

# MODELING AND SAFETY ANALYSIS OF REINFORCEMENT WITH BUNDLING STRAP IN RAILWAY FREIGHT TRANSPORTATION

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***Summary:** In view of the defects of recent safety assessment of reinforcement, this paper demonstrates the safety assessment of reinforcement through dynamics simulation. Through the development of the mechanical model of bundling strap, a detailed freight bundling strap reinforcement model is established to formulate a complete vehicle-freight-reinforcement system dynamics model. This paper calculates the internal force of bundling strap and freight acceleration under different speed to obtain the variation rules, conducts a simulation of longitudinal impact on operating condition with both reinforcement normal and failure and assesses the safety of reinforcement under the longitudinal impact. The results of simulation indicate that the reinforcement is safe and feasible and the safety assessment of reinforcement through dynamics simulation is more accurate and detailed.*

***Keyword:** Railway vehicle dynamics, bundling strap model, vehicle-freight-reinforcement model, reinforcement safety.*

## I. INTRODUCTION

Freight reinforcement refers to that the freight shall be fastened with certain method so as to ensure no occurrence of movement, rolling and overturn during the transportation and maintain original displacement under impacts of various forces. Therefore, a reasonable and feasible reinforcement scheme is the solid foundation for safe transportation<sup>[1-2]</sup>.

After finalizing the loading scheme, an appropriate method shall be selected to design the corresponding reinforcement scheme. The common reinforcement methods are lashing reinforcement, wooden or steel stopper, hoarding, barrier and integral bundling, etc. The reinforcement scheme mainly concerns the force status of freight and the properties of reinforcement materials. Ensure the magnitude of force applied to freight and the reinforcement devices, guarantee the reinforcement materials meet the criterion, and determine the category

and quantity of reinforcement devices. Different reinforcement methods like lashing, bundling or waist strap reinforcement shall be adopted in accordance with different types and shapes of freight. In addition, steel stopper, wooden stopper or block shall also be adopted in the auxiliary reinforcement. The reinforcement scheme shall be determined in accordance with the specific structure of freight, for example, for the cylinder-shaped freight without lashing knots, the method of waist strap reinforcement with the quantity, materials and strength of extension of every straps determined; or the method of bundling strap reinforcement with the quantity, bundling methods and strength of extension of every straps determined shall be adopted. For irregularly-shaped freight like large-sized excavators, the method of lashing reinforcement shall be adopted, determine the place and quantity of lashing reinforcement and select the diameter and strength of lashing wire so as to formulate the reinforcement scheme. For freight adaptable for multi-reinforcement scheme, the main technical-economic indicators of all the reinforcement schemes shall be compared so as to adopt the optimal scheme with simple operation and economical materials <sup>[3-4]</sup>.

The safety of freight reinforcement is the fundamental principle for assessing the feasibility of reinforcement scheme, which can be evaluated in the following aspects: 1) no occurrence of relative displacement for reinforced freight; 2) the vibrational status of the reinforced freight shall maintain within its vibration limits 3) the force the reinforced freight born shall not exceed its resistance strength. The reinforcement scheme has higher requirements for special freight like hazardous and explosive goods. For example, it requires that certain reinforcement devices shall still ensure the safety of freight in the event of a failure. The safety of reinforcement scheme are generally assessed in accordance with previous experience and simplified force analysis recently, which lacks of fully considering the operation status and extreme operating condition of freight and vehicles, resulting in safety accidents due to insufficient reinforcement or over reinforcement, transportation costs increasing and resources wasting.

In view of the defects of recent safety assessment of reinforcement, this paper assesses the safety of reinforcement through establishing a complete vehicle-freight system dynamics model and a detailed modeling of the reinforcement with full consideration of the operation status and extreme operating condition of vehicle. This paper takes the example of transporting specific cylinder-shaped freight by the covered wagon, adopts the method of bundling combined with wooden stopper reinforcement scheme, analyzes the internal force of bundling strap and freight vibration acceleration through dynamics simulation so as to further assesses the safety and feasibility of the reinforcement scheme.

## **II. RAILWAY VEHICLE-FREIGHT-REINFORCEMENT MODELING**

The cylinder-shaped freight mentioned in this paper shall be transported by TP<sub>9</sub> Type Special Covered Wagon <sup>[9]</sup>, which is composed by the car-body of covered wagon and the welded frame bogie of Z26 Type Special Freight Car <sup>[11]</sup>. The cylinder-shaped freight shall be loaded and reinforced in the container and the container shall be placed in the car-body. The

car-body, bogie, container and freight shall formulate a complicated dynamics system. For the purpose of establishing a three-dimensional dynamics model, the vehicle transportation system can be simplified to a multibody system composed by a series of rigid bodies, forces and constraints. The mathematical model of the system can be demonstrated by differential algebraic equations.

## 2.1. Modeling of Special Railway Covered Wagon

The topology structure of the special covered wagon shall be primarily analyzed. As shown in figure 1 that the topology structure precisely reflects the association relationships among all the components in the system, which lays the solid foundation for establishing dynamics model<sup>[5]</sup>. From the figure we can see that wheelsets, bogie frames and bolsters are combined through spring, side bearing and other forces to form the bogie, and the bogie, car body and container are combined through forces and joints to form the covered wagon system. 6 degree of freedoms (DOFs) are applicable for the wheelsets, bogie frames and bolsters with respect to the track. The container has zero DOF with respect to the car body. And the bolsters have 3 DOFs with respect to the car body. There are wheel-rail force elements between the wheelsets and track. Wheelsets and bogie frame are connected by conical metal-rubber compound spring. The central suspension which includes steel spring, rubber blanket, lateral vibration damper and longitudinal traction rod and lateral elastic stopper are installed between bogie frame and bolster. The bolster and car body shall be connected through the side bearing and central plate and the container and the carbody shall be connected through joint. Base on the dynamic parameters of topology structure and railway vehicle, the dynamics software SIMPACK shall be employed to establish the special covered wagon model.

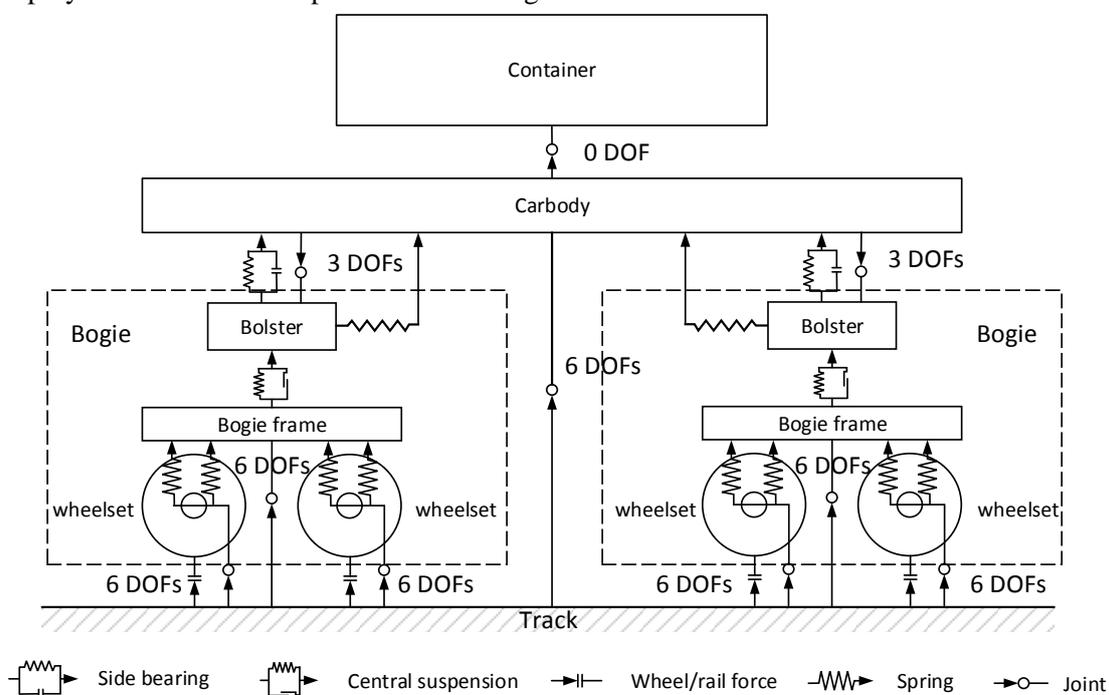


Figure 1. Topological graph of special covered wagon

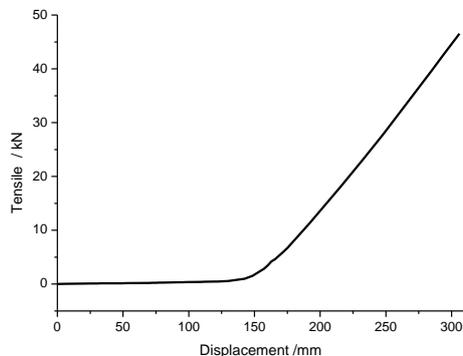
## 2.2. Bundling Strap and Modeling of Freight Bundling Reinforcement

Bundling refers to that freight shall be fastened to the fixed place or piles of freight shall be bundled so as to prevent them from moving. Bundling materials in common use are galvanized iron wire, steel strap, wire rope, fiber rope, etc<sup>[7-8]</sup>. The material in employed in this paper is compound fiber strap, which has sound elasticity. The bundling strap fastened to the freight may loose on account of the vibration and impact during transportation. Therefore, appropriate pretension force shall be selected when conducting reinforcement which not only ensure the reinforcement effect but also avoid the risk of fracture of bundling strap because of the over pretension force.

The mechanical characteristic curve of the bundling strap shall be obtained through tensile test. Figure 2 shows the test result of the bundling strap with the length of 50mm. The model of the compound fiber bundling strap shall be the spring with pretension force. The more the strap is deformed, the larger the tension force will be. When the strap stretches larger than 150mm, its stiffness characteristic presents as linearity. The tensile rigidity  $k_l$  of the strap within linear interval shall be presented as follows:

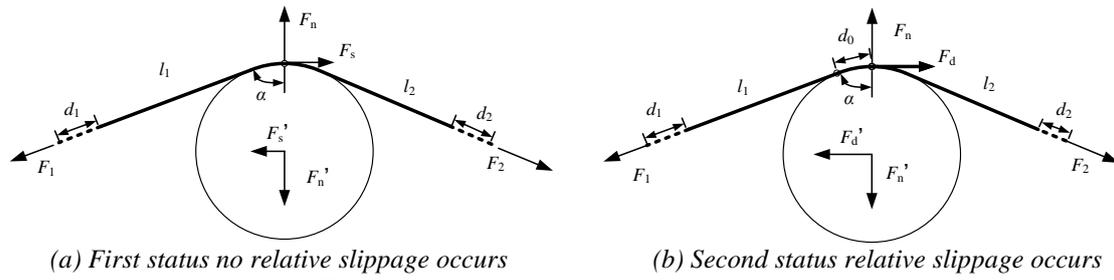
$$k_l = \frac{f}{\delta l} \quad (1)$$

In the above formula,  $f$  refers to the tension force,  $\delta$  stands for the deformation rate and  $l$  is the length of the strap. The tensile fracture value of the strap is 46.54kN and the deformation rate is 613%. Therefore, when verifying the reinforcement of the freight, the force imposed by the strap shall be smaller than the tensile fracture value 46.54kN.



**Figure 2.** The mechanical characteristic curve of the bundling strap

When model the freight bundling reinforcement, on account of the complex relationship between the bundling strap and freight, no proper force can be applied to simulate the force of bundling strap in SIMPACK, thus a secondary developed force model of bundling strap is needed. The relationship between the strap and the cylinder-shaped freight shall be primarily analyzed, which has two statuses: 1) no relative slippage occurs between the strap and freight with only the length change of the sides straps; 2) relative slippage occurs between the strap and freight while the length of the straps changes. The slippage between strap and freight in the first status is static friction, while in the second status is dynamic friction. The force analyses are as follows:



**Figure 3.** Force analyses between strap and freight

The contact point of the strap and the cylinder-shaped freight divided the strap into two parts, and suppose that the initial lengths are respectively  $l_1$  and  $l_2$ , for the first status.

$$\begin{cases} F_1 = F_0 + d_1 k_1 \\ F_2 = F_0 + d_2 k_2 \\ F_n = (F_1 + F_2) \sin \alpha \\ F_s = (F_1 - F_2) \cos \alpha \\ F_s < F_n \mu \end{cases} \quad (2)$$

For the second status, suppose that the relative slippage is  $d_0$ , and  $d_0 \neq 0$ :

$$\begin{cases} F_1 = F_0 + (d_1 - d_0) k_1 \\ F_2 = F_0 + (d_2 + d_0) k_2 \\ F_n = (F_1 + F_2) \sin \alpha \\ F_d = F_n \mu = (F_1 - F_2) \cos \alpha \\ l_1 = l_1' + d_0 \\ l_2 = l_2' - d_0 \end{cases} \quad (3)$$

In the above formula,  $F_0$  is pretension force,  $d_1$ ,  $d_2$  and  $\alpha$  are known,  $k_1$  and  $k_2$  vary in accordance with the deformation rate of the strap. The equation (4) shall be used to obtain  $d_0$ , change the value of  $l_1$  and  $l_2$  as the new lengths of the strap, and  $l_1'$  and  $l_2'$  are the lengths of the strap in the previous moment.

$$d_0 = \frac{(2F_0 + d_1 k_1 + d_2 k_2) \mu \tan \alpha - d_1 k_1 + d_2 k_2}{\mu \tan \alpha (k_1 + k_2) - k_1 + k_2} \quad (4)$$

The whole freight is arranged in two layers with two cylinder-shaped freights on each layer. The wooden mat lies between the first layer of freight and the container, which shall be modelled as the contact and dry friction between timber and steel, in the vertical direction is the unilateral spring contact model and in the horizontal(lateral and longitudinal) direction is the dry friction connection. In addition, springs shall be employed as the fastening bolts between freight in two layers and between freight in the same layers. The wooden stopper lies between both ends of the first layer of

freight and the container, and the same model of the contact and dry friction between timber and steel shall also be adopted to maintain the longitudinal reinforcement of the freight. The compound bundling strap shall adopt the above mentioned secondary developed force model of bundling strap which has certain pretension force. The circles on the forces in the figure represent the contact between strap and cylinder-shaped freight. The topological relationship of freight reinforcement is shown in figure 5(a). The dynamic model of freight reinforcement in accordance with the topological relationship and the number of freight and straps are shown in figure 5(b). The total mass of container and freights is 16.1 ton. It's about 3.65 ton for each freight.

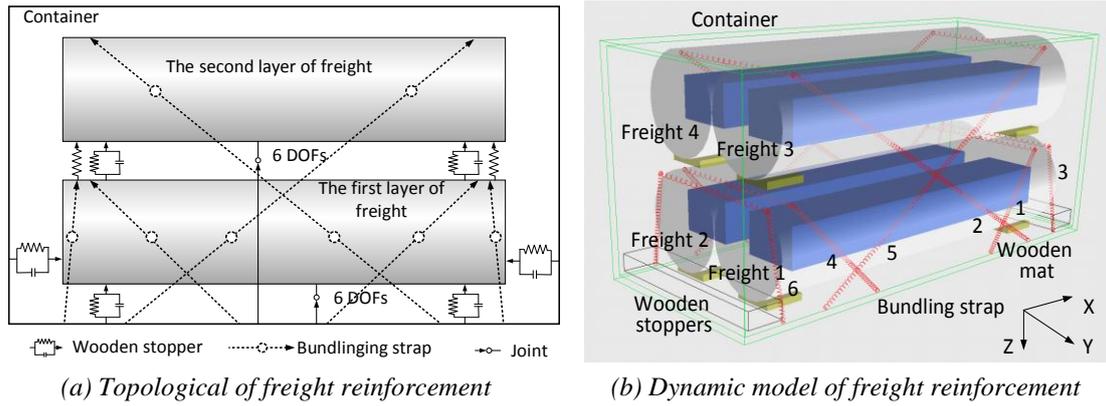


Figure 5. Topological relationship and dynamic model of freight reinforcement

### 2.3. Modeling of Railway Vehicle-Freight-Reinforcement

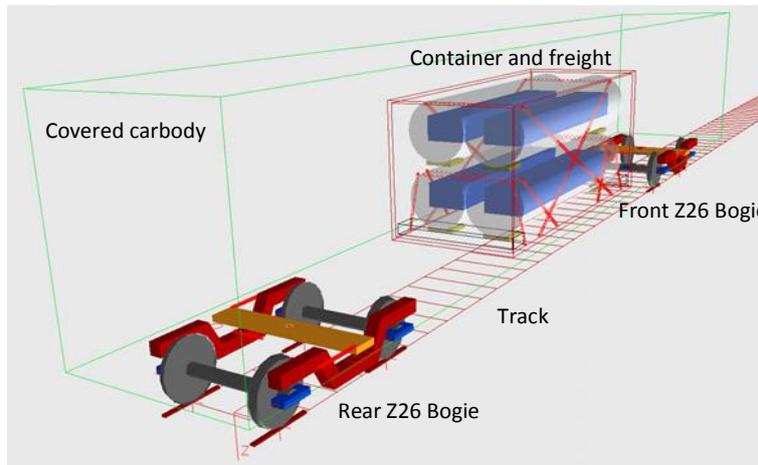


Figure 6. Dynamic model of railway vehicle-freight-reinforcement system

The covered wagon system model shall be assembled with the freight reinforcement model to form the vehicle-freight-reinforcement dynamic model which adopts the dynamic software SIMPACK as shown in Figure 2, including track, Z26 bogies, car body, container and freights. The mathematical model of this system is shown in the following differential algebra equation sets:

$$\begin{cases} \mathbf{M}\ddot{\mathbf{q}} + \Phi_{\mathbf{q}}^T \boldsymbol{\lambda} = \mathbf{F} + \mathbf{F}_{\text{wr}} + \mathbf{F}_{\text{i}} \\ \Phi(\mathbf{q}, t) = 0 \end{cases} \quad (5)$$

In the equation,  $\mathbf{q}$  is the column vector of generalized coordinate,  $\mathbf{M}$  is the generalized mass matrix,  $\mathbf{F}_{wr}$  is the generalized force vector of wheel-rail force,  $\mathbf{F}_i$  is the generalized force vector of external impact force,  $\mathbf{F}$  is the other generalized force vector,  $\Phi$  is the algebra constraint equation and  $\Phi_q$  is the Jacobian matrix of the algebra constraint equation. 68 DOFs are contained in the system with nonlinear factors like contacts, frictions, gaps and piecewise linear spring included which largely increases the difficulty of solving the equation.

### III. SIMULATION AND SAFETY ANALYSIS

#### 3.1. Calculation of Operating Condition and Load

The safety of the reinforced straps shall be inspected from mainly two aspects in this paper:

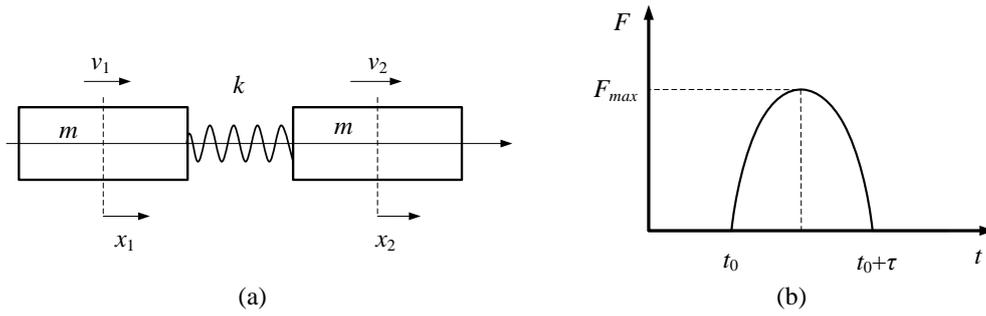
1) Tangent track operating simulation: calculate the internal force and the acceleration of freight when the vehicle runs linearly with different speed.

2) Longitudinal impact simulation: calculate the internal force and the acceleration of freight under the impact of longitudinal load in the condition of both reinforced normal and failure.

For the tangent track operating simulation, when the vehicle operates normally, the external load comes from the track irregularity, producing excitation which increases in accordance with the increasing speed. The calculation shall base on the speed of the vehicle operating on respectively 80 km/h, 100 km/h, 120 km/h, 140 km/h and the track irregularity shall adopt the fifth grade PSD of America.

For the longitudinal impact simulation, the time history of the longitudinal impact load shall be calculated. During the railway transportation, vehicles shall operate in train marshalling, where shunting operation shall be employed<sup>[10]</sup>. When conducting marshalling, one vehicle shall operate at certain speed with another static vehicle coupled behind. In addition, the train will start emergency braking when encounters emergency situation. The braking of the train adopts the air-compress driven system, and the air-pressure drop in the train pipe will be spread from former to latter, which causes the unsynchronized braking of all vehicles, resulting in the speed vary and gaps among the vehicle couplers, so as to activate the impact among vehicles. In view of the longitudinal impact load is much larger than the normal load, the safety of reinforcement shall be analyzed only in circumstance of the longitudinal impact operating condition.

Suppose the mass of two vehicles are both  $m$ , operating at the speed of  $v_1$  and  $v_2$  respectively and  $v_1 > v_2$ , in the event of elastic collision, the impact calculation of the two vehicles is shown in figure 7(a), and  $k$  is the stiffness of the buffer of the coupler.



**Figure 7.** Vehicle impact model and load curve

Suppose that the absolute displacements of the barycenter of two vehicles are respectively  $x_1$  and  $x_2$ , and the differential equations of the two vehicles are:

$$\begin{cases} m\ddot{x}_1 + k(x_1 - x_2) = 0 \\ m\ddot{x}_2 - k(x_1 - x_2) = 0 \end{cases} \quad (6)$$

The above differential equations shall be solved on in accordance with the initial speed of collision and the action time of longitudinal force  $\tau$  and the amplitude value  $F_{\max}$  of longitudinal impact are respectively:

$$\tau = \pi / \sqrt{2k/m}, F_{\max} = v_r \sqrt{km/2} \quad (7)$$

$v_r$  is the relative speed  $v_r = v_1 - v_2$ , the time domain waveform of the impact is shown in 7(b) and the function representation is:

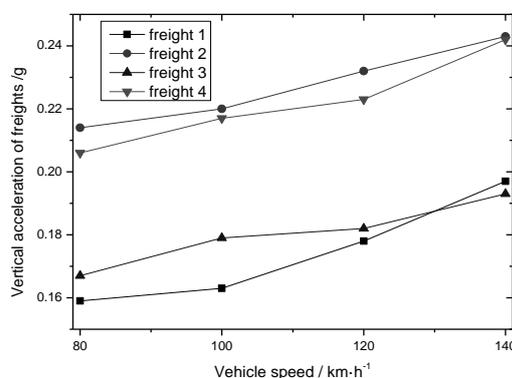
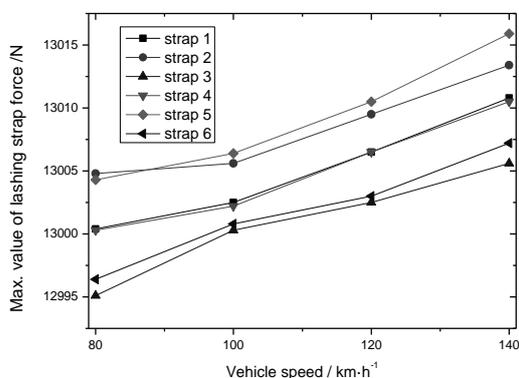
$$F(t) = \begin{cases} F_{\max} \sin \frac{\pi}{\tau} (t - t_0) & t_0 \leq t \leq \tau + t_0 \\ 0 & t < t_0 \parallel t > \tau + t_0 \end{cases} \quad (8)$$

In the above formula,  $t_0$  is the starting time of impact, the maximum impact speed of vehicle shall not exceed 5.0 km/h in accordance with the “Regulations on Railway Technical Management”. The relative speed shall be set at 2.0 m/s so as to calculate with high safety coefficient. The parameter of vehicle shall be set as: mass  $m = 62.6$  t and the equivalent stiffness of the buffer of the coupler  $k = 7.0$  MN/m. Therefore, the impact time and maximum impact force are respectively  $\tau = 0.21$ s and  $F_{\max} = 936$  kN in accordance with the Equation (7). Then, put the time history of impact load as  $F_i$  in Equation (5) into the whole dynamics equation so as to conduct impact dynamics simulation of coupling. The largest acceleration of emergency braking is about 0.1g, which is far less than the longitudinal impact acceleration in train marshalling, so only the more seriously case was considered for safety analysis in this paper.

### 3.2. Tangent Track Operating Simulation Analysis

Through the calculation we find that under the circumstance of the vehicle normally operate at the speed of  $v = 140$  km/h, the variation of the internal force of straps and the acceleration of cylinder-shaped freight is relatively small if the pretension force stands at 13kN. Therefore, the pretension force shall be set as 13kN in this paper. The straps operate in linearity work region and are far smaller than their limit fracture value, which is a reasonable setting.

The maximum value of the internal force of straps shall be calculated with different speed through simulation. As shown in Figure 8, we can see that the maximum internal force of those six straps increase as the speed increase, and the internal force and deformation of strap 2 and 5 are larger than the rest straps for the reason that strap 2 and 5 connect freight in two layers. Under some circumstance the internal force of straps are smaller than the initial pretension force 13kN for the reason that the system does not completely reach the balanced condition at the starting time. After reaching the balanced condition, the length of some straps is shorter than the initial length and the internal force of which thus are also smaller than the initial pretension force. The acceleration of freight also increases as the speed increases and figure 9 illustrates the variation law of vertical acceleration of freight, while the speed variation laws of freight in other directions are basically the same. The increasing operating speed results severe excitation and larger acceleration.



**Figure 8.** Force of strap for different speed

**Figure 9.** Acceleration of freight for different speed

The maximum internal force of strap is 13.015kN which is far smaller than the fracture value 46.54kN and the maximum vector sum of acceleration is 0.65g which is far smaller than the limit value 5g. Therefore, the reinforcement scheme of freight in tangent track operation is safe and feasible.

### 3.3. Longitudinal Impact Simulation Analysis

In view of the impact force is far larger than the load in normal operation, this part shall emphasize on the analysis of the safety of strap reinforcement under the impact of longitudinal impact load. Fastening bolts was used to connect freights to reduce relative motion between the freights, and increase reinforcement strength. In some extreme cases fault condition (hereinafter refers to as fault case), the fastening bolts may break, which makes connect strength reducing greatly. Whether bundling reinforcement is still sufficient safety in this fault cases should be clarified. Fault model was built without all the fastening bolts between the freight of two layers, and only exist the friction force between wooden mat and freights (consider the coefficient of friction as 0.25). In this model bundling straps still work well. To figure out the safety of fault case, the result of normal operating condition and extreme for longitudinal impact simulation shall be compared and analyzed.

Under longitudinal impact operating condition, the calculation result of the maximum internal force of compound fiber strap is shown in Figure 8. From Figure 8 we can find that the maximum internal forces of straps under longitudinal impact operating condition vary slightly and are all smaller than 13.1kN and larger than the pretension force 100N. Compared with the

normal operating condition, except for strap 2 and 5, the internal forces of the other strap basically maintain unchanged under fault case. The reason internal force of strap 2 and 5 increased is that the connection of the freight in two layers become loose under fault case. The maximum longitudinal acceleration of freight is shown in Figure 9, the accelerations under fault case all increase as compared with normal case. Relative movements frequently occur between freight and wooden stopper and among freight under fault case, and acceleration reaches larger value under larger impact.

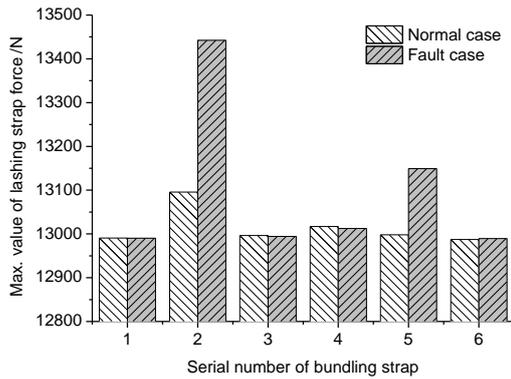


Figure 10. The maximum internal force of strap

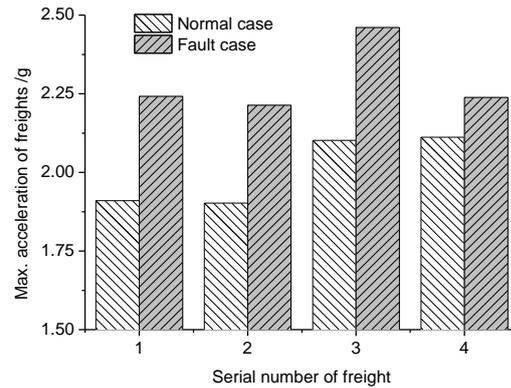


Figure 11. The maximum longitudinal acceleration of Freight

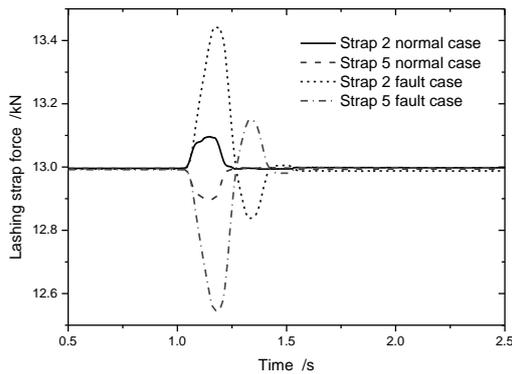


Figure 12. Time history of internal force of strap

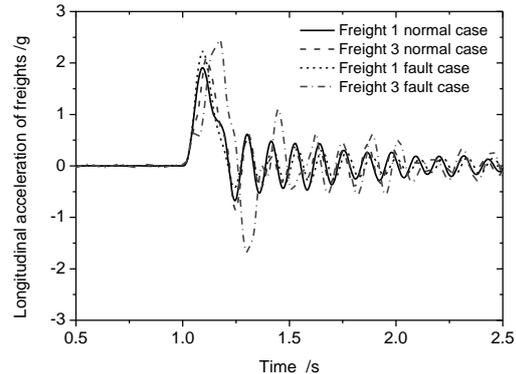


Figure 13. Time history of longitudinal acceleration of freight

Strap 2 and 5 are significantly influenced by the longitudinal impact. Figure 12 shows the time history of internal force of the two straps. From the Figure we can find that with impact load, freight in second layer has slight displacement with respect to freight in first layer, resulting in the stretching of strap 2 and compression of strap 5. Under the circumstance of all the fastening bolts between the two layers fractured, the relative displacement of the two layers will increase which means the value of stretching and compression of strap 2 and 5 will also increase, resulting in the internal force changing. Because of the elasticity of the bundling strap, the strap of freight in second layer will be hauled back with certain extent and there exists bounce in the internal force.

Figure 13 illustrates the time history of the longitudinal acceleration of freight 1 and 3 under impact load. From the Figure we can find that the acceleration waveform of freight 1 under normal reinforced case and fault reinforced case are basically the same with only slight

increase of the amplitude value, while the acceleration waveform of freight 3 in second layer under normal reinforced case and fault reinforced case largely changes. The acceleration waveform of freight 3 occurs hysteresis which results from that the constraint between freight 3 and 1 decreases, and freight impact longitudinally on freight 1, the load of which spread through straps to other freights, but the stiffness of strap is much smaller than the fastening bolts and the deformation costs much time, thus causing the disparity of the acceleration waveform.

Through the longitudinal impact simulation analysis under normal case and fault case, the maximum internal force of strap is 13.442kN which is far smaller than the fracture value 46.54kN and the maximum acceleration is 2.5g which is also smaller than the limit value 5g. The longitudinal impact simulation demonstrates that the reinforcement scheme is feasible.

#### IV. CONCLUSION

Through the development of the mechanical model of bundling strap, a detailed freight bundling strap reinforcement model was established to formulate a complete vehicle-freight-reinforcement system dynamics model, and two-mass model and the linear collision model were adopted to calculate the impact force. This paper makes dynamics simulation of the typical operation condition of transportation and employs the simulation results to further assess the safety and feasibility of reinforcement scheme.

In the reinforcement scheme described in this paper, the tangent track operating and longitudinal impact simulation are analyzed with the results that the maximum internal force of strap is 13.442kN which is far smaller than the fracture value 46.54kN and the maximum acceleration is 2.5g which is also smaller than the limit value 5g, which demonstrates the feasibility of the reinforcement scheme.

The dynamics simulation makes the assessment of reinforcement scheme more accurate and detailed with all complex and extreme circumstances considered which is unrealizable for the traditional assessment method of reinforcement scheme.

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