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The Several Analysis Methods of Railway Vehicles Bolt Coupling Strength

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***Abstract*—The bolt connection is one of the main connection ways of railway vehicles connection. The reliability of its connection determines the dynamic performance, safety and reliability of railway vehicles. Checking methods of bolt coupling strength: mechanical design calculation, finite element calculation, and "VDI2230" calculation are recognized at home and abroad. But at present, it is less to systematically analyze basic calculation flow, finite element modeling, advantages and disadvantages of these three methods, especially to check railway vehicles bolts at the same time in the three ways. This article detailed introduces the principle and characteristics of three methods. And combined with the engineering example on EMU pillow beam structure, bolt strength calculations were given. Calculation results show that using mechanical design method, the bolt model is simple and computed stress is more conservative; Using FEM, the bolt model is complex, computing time is long, computed stress is more intuitive and the stress of each part of the bolt can be given; Using VDI, the bolt model is simple, work stress is between the first two methods, calculation involves more parameters, can give a more detailed check different states at different positions of the bolt.**

Keywords-railway vehicles; bolt; mechanical design; the finite element; VDI2230

I. INTRODUCTION

In recently, China's economy has entered a new normal. One Belt And One Road's national development strategy is bringing unprecedented opportunities for China's rail transit industry. Bolt as important connection, which directly determines the dynamic performance, safety and whole reliability of railway vehicles. Because high speed trains have the special structure, the main equipment (e.g., corbel, main transformer, traction converter, brake control devices, etc.) are connected by bolts hanging installation in the trains. In order to ensure the reliability of these structures, there are strict requirements for the bolts used. With the development of track transportation enterprise, more and more researches have been made on the check of rail vehicle bolts.

The overseas research on the strength of bolted connections is relatively early. Nowadays the experimental and theoretical study techniques of bolted joint strength are relatively mature [1~4]. Croccolo made correlation analysis that it combined the "VDI2230 Systematic Calculation of High Duty Bolted Joints with One Cylindrical Bolt"(hereinafter referred to as VDI2230) and experimental research method about high strength bolt connection, finally the calculation formula can be get to calculate the maximum equivalent stress[5];The method of applying preload the bolt connection of the equipment of EMU was studied by Q. Wen [6];Y. M. Mo had studied the friction coefficient of the control bolt, which can control the stability of torque coefficient and improve the stability of friction relaxation[7];Y. Tan used VDI2230 to check the strength of mounting bolts for anti roll installation of Macedonian EMU[8].

The static load and fatigue load of hanging equipments of rail vehicle are more complex because of more connecting bolts. The lateral load of static load of rail vehicle is $\pm 1\times g$, the longitudinal load is $\pm 3\times g$, the vertical load is $(1\pm c)\times g$, (the vehicle side c=2, in the center of the vehicles the value is down to 0.5); The lateral load of fatigue load of rail vehicle is $\pm 0.15\times g$, the longitudinal load is $\pm 0.15\times g$, the vertical load is $(1\pm 0.15)\times g$. So it is very difficult to check the bolt in theory.

In this paper, three methods of checking bolts are introduced in detail, including mechanical design calculation method, finite element calculation method and "VDI2230" calculation method. This paper analyzes basic calculation flow, finite element modeling, advantages and disadvantages of these three methods. And combined with the engineering example on EMU pillow beam structure, bolt strength calculations are given based on the three methods. It provides the calculation basis for the design and selection of the bolt coupling of the rail vehicle.

II. BOLT CHECKING METHOD

A. *TheCalculationProcess of BoltCheckingMethods*

1) Mechanical design calculation method

The load of bolt is either axial force or lateral force. The ordinary bolt connections are mainly driven by axial force. The bolt shank and screw thread of ordinary bolts are cracked by axial force. So the tensile strength and fatigue strength of the bolt are very important. The connection surfaces of hinged bolt shank and hole wall are collapsed by lateral force. So the shear strength and compressive strength of the bolt are very important [9].

Using mechanical design method to check the bolt strength, the various parameters of bolt such as axial force, horizontal force and torque should be calculated. If the bolt of rail vehicle on the variety, quantity or the load is complex, it is very difficult to calculate the parameters of bolts with the theory of material mechanics and theoretical mechanics. Firstly the parameters of bolt such as axial force, horizontal force and torque are obtained based on the finite element model on the complicated situations. Then the tensile strength, compressive strength, shear strength and fatigue strength of bolt are calculated based on the mechanical design calculation

method. This is more convenient than using mechanical design method purely to check bolts. The flow of checking bolt based on mechanical design calculation method is as shown in figure Ⅰ.

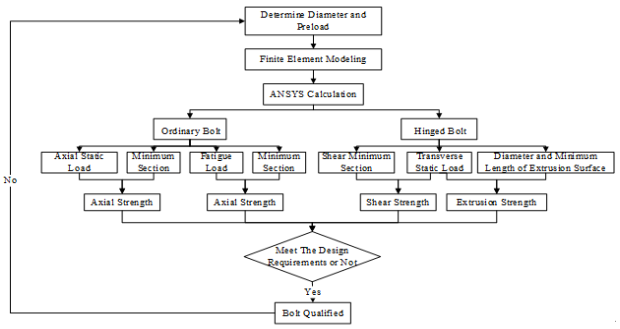

FIGURE I. MECHANICAL DESIGN CALCULATION METHOD FLOW CHART

2) Finite element calculation method

When the bolt is analyzed by finite element method, the effect of bolt preload is taken into account. The various components need finite element analysis with contact nonlinearity. Base on the calculation results, the stress (Von.Mises) on the bolt is compared with the allowable stress of the material, and the static strength of the bolt is finally determined.

If the fatigue load is used, the fatigue stress of the bolt can be calculated based on the BS-7608.By comparing the fatigue stress and allowable stress of bolts to evaluate whether the fatigue strength of bolts is meet the requirement of work.

Based on the BS-7608, the range of the allowable stress $[\Delta\sigma]$ is:

$$[\Delta\sigma] = \sigma_b \times n_f, n_f = 0.06 \quad (1)$$

Where, the value of n_f is shown in figure Ⅱ, σ_b is the tensile strength.

The bolt internal force ΔF is extracted according to the calculation case and the stress range in the working state of the bolt is obtained by (2).Evaluate whether the fatigue strength of the bolt meets the requirement.

$$\Delta F/A = \Delta\ \sigma \quad (2)$$

Where, the value of ΔF is bolt internal force, the value of A is bolt section area.

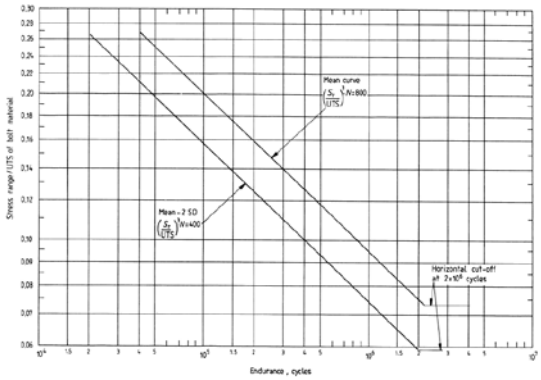

FIGURE II. CURVE OF BOLT UNDER AXIAL LOAD (X CLASS)

The flow of checking bolt based on finite element calculation method is as shown in figure Ⅲ.

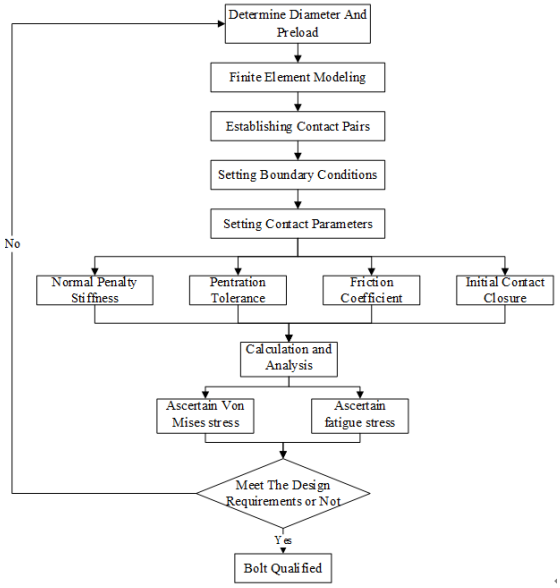

FIGURE III. FINITE ELEMENT CALCULATION METHOD FLOW CHART

3) VDI2230 calculation method

VEREIN DEUTSCHER INGENIEURE (VDI) enacted new design criteria VDI2230 calculation method to check high strength thread connection. The VDI2230 was published in 1986, which practice more than 30 years. The latest version released in 2003, which has been widely recognized and referenced [10].

Nowadays, VDI2230 is not only used in the German language area, but also other countries besides German. The purpose of VDI2230 is to provide the design engineers with an advanced standard for the calculation of bolts. The method can design more reliable bolts, and realize the maximization of the utilization of bolts.

The calculation steps of VDI2230 are divided into 14 steps. The preload and type of bolts are selected from step0 to step7.If the selected bolt cannot meet the requirements, the preload and type of bolts should be selected again. From step8 to step13, the bolt shank strength, fatigue strength, nut

strength, thread meshing length, maximum shear stress, anti-slip and torque can be checked. When the safety coefficients meet the design requirements, the preload and type of bolts are right.

The flow of checking bolt based on the VDI2230 calculation method is as shown in figure Ⅳ.

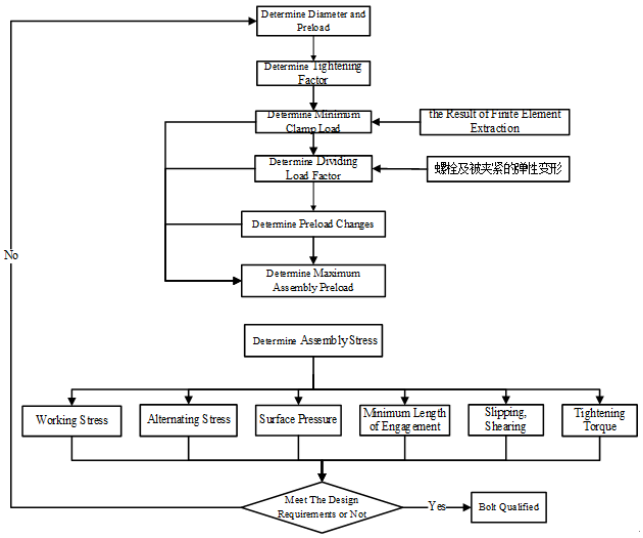

FIGURE IV. VDI2230 CALCULATION METHOD FLOW CHART

B. Finite Element Model of Bolt Check Method

1) Modeling method of mechanical design calculation

Using mechanical design calculation method check bolts, the bolt is simulated by beam element. Connections are simulated by Two-dimensional (2D) elements or three dimensional (3D) elements. When the connections are simulated by 3D element, each connection should be linked by common nodes or established contacts. In order to obtain the various forces on the bolt, a beam element is used to simulate the bolt instead of multi beam elements. The beam is connected with the outer end of the connected part through the rigid element. The join effect is shown in figure Ⅴ.

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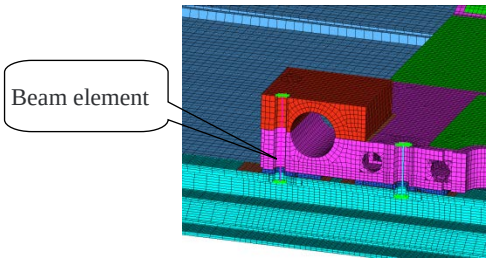

FIGURE V. MODEL AND JOIN EFFECT

2) Modeling method of finite element calculation method

Using finite element calculation method to check bolts, should detail the bolt connection model. The main connections and bolts are simulated by 3D elements. The other parts of model are simulated by 3D element or 2D-3D element according to the importance of the parts. The contact pairs should be established between the connections. The model and the contact pairs are shown in figure Ⅵ. The preload case analysis is firstly carried out to ensure that the structure has no rigid body displacement. Then the corresponding contact parameters should be set, such as normal penalty stiffness, penetration tolerance, friction coefficient and initial contact closure [4].

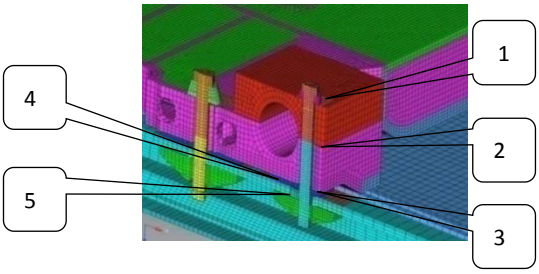

FIGURE VI. MODEL AND CONTACT PAIRS

3) Modeling method ofVDI2230 calculation method

Using VDI2230 calculation method to check bolts, the modeling method is same as the model of mechanical design calculation method.

C. The Advantages and Disadvantages of the Check Methods of Bolt

The advantages and disadvantages of the three kinds of check methods are shown in table Ⅰ

TABLE I. THE ADVANTAGES AND DISADVANTAGES OF THE CHECK METHODS OF BOLTS

The methods of checking bolt	Advantages	Disadvantages
Mechanical design	1) The bolt is simulated by beam element. The connections are simulated by 2D elements or 3D elements. Modeling is simple. And the method is suitable for multiple layers of bolt connections; 2) The calculation process is linear static analysis and data extraction is more convenient; 3) The bolt is subdivided into ordinary bolts and hinged bolts, to check the different strength according to the different kinds of bolts.	1) Bolt connections are connected through the rigid elements. The rigid elements should not be evaluated where the stress singularity in the connections of bolt; 2) In the evaluation process, the bolt stress is mean stress, ignoring the stress concentration of the bolt root; 3) Compared with the process of VDI2230 method, the process of finite element analysis is simple, with more detailed checking on different parts of the bolt.
Finite element analysis	1) The bolt is simulated by 3D elements. The status of the bolt connections is considered in this modeling process, which is most consistent with the bolt reality; 2) The calculation result is direct and the stress concentration effect of bolt root is considered fully; 3) It is possible to carry out the strength assessment of the other parts of the bolted connections; 4) The bolt anti-slip analysis can be performed on this basis.	1) The more workload is necessary in this analysis method because of large amount of 3D elements, especially the edge of structure, corner position and the existence of stress concentration. The model need to be refined if there are stress concentration; 2) The analysis process is longer. The calculation process is nonlinear and the contacts are difficult to converge; 3) It is necessary to analyze the rationality of the calculation results and adjust the contact parameters multiple times before the reasonable results can be obtained.
VDI2230	1) The modeling is simple and the bolt is simulated by beam element. The connections are simulated by 2D element or 3D element; 2) The analytical process is the linear statics analysis, and the data extraction is more convenient; 3) The bolt is refined, and more detailed checking of different parts of the bolt is carried out, and the result is more comprehensive.	1) Bolt connections are connected by the rigid elements. And there are the stress singularity of rigid element connections, which should not be evaluated; 2) This method is similar to the mechanical design calculation process. In the evaluation process, the bolt stress is mean stress, ignoring the stress concentration of the bolt root; 3) Too many parameters are required in the process of evaluation, which engineers are difficult to provide. The veracity of parameters based on the experience is difficult to guarantee. So the method is only suitable for less connections.

III. CASE CALCULATION

In this paper, combined with the engineering example on EMU pillow beam structure, bolt strength calculations were given. And the calculation results of three kinds of bolt checking methods were analyzed.

A. Finite Element Model

The EMU pillow beam structure was connected by six M30 bolts and two M24 bolts (ordinary bolts 8.8 grade, yield strength is 640MPa).The geometric model were shown in figure Ⅶ. In the figure, X axis was the longitudinal direction of the EMU body, Y axis was the lateral direction and Z axis was the vertical direction.

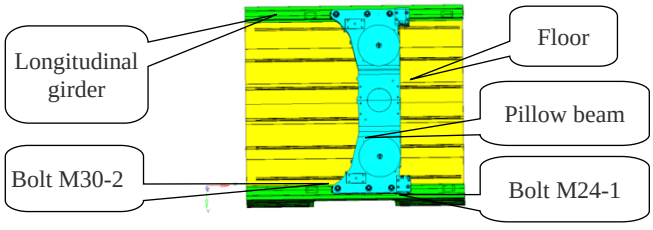

FIGURE VII. MODEL OF THE EMU PILLOW BEAM STRUCTURE

According to EN 12663, railway vehicles lifting equipment had eight load case of static strength and three load case of fatigue strength (vertical, longitudinal and lateral acceleration).In this paper, the bolt is checked under the maximum static and maximum fatigue load case because the length of the article is limited. The load cases are as follows:

1) Load case of static strength: longitudinal load: -3g, vertical load: 1g;

2) Load case of fatigue strength: vertical load: ±0.15g.

The maximum stress bolts M24-1 and M30-2are selected to check in this paper.

B. Calculation Results

According to three methods of bolts checking, the results of M24-1 and M30-2 are shown in table Ⅱ.

TABLE II. CHECKING THE CALCULATION RESULTS OF BOLT CHECKING METHODS

Stress unit: MPa

Method	Bolt type	Relevant parameters	Calculation results			
			Tensile strength	***Safety factor***	***Fatigue strength***	***Safety factor***
Mechanical design	M24	Axial force; Minimum section.	360.8	1.77	0.39	27
	M30		364.1	1.75	0.47	25

Method	Bolt Type	Relevant parameters	Calculation results				
			Maximum stress	***Middle stress of bolt shank***	***Safety factor***	***Alternating stress***	***Safety factor***
Finite element calculation	M24	Axial force; Preload; Minimum section.	409	227	2.57	0.26	35
	M30		520	289	1.97	0.484	21

Method	Bolt Type	Relevant parameters	Calculation results									
			Step 8	***Safety coefficient***	***Step 9***	***Safety coefficient***	***Step 10***	***Safety coefficient***	***Step 11***	***Safety coefficient***	***Step 12***	***Safety coefficient***
VDI 2230	M24	Bolt axial force and nearly 100 related parameters	298	2.21	0.30	141	21	11	206	309	0.47	422
	M30		298	2.21	0.36	121	27	8.5	885	157	0.15	219

Note: Step 8 is working stress; Step 9 is alternating stress; Step 10 is surface pressure; Step 11 is minimum length of engagement; Step 12 is slipping and shearing..The calculation formulas of the relevant parameters involved in the table are not listed in one by one.

C. Results

In the analysis of the behavior of bolt under the three methods (Table 2-1), it is always resulted that:

1) The ordinary bolts are evaluated by mechanical design calculation method, which involved less parameters. The tensile strength, fatigue strength and their safety coefficients should be calculated in this method. The tensile strength and fatigue strength is mean stress of bolt shank (bolt minimum diameter).The value of axial tensile strength is between the value of maximum stress and the value of mean stress of bolt shank(bolt nominal diameter). The calculation value of mechanical design calculation method is bigger than the value of VDI2230calculation method.

2) The bolts are evaluated by finite element calculation method, which involved less parameter. The maximum stress and middle stress of bolt shank, alternating stress and their safety coefficients should be calculated in this method. The maximum stress of bolts is the stress at the head of bolts. The middle stress of bolt shank is the mean stress. Compared with the average stress calculated by mechanical design, the value of Finite element calculation is less. More conservative in mechanical design calculation. There are similar with the alternating stress and the fatigue safety coefficients of the bolt calculated by the two methods.

3) The bolts are evaluated by the VDI2230 calculation method, which involved more parameters. The bolt working stress, alternating stress, surface pressure, minimum length of engagement, slipping, shearing and their safety coefficients should be calculated in this method. The value of working stress is between the values of other two methods. The result of fatigue alternating stress is similar with the value of other two methods. The safety coefficients are completely different, because the calculation formulas of fatigue alternating stress among the three methods are completely different.

IV. CONCLUSION

The three kind methods of checking bolts are given in this paper. And the calculation results of bolt connection strength combined with the example of the EMU pillow beam are given. The three methods are both similar and different in terms of basic processes, modeling techniques, advantages, disadvantages, and results. The conclusions are as follows:

1) Using the mechanical design calculation method check bolt, it is necessary to first determine whether the bolt is ordinary bolt or hinged bolt. The ordinary bolt is mainly driven by axial force. So the tensile strength and fatigue strength of the bolt must be checked. The ordinary bolt has less shear force, so the shear strength need not be checked. The shear strength of the bolt shank and the compressive strength of the connection surface of bolt shank and hole wall should be checked, if the bolt is hinged bolt. The bolt is simulated by beam element in this method. The mean stress of the bolt shank is given and the result is conservative.

2) Using the finite element calculation method check bolts, the bolt is simulated by 3D element. Contact nonlinearity is considered in this method. The maximum stress, the different parts stress of the bolts and the stress distribution of the connecting piece can be obtained directly. It spends long time in this calculation process because the contact is difficult to converge. The stress of the bolt root is larger, but the stress of middle of the bolt shank is less. The stress situation of each part can be reflected well in this method, and the result is more intuitive;

3) Using VDI2230 calculation method check bolts, the first eight steps is the selection of preload and type for the bolt. Starting from step 9, the working strength, fatigue strength, the strength of nut, minimum length of engagement, slipping, shearing and torque are checked respectively. Compared to the other two kinds of checking methods, there are more calculation parameters and it is difficult to determine the

calculation parameters of the bolt in this method. The calculation result is more comprehensive and the value of working stress in this method is between the values of other two methods.

These main contents of the three methods of checking bolts are introduced in this paper, which plays an important guiding role in the design and selection of the bolt connection of rail vehicles.

ACKNOWLEDGMENTS

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