

Strength Analysis of Bolts Connection of Composite Plywood of Low-Noise Brake Beam

Zhiping Tu

Signal and Communication Research Institute, China Academy of Railway Sciences,
Beijing 10081, P.R. China

Abstract. As the key subsystem of the locomotive, the braking performance of the brake system has a crucial impact on the safety of the vehicle, as the most critical connecting component in the braking system, the connecting bolts have a direct impact on the braking performance of the braking system. Therefore, the strength of the bolt must be checked and analyzed before the braking system is installed. Aiming at the braking system of a freight train, this paper adopts the method of combining theory with finite element numerical analysis to check and analyze the strength of the bolts during the braking process. Firstly, the bolt is subjected to force analysis and the reasonable preload range of the bolt and the critical friction coefficient between the friction plate and the brake caliper are deduced theoretically. Then by using finite element numerical analysis method, the influence of preload on the bolt and friction coefficient between friction plate and brake caliper on force loaded bolts during braking is analyzed by simulating the actual braking process. The results show that the bolt pretension is uneven and the friction coefficient between the friction plate and the brake caliper has a great influence on the bolt strength.

1. Introduction

The retarder is the main equipment of speed control which is arranged in the hump marshalling station or track in the harness of rolling cut. With the hump control system, the retarder is used for speed control of rolling cut and keeping proper intervals or staying in line speed and train safety coupling. In the rolling process, the retarder will produce high-frequency and high levels of noise, seriously affect the surrounding living environment and field workers hump marshalling operations environment. In order to solve the brake noise of the retarder, a low-noise brake beam is developed to replace the existing retarder brake rail. The low-noise brake beam is composed of welded variable cross section base beam and composite plywood, each composite plywood length is 600mm, which is connected with the base beam through 3 high strength bolts. Due to the complexity of the composite clamping force during the braking process of the retarder, it is necessary to check the strength of the bolt in the braking system in order to avoid the stress that the bolt is subjected to stress exceeds the strength limit of the bolt material during the braking process.

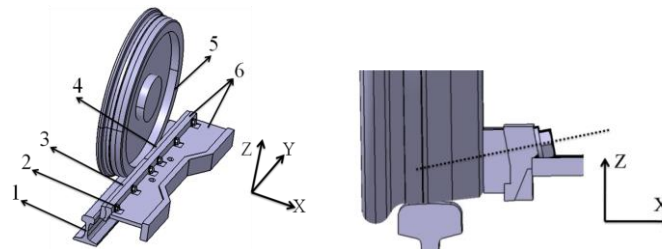
2. Structure and braking principle of low noise brake beam

The main reducer of hump marshalling station in China is mainly pneumatic gravity clamp type retarder. The principle is to use the weight of the vehicle to be braked, passing through the floating basic rail and the brake beam. Its principle is to use the weight of the vehicle transferred by the



floating rail and brake base beam; the braking rail will produce lateral pressure on both sides of a wheel, brake of rolling cut, so as to control the speed of rolling cut. In order to reduce the braking noise in the braking process of the retarder, a low noise brake beam is used to replace the retarder brake rail, which is composed of composite plywood, variable cross section base beam and high strength bolt, as shown in Fig.1. The X axis is perpendicular to the side of the wheel, the Y axis is parallel to the direction of rolling cut, and the Z axis is perpendicular to the direction of the basic track bed.

In the braking state, because the opening size of the retarder is smaller than the thickness of the wheel, When the vehicle passes the retarder, the wheel squeezes the brake beam of the retarder, which will produce friction braking force, then the spread of rolling cut will be adjusted to reach the preset speed so as to ensure the safety of rolling cut up. In order to slow down the force acting on the connecting bolt, the low noise brake beam is designed as a ramp and step structure to ensure that the bolt will be not broken during the braking process, so as to improve the reliability of the connection.



1- Basic rail 2- high strength bolts 3- composite plywood 4-friction plate 5-wheel 6-variable cross section base beam

Fig 1. Diagram of low-noise brake beam

3. Force analysis of the bolt

3.1. Calculation of frictional force between composite plywood and wheel

Bolt stress analysis during braking is the basis of its strength check. To analysis the force loaded on the bolt, the analysis of friction that between the friction plate and the wheel must be analyzed firstly. The shape of contact area of each composite plywood and wheel is shown in Fig.2, where ad is a radius of 407mm and radian is 32° , bc is a radius of 355mm and radian is 16° , ab is a horizontal section of the distance from the wheel center of 335mm, bc is a vertical line, and its upward elongation line passes through the wheel center to indicate the braking width, the size of bc is 70mm. The contact area between the wheel and the other composite plywood is symmetrical. It can be seen from the Fig. that the contact area between the composite plywood and the wheel is an irregular region, which leads to great difficulties in analyzing the friction between the composite plywood and the wheel.

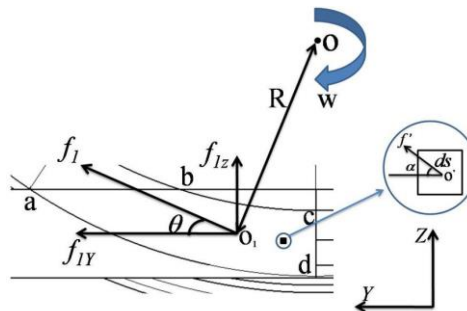


Fig 2. The shape of contact area between composite plywood and wheel

Assuming that the braking pressure is 18t (the heavy axle load is 25 t), so the positive pressure acting on the wheel is:

$$F = 18 \times 9800 \text{ N} = 1764000 \text{ N} = 176.4 \text{ KN} \quad (1)$$

Then the friction between the composite plywood and wheel is calculated as:

$$f = u_1 F = 0.2 \times 176.4 \text{ KN} = 35.28 \text{ KN} \quad (2)$$

Where u_1 is the friction coefficient between the composite plywood and the wheel, and $u_1 = 0.2$. And because the contact area is irregular, which is difficult for determining the direction of the friction force. In this paper, it is assumed that the positive pressure between the composite plywood and the wheel is uniform; it is shown by the formula (2) that when the area is divided into innumerable infinitesimal bodies, the friction force of each infinitesimal element will be uniformly distributed, and the scale is calculated as:

$$\rho = \frac{f}{2S_A} \quad (3)$$

Where S_A represents the area of the contact area between each composite plywood and the wheel, the friction between each composite splint and the wheel can be calculated as formula (3):

$$f_1 = \rho \times S_A = \frac{1}{2} f = 17.64 \text{ KN} \quad (4)$$

In Fig.2, it is assumed that O_1 is the action point of equivalent friction force, The action point and direction of the equivalent friction force between the composite plywood and the wheel can be calculated by the follow formula, where R represents the distance between the action point of the equivalent friction force and the center of the wheel, θ represents the angle between the direction of equivalent friction and the Y axis, α is the angle between the direction of friction on each element contact surface and the Y axis.

$$R = \frac{\iint \rho ds}{\iint ds} = \frac{\int_0^{\frac{4\pi}{45}} d\theta \int_{355}^{420} \rho^2 d\rho + \int_{\frac{4\pi}{45}}^{\frac{8\pi}{45}} d\theta \int_{335 \sec \theta}^{420} \rho^2 d\rho}{\int_0^{\frac{4\pi}{45}} d\theta \int_{355}^{420} \rho d\rho + \int_{\frac{4\pi}{45}}^{\frac{8\pi}{45}} d\theta \int_{335 \sec \theta}^{420} \rho d\rho} = 383.75 \text{ mm} \quad (5)$$

$$\theta = \frac{\iint \alpha ds}{\iint ds} = \frac{\int_0^{\frac{4\pi}{45}} 65\theta d\theta + \int_{\frac{4\pi}{45}}^{\frac{8\pi}{45}} (420 - 335 \sec \theta) \theta d\theta}{\int_0^{\frac{4\pi}{45}} 65\theta d\theta + \int_{\frac{4\pi}{45}}^{\frac{8\pi}{45}} 420 - 335 \sec \theta d\theta} = 13.89^\circ \quad (6)$$

3.2. Force analysis of composite plywood

In order to make bolt force analysis more convenient, the composite plywood, base beam of the brake beam is considered in the analysis model, and following local coordinate system is established with X axis as the locomotive group movement direction, and Y axis as upward slope of the composite plywood and the base beam of brake, and Z axis as axial of bolt. As shown in Fig.3 below, only the

upper composite plywood in Fig.1 is selected to analyze when taking into account the symmetry of the geometry and boundary conditions of the two composite plywoods.

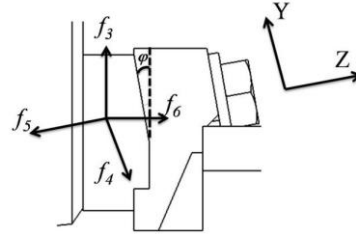


Fig 3. Force diagram of composite plywood in X-Y plane of global coordinate system

In Fig.3, φ is the tilt angle of contact surface between base beam of brake and composite plywood; f_3 represents the force in the vertical direction of the force acting on the composite plate by the wheel; f_4 represents the force acting on the composite plate in the direction of the inclined plane; f_5 represents the force that base beam of brake act on the composite plate; f_6 represents the force that wheel act on composite plywood. When the braking force is applied to the wheel through the composite plywood, the composite plywood will be exerted an upward force f_3 by wheel, which will gradually increase with the increase of braking force. The composite plywood is in the balance at the maximum value of f_3 when the braking force F reaches its maximum value. Moreover, when the composite plywood is in equilibrium state, if the friction force is inclined to the composite plywood, the direction of the friction must be downward along the inclined plane, and the step exert no force to composite plywood. Above force can be solved based on formula (3).

$$f_3 = f_{1z} = f_1 \times \sin \theta = 4.23\text{KN} \quad (7)$$

$$f_2 = f_{1y} = f_1 \cos \theta = 17.12\text{KN} \quad (8)$$

$$f_4 = f_3 \cos \varphi + f_6 \sin \varphi = -11.04\text{KN} \quad (9)$$

$$f_5 = f_3 \sin \varphi + f_6 \cos \varphi = 87.61\text{KN} \quad (10)$$

Because f_2 and f_4 do not pass through the center of bolt group, they will cause the bolt to bear torque and overturning moment during braking.

$$M_1 = f_2 L_1 + f_4 L_2 = 11.04 \times 207.88 - 17.12 \times 9.32 = 2135.44\text{N}\cdot\text{m} \quad (11)$$

$$M_2 = f_5 L_3 = 87.61 \times 208.09 = 18230.76\text{N}\cdot\text{m} \quad (12)$$

In the formulas above, M_1 and M_2 respectively represent torque and overturning torque; L_1 and L_2 represent the distance of the equivalent friction force acting point between the farthest hole center and the closest screw hole center in the composite plywood respectively. The torque M_1 will produce a tangential force f_9 to the bolt along the Y axis in the local coordinate system, while the overturning moment will cause the working tension f_{10} of bolt to increase.

$$f_9 = \frac{M_1}{2L} = 4.45\text{KN} \quad (13)$$

$$f_{10} = \frac{M_2}{2L} = 37.94\text{KN} \quad (14)$$

3.3. Force analysis of bolt group

Because each composite plywood is fastened at the base beam of brake by the three bolts, which are symmetrically arranged in the two composite plywoods. Therefore, only one bolt group of three bolts in composite plywood can be taken to analyse. In order to match the former analysis object, the three bolts in the upper composite plywood in Fig.1 are select to analyse. Suppose that the force f_5 between the two inclined planes in the Fig.3 is bearded evenly by the three bolts, then the worst tensile force f_{11} of the bolt is calculated as:

$$f_{11} = f_{10} - \frac{1}{3} f_5 = 39.01\text{KN} \quad (15)$$

When the bolts bear axial load at the same time, the total tension of bolt is not equal to the sum of preload and working load due to the elastic deformation of bolt and the connector. The total tension is related to the preload and the work tension, and in addition to the bolt stiffness and the stiffness of the connection, and the relationship between them is shown in the following formula (15).

$$F_T = f_p + \frac{C_b}{C_b + C_m} f_T \quad (16)$$

In the upper formula, F_T represents the total tensile force of the bolt; f_p means bolt pretension; C_b represents the stiffness of the bolt; C_m represents the stiffness of the connector; f_T represents the working pressure of the bolt; $\frac{C_b}{C_b + C_m}$ represents the relative stiffness of the bolt. Based on the relevant experience standards, the relative stiffness of the bolt is approximately equal to 0.2 when the bolt is used with metal gasket.

When the bolt bears the preload and the work tension, the maximum tensile force of the bolt must satisfy formula (16) and formula (17). In the formula, σ_s represents the yield strength of bolt material; $[\sigma]$ indicates the allowable tensile stress of bolts; S represents the tensile stress safety factor; d represents the diameter of bolt dangerous section; d_1 means bolt minor diameter; d_2 means bolt middle diameter; p represents pitch $f_{p\max}$ indicates the maximum pretension allowed by bolt. The relevant parameters of the bolt in the actuator are shown in table 1.

Table 1. Bolt parameters in structure

Type	Level	Pattern	d_1 (mm)	d_2 (mm)
M20	12.9	Coarse	17.294	18.376
p	σ_s (MPa)	S	$f_{p\max}$	Angle
2.5	1080	1.25	123.43KN	60°

$$\sigma = \frac{F_T}{\pi d^2 / 4} \leq [\sigma] = \frac{\sigma_s}{S} = 864\text{MPa} \quad (17)$$

$$d = \frac{d_1 + d_2 - \sqrt{3}p/12}{2} = 17.655\text{mm} \quad (18)$$

In order to provide enough friction, it is necessary for the bolt to exert force to the two composite plates. When the friction between the two plates is insufficient, the bolt will be broken by shearing force because the relative sliding between the two plates will occur. Therefore, in order to ensure the reliability of bolt connection, the bolt must be applied to a certain preload, the value of which must meet formula (19). In formula, K is the reliability coefficient, 1.2 is used in this paper, u represents the friction coefficient between the joint surfaces, which takes 0.4 based on Mechanical Design Handbook. z represents the number of bolts. m represents the number of contact surfaces. f_r represents the radial load on the bolt.

$$f_r = f_2 - uf_5 = 8.36\text{KN} \quad (19)$$

$$f_T \geq \frac{Kf_r}{uzm} = 40.53\text{KN} \quad (20)$$

Under the premise of uniform braking pressure in composite plywood and even preload of bolt, if the bolt preload is less than 40.53KN, the force of composite plywood along horizontal direction in braking process will make two pieces of composite plywood relative sliding, causing the failure of the bolt. If the bolt preload is greater than 123.43N, bolt will directly be pulled off. Therefore, the preload of each bolt must be between 40.53KN and 123.43KN, and the preload of six bolts should be ensured even as much as possible.

4. Influencing factors of bolt strength analysis

From the previous analysis, it can be seen that the inclined angle and friction coefficient of the composite plywood and base beam of brake contact surface have great influence on the bolt force. In the actual manufacturing process, it is likely to produce composite plywood and base beam of brake contact surface slope angle and design value deviation due to manufacturing deviation, thereby affecting the reliability of bolt connection. Therefore, the paper analyzes the influence of the change of the friction coefficient and inclination angle between the composite plywood and base beam of brake on the bolt force, combining the schematic diagram of the force diagram of Fig.3. Based on the obliquity of inclined plane, the critical friction coefficient of inclined plane can be calculated.

$$u' = \tan 10^\circ = 0.174 \quad (21)$$

The change of the friction coefficient and inclination angle will not affect the value of f_2 . But to make two composite plywood and beam of brake beam does not break off, bolt force must satisfy formula (21) and formula (22), u'' represents the change of the friction coefficient between the slope, φ' represents the slope angle after change. At this point, formula (23) shows the value of the pressure between the slope:

$$f_4 = f_3 \cos \varphi' - f_6 \sin \varphi' \geq 0 \quad (22)$$

$$f_5 = f_3 \sin \varphi' + f_6 \cos \varphi' \quad (23)$$

Without considering the effect of the force loaded the composite plate along the inclined plane in the down direction. The premise that the bolt will not be cut off is that the two plates will not slide

relatively. At the moment, the value of bolt force needs to be satisfied formula (23), that is to say, the minimum friction coefficient between the inclined planes must satisfy the formula (24).

$$f_2 - u'' f_5 \leq u'' (f_p - 0.2 f_5) \quad (24)$$

$$u'' \geq \frac{f_2}{f_p + 0.8 f_5} \quad (25)$$

5. Numerical analysis

The braking process is a dynamic process, and there is a nonlinear contact relationship between bolt and connector, which leads to bolt force is very complex. In the analysis of theory methods based on certain assumptions, this nonlinearity is not taken into account in the process of force analysis. However, the finite element method, as an important numerical analysis method, can take into account the nonlinear contact behavior as compared with the theoretical calculation method. Therefore, it is very suitable to use finite element method to analyze the nonlinear contact behavior of bolted connections.

In this paper, the finite element method is used to analyze the bolt based on ABAQUS software: (1) bolt strength only under the pretension; (2) how bolt force affected while the pretension is larger or smaller during the braking process; (3) how bolt force impacted by the friction coefficient between the friction plate and the brake caliper in the braking process; (4) how bolt force affected by the uneven pretension during braking.

5.1. Finite element modeling

As the focus of the analysis, the bolt finite element model quality has a great influence on the calculation results. In order to reduce the difficulty of modeling and calculation cost, the paper doesn't build screw thread in the bolt model, instead of setting the thread angle, pitch and bolt path parameters in ABAQUS to consider the influence of screw thread on the results. Because only concerned with the contact part between the wheel and the friction plate, the wheel can be simplified in modeling. In order to obtain more accurate results and facilitate the convergence of model solution, the contact area of the model is refined in modeling for the nonlinear contact relationship between bolt and friction plate and between bolt and brake caliper in braking process. The established finite element model of the execution structure is shown in Fig.4.

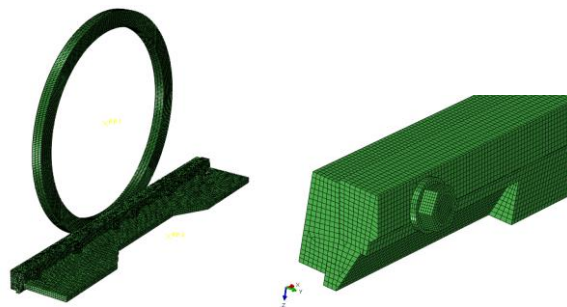


Fig 4. The finite element model of executive structure

5.2. Definitions of attributes and boundary conditions

The material parameters of the bolt, wheel and brake caliper are listed in Table 2. The running speed of the train is 25Km/h. According to the train braking standard, the friction coefficient between the wheel and the friction plate is 0.2, and the friction coefficient between the two friction pieces is 0.2. Refer to Mechanical Design Handbook [1], the friction coefficient between the bolt and the friction piece and the gasket is 0.15. The brake pressure is equal to 176.4KN, which is exerted on the brake

caliper by coupling. The three translational degrees of freedom and the rotational degrees of freedom around the Y axis and the Z axis of the wheel center are restrained, and a rotational speed 60Km/h around the X axis is applied to the center of the wheel. A brake pressure is applied to the brake caliper with negative 176.4KN along the X axis. The bolt pretension is applied to the bolt cross section, as shown in Fig.5.

Table 2. Material parameters of each component in the model

	wheel	friction plate	brake caliper	bolt
E(MPa)	2.0e5	2.10e5	2.1e5	2.06e5
v	0.285	0.3	0.3	0.3

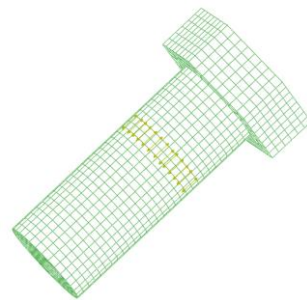


Fig 5. Schematic diagram of bolt preload

5.3. Analysis results

5.3.1. Bolt force analysis only under the preload. The function of bolt preload is to fasten the friction plate and the brake caliper together. But when tightening, the bolt preload will be larger or smaller, which may have a great influence on the strength of the bolt during the braking process. Therefore, it is very important to choose a reasonable bolt preload value. Based on this, this paper firstly analyzes the bolt strength only under the preload (when the braking system is not working).

According to the previous theoretical calculation, the safety preload range of the bolt is obtained, assuming that each bolt bears the 10000N preload uniformly. According to the Mechanical Design Handbook, the required tightening torque and the maximum stress on the dangerous cross section of the bolt can be calculated.

$$T = 0.2F'd = 0.2 \times 100000 \times 20 = 400\text{N}\cdot\text{m} \quad (26)$$

$$[\sigma_{ca}] = \frac{1.3F}{\pi d_1^2 / 4} = \frac{1.3 \times 100000}{235} = 553.2\text{MPa} \quad (27)$$

Where d_1 represents the thread inner diameter, and F represents the pretension of the bolt. Because of the analysis of the bolt strength only under the preload, not involved in the braking, the wheel can be completely fixed in the analysis model. In the analysis model, the friction coefficient between the friction plate and the brake caliper is 0.2. To facilitate the calculation convergence, the preload is distributed to the model in the process of exerting the bolt pretension. The calculation results are shown in Fig.6.

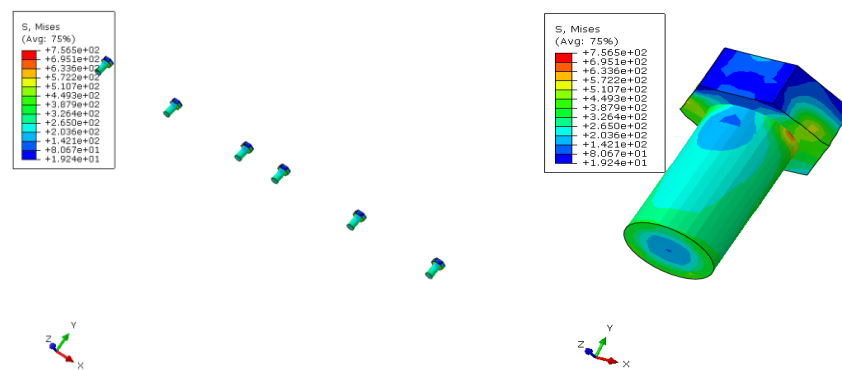


Fig 6. The stress contour of bolt only under pretension

It can be seen from the diagram that the force act on the six bolts are uniform, the maximum stress act on the bolt is 756.5MPa, and the maximum stress is located at the junction of the bolt head and the screw. This is mainly due to the large change in the size of the transition area between the bolt head and the screw, which is easy to produce stress concentration. Compared with the Eq. (25), it can be seen that there are some differences between the theoretical calculation results and the simulation results. This is mainly due to the theoretical calculation does not consider the effect of stress concentration, and simplifies the fillet of the region in the finite element modeling of the bolt, which leads to the larger simulation results.

5.3.2. Influence of friction coefficient between friction plate and brake caliper on bolt force. The friction coefficient between the friction plate and the brake caliper directly determines the reliability of the bolt connection. When the friction coefficient between the two is smaller than the critical value, the friction plate will produce a moving trend under the friction under the wheel, thus causing the bolt to be subjected to a large shear load, which will cause the bolt to be sheared seriously. According to the minimum value and critical value of the friction coefficient between the inclined planes, three groups of different friction coefficients are selected for analysis. In the analysis process, it is assumed that each bolt acts uniformly on the 10000N preload. The strength of bolt in braking process is analyzed by quasi static calculation method. Fig.6- Fig.8 shows the stress contour of the bolt when the friction coefficients between the friction plate and the brake caliper are equal to 0.15, 0.18 and 0.2 respectively. Fig.7 (a), 8(a), 9(a) denote the initial bolt stress contour of the brake, Fig.7 (b), 8(b), 9(b) indicate the stress contour of the bolt during steady braking.

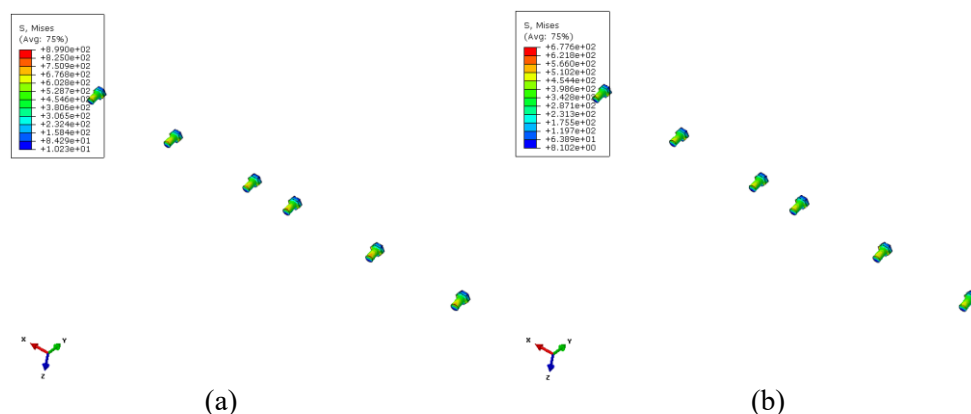


Fig 7. The stress contour of bolt when the friction coefficient is equal to 0.15 between friction plate and brake caliper

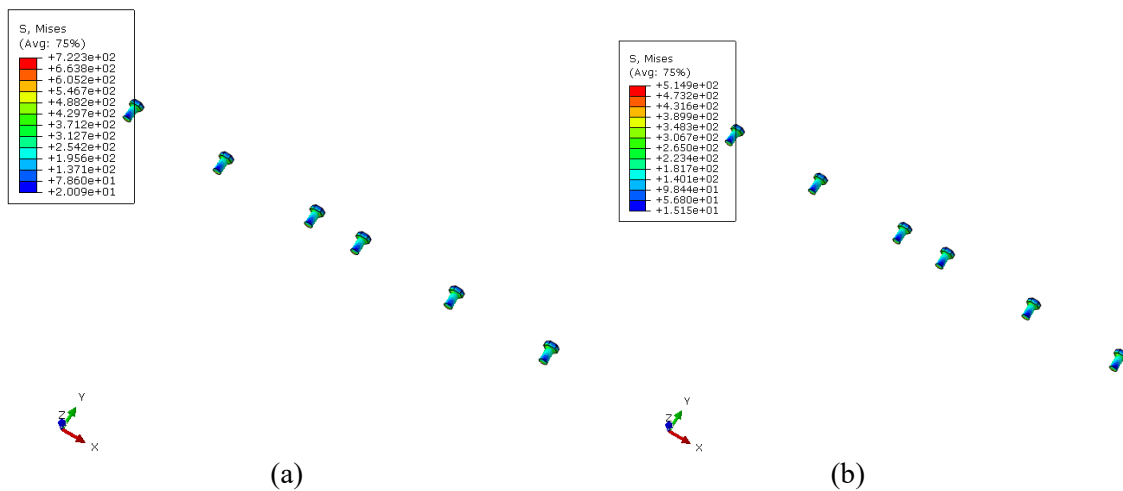


Fig 8. The stress contour of bolt when the friction coefficient is equal to 0.18 between friction plate and brake caliper

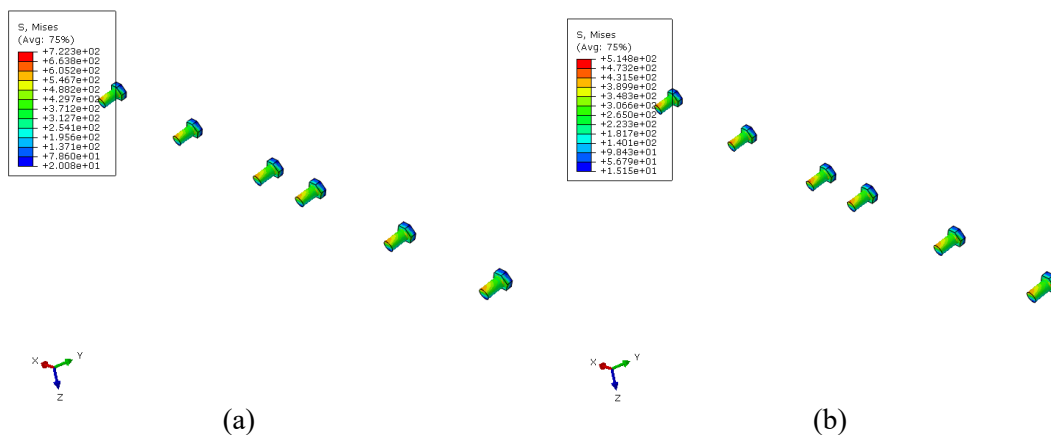


Fig 9. The stress contour of bolt when the friction coefficient is equal to 0.2 between friction plate and brake caliper

Comparing the three stress coefficients of the bolt stress contour, it can be concluded that when the friction coefficient between the friction plate and the brake caliper is greater than the critical friction coefficient of the inclined plane, the maximum stress of the bolt is basically unchanged during the braking process. However, when the friction coefficient between the friction plate and the brake caliper is smaller than the critical friction coefficient of the inclined plane, the maximum stress of the bolt will increase significantly during the braking process, with an increase of about 160MPa. This is due to the slippage between the friction plate and the brake caliper due to the small friction coefficient, which results in a large transverse load on the bolt. Therefore, in order to ensure the reliability of the bolt connection, the friction coefficient between the inclined planes must be greater than the critical friction coefficient.

5.3.3. Influence of preload on bolt force. While tightening the bolt, not only the tightening torque has an impact on the strength of the bolt, but also the uniformity of each tightening torque has a very big impact on the bolt strength during the braking process. The front bolt stress analysis process is based on the uniform preload. Therefore, in order to comprehensively analyze the influence of various factors on the bolt force during the braking process, this paper analyzes the influence of uneven

pretension on the bolt strength. Assuming that the preload of the third bolt from left is 90000N and the rest bolt preload is 100000N. The friction coefficient between the friction plate and the brake caliper is 0.2. The strength of bolt in braking process is analyzed by quasi static calculation method. The calculation results are shown in Fig.10.

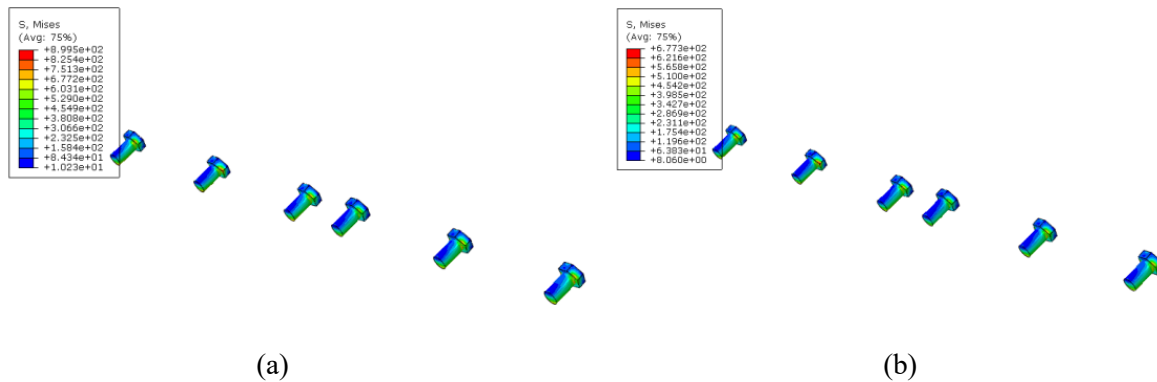


Fig 10. The stress contour of bolt under uneven preload

Fig.10 (a) indicates that the braking brake pressure is very small at the beginning, and the maximum stress is in the screw bolt junction at the value of 899.5MPa; Fig. 10 (b) indicates that the braking pressure of 18t, and the bolt maximum stress is 677.3MPa which located at the junction of nut and screw. By comparing with Fig.6, the bolt maximum stress will increase significantly with uneven preload at the brake initial time and while stability braking. Therefore, in order to improve the reliability of the bolt connection, the preload of each bolt should be guaranteed when tightening.

6. Conclusion

In this paper, the bolt strength of freight train braking system is checked and analyzed from two aspects of theory and finite element numerical analysis. Firstly, analyzing the bolt force, the influence of the bolt preload and the friction coefficient between the friction plate and the brake clamp on the bolt force is analyzed theoretically, and the reasonable preload range of the bolt is deduced according to the mechanical performance parameters of the bolt. Then, considering the nonlinear contact behavior between bolt and connector, the strength of bolt under the uneven preload is analyzed by finite element numerical analysis method. Based on this, the influence of the uneven preload and the friction coefficient between the friction plate and the brake caliper on the bolt force is analyzed. The analysis results show that the uneven preload of each bolts and the friction coefficient between the friction plate and the brake caliper have great influence on the reliability of the bolt connection. Therefore, in order to improve the reliability of bolt connection, the preload between the six bolts should be kept the same, and the friction coefficient between the friction plate and the brake caliper is greater than the critical friction coefficient 0.174.

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