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Static strength calculation of auxiliary converter equipment and verification of bolt VDI2230 standard

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Abstract. Aiming at the safety performance of metro equipment structure and bolt connection strength during running, the auxiliary converter was taken as the research object. Finite element analysis of auxiliary converter box and related bolt seat, car body crossbeam and side beam had been studied under various working conditions according to load requirements in EN12663 standard. With VDI 2230 standard, bolts strength of connecting equipment and beams had been checked. The calculation results show that the stress of each part of the auxiliary converter model and bolt meet the application requirements.

1. Introduction

In recent years, the subway has become a key transportation hub in the city with the rapid development of urbanization. Metro is becoming more high-speed and overloading, so its safety and reliability has always been issues for people^[1]. The metro circuit system is the guarantee to ensure its safe operation. The main function of auxiliary converter is to provide normal power supplies for train compartments^[2] and this equipment, connecting the equipment seat on the car body chassis with bolts, is usually placed at the bottom of the metro^[3]. If the equipment seat is broken or damaged during the operation of the metro, then the equipment will fall off from the chassis onto the track, as well as it will pose a serious threat to the safety of passengers on board. Bolts are the key joints connecting equipment and car body. So the safety and reliability of bolts are also concerned by people.

In this paper, the auxiliary converter model was used as the research object and the safety of the suspension equipment and bolt was checked, as well as the static strength of converter equipment and suspension was studied. According to VDI 2230 standard, the strength of bolts is checked to provide basis for equipment reliability calculation.

2. Auxiliary converter model

2.1. Performance Parameters

The total weight of auxiliary converter hoisting equipment is 2.12t. The whole model consists of converter box, crossbeam, crossbeam suspension and side beam. The converter box is connected with the crossbeam suspension through 14 M20 bolts (grade 8.8) and crossbeams are welded to side beams through connecting plates.



2.2. Finite Element Model

Considering the main inspection of hoisting and box safety, more accurate hexahedral solid elements were used to simulate the crossbeam suspension and box. Four-node thin shell elements were used to simulate crossbeam and side beam. For solid-shell elements smooth transition between the crossbeam and the suspension of the crossbeam, some solid elements were used. The total number of elements in the whole model was 237003 and the number of nodes was 380288. The finite element model and bolt number were shown in figure 1. In the figure, X direction is the longitudinal direction of the car body, Y direction is the lateral direction of the car body, and Z direction is the vertical direction of the car body.

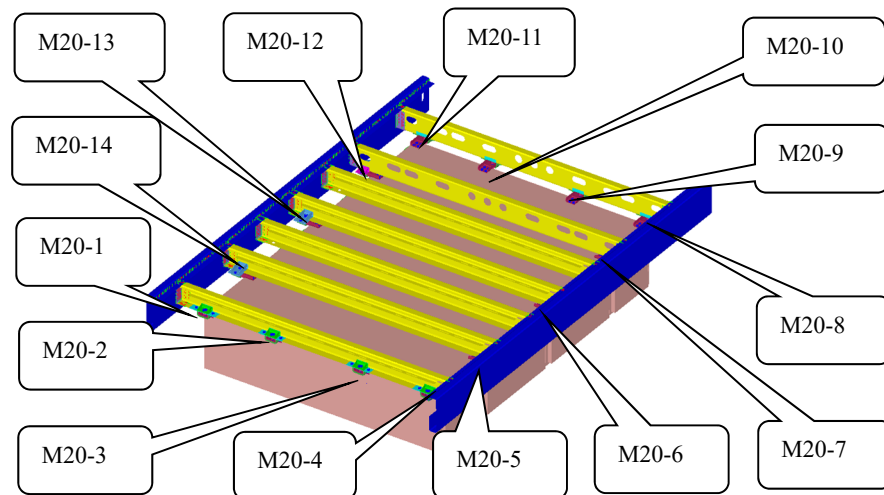


Figure 1. Auxiliary converter equipment and bolt distribution map

There are two finite element modeling methods for bolts^[4]. One method is to build bolt model with solid element. This method can calculate the working stress of each position on the bolt and the model is closer to the actual structure. However, it is necessary to establish contact pairs between bolts and clamps and calculate them by non-linear method, so it takes more time to model and compute. The second method is to use beam element to simulate bolts. The advantage of beam element is that when there are more bolts and more complicated working conditions, modeling and calculate time is shorter and the force acting on the bolt under working conditions can be quickly put forward. In this article, due to bolt numbers, the complex working conditions and VDI 2230 standard requirements, bolts were simulated using beam elements to put forward the force acting in operation which were used to check bolts strength.

2.3. Calculation Conditions

Acceleration values of equipment and its components were determined according to EN 12663^[5]. Considering the acceleration of metro vehicles in all directions during operation, there were five calculation conditions for static strength analysis of auxiliary converter hoisting equipment as shown in Table 1. The longitudinal, transverse, vertical displacements were restrained at both ends of the side beam of the car body.

Table 1. Calculating conditions for static strength analysis

working condition	Longitudinal acceleration (x)	Transverse acceleration (y)	vertical acceleration (z)
1	-3g	0	1g
2	3g	0	1g
3	0	-1g	1g
4	0	1g	1g
5	0	0	3g

$g=9810\text{N/kg}$

3. Calculating results of static strength

The calculation stresses of the four components of crossbeam, crossbeam suspension, side beam and box body of auxiliary converters under five working conditions were analyzed to meet the requirements of the equipment. The maximum stress result of each component was shown in Table 2.

Table2.Calculations of static strength (Von Mises Stress)

component	working condition1	working condition2	working condition3	working condition4	working condition5	Unit:MPa
						Yield stress
Crossbeam	230	237	221	220	214	410
Crossbeam suspension	182	187	109	101	133	410
Side beam	98	98	73	65	145	410
Box	180	195	92	99	114	205

Because the auxiliary converter is bolted to the crossbeam suspension of the car body underframe and the crossbeam suspension is fixed on the crossbeam of the underframe, crossbeam is the maximum stress position as the main force-bearing structure under each working condition. The stress magnitude of each component under symmetrical working condition was basically the same. Stress results was reasonable and the calculated stress was less than the yield stress, so the auxiliary converter met strength requirements.

Displacement and stress nephograms of auxiliary converter equipment under the worst working condition were given here. Due to the longitudinal impact, crossbeam and crossbeam suspension had squeezing action between each other. The maximum stress point occurred at the squeezing point of the crossbeam and the crossbeam suspension as shown in Figures 2 (c) and 2 (d). When the box was impacted by longitudinal 3g acceleration, the stress value was maximum and the maximum stress point occurred in bolt hole place as shown in Figure 2 (e).

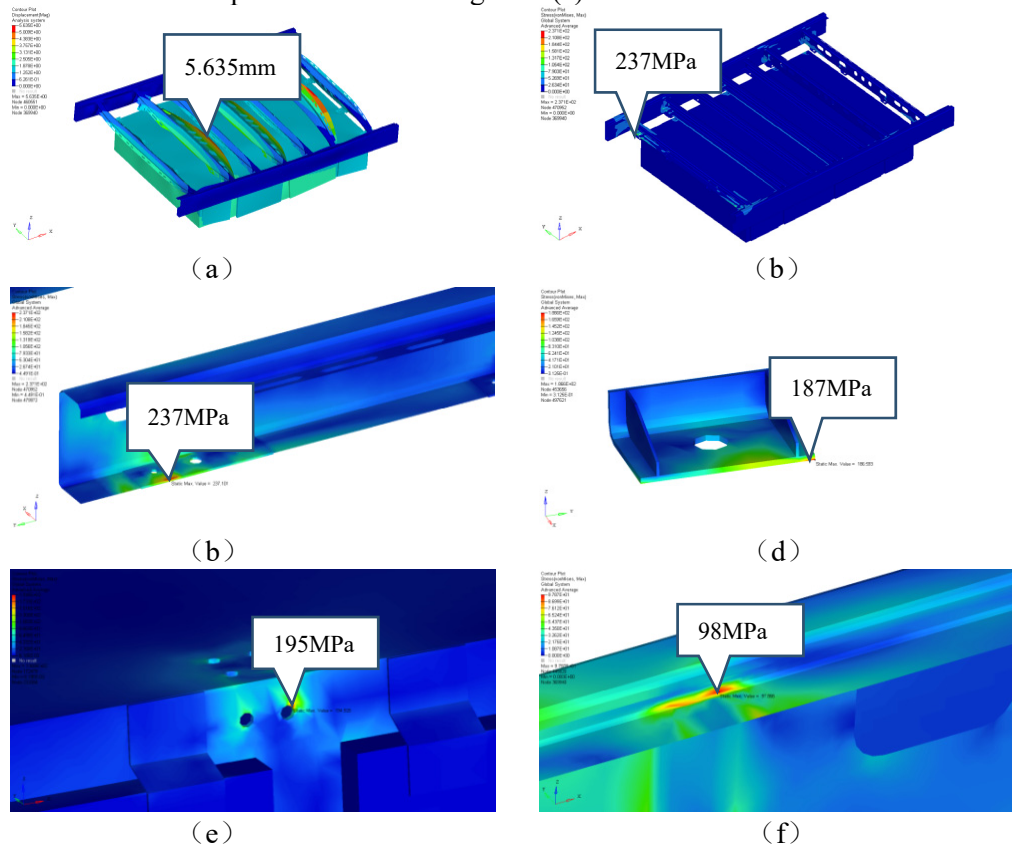


Figure2.Result nephogram under condition 2

4. Key calculation steps of VDI^[6] and bolt check calculation results

In VDI 2230 standard, each bolt stress is mainly investigated and if the stress is less than the allowable stress of the bolt, the bolt is qualified. There are 14 steps in VDI 2230 standard and many calculation parameters. The main calculation parameters and steps were listed in this section.

In this paper, M20 bolts (grade 8.8) were used in the auxiliary converter. The specific parameters were shown in Table 3.

Table 3. Bolt connection parameters

Bolt type	Nominal diameter of thread d	Grade	Thread pitch p	Bolt hole diameter d _h	Diameter of bearing surface of bolt head d _w	Length unit:mm		
						Bolt Threadless Rod Length l _l	Load-free thread length l _{Gew}	Screw length l _l
M20	20	8.8	2.5	22	27.7	44	46	90

4.1. The Minimum Clamping Load Required F_{Kerf}

$$F_{Kerf} \geq F_{KQ} = \frac{F_{Qmax}}{q_F \cdot \mu_{Tmin}} + \frac{M_{Ymax}}{q_M \cdot r_a \cdot \mu_{Tmin}} \quad (1)$$

In the formula F_{Qmax} , M_{Ymax} was the lateral force and torque of the bolt and q_F , q_M was the number of interfaces for transverse force and torque transfer. There was only one surface between each component, so q_F , q_M was μ_{Tmin} was minimum friction coefficient of clamped interface. In this model μ_{Tmin} took 0.21. Measuring the shortest distance from the center position of the bolt head to the model boundary was r_a which was named friction radius.

The calculation results of selecting the most dangerous bolts under each working condition were shown in Table 4.

Table 4. Basic parameters and calculation results for minimum clamping load

working condition	Select bolts	$F_{Qmax}(N)$	q_F	μ_{Tmin}	$M_{Ymax}(N \cdot mm)$	q_M	$r_a (mm)$	$F_{Kerf}(N)$
1	M20-1	848.86	1	0.21	34102	1	40	8625
2	M20-8	854.51	1	0.21	36192	1	40	8350
3	M20-8	545.98	1	0.21	6605.3	1	40	4855
4	M20-11	541.86	1	0.21	7278.7	1	40	3466
5	M20-8	759.31	1	0.21	8329.2	1	40	3571

4.2. The Loss of Pre-tightening Force Caused by Embedding F_Z

Pre-tightening loss due to embedding without considering thermal expansion F_Z .

$$F_Z = \frac{f_Z}{(\delta_s + \delta_p)} \quad (2)$$

In the formula δ_s was elastic deformation of bolts. It can be obtained by calculating the standard formula of VDI 2230 from 5.1/1 to 5.1/15 $\delta_s = 2.08e-6 mm/N$. δ_p was elastic deformation of clamped parts. It can be obtained by calculating the standard formula 5.1/25 of VDI 2230 $\delta_p = 5.42e-7 mm/N$. According to actual model, the contact surface inside the bolt was 2. Connection embedding quantity of bolts was calculated by standard table 5.4/1 of VDI 2230 $f_z = 13 \mu m$. Thus, the loss of pre-tightening force of bolts was 4958N.

4.3. Determining maximum assembly pre-tightening force and permissible pre-tightening force of bolts

The parameters of bolt axial force, loss of pre-tightening force and material and property of bolt itself were substituted into the relevant formula of VDI 2230 standard to calculating the maximum assembly pre-tightening force of M24 bolt $F_{Mmax} = 25605N$ and allowable pre-tightening force for bolts $F_{Mzul} = 119376N$.

The design pre-tightening force of bolt is calculated at design time $F_v = 83000N$. When the

pre-tightening force of bolt design is between the maximum assembly pre-tightening force and the allowable pre-tightening force of bolt. The design value as pre-tightening force is used to continue checking bolts.

4.4. Checking Results

The working stress, minimum residual load and maximum shear stress of the most dangerous bolt under each working condition were checked according to VDI 2230 standard steps. Calculating the safety factor of bolts that need to be checked. The calculation results are shown in Table 5.

Table 5. Calibration results

Bolt Model	work Stress (MPa)	safety factor	surface Stress (MPa)	safety factor	Minimum residual load (N)	Anti-slip safety factor	Maximum shear stress (MPa)	Shear safety factor	working condition
M20-1	380.53	1.68	39.78	12.31	40508	4.69	848.86	73	1
M20-8	380.55	1.68	39.79	12.31	40400	4.83	854.51	73	2
M20-8	380.48	1.68	39.75	12.32	40786	8.40	545.98	115	3
M20-11	380.48	1.68	39.75	12.32	40816	11.77	541.86	115	4
M20-8	380.58	1.68	39.81	12.31	40218	11.26	759.31	82	5

The table showed that the most dangerous bolt working stress, surface force and minimum safety coefficient of residual load and maximum shear stress is greater than 1.15 which indicated connecting bolt properties of auxiliary converter met the normal operation of the metro in various working conditions.

5. Conclusion

(1) The static strength of auxiliary converter was calculated under impact condition in EN12663 standard. The modeling method for finite element calculation of equipment was provided. The simulation results showed that the stress of the inspected part under each working condition met the requirements of operation.

(2) Based on the VDI 2230 standard, the bolts under main loads condition were checked. The bolts were simulated by beam element in finite element modeling and the main calculation parameters and steps were given. The results showed that the safety factors of bolt working stress, surface stress, minimum residual pre-tightening force and maximum shear stress of auxiliary converter are all greater than 1.15.

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