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Sensitivity Analysis of the Waterproof Performance of Elastic Rubber Gasket in Shield Tunnel

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Abstract

In order to study the waterproof performance of elastic rubber gasket in shield tunnel lining joints, an innovative sensitivity analysis method is proposed by combining the Monte Carlo method with the stochastic finite element method (FEM) in this paper. The sensitivity values of the waterproof performance respecting to elastic rubber gaskets are obtained via the ANSYS Probabilistic Design System (PDS) module, in which the parameters of material hardness, coordinates of the hole center, apertures are selected as random input variables. Meantime, the extent of the tolerance effect of the random parameters on the waterproof performance is explored.

Keywords: elastic rubber gasket, sensitivity analysis, waterproof performance, Monte Carlo method, stochastic FEM.

1 Introduction

Waterproofing is one of the cruxes for underground projections, which should be paid especial attention to in shield tunnels. Segment joints are the main leakage points and rubber gaskets are generally used for joints waterproofing. Therefore, waterproof properties of the rubber gasket should be strictly controlled.

There are many researches focusing on the impermeability performance of waterproof materials. Shalabi et al. [1,2] investigated the waterproof performance of gasket-in-groove under different contact stress states and studied the differences of waterproof ability between circular and longitudinal seams under the action of cyclic loading. Based on the variation law of mechanical properties of materials, Shi et al. [3] proposed a time-dependent constitutive model of rubber gaskets, and the relevant parameters were obtained by the material ageing test. Gong et al. [4] studied the water resistance characteristics of rubber gaskets for river crossing tunnels by using the new high-water pressure and automatic loading device.

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In addition to the impermeability of waterproof materials, the optimization design method of rubber gaskets has also attracted considerable attention. Xiang and Shi [5] analyzed the deforming characteristics of elastic gaskets under different levels of compression, the distribution of contact stress and the compressive force needed during installation through Finite Element Method (FEM). Then the section that satisfied all design requirements was found based on the FEM analysis results by repeated adjustments and trials. Novak et al. [6] developed a probabilistic technique to evaluate gasket designs under different assembly conditions. Jones [7] outlined the procedures about optimizing gasket geometries and presented a comparison which showed the benefits of using such techniques. Krishnan [8] proposed a Computer Aided Engineering (CAE) approach to design, evaluate and optimize automotive powertrain gaskets, seals and gasket/seal assemblies.

Due to the elasticity of rubber materials, the gasket deforms easily when it is squeezed. Some sections of elastic gaskets, provided by different manufacturers, were measured by researchers which were used in the shield tunnel of a city subway, as shown in Figure 1. It can be seen from Figure 1, all of the geometry sizes, locations and shapes of the internal holes are wrong. Based on the optimization design experience, those incorrect parts have significant influences on the waterproof performance of rubber gaskets.

Fig. 1 Comparison of the product and design drawings of two manufacturers (Note: dotted line refers to the design drawing):(a) No.1 product of manufacturers,(b) No.2 product of manufacturers.

In addition, mechanical parameters, such as hardness of synthetic rubber materials, are largely influenced by places of production, compositions and temperatures. Generally, it is required that the hardness should change in a range of ± 5 degrees by considering the randomness of mechanical properties.

Although many studies have been conducted to analysis the waterproof performance of EPDM (Ethylene Propylene Diene Monomer) rubber materials and the gasket optimization design method, the effect on the waterproof performance of rubber gaskets due to the continuous change of the structural parameter still remains unknown. In addition, the effects of the uncertainties of geometry sizes, machining errors and material parameters on the waterproof performance of rubber gaskets are not considered in previous optimization processes.

Based on the aforementioned, it is known that traditional design methods for the elastic rubber gasket have many defects. Therefore, aiming at dealing with the problems involved in the traditional methods, an innovative sensitivity analysis method is proposed, where the material hardness, coordinates of the hole center, apertures are regarded as random input variables instead of deterministic ones. Monte Carlo method and FEM are combined to acquire the sensitivity values of the waterproof performance with regard to the uncertain structural parameters.

The rest of the paper is organized as follows. After the introduction, we briefly explain the background theory of stochastic FEM based on the Monte Carlo method and ANSYS PDS module in section 2. Section 3 discusses a new method for the sensitivity analysis of elastic rubber gaskets in shield tunnel lining joints. Finally, we close the paper with some conclusions and remarks.

2 Stochastic FEM based on the Monte Carlo method and ANSYS PDS module

Since the geometry sizes, machining errors, materials, actual working loads are all random for the same batch of products in practical engineering, we need to use stochastic FEM to carry out the detailed analysis. The stochastic FEM [9] used in this paper is a combination of the Monte Carlo method and the FEM.

2.1 The principle of Monte Carlo stochastic method

Monte Carlo method [10], also known as statistical test method or random simulation method, is based on the theory of statistical sampling. The structural stochastic analysis process carried out by using Monte Carlo method can be summarized as following three basic steps.

(1) Sampling random variables. Random sampling based on the known probability distribution of the basic random variables.

(2) Solving structural response. For each sample, the finite element method is used to calculate the response of the structure.

(3) Statistical analysis of the response. According to the calculation results of all samples, the mean value, variance and even probability distribution function of the response are obtained.

2.2 Sampling methods for random variables

A major drawback of the Monte Carlo method is the need of large sampling space. In order to overcome this shortcoming, this paper uses the Latin Hypercube Sampling (LHS) method [11] which reduces the sampling number by improving the convergence rate. LHS [12] method does not change the mean and variance of sampling space, and can greatly improve the computing efficiency. Therefore, it is more suitable for solving the stochastic response of engineering structures.

2.3 Probabilistic Design System (PDS) of ANSYS

The PDS module of ANSYS combines the finite element method with the probability design technology. Based on the probability design of FEM, it can be used to study the uncertain effect on waterproof properties of rubber gaskets. The parametric modeling in ANSYS-PDS is often employed to carry out probability design analysis and the APDL (ANSYS Parametric Design Language) command flow is generally used to build the parametric model for probability design analysis. Based on the parametric model, the new model can be built by just changing some parameters, so it is more efficient and less costly to repeatedly analyze the effects of parameters on the waterproof performance, such as hardness, size, etc. The probability design analysis process based on ANSYS-PDS is shown in Figure 2.

3 Sensitivity analysis method

In order to tackle the problems produced in the traditional design methods, a new sensitivity analysis method of the waterproof performance with regard to the uncertain structural parameters has been presented in this section.

3.1 Constructing parameterized model

The geometry sizes of the rubber gasket and segment groove studied in this paper are shown in Figure 3. The selected random parameters are as follows.

(1) Material parameters of rubber C_{10} , C_{01} . The constitutive model used in this paper is the Mooney-Rivlin two-parameter model [13]. The model can describe the deformation characteristics of rubber materials in 150%.

(2) The center coordinates of all the holes in the cross section x_i , y_i , $i = 1 \sim 4$. The effect of the position of the hole on the waterproof property of the sealing gasket is analyzed. The section of the sealing gasket is

Fig. 2 ANSYS-PDS analysis process.

Fig. 3 The sizes of the gasket and groove/mm.

symmetrical, and there are eight holes totally in the cross section and the number is 1 ~ 4.

(3) Radius of each round hole R_i , $i = 1 \sim 4$.

3.2 Statistical characteristics of random parameters

The elastic rubber gasket in shield tunnel lining joints is EPDM synthetic rubber. In general, the hardness of rubber materials is clearly defined and the hardness of IRHD (International Rubber Hardness Standard) is often adopted, and the hardness tolerance required is ± 5 degrees [14]. The relationship between hardness H_r , elastic modulus E and mechanical characteristic constants C_{01} , C_{10} are:

$$\lg E = 0.0198H_r - 0.5432 \quad (1)$$

Table 1 Statistical characteristics of random input variables

Variable name	Distribution pattern	Mean value	Standard deviation	Min limit value	Max limit value
C_{01}/MPa	truncated normal	0.035	$0.05C_{01}$	0.0279	0.044
C_{10}/MPa	truncated normal	0.700	$0.05C_{10}$	0.5578	0.88
$x_i, i = 1, 2, 3, 4/\text{mm}$	truncated normal	x_i	0.15	$x_i-0.15$	$x_i+0.15$
$y_i, i = 1, 2, 3, 4/\text{mm}$	truncated normal	y_i	0.15	$y_i-0.15$	$y_i+0.15$
$R_i, i = 1, 2, 3, 4/\text{mm}$	truncated normal	R_i	0.03	$R_i-0.05$	$R_i+0.01$

$$E = 6C_{10}\left(1 + \frac{C_{01}}{C_{10}}\right) \quad (2)$$

where $\frac{C_{01}}{C_{10}}=0.05$, $C_{10}=0.700\text{MPa}$, $C_{01}=0.035\text{MPa}$, $E=4.41\text{MPa}$, Poisson's ratio $\mu=0.499$. The maximum and minimum limit values of C_{01} and C_{10} of the equations (1) and (2) can be obtained as follows:

$$C_{10} = \begin{cases} 0.88\text{MPa} \\ 0.5578\text{MPa} \end{cases} \quad C_{01} = \begin{cases} 0.044\text{MPa} \\ 0.0279\text{MPa} \end{cases} \quad (3)$$

The center coordinates of the holes are $x_1=x_3=2.75\text{mm}$, $x_2=3.5\text{mm}$, $x_4=9.5\text{mm}$, $y_1=3.5\text{mm}$, $y_2=8.3\text{mm}$, $y_3=13\text{mm}$, $y_4=11.5\text{mm}$, respectively. The apertures are $R_1=R_3=1.75\text{mm}$, $R_2=R_4=2\text{mm}$. The C_{01} , C_{10} , center coordinates x_i and y_i of all holes and radius of each hole R_i are selected as random input variables. The correlation between the variables is ignored. The random distributions and corresponding characteristic values of each random variable are as shown in Table 1. The main characteristics of each variable are determined according to the reference [15].

3.3 Finite element model

In this paper, the unilateral compression model is employed to simulate the compression process of the rubber gasket, as in Figure 4. The rubber gasket can be considered as the flexible body and the concrete groove can be regarded as the rigid body. There are rigid-flexible contacts between the groove and the rubber and flexible-flexible contacts between the rubber and the rubber.

Fig. 4 Unilateral compress FE model of the rubber gasket.

Due to the hyper elasticity characteristic of rubber materials, the model is established with the PLANE182

element. The contact elements use TARGE169 and CONTA172 elements with friction coefficient of 0.25 for rubber materials.

According to the maximum allowable opening amount in engineering, the unilateral compression can be set as 5 mm. All the degrees of the nodes of the groove are constrained and the X-direction degrees as well as the rotational degrees of the nodes of the upper pressure plate are constrained. All nodes of the upper pressure plate are specified to have a Y-direction displacement of 5 mm (compression direction).

3.4 Sensitivity calculation and analysis

3.4.1 Sensitivity analysis based on Spearman rank correlation coefficient

Sensitivity analysis (SA) [16-20] is an important step in the process of model establishment and result discussion. In this section, the sensitivity analysis method based on the Spearman rank correlation coefficient is adopted [21].

The sequence of random structure parameters of the sealing gasket is $x = \{C_{10}, C_{01}, x_i, y_i, R_i\}$, ($i = 1 \sim 4$) and the 14 random variables are all subject to the truncated normal distribution. Assuming that the n times random simulation is carried out, the structure response values of n times are obtained. Since the sealing property of non-expansion elastic gaskets is mainly subjected to the elastic pressure produced by the surface contact stress [5], the average contact stress $\bar{\sigma}_u$ on the upper surface and the average contact stress $\bar{\sigma}_d$ on the bottom surface are set as random output variables, recorded as $\bar{\sigma}_{i1}, \bar{\sigma}_{i2}, \dots, \bar{\sigma}_{in}$, $i = u, d$, respectively.

Let $\{(x_{jn}, \bar{\sigma}_{in})\}_{j=1}^{14}$ denote 14 independent and identically distributed data pairs which are composed of the sample values of the n random simulation operations $x_{j1}, x_{j2}, \dots, x_{jn}$ and the structure response values of the n random simulation operations $\bar{\sigma}_{i1}, \bar{\sigma}_{i2}, \dots, \bar{\sigma}_{in}$.

For each data pair, the Spearman rank correlation coefficient r_{sj} [22] is calculated by the equations (4) and (5).

$$r_{sj} = -\frac{6 \sum_{k=1}^n (P_{kj} - Q_{kj})^2}{n(n^2 - 1)} \quad (j = 1 \sim 14) \quad (4)$$

$$-1 \leq r_{sj} \leq 1 \quad (5)$$

Let P_{kj} be the rank of x_j among $x_1, x_2, \dots, x_{14}$; Q_{kj} be the rank of the corresponding structural response $\bar{\sigma}_{ij}$; n is the total sampling times.

The Spearman rank correlation coefficient is an important parameter used to test the correlation between variables in nonparametric statistics. If the coefficient is close to 1 or -1, it indicates that the input variables significantly affect the output variables. If the coefficient is close to 0, it illustrates that the effect is weak. Besides, if the coefficient is positive, the output variables increase with the increase of the input variables. If the coefficient is negative, the output variables decrease with the increase of the input variables [23].

3.4.2 Sensitivity calculation results

In the ANSYS-PDS module, the Monte Carlo method and Latin Hypercube Sampling method are chosen as the probability analysis methods and the cycle times is set to be 500 times for performing probability design analysis. Then, the trends of $\bar{\sigma}_u$ and $\bar{\sigma}_d$ can be obtained and are shown in Figure 5. It can be seen that with the increase of sampling frequency, the width of the confidence interval becomes smaller. Meantime, the trends of $\bar{\sigma}_u$ and $\bar{\sigma}_d$ gradually tend to horizontal, which indicates that 500 sampling times is enough.

The specific sensitivity values of the random input variables based on the Spearman rank correlation coefficient are listed in Table 2.

As can be seen from Table 2, the C_{10} is the most effective factor for the average contact stress of the bottom surface, followed by R_3, x_1, R_4, x_2 , and the influence of C_{10} is greater than that of the other four variables. The C_{10} is also the most significant factor for the average contact stress of the upper surface, followed by x_4, x_2 , and the influence of C_{10} is greater than that of the other two variables. Furthermore, in the random input variable space, it will make the average contact stresses of both the upper and bottom surfaces increase by increasing the

Fig. 5 Trends of average contact stresses:(a) Average contact stress on the bottom surface, (b) Average contact stress on the upper surface.

Table 2 The sensitivity values of the input variables

Var.	C_{01}	C_{10}	x_1	x_2	x_3	x_4	y_1	y_2	y_3	y_4	R_1	R_2	R_3	R_4
$\overline{\sigma_d}$	0.049	0.971	0.126	-0.102	0.094	0.011	0.010	-0.019	0.010	0.032	-0.072	-0.040	-0.138	-0.102
$\overline{\sigma_u}$	0.036	0.918	0.080	-0.107	0.074	-0.277	-0.027	0.031	-0.002	0.035	-0.069	0.031	-0.062	-0.065

rubber hardness C_{10} . Besides, it will make the average contact stress of the bottom surface increase by increasing x_1 . The average contact stresses on both the upper and bottom surfaces will decrease with the increase of x_2 . The average contact stress on the upper surface will decrease with the increase of x_4 . The average contact stress on the bottom surface will decrease with the increase of R_3 or R_4 .

3.4.3 Sensitivity influence of tolerance

The maximum and minimum limit values of random input variables are calculated by the mean values and tolerances. In this section, the tolerances of random input variables are changed in order to analyze their influence on the sensitivity.

(1) Rubber hardness tolerance

The rubber hardness tolerances are chosen as ± 5 degrees, ± 4 degrees, ± 3 degrees, ± 2 degrees, ± 1 degrees, respectively. The maximum and minimum limit values of C_{01} and C_{10} can be calculated using the equations (2), (4) and (5). The statistical characteristics of the other input variables are the same as those in Table 1. The same analysis method and sampling times as the above are used to get the sensitivity values of average contact stresses on upper and bottom surfaces, as shown in Figure 6. From Figure 6, it can be found that the rubber hardness tolerance has little effect on the contact stress sensitivity when the rubber hardness tolerance is in the ranges of $\pm 5 \sim \pm 3$ degrees. When the rubber hardness tolerance is restricted within the range of ± 2 degrees by taking stricter production standards, the effect of the rubber hardness on the contact stress decreases significantly and the effects of other variables on the contact stress increase significantly, such as the hole center location and aperture.

(2) Coordinate deviation

Fig. 6 The sensitivity influence of rubber hardness tolerance (Only list the top five variables with great influence):(a) Average contact stress on the bottom surface, (b) Average contact stress on the upper surface.

The abscissa deviations are selected as ± 0.2 mm, ± 0.17 mm, ± 0.15 mm and ± 0.13 mm, respectively. The maximum and minimum limits of abscissas of hole centers can be obtained by adding these deviations with the mean values. The statistical characteristics of the other input variables are the same as those in Table 1. The same analysis method and sampling times as the above are used to get the sensitivity values of average contact stresses on the upper and bottom surfaces, as shown in Figure 7. From Figure 7, it can be obtained that the influence of the change of abscissas on the average contact stress on the bottom surface decreases if the abscissa deviation is strictly controlled. Because the variation range of sensitivity values is small, it may be due to the influence of rubber hardness on the contact stress is more significant than other variables when the tolerance of rubber hardness is in the range of ± 5 degrees in this condition. If the abscissa position deviation is strictly controlled, the influence of the abscissa change of the 4th hole center on the average contact stress on the upper surface decreases and the change value of the sensitivity is 0.113. The change of other abscissas has little effect on the average surface contact stress.

Fig. 7 The sensitivity influence of horizontal position deviation:(a) Average contact stress on the bottom surface, (b) Average contact stress on the upper surface.

From Table 2, it can be found that the ordinates of hole centers have little effect on the contact stress.

Therefore, the influence of the change of the vertical position deviation on the contact stress sensitivity is not discussed in this paper.

(3) Aperture deviation

The maximum limit of aperture is kept as $R_i+0.01$, and the minimum limits of aperture are separately set as $R_i-0.1$, $R_i-0.07$, $R_i-0.05$ and $R_i-0.03$. The statistical characteristics of the other input variables are the same as those in Table 1. The same analysis method and sampling times as the above are used to get the sensitivity values of average contact stresses on the upper and bottom surfaces, as shown in Figure 8. From Figure 8, it can be seen that the stricter the control of the aperture deviation, the less influence on the average contact stress on the bottom surface. The largest variation value of the sensitivity is 0.048. The stricter the control of the R_1 and R_4 deviations, the less influence on the average contact stress on the upper surface. The stricter the control of the R_2 and R_3 deviations, the more influence on the average contact stress on the upper surface. But the change extents are small because the rubber hardness has a greater effect on the contact stress than the aperture.

Fig. 8 The sensitivity influence of aperture deviation:(a) Average contact stress on the bottom surface, (b) Average contact stress on the upper surface.

4 Conclusions and remarks

(1) This paper focuses on the sensitivity analysis of elastic rubber gaskets in shield tunnel lining segments. In order to obtain the correlation between the parameters and the average contact stress of sealing gaskets, the ANSYS-PDS module is employed by combining the Monte Carlo method with the FEM, and the parameters of material hardness, hole center coordinates and apertures are selected as the random input variables. The analysis method and the results of this paper have a certain reference value on optimal design of elastic rubber gaskets in the future.

(2) By controlling the tolerance of the parameters in turn, the influence of various parameters on the average contact stress of the sealing gasket is obtained. The mechanical parameters of rubber materials are the main factors that influence the water pressure resistance, especially C_{10} . The influence of rubber hardness on the contact stress is the most significant when the tolerance of rubber hardness is in the range of $\pm 5 \sim \pm 3$ degrees. When the rubber hardness tolerance is restricted in the range of ± 2 degrees under strict production standards, the influence of the rubber hardness on the contact stress decreases significantly, while the influence of other parameters on the contact stress increases remarkably.

(3) As for geometric parameters, the greatest impact on the contact stress is the position of bottom hole 1. The effect of the size of the two round holes in the middle part of the section on the surface contact stress is larger than that of the other round holes.

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