Research on Key Parameters and Mechanical Behavior of the Rectangle Earth Pressure Balance Tunnel Shield Machine

Cao Qiang[1,a], Huang Jingyu[1,2,b,*], Wang Renpeng[1],Zhang Long[1],Wang Peng[1],Wu Di[1]

[1]Department of Building Engineering, Tongji University,Shanghai,200092,China

[2]National Maglev Transport Research Center, Tongji University,Shanghai,201800,China

[a]caoqiang6188@163.com, [b]hjymaglev@sina.com

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Abstract. In the last few decades, rectangle earth pressure balance shield machine have been introduced as primary tunneling tools in soft soil excavation around the world. This paper presents research on the performance of the rectangle shield machine. Analytical studies have been carried out to establish the relation between rectangle shield machine design key parameters, such as segments support, tail thickness and soil layer harness, and the strength, stiffness and buckling analysis of the shell structure. The results of these are presented. And the results show that good stiffness, displacement and stability capacities have been achieved.

Introduction

The EPB shield machine, as specialized high-tech composite construction equipments for large tunnel project, have been greatly used in the soft soil layer, especially after the EPB shield machine were introduced. In recent years, some scholars have conducted a lot of research about the shield machine. MarcIsambard Brunel developed a shield construction technology and patented [1]. Sugimoto [2] raised the load theoretical model acting on the shield machine in 1991. Shimizu and Suzuki [3] also put forward the relationship of the shield's shapes and the jack moment's, and tested the relationship according to the measurement dates of the field and model tests in 1992. Zhu Hehua et al [4] studied the law of jack, and elaborated the mechanism of friction between the soil and the shield shell especially.

From the point view of the shield machine function, it is necessary for tunnels formed by the circular shield machine to be filled again in the upper and lower part, so the utilization of space of these tunnels is much lower than that of tunnels formed by rectangular shield machine. It is not only because there is a good correlation between the rectangular cross-section tunnels and the vehicle shape, but also the rectangular shield machine has the virtue of no baffles and bed plates, low cost, easy installation and so on. However, there are also some drawbacks in rectangular shield machine. The stress condition is more complex and more easily deformed than that of the circular shield shell. Due to the safety of the shield machine enclosure should be attached importance, the current design methods in domestic, that mostly cited empirical formulas from abroad and design and research of the rectangular shield machine is relatively few. Therefore, it is necessary to conduct the analysis of strength, stiffness and stability of the structure in order to ensure the safety of the structure.

The main task of this paper is to research the mechanical behavior of the actual project rectangular shield machine. Three-dimensional finite element model was built and parametric analysis of EPB shield machine research was carried out to study the internal force and deformation variation of the rectangular shield machine, including impact of soil foundation soft and hardness degree, different thickness and support of wire brushes in tail part of shield machine.

Fig 1 shows the profile of the rectangular shield machine located in the starting well, consisting cutting, supporting and tail, and the sectional dimension is 9.9 m × 9.1m × 5.0 m.

Fig.1 the profile of rectangular shield machine

Fig.2 rectangular shield machine is in the starting well

And the analysis results are not only beneficial to verifying the safety of the shield shell structure during the construction process, and guiding the running of the rectangular shield tunneling machine, but also optimizing the size of each part of the shield shell structure.

Establishing and checking a finite element model

Material Properties and meshing

The material of shield machine shell in this project is Q345 steel, of which the elastic modulus E = 2.06 × 105MPa, thermal expansion coefficient 1.2 × e-5, the yield strength f_y 345MPa, ultimate tensile strength fu 550MPa. According to "Steel Design Code in China the code for design of steel structures in China" (GB50017-2003) the relevant provisions of 3.4.1, the design strength values f values are as follows:

(1) If the member thickness t <16mm, then f = 310 MPa;
(2) If the member l thickness t> 16 ~ 35 mm, then f = 295 MPa;
(3) If the member thickness t> 35 ~ 50 mm, then f = 265 MPa;
(4) If the member thickness t> 50 ~ 100 mm, then f = 250 MPa;

The material of wire brush at the end of the shield machine, is Teflon, density ρ 2320 kg / m^ 3, the elastic modulus E = 280 MPa, ultimate tensile strength f_u 27.6 MPa, compressive ultimate strength $f_u{}'$ 12.0 MPa.

In order to consider the material nonlinearity, multi-linear hardening model is adapted shown in the fig 1. And materials comply with von Mises yield criterion and relevant flow rule. Fig 3 shows the finite element meshing of the whole machine shell.

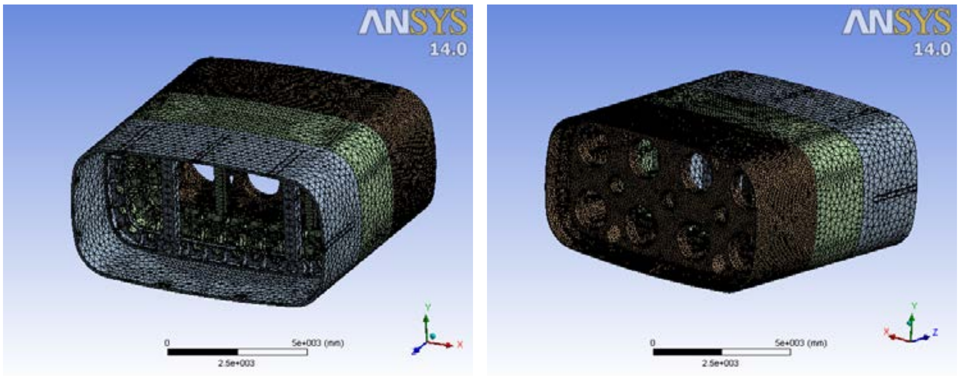


Fig.3 meshing of the whole shell

Loads of shield machine

Shell loads mainly include top earth pressure, lateral earth face, bottom earth pressure and earth pressure of chest plate. The top earth pressure is calculated according to the equation (1); lateral earth pressure and chest plate pressure are shown in fig.4.

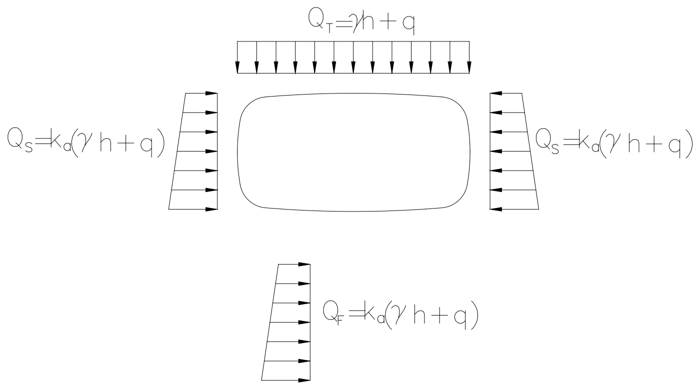


Fig 4 Loads of rectangle shield machine

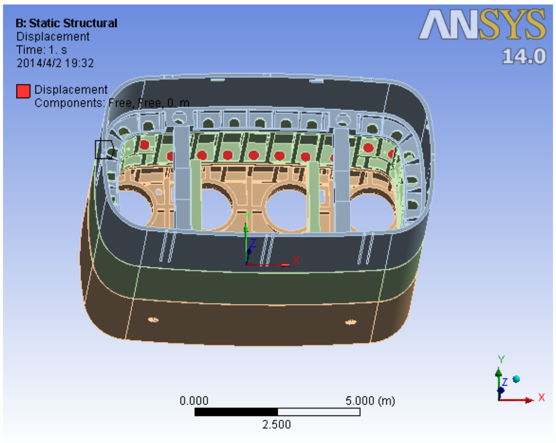
Boundary conditions

The bolted Connection of three components, cutting, supporting and tail, are regarded as rigid connection.

The connection between the shell and chest plate and the contact between the shell and soil are all considered as elastic support. And the foundation stiffness value of the elastic support is shown in table 1.

Table 1 Spring stiffness values

Component type	Connection chest plate and soil	Connector housing and the bottom surface of the soil
Boundary conditions	Elastic support	Elastic support
Foundation Stiffness K(kN/m^3)	1.0×10^{21}	1.0×10^{21}



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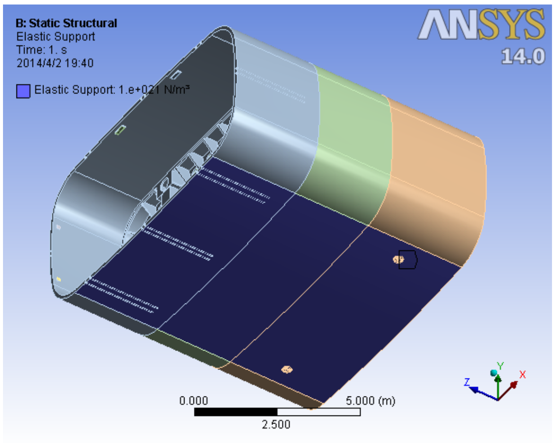
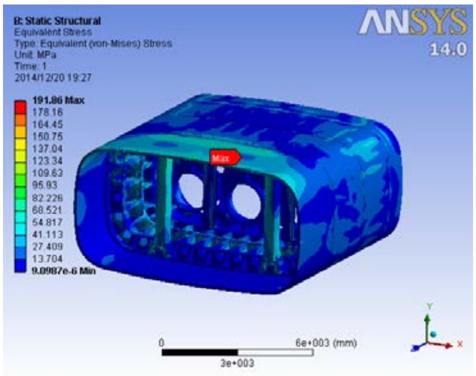


Fig.5 Jack support at the supporting

Fig.6 Elastic support at bottom shell

The most unfavorable conditions of the rectangle shield machine in construction occurred at the point when the jack is on full power operation. In the computational model, in the direction of shield machine travel, spring supports are applied on the surface of chest plate, and supporting springs are applied at the bottom of the shield machine. And the corresponding boundary conditions as shown in figure 5 and figure 6.

Static performance analysis of rectangle machine



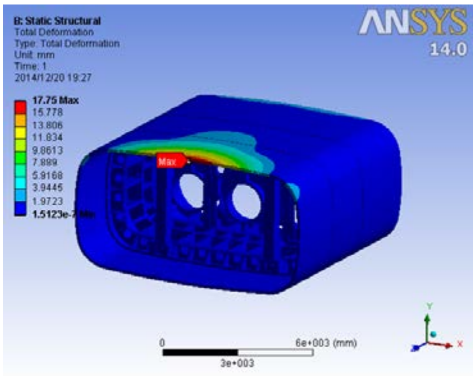


Fig.7 Stress distribution of rectangle shield machine Fig.8 Deformation distribution of rectangle shield machine

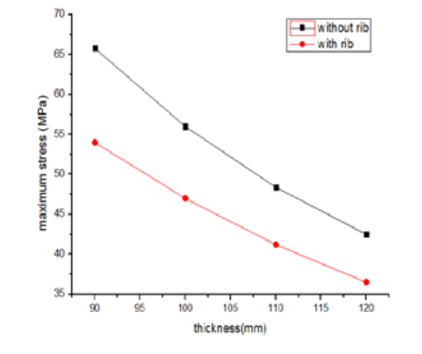
Under 6 meters covering soil layer, stress distribution of rectangle shield machine is shown in fig 7. From the whole structure, the maximum stress value is 191.9 MPa, and it occurs on the flange of tail. In addtion the maximum deformation of the shell structure is 17.8 mm, shown in fig 8, and it takes place at the free end of tail. The stress of the cutting is 180.9 MPa in the transverse rib of top of the cutting, and the corresponding maximum displacement is 3.5 mm. The stress of the supporting is 116.7 MPa in the top flange of the supporting, and the corresponding maximum displacement is 3.2 mm.

Stress of all the components of structure are all less than the yield strength， so the strength of the shield machine satisfy requirements of steel structure design code in China.

Effect of Key parameters on performance of shield machine shell

According to the above analysis, the tail is the smallest stiffness part of the shield machine, which is the largest deformation part. Because of the need of construction, Needs of the construction, require a certain stiffness shield tail, large deformation can not happen, so as not to affect the assembly segments.

Keeping the parameters of the thickness of cutting and supporting constant, then set the thickness of 800 mm length of tail which is the latter part of the tail as 45mm, and change the thickness of the front half of the shield tail thickness 90mm, 100mm, 110mm 120mm respectively, intend to consider the thickness of the shield machine shield tail effect on the mechanical property of the whole structure.



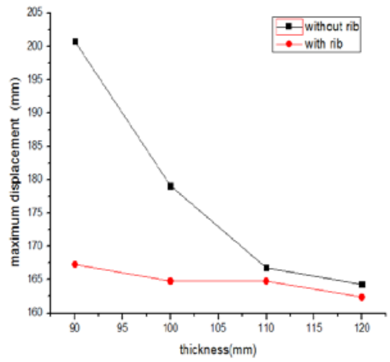


Fig.9 the maximum stress versus the thickness of tail Fig.10 the maximum deformation versus the thickness of tail

Fig 8 the maximum stress versus the thickness of the shield tail curve

As can be seen from fig.8, the maximum stress increases with the increase of thickness of the shield tail, the tail shield without ribs maximum stress decrease from 65.8 MPa to 42.5 MPa by 35%, and the maximum deformation decreases from 65.8mm to 42.5 mm;

Influence of slide block support

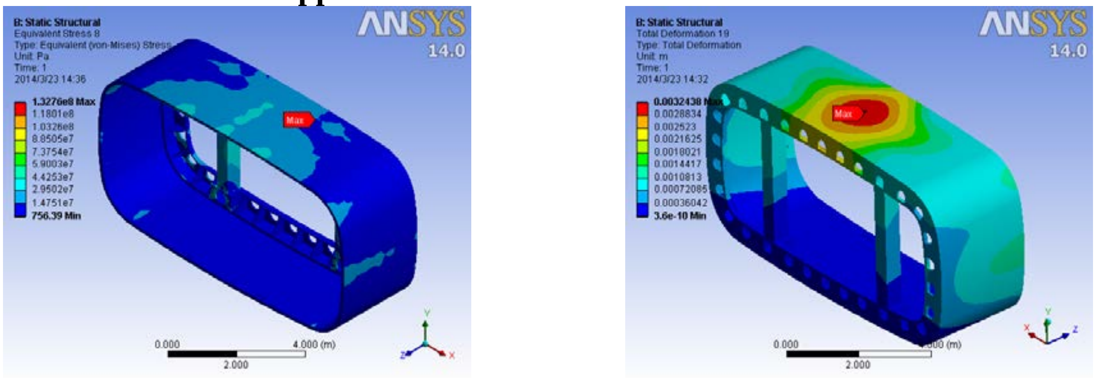
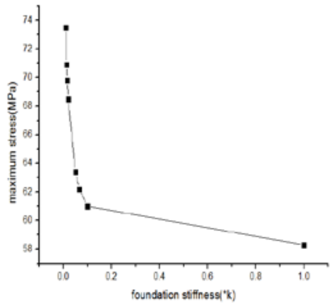


Fig.11 the maximum stress and the maximum deformation versus the thickness of tail with segment support

Under 6 meters covering soil layer, stress distribution of rectangle shield machine shows in fig 11. From the whole structure, the maximum stress value is 162.6 MPa, and it occurs on the cutting. While the maximum deformation of the shell structure is 3.2 mm, shown in fig 11, and it takes place at the middle part of the tail. The stress of the tail is 132.8 MPa in the transverse rib of top of the cutting, and the corresponding maximum displacement is 3.2 mm. The stress of the cutting is 175.9 MPa in the top flange of the supporting, and the corresponding maximum displacement is 3.6 mm.

From the above analysis, the support provides constrain at the end of the tail. The segment provides support by the slide block. In the support condition, the value and distribution of stress deformation of the structure have decrease.

The influence of the soil hardness



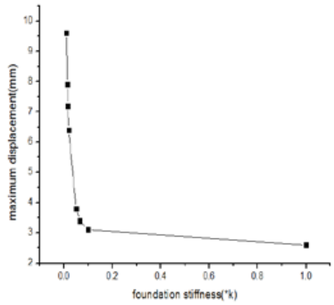


Fig.12 The maximum stress versus foundation stiffness Fig.13 The maximum deformation versus foundation stiffness

When the shield machines are in the process of tunneling, the shield machine will meet various types of soil. In order to inspect the hardness of soil factors on strength and stiffness properties of shield machines by changing the foundation bed stiffness k (k represents 1.0×10^{7} N/m) ,k / 10, k / 20, k / 50, k / 60 , k/70 respectively.

The results in fig 12 and fig 13 shows that the foundation bed stiffness magnitude has a great impact on the strength and deformation of the shell. The internal force and deformation will decrease with the increase with the increase with the value of foundation bed. This is because that the shell structure is a shell when stiffness of the foundation bed is large, the loads of top shell, is transferred from the two vertical shells, to the ground. So the stress of the part close to two vertical shells is large, and the farer the distance from the two vertical is, and the less stress of the part from the two vertical shells is. Otherwise, when stiffness of the foundation bed is little, the loads are partly transferred from the part close to the two vertical shells to the middle of middle part of the bottom shell. So the stress of the part close to two vertical shells is less than that of shell of which stiffness of the foundation bed is larger.

Stability analysis of shell

The overall stability of the rectangle is not good as that of the circular shield machine. At the top, side and front earth pressure, parts of the shell structure is under compressive stress state. Meanwhile depth-width ratio and width-to-thickness ratio of members of shell structure is large. It is the compressive stress that makes the overall stiffness of structure reduces. So it is necessary to conduct the stability analysis of rectangle shield machine. And the analysis includes stability analysis of shell with sliding block, and stability analysis of shell with sliding block.

Stability analysis of rectangle shield machine shell without Teflon slider block support

Table 2 Shield shell linear buckling coefficient of modes without segment support

buckling mode	Mode 1	Mode 2	Mode 3	Mode 4	Mode5
buckling coefficient	28.4	29.4	40.8	41.45	45.0

Fig.14～fig.17 show the linear buckling modes of shell structure without Teflon slide block support. And the table.2 shows buckling coefficient of modes . The case occurs when there are gaps between the tail and segment. The first and second buckling modes are local buckling of tail, and the corresponding buckling coefficients are 28.4 and 29.4, shown in fig.8 and fig.9. From the third buckling mode to the twentieth buckling mode, the forms of the buckling modes are local buckling of transverse ribs of top part of cutting, show in fig.14 and fig.15.

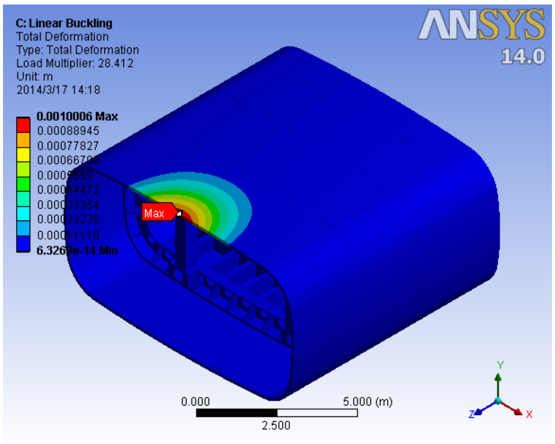


Fig.14 first order buckling mode

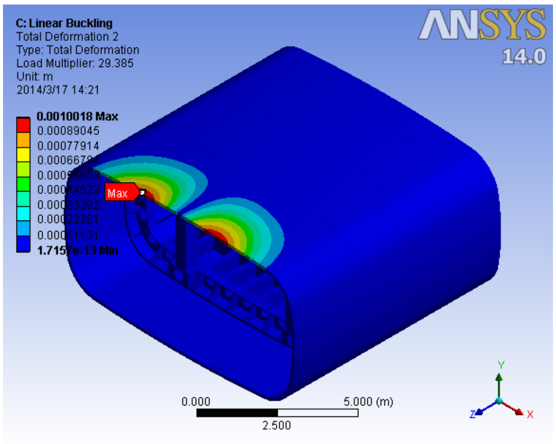


Fig 15 second order buckling mode

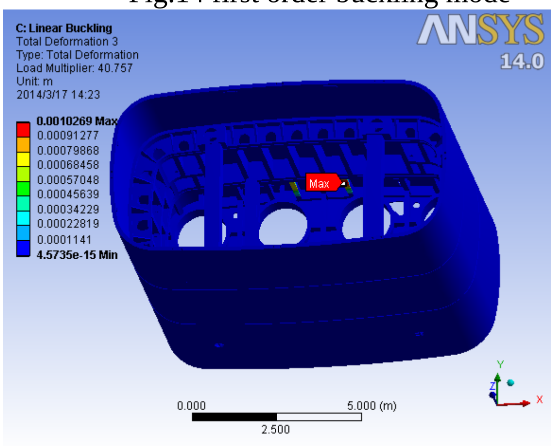


Fig 16 third order buckling mode

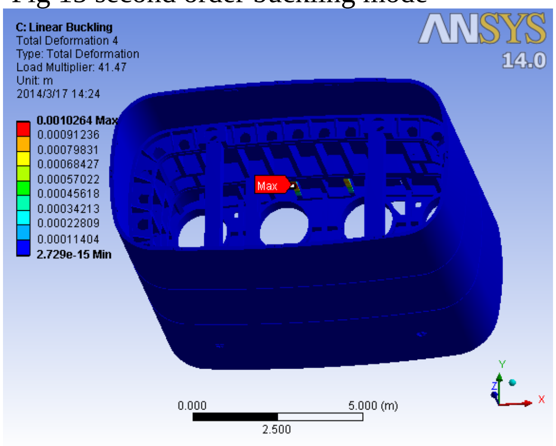


Fig 17 fourth order buckling mode

Stability analysis of rectangle shield machine shell with Teflon slider block support

Table 3 Shield shell linear buckling coefficient of modes with segment support

buckling mode	Mode 1	Mode 2	Mode 3	Mode 4	Mode5
buckling coefficient	39.05	39.65	43.40	45.83	46.18

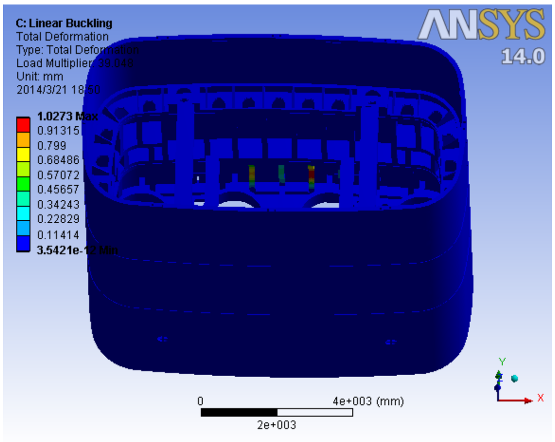


Fig 18 first order buckling mode

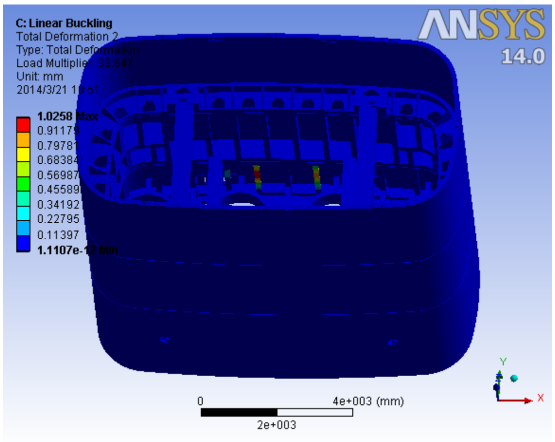


Figure 19 second-order buckling mode

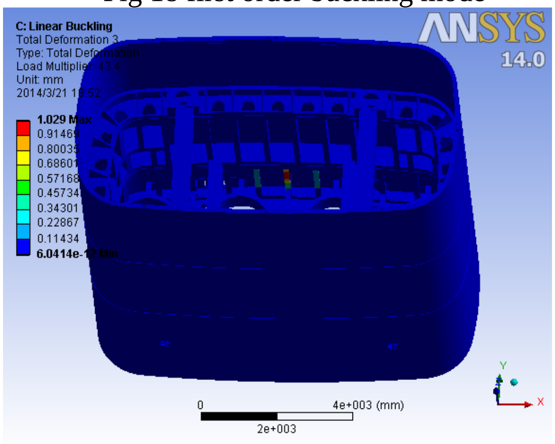


Fig. 20 third order buckling mode

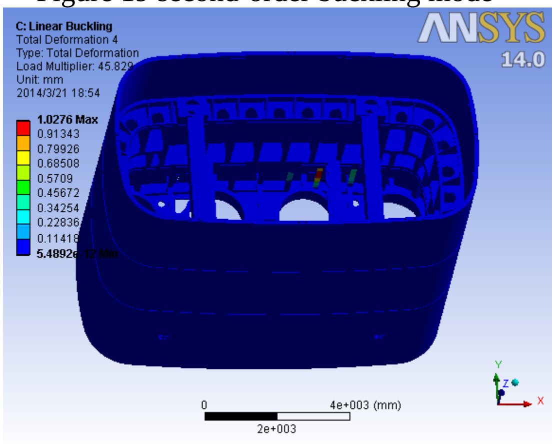


Figure 21 fourth order buckling mode

Fig.18～fig.21 show the linear buckling modes of shell structure with Teflon slide block support. And the table.3 shows buckling coefficient of modes. The case occurs when there no gaps between the tail and segments. That is the segments provide support for the tail. There is some distinguish from that of shell structure without Teflon slide block support. And the distinguish is that, the forms of the buckling modes are all local buckling of transverse ribs of top part of cutting, from the third buckling mode to the twentieth buckling mode, show in fig.18 ～fig.21.

Conclusions

Under 6 meters covering soil pressure, The rectangle shield machines shows good performance and overral stability:

1) The material utilization of Rectangle shield machine is low,so the safety factor of structure is high.The tail of rectangle shield machine is the smallest stiffness part,also the largest deformation part.And the deformation meet the demand of constuction. And The first and second buckling modes are local buckling of tail, of which value is 28.4 when shell structure without Teflon slide block support. In other words, the structure has a good safety reserve.

2) wheher the Teflon slide blocks provide support for the tail has a great influence on the performances of structure. When there are gaps between the tail and segment, The first and second buckling modes are local buckling of tail, and the corresponding buckling coefficients are 28.4 and

29.4, From the third buckling mode to the twentieth buckling mode, the forms of the buckling modes are local buckling of transverse ribs of top part of cutting; And when there are no gaps between the tail and segment, which means the segment provide support for the tail, the forms of the buckling modes are all local buckling of transverse ribs of top part of cutting, from the third buckling mode to the twentieth buckling mode, which first buckling mode is larger than that of shell structure without segment support.

(3) Tthe thickness of the shield tail is an important factor affecting the stiffness and stability of shield machine.And the stiffness and siffiness will inareasw with the increase of thickness of the shield tail.

(4) The soil hardness magnitude is another import factor on strenth and deformation of the rectangle shiled machine. The internal force and deformation will decrease with the increase with the increase with the value of foundation bed

The results shows that under 6m casing, the shield shell has a better performance and stability.

Acknowledgments

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Bibliography: Huang Jingyu Prof. of structural engineering in Tongji University, E-mail: hjymaglev@sina.com.

References

[1] Guan Huisheng, Gao Bo, Life Calculation of cutting tools in shield machine life [J] Construction Machinery .2006, (l): 25-28.

[2] Sugimoto,M.etal.(1991),Examination of In-situ data, Researeh Report on Face Stability of Inclined Shield Driven Method ,Deep Subway Research committee,pp.94-101.

[3] Shimizu,Y.and Suzuki, M. (1992),Study of the moving characteristics of a shield tunneling machines, Journal of Japan Society of Mechanical Engineers,JSME,Vol.58,No.550,pp.155-161.

[4] ZHU He-hua,XU Qian-wei, LIAO Shao-ming, et al. Experimental study on thrust force during tunnel excavation with earth pressure balance shield machine[J]. Rock and Soil Mechanics, 2007,28(8).