Reliability analysis of mixer structure under mixing simulation

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Abstract. When the forced two-horizontal shaft mixer is used to mix concrete, the mixing drum and the mixing components are subjected to random loads of the mixture. Structural static analysis usually ignores the randomness of the load, resulting in a large calculation error. Based on the EDEM software, this paper simulates the mixing process of the mixture, obtains the random load data of the mixture on the mixing drum and the mixing parts, and describes the variation law of the random load with a probability distribution, establishes the stress-strength interference reliability model of the mixer structure, and Monte Carlo simulation method is used to solve the structural reliability of the mixer. The results show that the load distribution of the mixing arm is the same as the mixing blade, the load distribution follows the gamma distribution, and the mixing shaft also follows the gamma distribution; the load distribution of the mixing drum follows the normal distribution. After calculation, the above load probability distribution and its intensity distribution do not interfere, and the structural reliability of the mixer meets the requirements, which can ensure the safe operation of the mixer. This method solves the reliability calculation error caused by random loads.

1. Introduction
When the concrete mixer is in operation, the mixing drum and the agitating member are subjected to the load applied by the mixture, and the load is found to be a randomly varying load. Structural static analysis of the mixer is usually carried out in three ways: First, after obtaining the force data of the mixer, the force value at a certain moment is selected as the load, which causes the data to be distorted; Second, the maximum force is selected as the load, which is too safe to design, resulting in a large equipment structure; Third, the force average is used as the load, which can represent the load more realistically to a certain extent, but a small probability failure occurs at the maximum value of the load.
If the safety factor obtained by the above three methods is greater than 1, the load stress and the structural strength are both discrete, and there will be negotiations at the discrete edges, resulting in unreliable structure. Structural reliability design fully analyzes the distribution law of load stress and structural strength, and establishes a mathematical model between stress and strength to achieve strict control of structural reliability.

In the structural reliability analysis, the structural failure of the equipment is caused by the external stress exceeding the strength that can be withstood by the stress of the equipment [1]. In order to express the relationship between stress and strength, Freudenthal et al. proposed a stress-strength interference reliability model [2-3]. In the stress-strength interference reliability model, stress and strength are generalized, and stress is regarded as physical quantity applied to products and parts, such as load, stress, pressure, temperature, humidity, impact value, and the like. Strength is the ability of a product or part to withstand such stress. The stress and strength are random variables, and the structural reliability is expressed by calculating the number of interference between them. If the stress is greater than the strength, the structure fails, otherwise, failure will not occur. In order to understand the structure state conveniently, the limit state function equation is established. As the interface between the failure state and the safety state of the equipment, the limit state function equation can fully describe the reliability of the structure. In this paper, depending on the stress applied to the structure of the mixer, the strength of the mixer structure can withstand the stress, and the reliability of the mixer structure is analyzed.

In order to solve the calculation of the limit state function equation, consider the Monte Carlo method. In order to ensure the convergence of statistical results, the Monte Carlo method requires a large number of repeated experiments. The specific calculation steps are as follows: (1) determining a probability distribution form of the random variable; (2) randomly generating samples from probability density functions of random variables; (3) According to the random samples generated, the limit state function equation is simulated and the reliability is calculated.

In order to obtain the load spectrum of the mixture affected by the mixer structure, the mixing process of the mixture in the mixing drum should be numerically simulated [4]. The discrete element method (DEM) is suitable for analyzing the motion characteristics of particles [5]. In recent years, DEM has developed rapidly, and it is mostly used in the analysis of particle mixing process to reveal the movement law of materials. In this paper, the mechanical relationship between materials and structural components is analyzed by DEM method to obtain the load spectrum of material structural components. In order to further clarify the distribution of the load spectrum of the structural components of the mixer, this paper uses the hypothesis test method for load data analysis. Hypothesis testing is a method of inferring data distribution under certain assumptions. Obtain the observations from the random data by sampling, compare the empirical distribution function of the random data with the given distribution function, and assume that the empirical distribution function obeys the given comparison distribution function and judge whether the maximum value of the difference between the two distribution functions is within the set threshold (general 0.05) [6]. The hypothesis is recorded as H0, and the appropriate statistics are selected so that the distribution of H0 is known when the hypothesis is valid; From the measured sample, the value of the statistic is calculated, and the test is performed according to the predetermined saliency level, and the judgment of rejecting or
accepting the hypothesis H0 is made.

This paper establishes the flow of the reliability analysis method of the mixer structure, as shown in Figure 1. Combined with the discrete element method, probability and statistics theory, mechanics theory, and reliability theory, the structural limit state function equation of the mixer is established, and each static analysis method is used to realize the simulation of a large number of repeated tests. The Monte Carlo method is used to solve the limit state function equation, and the application module of the mixing field numerical simulation, load data analysis and structural static analysis is designed and called. Each module automatically realizes the respective operation steps through the command flow.

Figure 1. flow of structural reliability analysis method of mixer

2. Mixer structure and mixing process design

2.1. Preliminary design of main parameters of mixer

Figure 2 shows a forced twin-shaft mixer with two parallel mixing shafts installed in the mixing drum and a mixing blade is arranged spirally on each of the mixing shafts, and the mixing blade is attached to the end of the mixing arm, and the mixing arm is fixed to the mixing shaft by a nut. The two mixing shafts are synchronously rotated to achieve forced mixing of the mixture.
The main structural dimensions of the mixer are as follows: the wall thickness of the mixing drum is 8mm; The stirring shaft has a quadrangular cross section and a side length of 60 mm; The mixing arm has a diameter of 30 mm and a length of 149 mm; The shape of the mixing blade is a sickle type and the thickness is 8 mm.

![Figure 2. Structure diagram of forced twin-shaft mixer](image)

The filling rate of the mixer has an effect on the evenness and productivity of the mixture. If the filling ratio is too large, it will lead to the increase of the bearing capacity of the mixer, the decrease of material evenness and the occurrence of stuffing problems. If the filling rate is too low, it will affect the material flow and reduce the production efficiency [7]. The filling rate for the mixing equipment is generally in the range of 0.3-0.6.

The mixer studied in this paper, through measurement and calculation, knows that the total volume in the mixing drum is 53471206.359 mm³; The volume of the stirring component is 2497206.8995 mm³; Calculate the effective volume in the mixing drum:

$$V = V_1 - 2 \times V_2 = 0.0484767925 \ m^3$$  \hspace{1cm} (1)

The maximum material mass in the mixing drum is:

$$M = \rho \times V \approx 80Kg$$  \hspace{1cm} (2)

Among them, $\rho$ is the density of mixture. $\rho = 1.6 - 1.7 t/m^3$

According to the filling ratio of 0.3-0.6, it can be calculated that the mixing range of the mixing drum can be 24-48kg.

2.2. Mixture process design

Concrete is a mixture of aggregate and binder. Commonly used aggregates include: coarse aggregate, fine aggregate, mineral powder, and the like. The binder is cement, asphalt, emulsified asphalt, foamed asphalt, and the like. In the mixture, the coarse aggregate acts as a skeleton, the fine aggregate is filled in the voids of the skeleton, and the cement formed by the binder and the mineral powder filler cements the coarse and fine aggregates to form concrete having a certain strength [8].

According to the nominal maximum particle size of the aggregate, the aggregate gradation can be divided into: coarse graded, medium graded type, fine grain type. The nominal maximum particle size
of coarse-grained mixture is 26.5mm or 31.5mm, that of medium-grained mixture is 19mm or 16mm, and that of fine-grained mixture is 13.2mm or 9.5mm [9].

According to the technical specifications for road asphalt pavement construction (JTG F40-2004), the gradation of foam asphalt mixture is designed for the application of grade classification of asphalt mixture.

Table 1. Mixture Parameter Table

| Mass (kg) | Grain diameter (%) | Viscosity (J/m³) |
|-----------|--------------------|------------------|
| 25        | 13.2 (38%) , 9.5 (27%) , 4.75 (35%) | 15               |

3. Mixture mixing process simulation

3.1. Establishment of particle model and mechanical model of mixture

In the numerical calculation process, the soft sphere model and hard sphere models can be used to describe the particle collision. The hard sphere model assumes that the collision between particles is instantaneous, while the soft sphere model assumes that the particles have deformation, overlap, etc. when they collide, and allows contact of multiple particles. The hard sphere model is suitable for simulating two-phase flow analysis with a small number of particles. For example, when the particles are dispersed in a gas or a liquid, the probability of collision with each other is small, and at this time, it is suitable for the hard ball model. The soft sphere model is suitable for applications where the particle density is large and the force between the particles is large. Obviously, a material composed of a mixture of particles of different particle sizes with a large density involves many particles colliding with each other and has a strong collision [10], so the soft sphere model is more suitable for describing the particle motion.

In the material mixing, there are normal force, tangential force, and friction between any two particles, as shown in Figure 3. Both the normal force and the tangential force are calculated in the form of elastic force and damping force, respectively, to express the deformation and motion trajectory generated when the particles are in contact.
The process of mixing concrete involves contact and collision between the particles, as well as the bond force between the binder and the particles. The particle contact was calculated using the Hertz-Mindlin with JKR Cohesion particle contact model, taking into account the calculation of the adhesion between the particles. Based on the Hertz-Mindlin with JKR Cohesion particle contact model, the contact model of aggregates with different particle sizes was constructed. On the original contact model, the surface energy was increased and the value was given according to the viscosity. At $\gamma = 0$ time, the bond force disappeared.

In the mixing process of the mixture, the numerical calculation principle of particle motion is shown in Figure 4, using the Hertz-Mindlin contact algorithm to detect contact between particles and calculate the interaction between particles, then Newton's law of motion and numerical integration are then used to calculate the acceleration, velocity and position of the particles. Thus, the two cycle calculations simulate the particle motion.
3.2. Set the material properties and contact parameters of the mixture

In the mixing process of the mixture, the aggregate is sandstone material, and the parts of the mixer are steel. Numerical calculations need to add the material properties of sand and steel, sand and gravel, and the contact properties of sand and steel, see Table 2 and Table 3.

Table 2. Material properties

| Name         | Density (kg/m³) | Shear modulus (Pa) | Poisson ratio |
|--------------|-----------------|--------------------|---------------|
| Freestone    | 2630            | 5.57E+8            | 0.35          |
| Steel        | 7800            | 7E+10              | 0.3           |

Table 3. Contact properties

| Contact object | Coefficient of restitution | Static friction coefficient | Rolling friction coefficient |
|----------------|----------------------------|----------------------------|------------------------------|
| Sandstone      | 0.2                        | 0.5                        | 0.001                        |
| sandstone sandstone steel | 0.25                    | 0.7                        | 0.001                        |

3.3. Simulation mixing process

The numerical simulation process is established based on the discrete element method, specifically:
(1) Introduce a three-dimensional model of the mixer;
(2) establish a particle factory and generate particles according to the gradation;
(3) capturing the moving position of the particles, detecting the amount of deformation caused by the contact of the particles, and calculating the force of the structure of the mixer;
(4) Calculate the acceleration, velocity, and displacement of the particles in a single time step based on Newton’s law of motion, and update the above parameter values.
(5) The calculation
process continues to reciprocate and cycle to achieve the simulation of the mixing field. Mixer mixing mixture mixing process is shown in Figure 5.

**Figure 5.** Schematic diagram of the mixing process of the mixer and the mixture

After the numerical simulation is completed, the load spectrum of the derived mixture acting on the mixing blade is shown in Fig. 5. The abscissa is the mixing time and the ordinate is the force load. It can be seen from Fig. 5 that the force of the mixing blade changes periodically with time, and the cycle time is consistent with the rotating position of the stirring shaft, specifically: When the mixing blade is in the middle of the rotation, the mixture on the mixing blade falls due to gravity. At this time, the mixing blade is not subjected to any load, which coincides with the load in FIG. 5 at 0N. The mixing blades are rotated to the lower side, and when the mixture is forcibly stirred, the blades are subjected to the mixture and are in agreement with the peak load in FIG 5. The mixing blades circulate and mix the mixture to produce a load spectrum having a periodic variation as shown in FIG 6.

**Figure 6.** Forced loading of stirring blades

For the mixing shaft, it is mainly subjected to the resistance torque from the mixture, as shown in Fig. 7, the abscissa is the mixing time, and the ordinate is the received torque. From Figure 6, it can be seen that there is no obvious regularity of the torsion on the mixing shaft.
The mixing drum is mainly subjected to the impact load from the mixture, as shown in Fig. 8, the abscissa is the mixing time, and the ordinate is the force load.

In order to further analyze the distribution form of the load of the above components, the hypothesis test method is used for data fitting.

4. Mixer force probability distribution
The hypothesis test method is used to judge the distribution pattern of the load on the mixing blade, the mixing shaft and the mixing drum. The workflow is shown in Figure 8. First, the probability density function of the load data of the mixing blade, the mixing shaft and the mixing drum is respectively established; Secondly, using the K-S hypothesis test method, the normal distribution, the gamma distribution, the exponential distribution, the Ruili distribution, and the Weibull distribution are used as the contrast distribution, and the confidence is set to 0.05, and the hypothesis test is
performed. If the null hypothesis is true, $H=0$ is output, and if the null hypothesis is not true, $H=1$ is output. Finally, after the assumption is made, output its distribution parameter values.

![Hypothesis test method flow](image)

**Figure 9.** Hypothesis test method flow

As a result, a reasonable load data distribution curve is obtained. Figure 10 shows the load distribution of the mixing blade, figure 10 shows the load distribution of the mixing shaft, and figure 11 shows the load distribution of the mixing cylinder.

![Load distribution graph](image)

**Figure 10.** Comparison of load distribution of agitating blades

After calculation, the hypothesis test results are as follows:

$H = 1 0 1 1 0$

$p = 0.0007 \ 0.2251 \ 0.0000 \ 0.0002 \ 0.2225$
Combined with Fig. 8 and the hypothesis test results, the results of the gamma distribution and the Weibull distribution are $H = 0$ and $p > 0.05$. It shows that the original hypothesis is established, the force data of the stirring blade obeys the gamma distribution and the Weibull distribution. Further comparison shows that the $P$ value of the gamma distribution is higher than the Weibull distribution, indicating that the gamma distribution is more suitable. After calculation, it can be seen that the shape parameters and scale parameter values of the gamma distribution are 6.2752 and 38.2033, respectively, and the distribution of load data is fully expressed in the structural reliability analysis.

The mixing arm is a support for the mixing blade, and the main load source is the mixing blade. Therefore, the load distribution pattern of the mixing arm is the same as that of the mixing blade.

Data analysis of the agitator shaft torque load was performed in the distribution step of Fig. 8. The comparison of the probability density curve of the torque load data with the contrast distribution is shown in Fig. 11.

![Figure 11. Comparisons of Torque Load Distribution Data of Stirring Shaft](image)

After calculation, the hypothesis test results are as follows:

$H = 1 \ 0 \ 1 \ 1 \ 1$

$p = 0.0002 \ 0.0546 \ 0.0000 \ 0.0002 \ 0.0018$

As shown in Fig. 10 and the hypothesis test results, the result of the gamma distribution is $H = 0$ and $p > 0.05$. It can be seen that the torque load data of the mixing shaft exhibits a gamma distribution. The shape parameters and scale parameter values of the gamma distribution are further calculated to be 19.8332 and 12.9493, respectively.

Data analysis was performed on the mixer drum load data in the distribution step of Fig 8. The comparison of the probability density curve of the mixer drum load data with the contrast distribution is shown in Fig. 11.
After calculation, the hypothesis test results are as follows:

\[
H = 0 \quad 0 \quad 1 \quad 1 \quad 1 \quad 0
\]

\[
p = 0.4589 \quad 0.0754 \quad 0.0000 \quad 0.0061 \quad 0.2085
\]

Combined with Fig. 11 and the hypothesis test results, it can be seen that the hypothetical results of the normal distribution, the gamma distribution and the Weibull distribution are \( H=0, p>0.05 \). Comparing the P values of the normal distribution, the gamma distribution and the Weibull distribution, it can be seen that the normal distribution can more accurately describe the load distribution form of the mixing drum. The mean and variance values of the normal distribution are further calculated to be 1258.2 and 556.6925.

The load distribution form and distribution parameters of the above-mentioned mixing drum, mixing shaft, mixing arm and mixing blade are used as the stress input variables for calculating the stress-strength interference reliability model. Based on this, the reliability analysis of the mixer structure is carried out.

5. Mixer structural reliability analysis

5.1. Stress-strength distribution interference model

Since the stress and the intensity are random variables with a certain range of pseudo-distribution, the probability density function of stress and intensity is negotiated under certain conditions or at a certain time. As shown in Fig. 13, the shadow region of the negotiation is the interference region, that is, the structure may be The area where the failure occurred. The area of the interference zone only represents interference and does not represent the degree of interference. The area of the interference zone only represents and does not represent the degree of interference.
Figure 13. Schematic diagram of the stress-intensity distribution interference model

When the strength of the structure and the degree of dispersion of the stress are large, the interference portion increases and the reliability decreases. When the material strength is high and the stress is stable, the degree of dispersion is small, the interference portion is reduced, and the reliability is increased.

During the long-term use of the mixer structure, its structural strength will be attenuated. As shown in Figure 14, even if there is a safety margin in the design, when the working time is reached, the strength is attenuated from the a position to the b position, and the stress and strength interfere, and the structure appears invalid. Therefore, a proper safety margin should be left in the design stage to avoid interference between stress and strength.

Figure 14. intensity decay process

5.2. Establishing the limit state function equation

In the structural reliability analysis, the reliability state of the structure is expressed by the limit state function equation. The expression of the polar state function equation is:

\[ g(x) > 0, \text{ The device is in a safe state} \]

\[ g(x) = 0, \text{ The device is in a critical state} \]
\[ g(x) < 0. \text{ The device is in a failed state} \]

In order to keep the product structure in a reliable state, it must satisfy the structural limit state function equation and keep it in a safe state, that is, \( g(x) > 0 \).

The safe state of the mixer structure is that the mixer does not break under the load of the mixture. According to the stress-strength interference model, the limit state function equation of the mixer structure is established:

\[
g(x) = r(x) - r^*(x)
\]

(4)

Where \( r(x) \) represents the intensity distribution of the mixer structure and \( r^*(x) \) represents the stress distribution on the structure.

In order to calculate the limit state function equation, the Monte Carlo method is used for simulation calculation. The Monte Carlo method calculates the expression as:

\[
P = \frac{N_f}{N}
\]

(5)

Formula: \( P \) is the structural reliability of the product, \( N \) is the total number of tests, \( N_f \) is the number of tests to produce \( g(x) > 0 \).

In order to ensure the convergence of the limit state function equation, a large number of repeated simulation experiments were performed.

5.3. Calculation Of Structural Reliability Of The Mixer

The calculation process of the structural reliability of the mixer is shown in Figure 15. The load distribution parameters of the mixer structure are recorded in the Input1 module. In the Action1 module, the ANSYS software is called and the structural static analysis is performed by the command flow control. The Action1 module analyzes the structural stress data, and the structural strength distribution is recorded in the strength module. Using the stress module and the strength module as the input of the function module, writing the structural limit state function equation and the Monte Carlo simulation number in the function module, using the static analysis method in the calling manner, completing a large number of simulation calculations, and finally, adopting The Monte Carlo method calculates structural reliability.
The reliability is solved for the mixing drum, the stirring shaft, the stirring arm and the stirring blade. It can be seen that the stresses of the mixing drum, the mixing shaft, the mixing arm and the mixing blade are all less than their strengths, that is, the structural limit state function equation is in a safe state. It shows that under the load of the mixing drum and the stirring shaft, the structural reliability can reach 1, and no failure will occur. Therefore, the key components of the mixer do not experience a safety failure under the load of the mixture.

### 6. Conclusion

Aiming at the reliability analysis of the mixer structure, an integrated analysis idea is proposed. Combining discrete element method, probability and statistics theory, static theory, and reliability theory, the reliability of the mixer structure is analyzed.

1. Obtain the load spectrum of the composite components on the structural components based on the discrete element method.
2. Using the hypothesis test method to statistically infer the probability distribution form of the load spectrum, which can accurately describe the stress-intensity interference degree. As a result, the load data of the agitating members (including the agitating blades, the agitating arms, and the agitating shaft) are subjected to the gamma distribution, and the mixing drum load data is subjected to the normal distribution.
3. Using the stress-strength interference model to establish the limit state function equation of the mixer structure.
4. Solve the structural reliability of the mixer based on the Monte Carlo method. The results show that the reliability of the mixing part and the mixing drum are both 1, indicating that the key components of the mixer can be safely operated.

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References

[1] Zhang R. L and Si S 2018 Reliability Analysis of Systems with Common Cause Failure Based on Stress-Strength Interference Model *Journal of Shanghai Jiao tong University* **23** 707-10

[2] Bhuyan P, Mitra M and Dewan A 2018 Identifiability issues in dynamic stress-strength modeling *Annals of the Institute of Statistical Mathematics* **47** 63-81

[3] Huang B and Huang H Z 2009 A Discrete Stress-Strength Interference Model With Stress Dependent Strength *IEEE Transactions on Reliability* **101** 118-22

[4] Liu P 2016 *Structural reliability analysis based on improved Latin hypercube importance sampling method* Jinan University

[5] Y T, Tanaka and Ishida T 1992 Lagrangian Numerical Simulation Of Plug Flow Of Cohesionless Particles In A Horizontal Pipe *Powder Technol* **12** 239-50.

[6] Santos D A and Barrozo M A S and Duarte C R 2016 Investigation of particle dynamics in a rotary drum by means of experiments and numerical simulation using DEM *Advanced Powder Technology* **35** 692-703

[7] Zhang X M, He G and Feng C 2016 Design and experiment of flights in middle drum of triple-pass rotary drum dryer for organic fertilizer pellets *7 Chinese Society of Agricultural Machinery* **151**-8

[8] Tang X Y and M Luo M Y 2019 Nonparametric test of multi-sample scale parameters *Technology Wind* **6** 35-44

[9] Wei Y H, Wang B S and Xing Y Z 2018 Discussion on hypothesis testing based on Monte Carlo method *Statistics and Decision* **24** 75-8

[10] Kong X N, Yang H X and Li Y 2015 Research on reasonable filling rate of double horizontal Shaft Mixer based on EDEM *31 Cement Engineering* **9**-12

[11] Huang A N and Kuo H P 2014 Developments In The Tools For The Investigation Of Mixing In Particulate Systems-A Review *Advanced Powder Technology* **42** 163-73