b) On both sides of a single steel cord (c) On both sides of double steel cords

Figure 1. Finite element steel cord conveyor belt splice model.

2.2. The definition of material constitutive relationship
The numerical simulations were carried out using ABAQUS/ Explicit finite element code. The material model of the rubber, steel cord and failure unit was made in ABAQUS shows in figure 2. The rubber belongs to the hyper elastic material behavior, while the material of the steel cord was linear elastic, the failed unit are set to be the same as the steel cord and adding the material breaking behavior based on the physical criteria.

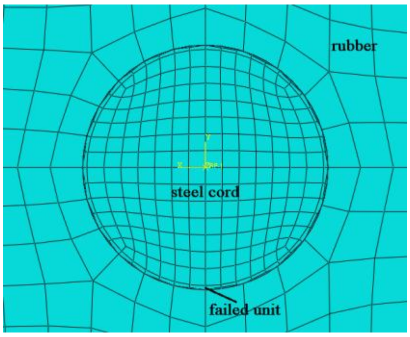


Figure 2. Finite element model material definition.

2.2.1. Rubber materials. In the numerical simulation, the upper and lower coverings of the steel cord conveyor belt are treated as rubber, and the rubber is a kind of polymer, belonging to the polymer material. Its stress-strain behavior belongs to the hyper elastic material behavior and uses the strain potential (U) (strain energy potential) to describe in ABAQUS. Strain potential has many forms, the polynomial strain potential is more commonly used [11]. And the Mooney-Rivlin model is used to describe the stress behavior of rubber in the numerical simulation. Mooney-Rivlin formal model is defined as:

$$U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{D}(J - 1)^2 \tag{1}$$

Where U is the strain potential, J is the elastic volume fraction, I_1 and I_2 are the torsional measures in the material, C_{10} and C_{01} are the shear properties of the material and D is the compressibility (coefficient).

2.2.2. Steel cord material. The steel cord is defined as an ordinary linear elastic material and the material parameters are set as follows: elastic modulus E=210 GPa, Poisson's ratio μ=0.28 and density $\rho = 7.85\times10^{-9}$ Ton/mm^3. In the present study, the amount of deformation of the steel cord relative to the rubber during the taping process is very small and in order to save calculation time and improve the efficiency, the steel cord was neglected since it is taken as rigid body.

2.2.3. Failure unit material. Failure unit plays a key role in the whole numerical simulation which is used to simulate the bonding between the steel cord and rubber, in order to get more accurate simulation results, the failure unit should be as small as possible in unit size. The failure of the basic parameters of the unit is set to be consistent with the steel cord, as well as add material plasticity behavior and material damage behavior based on physical criteria.

2.3. Definition of unit failure
The material fracture criteria of failure unit were carried out using shear damage in ABAQUS / Explicit. According to physical criteria, when the node's strain value is greater or equal to a given value, the failure unit will be deleted, thus the steel cord will be separated from the rubber. The detach between steel cord and rubber is based on the establishment of shear failure criteria, and the basis of shear failure criteria is based on the equivalent plastic strain ε. The breaking value of each unit can

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be determined by equation (2).

$$D = \frac{\varepsilon}{\varepsilon^{d}} = 1 \tag{2}$$

Where ε is the equivalent strain in the integral step, and ε^{d} is the failure strain under the current conditions. When D=1, the material fails and deletes the relevant unit.

3. Experiment

3.1. Universal testing machine pullout experiment

Figure 3 shows that carried out experiments in the universal testing machine pullout experiment platform. Figure 4 show the experimental sample with length of 50.0 mm single steel cord ,on both sides of a single steel cord and on both sides of the double steel cords were made in steel cord conveyor belt with strength specification ST630 [12].

Figure 3. Universal testing machine pullout experiment platform.

(a) Single steel cord (b) Both sides of a single steel cord (c) Both sides of the double steel cords

Figure 4. Experimental steel cord conveyor belt splice sample.

3.2. Numerical simulation

The numerical simulation with length of 50.0 mm single steel cord pullout of process were carried out using ABAQUS/Explicit in figures 5(a)-5(c). It shows the change of rubber, steel cord and failure unit in the steel cord pullout process.

During the initial stage of the simulation, both the steel cord and the rubber adhered closely and no detach occurred. With the increase of the force exerted on the steel cord, rubber will be pulled out a distance along with the steel cord. And the steel cord extracted constantly, the deformation of rubber is more and more prominent. Until the extraction force reaches the maximum, it happened some degree of de-bonding in the bonding interface between the steel cord and rubber which led to failure, and the steel cord and rubber will be separated. After the extraction force reaches the maximum value, the steel cord is separated from the rubber and is in a slippery state, then the extraction force rapidly drops

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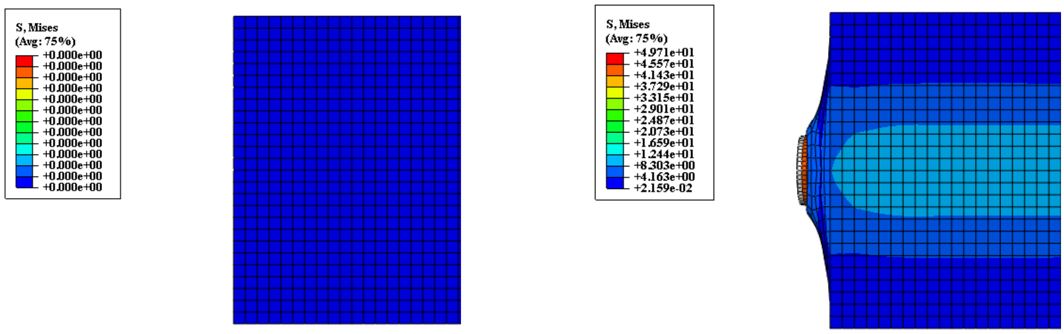
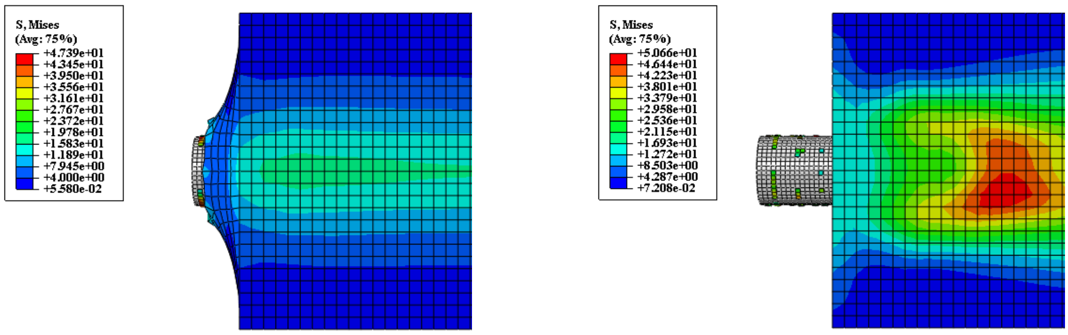
to a minimum.



(a) Steel cord is not stressed (b) Steel cord begins to be stressed

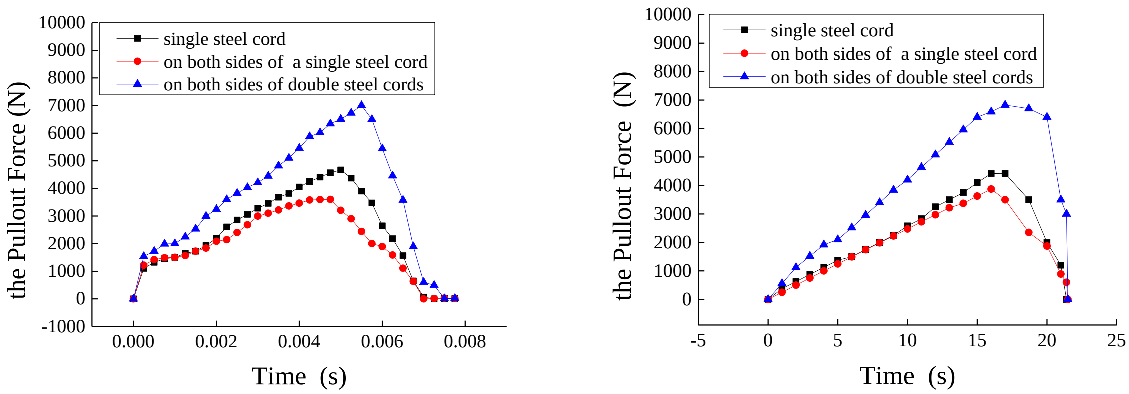


(c) Steel cord is stressed to the maximum (d) Steel cord and rubber are in a slippery state

Figure 5. Process of steel cord pulled out of rubber.

4. Results and discussion

Simulations were performed on 50.0 mm long models of single steel cord, on both sides of a single steel cord and on both sides of the double steel cords, and the varieties of pullout force with time of the numerical and experimental were obtained in figures 6(a) and 6(b), respectively. It can be seen that the trend of the pullout force with time almost the same by comparing (a) and (b). At the beginning, the extraction force is linearly increased to the maximum, and then quickly dropped to zero. For different numbers of the steel cords, the extraction force is also different.



(a) Numerical results (b) Experimental results

Figure 6. Pullout force - Time graph of different steel cord numbers.

Experimental and numerical results for 50.0 mm long models of single steel cord, on both sides of a single steel cord and on both sides of the double steel cords are shown in table 1. It can be seen that the relative error between simulation results and experimental results is within 10%. As the experiment is not only affected by external environmental factors, such as: surrounding temperature, humidity and damage in sample preparation etc., but the conveyor belt internal factors, for example, there are different degrees of aging or deformation because of the different time of the sample placement in the sample preparation process. Therefore, the error within 10% is acceptable, and it can be considered that the simulation model is reliable.

Table 1. The comparison of the numerical results with the experimental results.

steel cord	Numerical value (N)	Experimental value (N)	Relative error
Single steel cord	4669	4422	5.59%
On both sides of a single steel cord	3660	3995	8.39%
On both sides of double steel cords	7007	6827	2.64%

It shows that the relative error between simulation results and experimental results is within 10% and it can be considered that the simulation model is reliable. It provides a new method for studying the steel cord twitch fault of the steel cord conveyor belt splice.

5. Conclusion

Numerical simulations have been performed on ABAQUS / Explicit finite element code and typical results obtained have been validated by experimental results, close correlation of typical experimental and numerical results validated the numerical procedure and the model.

In this paper, it provides the value of the steel cord pullout force at different steel cord numbers, and the results provide a useful basis and reference for the performance of steel cord conveyor belt splice with theoretical research and application.

Acknowledgments

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