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Reliability Analysis of Dual-Spring Parallel Support Structure-A Comparative Study Between Deterministic Calculation and Monte Carlo Simulation

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Abstract. In civil engineering, the reliability of support structure stiffness and strength is crucial for overall project safety. The dual-spring parallel support, a simplified model for parallel force-bearing systems, is valuable in performance evaluation. This paper compares its stiffness and strength reliability using deterministic numerical calculation and Monte Carlo simulation. The deterministic analysis, based on mean values of key parameters, calculates equivalent stiffness, vertical deformation, and spring cross-sectional pressure using the parallel spring stiffness superposition principle, Hooke's law, and the pressure formula. Results show that vertical deformation meets the stiffness requirement (≤1.5 mm), and cross-sectional pressures comply with the strength standard ($\leq 1.25\times10^{6}$ kPa), confirming that the structure's basic mechanical properties meet standards. Monte Carlo simulation comprehensively addresses engineering parameter randomness. Using parameter probability distributions (force, stiffness, diameter, etc.), 1000 random samples were generated for mechanical response analysis. Results indicate that vertical deformation and spring pressure remain within limits, minimizing deformation and failure risks. This study validates the dual-spring support's reliability and contrasts deterministic analysis (efficiency) with Monte Carlo simulation (accuracy). It offers methodological guidance and data for similar structures' reliability analysis, aiding engineering design and safety assessment.

Keywords: Dual-spring support structure, Reliability analysis, Deterministic calculation, Monte Carlo method, Stiffness, Strength

1. Introduction

In civil engineering, support structures serve as the core component for load transfer and stability assurance. Their mechanical properties directly determine the safe service life of engineering facilities such as buildings, bridges, and industrial equipment. From high-rise buildings' lateral force-resistant support systems to the shock-absorbing support devices of precision instruments, support structures must maintain stable stiffness and strength under complex conditions, including long-term loads, environmental erosion, and parameter fluctuations [1]. Once insufficient stiffness leads to excessive deformation or strength failure causes structural damage, it may result in economic losses and threaten human life. Therefore, conducting scientific and accurate reliability

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analysis on support structures has always been a core issue in engineering design and safety assessment [2].

As a typical simplified mechanical model, the dual-spring parallel support structure, characterized by "balanced force-bearing and coordinated deformation", is widely used to simulate support systems with parallel force-bearing characteristics in practical engineering. Examples include parallel spring bearings in building isolation layers and multi-point elastic supports for mechanical equipment. The structure's mechanical behavior hinges on spring stiffness, cross-sectional size, and load. Conventional analysis uses deterministic methods, calculating deformation and stress from design mean values (e.g., standard load, rated material properties) via mechanical equations. Although this method can quickly obtain the "ideal value" of structural performance and provide a reference for preliminary design, it overlooks a key contradiction in practical engineering - parameter randomness. During the construction process, there exist processing errors in spring diameter and batch fluctuations in the elastic modulus of materials; during the service stage, the instantaneous impact of loads and the influence of ambient temperature on material performance can cause actual parameters to deviate from the design mean values. This deviation may further lead to a discrepancy between the deterministic analysis results and the actual structural performance, and even trigger safety misjudgments [3].

With the development of reliability engineering theory, the Monte Carlo simulation method has provided a practical approach to address the issue of parameter randomness. This method constructs probability distribution models of parameters (such as normal distribution, Weibull distribution, etc.), generates a large number of random samples for mechanical calculation, and finally evaluates the possibility of the structure meeting performance requirements in the form of statistical probability. Compared with deterministic analysis, Monte Carlo simulation can more truly reproduce the variability of engineering parameters. Its advantages have been verified in fields such as steel and concrete structures, especially in the reliability assessment of complex structures. For instance, in the analysis of seismic support structures, the Monte Carlo method can accurately predict the failure probability of structures under extreme working conditions by simulating the random characteristics of seismic loads [4]; in mechanical support systems, this method can also effectively quantify the impact of manufacturing errors on structural stiffness [5].

However, comparative analysis combining deterministic calculation and Monte Carlo simulation is still relatively scarce in the current research on dual-spring parallel support structures. Most studies only use a single method for analysis, making it difficult to fully reveal the differences in structural performance between "ideal design" and "actual working conditions", and are unable to provide a complete technical path of "efficient preliminary design + accurate reliability verification" for engineering practice. This paper takes the dual-spring parallel support structure as the research object and systematically integrates the two analysis methods. Firstly, deterministic calculation is used to obtain the stiffness and strength performance of the structure under the mean values of parameters, verifying the rationality of its basic design. Then, a Monte Carlo simulation is employed to consider the random distributions of parameters such as concentrated force, spring stiffness coefficient, and cross-sectional dimensions, to evaluate the structure's reliability level under the influence of actual variability. This study aims to verify the safety performance of the dual-spring parallel support structure and provide a reference technical framework for the reliability analysis of similar support structures by comparing the two methods. It aims to promote the transformation of engineering design from "deterministic safety" to "probabilistic reliability" and provide a scientific basis for improving engineering structures' safety, redundancy, and service stability.

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2. Research object and calculation method

2.1. Structural model

The research object is a structure supported by two parallel springs, with a vertical height of h = 0.75 m, as shown in Figure 1.

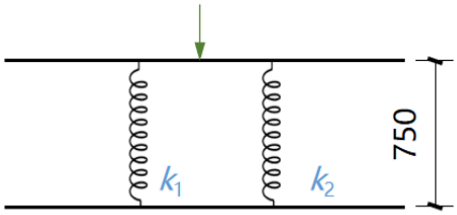

Figure 1. The two-spring model

2.2. Basic assumptions

① During the force-bearing process of the structure, the deformations of the two supports are coordinated, meaning that the vertical deformations of the two supports are correlated under the action of a concentrated load.

② The influence of lateral deformation of the structure and other secondary factors on the mechanical performance of the structure is not considered, and only the vertical strength and stiffness performance are focused on.

2.3. Calculation steps

①Calculation of equivalent stiffness coefficient: According to the superposition principle of parallel spring stiffness coefficients, $\mathrm{k} = \mathrm{k}_1 + \mathrm{k}_2 + \cdots + \mathrm{k}_\mathrm{n}$. After knowing the stiffness coefficients k1 and k2 of Spring 1 and Spring 2, respectively, the system stiffness coefficient k0 can be calculated as follows:

$$\cdot k_0 = k_1 + k_2$$

②Calculation of vertical deformation: According to Hooke's law $\mathrm{F} = \mathrm{kx}$, where F is the acting force, k is the stiffness coefficient, and x is the displacement. With the known acting force F0 and system stiffness coefficient k0, the (equivalent) system displacement x0 can be calculated as:

$$\cdot x = \frac{F_0}{k_0}$$

③Calculation of spring acting force: Similarly, with the known stiffness coefficients k1 and k2 of Spring 1 and Spring 2, and the (equivalent) system displacement x0, the acting forces F1 and F2 of Spring 1 and Spring 2 can be calculated respectively:

$$①F_1 = k_1 x_0 \quad ②F_2 = k_2 x_0$$

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④Calculation of cross-sectional area: The radius r can be obtained from the spring diameter d as $r = \frac{d}{2}$. According to $A = \pi r^2$, where A is the cross-sectional area, π is a constant, and r is the radius. With the known radii r1 and r2 of Spring 1 and Spring 2 respectively, the cross-sectional areas A1 and A2 can be calculated as:

$$①A_1 = \pi {r_1}^2 \ ②A_2 = \pi {r_2}^2$$

⑤ Calculation of cross-sectional pressure: According to $p = \frac{F}{A}$, where P is the pressure (strength), F is the acting force, and A is the cross-sectional area. With the known acting forces F1, F2 of Spring 1 and Spring 2, and the cross-sectional areas A1, A2, the strengths p1 and p2 can be calculated respectively:

$$①p_1 = \frac{F_1}{A_1} \quad ②p_2 = \frac{F_2}{A_2}$$

⑥ Reliability judgment: Judge whether the x0 obtained from each simulation is less than or equal to the strength requirement, and whether both p1 and p2 are less than or equal to the strength requirement, then count the number of simulations that meet the strength and stiffness requirements.

3. Analysis and calculation of deterministic model

3.1. Parameter setting

Concentrated force F0= 60 kN, acting on the tabletop

For Spring 1,

Stiffness coefficient k1 = 2×107 N/m, diameter d1 = 5 mm.

For Spring 2,

Stiffness coefficient k2 = 3×107 N/m, diameter d2 = 6 mm.

Strength Requirement preq : the sectional pressure is not more than 1.25×106 kPa

Stiffness Requirement xreq : the vertical deformation is not more than 1.5 mm

3.2. Calculation results and analysis

The calculation results are shown in Table 1:

Table 1. The first calculation result

k1	d1	A1	k2	d2	A2	k0	F0	x0	F1	F2	p1	p2	preq	xreq
N/m	mm	mm2	N/m	mm	mm2	N/m	kN	mm	kN	kN	kPa	kPa	kPa	kPa
20000000	5	19.6349	30000000	6	28.2743	50000000	60	1.2	24000000	36000000	1222309.963	1273239.545	1250000	1 1.5 1

(1)Stiffness Result Analysis

The calculated vertical deformation x0 is less than 1.5 mm, meeting the stiffness requirement. This indicates that under this condition, the probability of excessive vertical deformation of the dual-spring support structure is extremely low.

(2) Strength Result Analysis

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Regarding the cross-sectional pressures of Spring 1 and Spring 2, the calculated p1 and p2 are both less than the allowable pressure, meeting the strength requirement. This shows that under this condition, the possibility of strength failure of the two springs is very low.

4. Analysis and calculation of uncertainty model (Monte Carlo simulation)

4.1. Basic principle

The Monte Carlo method generates a large number of random samples that follow the distribution of each parameter, performs mechanical calculations for each sample, and then counts the number of samples that meet the requirements, thereby obtaining an approximate value of structural reliability. The more simulation times, the closer the result is to the actual probability.

4.2. Parameter setting

(1) Concentrated force: F0 follows a normal distribution N(60, 12), where the mean is 60 and the standard deviation is 12 (unit: kN).

(2) Spring 1:

·Stiffness coefficient k1 follows a normal distribution N(2×10^7, 2×10^6), where the mean is 2×10^7 and the standard deviation is 2×10^6 (unit: N/m).

·Diameter d1 follows a normal distribution N(5.1, 0.5), where the mean is 5.1 and the standard deviation is 0.5 (unit: mm).

(3) Spring 2:

·Stiffness coefficient k2 follows a normal distribution N(3×10^7, 2×10^6), where the mean is 3×10^7 and the standard deviation is 2×10^6 (unit: N/m).

·Diameter d2 follows a normal distribution N(6.1, 0.5), where the mean is 6.1 and the standard deviation is 0.5 (unit: mm).

(4) Strength requirement: cross-sectional pressure not greater than N(1.25×10^6, 2.5×10^5), where the mean is 1.25×10^6 and the standard deviation is 2.5×10^5 (unit: kPa).

(5) Stiffness requirement: vertical deformation not greater than 1.5 mm (unit: mm).

4.3. Simulation results and analysis

Based on the normal distribution of each parameter, a random number generation algorithm is used to generate 1000 sets of random samples of the acting force F0, stiffness coefficients k1 and k2, diameters d1 and d2, and the allowable maximum pressure pallow.

By statistically analyzing the results of 1000 Monte Carlo simulations:

(1)Stiffness Result Analysis

In 1000 simulations, the rate calculated of vertical deformation x0 meeting the stiffness requirement is 88.3%. This indicates the probability of excessive vertical deformation of the dual-spring support structure is small under a random concentrated force and spring stiffness coefficient.

(2)Strength Result Analysis

Regarding the cross-sectional pressures of Spring 1 and Spring 2, in 1000 simulations, the rate calculated of p1 and p2 both meeting the strength requirement is 40.4%. This shows that under the influence of random parameters, the possibility of strength failure of the two springs is high.

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5. Conclusions

The results of deterministic analysis show that when the mean values of various parameters are selected, the vertical deformation of the dual-spring support structure meets the stiffness requirement of not exceeding 1.5 mm, and the cross-sectional pressures of the two springs also meet the strength requirement of not exceeding the allowable pressure. This initially indicates that the structure has good mechanical properties.

Through generating a large number of random samples following the specified probability distribution for analysis, the Monte Carlo simulation results show that among the 1000 simulated samples, approximately 88.3% have a vertical deformation less than 1.5 mm, and 40.4% have a spring cross-sectional pressure less than the allowable pressure. The probability of excessive deformation of the structure is low, but the likelihood of strength failure is relatively high. The conclusion is consistent with the research on parameter randomness in similar support structures [2]. This exposes the design defects of the structure when affected by actual variability, requiring further design and improvement.

By comparing the two analysis methods, it can be concluded that deterministic analysis is concise and efficient, and can quickly obtain the general situation of structural performance; the Monte Carlo method can fully consider the randomness of parameters and evaluate the structural reliability more accurately. In the actual reliability analysis of engineering structures, the two methods can be combined according to requirements to fully and accurately grasp the safety performance of the structure. Future research can further explore the coordination between stiffness and strength of support structures by referring to the design ideas of energy-dissipative bracing systems [3].

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