Static and Dynamic Analysis of Coupled Vibration of Suspension Bridge Structure Under Earthquake Action

Xu XiaoJian[1,2,*], Xin GuangTao[1,3], Zhao Jian[1,2] and Chen Yu[1,2]

[1]*China Highway Engineering Consulting Corporation. 100089, Beijing, China*
[2]*Zhongzi Highway Maintenance & Test Technology Co., Ltd. 100097, Beijing, China*
[3]*CHECC DATA Co., Ltd. 100097, Beijing, China*
E-mail: xxjzhuanyong@126.com
[*]*Corresponding Author*

Received 30 November 2023; Accepted 28 December 2023;
Publication 24 February 2024

Abstract

This article investigates the coupled vibration problem of suspension bridge structures under earthquake action, and conducts static and dynamic analysis using computer algorithms. In terms of static analysis, complex structures are divided into many small elements, and the stress and deformation of each element are calculated through finite element analysis, thereby obtaining the static characteristics of the entire structure. In terms of dynamic analysis, the seismic response analysis method based on time history considers seismic action as a time-varying external excitation, and calculates and simulates the dynamic response of the suspension bridge structure. In order to achieve efficient and accurate calculations, this article also adopts optimization algorithms and numerical calculation methods. Through a comprehensive study of statics and dynamics analysis, the key characteristics and regularities of coupled vibration of suspension bridge structures under earthquake action have been obtained. These research results not only provide important theoretical

European Journal of Computational Mechanics, Vol. 32_6, 519–542.
doi: 10.13052/ejcm2642-2085.3261

guidance and technical support for related engineering practices, but also provide useful references and inspirations for dynamic analysis and optimization design of similar structures. Meanwhile, using computer algorithms and simulation software for static and dynamic analysis can significantly reduce analysis costs and time, improve analysis accuracy and efficiency, and have broad application prospects.

Keywords: Earthquake action, computer algorithms, suspension bridge body, structural coupled vibration.

1 Introduction

Suspension bridge is an innovative bridge structure with important transportation significance and engineering application value. With the increasingly prominent problem of urban traffic congestion, suspension bridges, as an efficient and flexible mode of transportation, have received much attention and praise; Simultaneously suspended bridge is a type of bridge that suspends the bridge in the air through a suspension system. Its main feature is that it does not require the support piers and abutments of traditional bridges [1], and can fully utilize water surface space to improve traffic capacity. Suspension bridges can be widely used in rivers, lakes, bays and other water bodies, connecting transportation between two continents, greatly facilitating people's travel. More and more cities both domestically and internationally are paying attention to and adopting suspension bridge technology. For example, the Hengqin Suspension Bridge in Zhuhai, China, as the world's first commercial suspension bridge, has successfully solved the transportation bottleneck problem between Zhuhai and Hengqin Island. Meanwhile, countries and regions such as Japan, South Korea, and the United States have also utilized suspension bridge technology to improve urban traffic conditions. However, suspension bridge structures also face certain challenges when facing seismic effects. Earthquakes are a highly destructive natural disaster, and the damage and losses caused to bridge structures cannot be ignored. Due to its special design form and working principle, the seismic response characteristics of suspension bridge structures differ greatly from traditional bridges [2, 3]. Therefore, studying the static, dynamic, and coupled vibration characteristics of suspension bridge structures under seismic loads is of great significance. Through in-depth research on the mechanism and laws of seismic response of suspension bridge structures, scientific basis can be provided for the seismic design of suspension bridges, further improving their seismic resistance and safety [4].

Earthquakes are a destructive natural disaster [5, 6], and for bridge structures, their damage and losses cannot be ignored. Although suspension bridges, as an innovative bridge structure, can fully utilize water surface space and improve traffic capacity, there are also certain challenges under earthquake action. This article will introduce the threats that earthquakes pose to suspension bridge structures [7] and emphasize the importance of addressing these issues. Possible bridge damage and safety hazards caused by earthquakes. During earthquakes, ground vibrations can cause strong vibrations in bridge structures, leading to problems such as vibration amplification, resonance, and damage. Compared with traditional bridges, suspension bridge structures have significant differences in seismic response characteristics due to their special design form and working principle [8]. The importance of addressing the threats posed by earthquakes is self-evident. Specifically, the following measures need to be taken: (1) Seismic design: In the design stage of suspension bridge structures, the impact of seismic loads on the structure must be fully considered, and scientific and reasonable seismic design methods must be adopted to improve the seismic capacity and safety of the structure. (2) Testing and monitoring: After the completion of the suspension bridge, regular testing and monitoring are required to timely detect changes and hidden dangers in the structure, take corresponding measures for repair and reinforcement, and ensure the safety and stability of the structure Emergency plan: In response to sudden events such as earthquakes, it is necessary to develop a scientific and reasonable emergency plan, timely organize personnel for evacuation and rescue, and predict and handle possible structural problems to reduce losses and risks.

With the rapid development of society and the advancement of urbanization, the demand for bridge structures is becoming more and more urgent. As an emerging bridge structure, the suspension bridge has the significant advantage of improving traffic capacity and saving construction costs. By studying the seismic response of suspension bridge structures, the development and application of suspension bridge technology can be effectively promoted, making contributions to the development of social transportation. Through in-depth research, the seismic resistance of suspension bridges can be improved, relevant design specifications and standards can be improved, and strong support can be provided for the development and application of suspension bridge technology. This is of great significance for ensuring the safety of people's lives and property and promoting social and economic development [9, 10].

The mechanical analysis of suspension bridge structures under earthquake action is an important and complex issue [11], which requires consideration of various factors such as seismic waves, suspension cables, main beams, and bridge decks. Research based on computer algorithms can improve analysis efficiency and accuracy, providing scientific basis for the design and seismic reinforcement of suspension bridges [12]. Computer algorithms can be used to explore the influence of seismic input on the structural response of suspension bridges. By establishing a reasonable seismic input model, considering factors such as the characteristics and intensity of different seismic waves, conducting parametric analysis and sensitivity analysis, further exploring the influence of seismic characteristics on the structural response of suspension bridge structures, and providing more scientific reference for structural design. Research based on computer algorithms can also be used to optimize the seismic design of suspension bridge structures. By using multi-objective optimization algorithms and combining multiple indicators such as engineering economy, structural safety, and construction feasibility, the optimal structural form and parameter configuration are sought to improve the overall performance of the suspension bridge under earthquake action.

In this study, a computer algorithm is used to analyze the mechanical structure of a suspended bridge under seismic action [13], which can effectively study the seismic response characteristics of the structure, analyze the structural response law under ground motion input, and propose an optimal design scheme, which provides strong support for the seismic design and engineering practice of the suspended bridge.

2 Static and Dynamic Analysis of Suspension Bridge Structure Under Earthquake Action

2.1 The Basic Principles of Mechanical Analysis

The static and dynamic analysis of suspension bridge structures under earthquake action involves basic principles in the field of mechanics, including relevant theories of statics and dynamics. Statics is a discipline that studies the laws of force and deformation of objects in a stationary or uniform linear motion state, while dynamics focuses on the laws of motion and deformation of objects under external forces [14].

In terms of statics [15], we first need to consider the stress and deformation of the suspension bridge structure under static loads. According to Newton's first law, when an object is in a state of rest or uniform linear motion, the resultant force it experiences is zero [16]. Therefore, we can analyze the stress situation of the suspension bridge under self weight and external loads through the balance equation and force balance conditions, and then obtain the static mechanical characteristics of the structure such as internal force, stress, and deformation. In addition, it is necessary to consider the stiffness and damping characteristics of the support, which are crucial for the stability and safety of the structure.

In terms of dynamics, the coupled vibration problem of suspension bridge structures under earthquake action needs to be analysed using relevant theories of dynamics [17]. Dynamics studies the motion laws of objects under external forces, including their dynamic responses such as acceleration, velocity, and displacement. Under earthquake action, seismic force is considered as a time-varying external excitation [18], therefore time history analysis methods such as Newmark integration or Wilson are needed – θ the method is used to solve the dynamic response equation of the structure. Through these methods, we can obtain the vibration characteristics of the suspension bridge structure under earthquake action [19], including parameters such as mode shape, amplitude, and frequency, in order to evaluate the seismic and comfort performance of the structure. The processing model of the mechanical algorithm is shown in Figure 1.

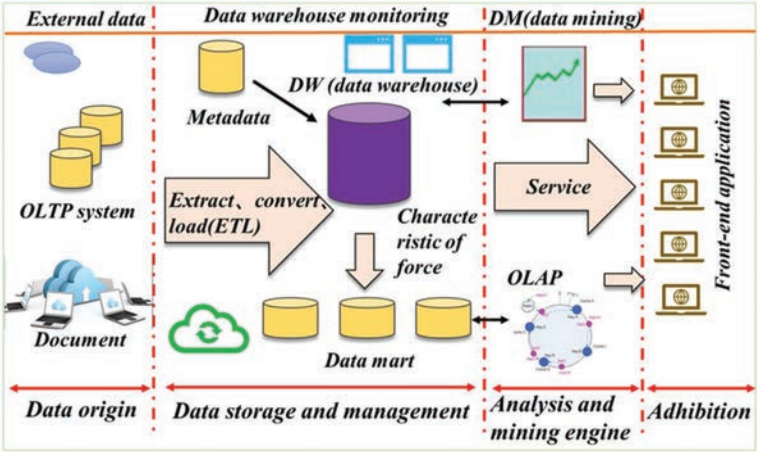


Figure 1 Mechanical algorithm processing model.

2.2 Seismic Mechanics Theory and Seismic Wave Input

In the static and dynamic analysis of suspension bridge structures under earthquake action, seismic mechanics theory and seismic wave input are very important aspects [20]. Earthquake mechanics studies the ground motion caused by earthquakes and the regularity of their forces and deformations on structures, while seismic waves describe the time displacement or time acceleration curves of seismic forces [21]. In computer algorithms, seismic wave input can be achieved by establishing appropriate input models. A common method is to use seismic record data, preprocess the seismic record data, extract key parameters such as acceleration time history, velocity time history, and displacement time history, and use them as seismic wave input models. Another method is to artificially synthesize seismic waves and generate seismic wave inputs using numerical simulation methods based on seismic wave characteristic parameters and seismic mechanics theory [22]. These seismic wave input models can be loaded in computer algorithms and used as external excitations for suspension bridge structures to simulate vibration responses under earthquake action.

At the same time, it is necessary to consider the spatial variation and spectral characteristics of seismic waves. Seismic waves typically have a wide range of frequency content, thus requiring spectral analysis. By using spectral analysis methods such as Fourier transform [23], seismic waves can be converted into frequency domain data to analyse the energy of seismic waves in different frequency bands. These spectrum analysis results can be used for seismic response spectrum analysis of structures to evaluate the response of suspension bridge structures at different frequencies.

2.3 Design Methods and Requirements for Suspension Bridges

In the design of suspension bridges, it is necessary to consider the static and dynamic issues of the structure. Static analysis can be simulated using computer algorithms, while dynamic analysis requires consideration of external factors such as seismic effects, wind loads, and traffic loads [24]. Coupled vibration analysis is required for suspension bridge structures under earthquake action. Coupling vibration analysis can be achieved by establishing appropriate structural models and computer algorithms to simulate vibration response under different conditions and evaluate the seismic resistance of suspension bridges. Material selection and structural form also need to be considered. The main structure of a suspension bridge includes bridge towers, bridge cables, bridge decks, and support systems. Among them, the bridge tower and cable are the main load-bearing parts of the suspension bridge, and high-strength and high stiffness materials need to be selected to ensure the stability and durability of the structure [25]. The bridge deck needs to consider anti slip performance and adapt to the requirements of different vehicle types. The support system needs to consider the impact on the vehicle and stability requirements; The safety of suspension bridges needs to consider various factors, such as natural disasters, adverse weather, and traffic accidents. The safety of suspension bridges can be evaluated by establishing a safety assessment model and computer algorithms. The maintainability of suspension bridges also needs to be considered, and the maintainability of bridges can be improved by selecting materials and structural forms that are easy to maintain [26].

The design of a suspension bridge needs to consider various factors [27], such as structural stability, durability, safety, and seismic resistance. Static and dynamic analysis can be conducted by establishing appropriate structural models and computer algorithms to evaluate the performance and seismic resistance of suspension bridges [28]. In terms of material selection and structural form, multiple factors need to be considered and comply with traffic flow and load requirements. At the same time, the safety and maintainability of the suspension bridge also need to be considered. The application of these requirements and methods can provide scientific basis for the design and optimization of suspension bridges.

2.4 Mechanical Analysis Results and Discussion

In terms of static analysis, the finite element method was used to model the suspension bridge structure [29], and the influence of multiple parameters such as seismic wave frequency, amplitude, and incidence angle on the structure was also considered. The displacement, acceleration, and other data of the suspension bridge under different seismic waves were calculated and analyzed. Through static analysis [30], the hysteresis curve and force characteristics of the suspension bridge in earthquakes were obtained, and analyzed and discussed [31].

In terms of dynamic analysis, modal analysis and time history analysis [32] were used to analyze the dynamic response of the suspension bridge. The dynamic response of the suspension bridge was calculated and analyzed under different seismic waves. The main vibration modes of the suspension bridge in earthquakes and the frequency, amplitude and other data of each vibration mode were obtained through dynamic analysis, and

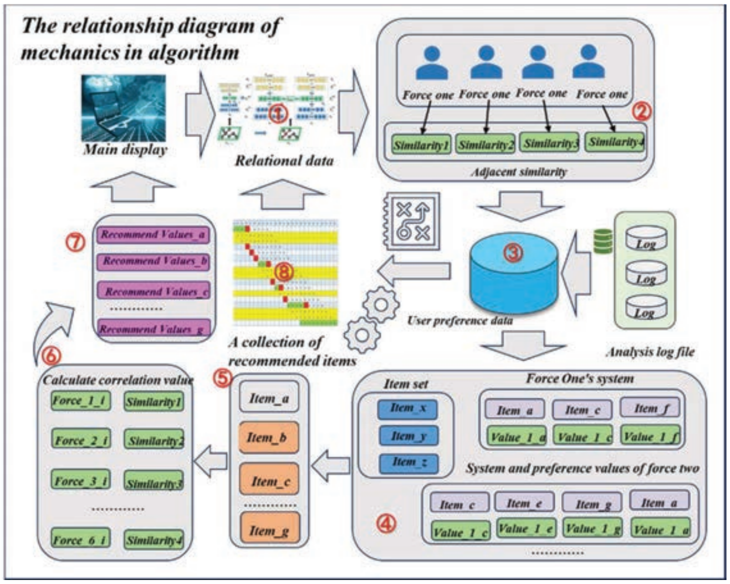


Figure 2 Algorithm recommendation of multi-objective algorithms in mechanical analysis.

discussed and analyzed. Using the data processing module in the computer to analyze and summarize the force situation of the suspension bridge body, the multi-objective algorithm recommended in mechanical analysis is shown in Figure 2.

In terms of coupled vibration analysis, the coupling vibration mechanism of suspension bridge structures was deeply explored by integrating the results of static and dynamic analysis. Research has shown that suspension cables have a significant impact on coupled vibration, with the stiffness and damping parameters of the suspension cables having a more sensitive impact on coupled vibration. Based on in-depth analysis of coupled vibration mechanisms, suggestions for optimizing suspension structures to improve the seismic resistance of suspension bridges have been proposed.

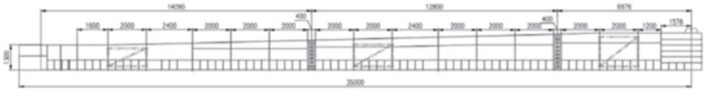
3 Coupling Vibration Analysis of Suspension Bridge Structure Based on Computer Algorithms

3.1 Establishment of Model Framework

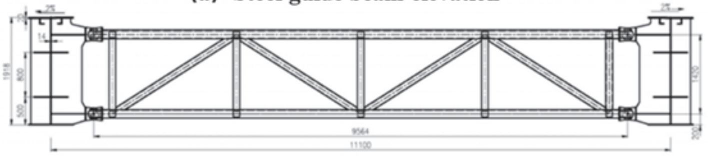
Establishing an accurate structural model is crucial in the coupled vibration analysis of suspension bridge structures based on computer algorithms.

In this paper, a three-dimensional structural model was established using finite element method, which includes components such as suspension bridge deck, suspension cables, and support systems. This model can reflect the true structural characteristics of the suspension bridge and accurately simulate the structural response of the suspension bridge under earthquake action. After establishing the structural model, use ANSYS software for simulation calculations. This software can perform static and dynamic analysis on structural models, and provide corresponding structural response results. The influence of multiple parameters such as frequency, amplitude, and incidence angle of seismic waves on the structure was considered, and the displacement, acceleration, and other data of suspension bridges under different seismic waves were calculated and analyzed. Using the mechanical algorithm data processing framework shown in Figure 3, establish a model framework in a computer to obtain an ideal structural coupled vibration analysis.

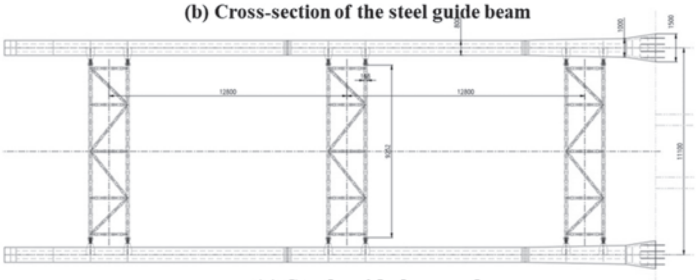
When constructing the structural model, the model construction method based on BIM technology is adopted. This method can integrate the geometric information, material information and mechanical information of the structure into a unified model to improve the accuracy and reliability of the model. MATLAB-based data processing and analysis methods are also used



(a) Steel guide beam elevation



(b) Cross-section of the steel guide beam



(c) Steel guide beam plan

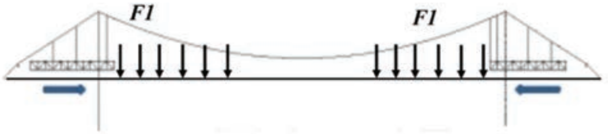
Figure 3 Schematic diagram of steel guide beam (unit: mm).

for kinetic analysis, which enables rapid processing of large amounts of data and corresponding results.

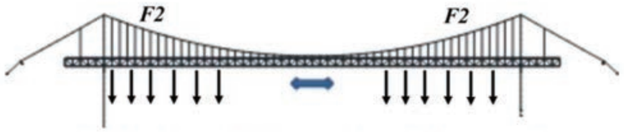
3.2 Coupling Method Between Statics and Dynamics Models

The coupling between static and dynamic models involves multiple aspects, mainly including the following:

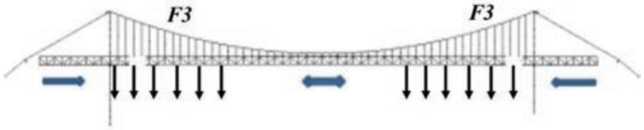
(1) The material properties of the static and dynamic models should be consistent. When establishing static and dynamic models, it is necessary to consider the material properties of the structure, including parameters such as elastic modulus, Poisson's ratio, density, etc. These parameters have a significant impact on the response of the structure, therefore, when establishing static and dynamic models, it is necessary to ensure the consistency of these parameters to ensure the correct coupling of the two models.
(2) The boundary conditions of the static and dynamic models need to be matched. When establishing static and dynamic models, it is necessary to consider the boundary conditions of the structure, including support constraints and load conditions. These boundary conditions should be matched between the static and dynamic models to ensure proper coupling between the two models. For example, when conducting dynamic analysis, it is necessary to use the results of static analysis as boundary conditions for dynamic analysis to ensure continuity and consistency between the two models.
(3) The static and dynamic models should use the same mesh division. When establishing static and dynamic models, it is necessary to consider the geometric shape of the structure. These geometric forms can be represented by meshing the structure. Therefore, when establishing static and dynamic models, it is necessary to use the same mesh generation method to ensure the geometric consistency between the two models. Otherwise, if the grids between the two models do not match, it may lead to coupling failure between the models, thereby affecting the accuracy of the calculation results.
(4) The static and dynamic models should use the same numerical methods. When conducting static and dynamic calculations, it is necessary to use the same numerical methods and algorithms to ensure consistency in the calculation results between the two models. For example, when conducting finite element calculations, the same integration methods, solvers, and convergence criteria need to be used. This can ensure that



Bridge installation scheme Diagram 1



Bridge installation scheme Diagram 2



Bridge installation scheme Diagram 3

Figure 4 Schematic diagram of bridge installation stress.

the calculation results between the two models are consistent, thereby ensuring the correctness of the model coupling.

On the basis of the coupling of the static and dynamic models, we further analyze the coupling model of the correlation pairs in the schematic diagram of the bridge installation force in Figure 4. With this analysis, we hope to be able to obtain the desired mechanical property targets. Specifically, we will consider the effects of statics and dynamics to ensure that the requirements of the bridge structure in terms of stability, bearing capacity and vibration response under different stress conditions are met. Through this analysis, we can provide targeted guidance for the optimal design of the bridge to achieve the expected level of mechanical properties in practical use.

3.3 Modeling

The suspension bridge body adopts a combination of modular steel structure and concrete, as well as reverse construction. Among them, modular steel structure buildings are prone to relative sliding during the bending deformation process of laminated steel beams, which in turn has a significant impact on the overall bending mechanical performance of the laminated steel beam structure. By using the basic differential equation of bending for composite steel beams and combining it with the basic physical equation of slip strain on the composite surface of double beams, the relative strength of composite steel beams is derived.

The slip differential control equation is used to establish a relative slip theoretical model for composite steel beams under different load conditions, load boundary conditions, and the degree of connection between the composite surfaces.

The basic assumption for the bending of a double beam structure is that: (1) the materials of the floor and ceiling beams in the composite steel beam are both linear elastic, and the deflection and beam end angle of the composite steel beam belong to the small deformation range; (2) The floor and ceiling beams in the composite steel beam have the same bending curvature, and there is no relative vertical displacement between the upper and lower beams; (3) The upper and lower beams in the composite steel beam do not consider shear deformation, and the upper and lower beams respectively conform to the assumption of a flat section; (4) The shear connection of the composite surface of the floor beam and ceiling beam is uniformly distributed along the beam span direction, and the tangential load distribution of the composite surface is proportional to the relative sliding of the layer beam. The following formula can be obtained based on the equilibrium condition of internal forces in the section:

$$N_{f'(x)} = t(x) = KS(x) \tag{1}$$

$$V_{f'(x)} = -q(x) + r(x) \tag{2}$$

$$M_{f'(x)} = V_{f(x)} + t(x)h_f/2 \tag{3}$$

$$N_{e'(x)} = -t_{f(x)} = -KS(x) \tag{4}$$

$$V_{e'(x)} = -r(x) \tag{5}$$

$$M_{e'(x)} = V_e(x) + t(x)h_c/2 \tag{6}$$

$$V'(x) = -q(x) \tag{7}$$

$$M'(x) = V(x) \tag{8}$$

According to the internal force balance conditions of the cross-section, establish the internal force balance equation of the composite steel beam:

$$N_f(x) + N_c(x) = 0 \tag{9}$$

$$V_f(x) + V_c(x) = V(x) \tag{10}$$

$$M(x) = M_f(x) - N_f(x)h_0 \tag{11}$$

According to assumption (2), the bending curvature of the floor beam and ceiling beam in the composite steel beam is the same. Combining the relationship between bending moment and curvature, it can be concluded that:

$$w''(x) = -M_f(x)/EI_f \tag{12}$$

$$w''(x) = -M_c(x)/EI_c \tag{13}$$

From formulas (11) to (13), it can be concluded that:

$$w''(x) = -[M(x) + N_f(x)h_0]/EI_c \tag{14}$$

$$F(t) = \frac{\sum \tau_{fi} l_i}{\sum \tau_i l_i} = \frac{\sum [c_i + \sigma_i \tan\alpha_i] l_i}{\sum \tau_i l_i} = \frac{\sum \{c_i + [\sigma_{si} + \sigma_{di}] \tan\phi_i\} l_i}{\sum [\tau_{si} + \tau_{di}] l_o} \tag{15}$$

$$\sigma_{si} = -\frac{\sigma_{xs} + \sigma_{ys}}{2} + \frac{\sigma_{xs} - \sigma_{ys}}{2} \cos 2\alpha_i + \tau_{xys} \sin 2\alpha_i \tag{16}$$

$$\tau_{si} = \frac{\sigma_{xs} - \sigma_{ys}}{2} \sin 2\alpha_i - t_{xys} \cos 2\alpha_i \tag{17}$$

Compared to the overall beam structure, the composite surface of the double beam structure generates a certain amount of slip strain. The relative slip of the composite steel beam is an integral function of the slip strain. Combined with the boundary condition equation, the integral solution of the slip strain equation is obtained to obtain the theoretical model of the relative slip of the composite steel beam.

4 Model Experiment and Result Analysis

Under the action of horizontal loads, the composite steel beam bears the bending moment load at the end of the beam, and the double beam structure undergoes antisymmetric bending deformation. The flange of the laminated beam composite surface produces strain difference, which in turn leads to slip strain and relative slip mechanical behavior of the double beam composite surface. According to the horizontal loading test and finite element analysis results of modular steel structure composite beam column elements, the composite beam column elements mainly undergo local deformation and failure at the beam end of the double beam structure under horizontal loading. The relative sliding behavior of the laminated beams has a significant impact on the mechanical properties of the modular steel structure composite beam column elements. Therefore, the sliding of the composite surface has an important impact on the bearing characteristics of the reverse bending moment at the beam end of the double beam structure. The bending deformation of composite steel beams under horizontal loads is different from that under vertical loads, and the relative sliding mechanical behavior of floor beams and ceiling beams is also different. Based on a modular composite beam column element three-dimensional finite element model that verifies rationality, four key points are arranged at equal intervals on the laminated surface of the layer beams to obtain the relative sliding curve of the upper and lower double beam structure over the entire span under horizontal loads, Furthermore, the focus is on analyzing the development and distribution of slip on the double beam composite surface under horizontal loads.

The development curve of interlayer relative slip of laminated steel beams under horizontal load is shown in Figure 5. The mechanical behavior of relative sliding in the same direction is generated under the horizontal load

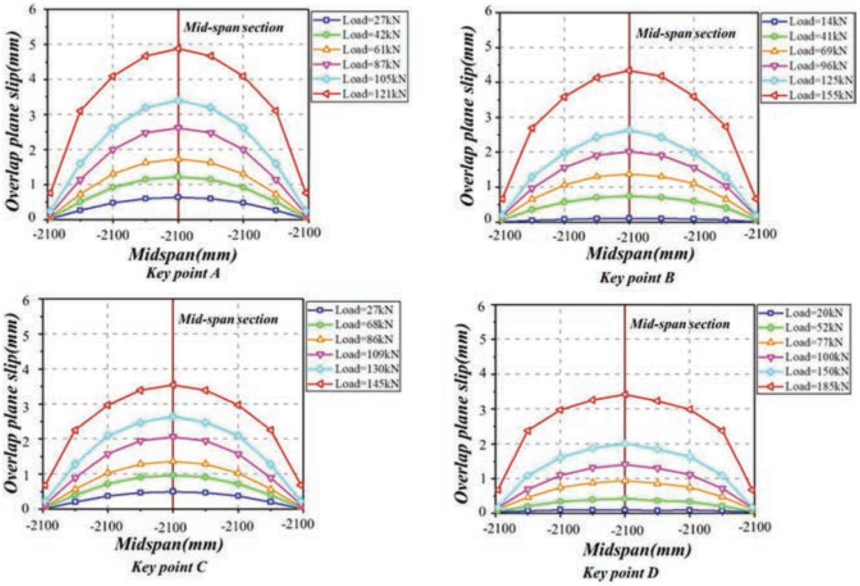


Figure 5 The slip curve of key points on the composite surface under horizontal load.

of the composite steel beam. The sliding curve of the composite surface defines the additional displacement in the horizontal loading direction of the floor beam relative to the ceiling beam as the positive sliding direction. Therefore, the sliding direction of the double beam structure is consistent with the horizontal loading direction throughout the entire span. For the distribution of slip on the overlapping surface, the relative slip curve shows a parabolic pattern throughout the span range, and the relative slip curves on the left and right half spans are symmetrically distributed. The relative slip of the double beam structure is most obvious at the mid span position, and the corresponding slip value is the peak point of the curve. In modular steel structure systems, the corner points of the upper and lower modules are connected by column column inserts, and the shear stiffness of the beam end is relatively high. Therefore, the beam end slip is the smallest in the slip curve of the composite surface, and the beam end slip remains basically 0 under horizontal loads. In the initial stage of horizontal loading, the relative sliding phenomenon of the composite steel beam is not obvious, and the sliding value of the composite surface is at a lower level. With the increase of horizontal load level, the increment of the sliding of the composite surface increases, and the amplitude of the sliding of the composite surface gradually increases accordingly. For modular steel structure pure friction composite beam column units MSF-LFCB-C and MSF-LFFB-C, there is no composite surface load between the floor beam and ceiling beam under horizontal load, and the double beam structure undergoes independent anti bending deformation. The shear slip stiffness of the composite surface is 0, so the composite surface slip increases rapidly with the increase of horizontal load level. When the composite beam column units MSF-LFCB-C and MSF-LFFB-C reach the ultimate load of 146 kN and 166 kN, There is a significant increase in the increment of slip on the overlapping surface, with the maximum slip at the mid span position of the double beam structure reaching 4.8 mm and 4.3 mm, respectively, as shown by key points A and B in the figure. The composite beam column elements MSF-LFCB-C-4B and MSF-LFFB-C-4B are connected by four high-strength bolts to strengthen the double beam flange overlap surface. The shear slip stiffness of the composite steel beam is significantly increased, and the degree of double beam overlap and structural integrity are significantly improved. Under the same horizontal load level, the relative slip amplitude of the mid span section of the double beam structure is significantly reduced. When the horizontal loads reach the failure loads of 160 kN and 185 kN for the composite beam column model, the relative slip increment of the laminated beam is significantly increased, and the mid span slip amplitudes of the composite surface reach 3.5 mm and 3.4 mm, as shown in key points C and D in the figure.

When the sliding distance is small, there is a slight change in the contact position between the suspension bridge structure and the foundation, and elastic recovery occurs. In this case, the slip curve exhibits a linear relationship and a relatively small slope. As the sliding distance increases, the contact position of the suspension bridge structure begins to undergo significant changes and gradually tends towards a stable state. At this point, the slope of the slip curve gradually increases and reaches its maximum value within a certain range. As the sliding distance continues to increase, the contact position of the suspension bridge structure begins to show significant displacement, and the sliding curve also shows a non-linear relationship, gradually tending towards saturation.

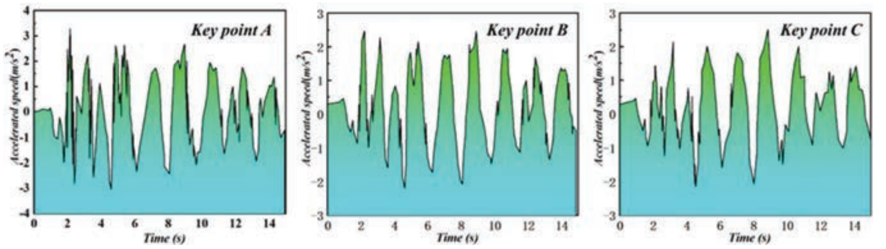
To verify the reliability and effectiveness of the seismic wave oblique incidence model theory in calculating dynamic stress in this article, ANSYS/ LS-DYNA was used to perform seismic explicit nonlinear dynamic analysis on rock slopes under the same model parameters. The dynamic stress at a point within the slope was calculated, and compared with the dynamic stress calculated through Matlab programming based on the seismic wave oblique incidence model theory.

The parameters of the structural theoretical model under oblique incidence of seismic waves are as follows: medium parameters, density 2000 kg/m^3, Elastic modulus $E = 5.454 \times 10^9 N.\ m^2$, Poisson's ratio $v = 0.25$; The finite element mesh size $Ax = Ay = 5$ m, with a time step of $\Delta t = 0.001$ s, an incident wave input model function, a duration of 0.15 s, and a calculation deadline of 0.5 s.

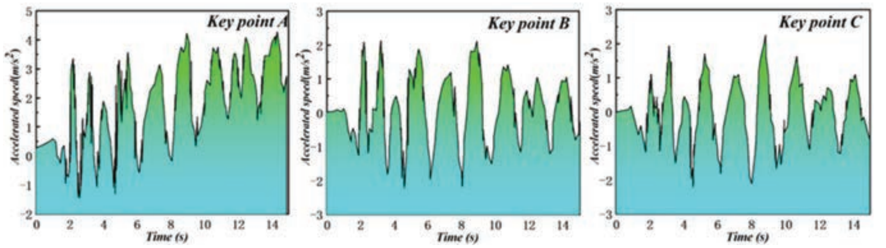
By utilizing the effect of seismic waves on the suspension bridge body, the time history curves of key points under two working conditions were obtained, as shown in Figure 6. Working condition one: seismic waves are P-waves; Condition 2: The seismic wave is an SV wave.

From Figure 6, it can be seen that by comparing the acceleration time history curves and peak acceleration sizes of the key nodes in the structure under the above two working conditions, it can be found that the peak acceleration size of the key nodes in each working condition changes with the position of the key points. As the depth of the soft soil interlayer deepens, the peak acceleration of the key nodes in the structure also decreases.

In the static and dynamic analysis of coupled vibration of suspension bridge structures under earthquake action, soil parameters are a key research object. The stiffness of soil directly affects the speed of seismic wave



a) Time history curves of key nodes under working conditions



b) Time history curves of key nodes under condition two

Figure 6 Time history curves of key points under different working conditions.

propagation and the energy transfer of vibration. The damping characteristics of soil directly affect the attenuation of seismic waves and the vibration response of structures. Different types of soil have different densities, humidity, and particle gaps, thereby affecting the propagation speed and attenuation characteristics of seismic waves. The thickness of the soil layer can affect the reflection and refraction of seismic waves in the soil, thereby altering the vibration response of the structure.

Figure 7 shows the range distribution of the maximum internal force and maximum displacement angle of the top and bottom plates of the structural characteristic points of the soil parameters around the suspension bridge under a single horizontal seismic action. As shown in the figure, among the four soil layer parameters shown, the variation of elastic modulus parameter has the most significant impact on the maximum axial force, maximum shear force, maximum bending moment, and maximum displacement angle of the top and bottom plates; The influence of the variation of Poisson's ratio on the maximum shear force is similar to that of cohesive force. Specifically, the variation of cohesion has a relatively small impact on the maximum axial force, maximum shear force, maximum bending moment, and maximum displacement angle of the top and bottom plates of the structure. This indicates

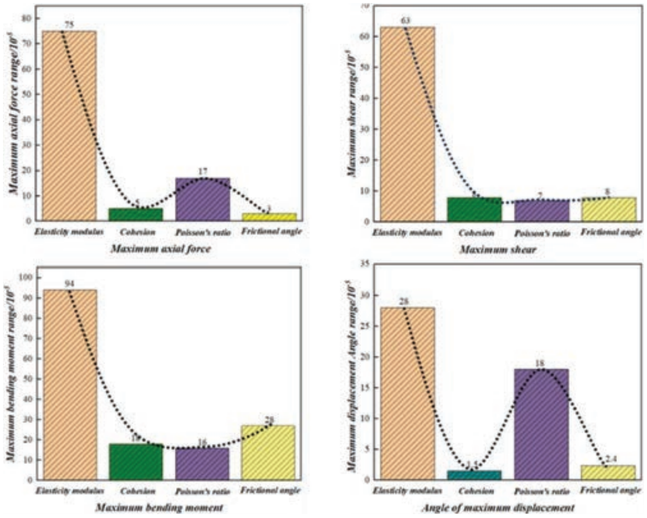


Figure 7 The structural dynamic response to changes in corresponding soil layer parameters is extremely poor.

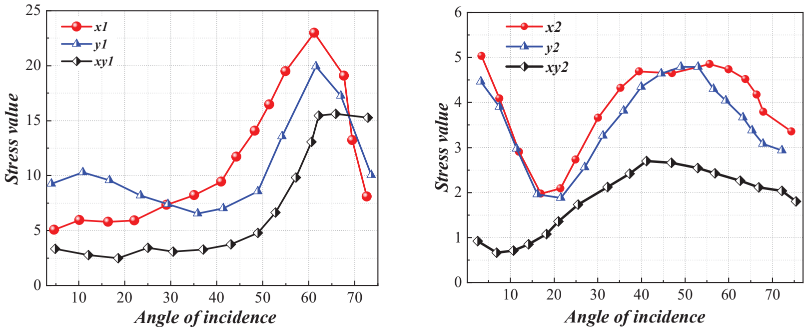


Figure 8 The variation of stress with incident angle.

that under a single horizontal seismic action, cohesion is the least sensitive parameter among the four parameters.

From Figure 8, it can be seen that when a seismic P-wave is incident at an angle of 60° and the slope angle gradually increases, the overall trend of stress change in the x-direction is to first gradually decrease, then increase and then decrease. Its minimum value appears at a slope angle of about 42°; The overall trend of stress change in the y direction is basically consistent with that in the x direction, and its minimum value appears at a slope angle of about 45°; The overall trend of stress variation in the xy direction is also basically consistent with that in the x direction, with its minimum value occurring at a slope angle of around 38°. The overall trend of the stress change of the maximum principal stress is also gradually decreasing, then gradually increasing, and then gradually decreasing. Its minimum value appears at a slope angle of about 42°; Its larger value occurs in the area with a slope angle of around 50° to 70°. The direction angle of the maximum principal stress within the range of slope angle of 35° to 48° is more consistent with the direction of the slope angle, making it more prone to sliding and cracking.

Computer algorithms have broad practicality in bridge structures and the field of bridges. It can assist engineers in structural design and optimization, evaluate seismic performance, conduct load and fatigue analysis, and conduct construction simulation and monitoring. By providing accurate and efficient analysis tools, computer algorithms can improve the design level and safety of bridge structures, and provide important support for the implementation and maintenance of bridge engineering.

5 Conclusions

Through this study, we have successfully conducted static and dynamic analysis of the coupled vibration of suspension bridge structures under earthquake action. We have achieved significant results in structural mechanics research using computer algorithms, providing important theoretical and practical value for seismic design and engineering practice of suspension bridges. At the same time, we have also provided feasible methods and technical routes for structural mechanics research based on computer algorithms. The following conclusions have been drawn:

(1) By establishing relevant models of the suspension bridge structure and considering the dynamic effects of seismic loads, efficient solutions for the stress, deformation, and vibration of the structure under seismic action have been achieved.

(2) Based on computer algorithms, the influence of seismic input on the response of suspension bridge structures was thoroughly studied, providing scientific basis for seismic design of structures. At the same time, multi-objective optimization algorithms were applied, combined with the static and dynamic characteristics of the structure, to seek the optimal structural form and parameter configuration, in order to improve the overall performance of the suspension bridge under earthquake action.

Future work will further deepen the research on the seismic response mechanism of suspension bridge structures, continuously improve the application of computer algorithms in this field, and provide more reliable support for engineering practice.

References

[1] M. H S P H E S G B S K A H R Á V F M P. Correction to: Deformation, seismicity, and monitoring response preceding and during the 2022 Fagradalsfjall eruption, Iceland[J]. Bulletin of Volcanology, 2023, 85(12).

[2] Taghi S. High-resolution seismic velocity structure using induced interevent interferometry at the geothermal sites, Geysers, Eastern California [J]. Geothermics, 2024, 116.

[3] Zihong Z G C X W. A three-dimensional numerical simulation method for seismic nonlinear response of underground structure in liquefiable site and analysis of structural damage[J]. Computers and Geotechnics, 2024, 165.

[4] M. M H W. Induced seismicity in the Groningen gas field – arrest of ruptures by fault plane irregularities[J]. Netherlands Journal of Geosciences, 2023, 102e11–e11.

[5] Xiang Y D B W H. Effect of earthquake-induced liquefaction of runout-path material on the movement of landslide[J]. Environmental Earth Sciences, 2023, 82(23).

[6] Xiangjun M Z Z. Statistical inference for mixed jump processes by Markov switching model with application to identify seismicity levels[J]. Physica A: Statistical Mechanics and its Applications, 2023, 632(P1).

[7] Min G X H Z D J F P. Seismic response analysis of connected dual-tower isolated structure under three-dimensional earthquakes[J]. Ain Shams Engineering Journal, 2023, 14(11).

[8] Ghlamallah G L C N. Soil-Structure Interaction and Near Fault Pulse-like Earthquakes Effects on Seismic Responses of Isolated Bridges[J]. International Journal of Structural and Civil Engineering Research, 2023, 12(4).

[9] Limin Y X Z A W. All-Weather Thermal Simulation Methods for Concrete Maglev Bridge Based on Structural and Meteorological Monitoring Data[J]. Sensors, 2021, 21(17): 5789–5789.

[10] Walter G G M M A C F F. “Himalayan Bridge”: A New Unstable Suspended Bridge to Investigate Rodents’ Venturesome Behavior#13;[J]. Frontiers in Behavioral Neuroscience, 2021, 15637074–637074.

[11] Chun B Z J H B F. Condition evaluation for through and half-through arch bridges considering robustness of suspended deck systems[J]. Advances in Structural Engineering, 2021, 24(5):962–976.

[12] Hui H X H W D D. Coupled vibration of an annular plate-cylindrical drum structure with material-nonlinearity damping patches considering position-mistuned and stiffness-mistuned connections[J]. Composite Structures, 2023, 321.

[13] Y.H. C J X C. Coupling vibration of composite pipe-in-pipe structure subjected to gas-liquid mixed transport by means of green’s functions[J]. Mechanics of Advanced Materials and Structures, 2023, 30(8):1604–1623.

[14] Zhibing A M Z T T G L T. A hybrid analytic–numerical formulation for the vibration analysis of a cylindrical shell coupled with an internal flexural floor structure[J]. Thin-Walled Structures, 2023, 183.

[15] Science – Mechanical Science; Report Summarizes Mechanical Science Study Findings from Northeastern University (Coupling Vibration Behaviors of Drum-disk-shaft Structures With Elastic Connection)[J]. Journal of Technology, 2019.

[16] S S T M H. Design and analysis of newly developed two-wheeler shock absorber helical spring[J]. Journal of Physics: Conference Series, 2023, 2601(1).

[17] Velauthapillai M B R W M N S H. In-Silico Prediction of Mechanical Behaviour of Uniform Gyroid Scaffolds Affected by Its Design Parameters for Bone Tissue Engineering Applications[J]. Computation, 2023, 11(9).

[18] Muammer R Y M U Z A R F M Z A. Design and development of a low-cost 5-DOF robotic arm for lightweight material handling and sorting applications: A case study for small manufacturing industries of Pakistan[J]. Results in Engineering, 2023, 19.

[19] Pinto C M C. A novel generalized sandwich-type replacement beam for static analysis of tall buildings: Inclusion of local shear deformation of walls[J]. Thin-Walled Structures, 2023, 190.

[20] Senthur S K P N A M. Investigation on Performance Evaluation and Thermal and Structural Analysis of Steam Turbine Blades[J]. Electrochemical Society Transactions, 2022, 107(1).

[21] Naushad A M A A A C. Coupled thermal and structural analysis of disc brake rotor with varying angle of rotation of ventilation holes[J]. Materials Today: Proceedings, 2022, 56(P2):834–844.

[22] Arun B V P S J. Computational design and structure dynamics analysis of bifunctional chimera of endoxylanase from Clostridium thermocellum and xylosidase from Bacteroides ovatus[J]. 3 Biotech, 2023, 13(2):59–59.

[23] Zhao L M H Y H. Dynamic Analysis of a Large Deployable Space Truss Structure Considering Semi-Rigid Joints[J]. Aerospace, 2023, 10(9).

[24] Angshuman S B. Analysis of the structural dynamics of the mutations in the kinase domain of PINK1 protein associated with Parkinson's disease[J]. Gene, 2023, 857147183–147183.

[25] Yanda W H L Z Q L. Machine learning prediction of structural dynamic responses using graph neural networks[J]. Computers and Structures, 2023, 289.

[26] S P S M A V V N N. Analysis of the Operation of Kinematic Seismically Isolated Foundations Taking into Account the Vertical Component of the Seismic Impact[J]. IOP Conference Series: Earth and Environmental Science, 2022, 988(5).

[27] M C Y W T G M A R L S. Can Artificial Intelligence Aid Diagnosis by Teleguided Point-of-Care Ultrasound? A Pilot Study for Evaluating a Novel Computer Algorithm for COVID-19 Diagnosis Using Lung Ultrasound.[J]. AI (Basel, Switzerland), 2023, 4(4):875–887.

[28] Costa J S C A O P E P. A rapid literature review on ensemble algorithms for COVID-19 classification using image-based exams[J]. International Journal of Hybrid Intelligent Systems, 2023, 19(3,4):129–143.

[29] L C M M W J L. Computer algorithms infer gender, race and ethnicity. Here's how to avoid their pitfalls[J]. Nature, 2023.

[30] Peng H Y Q Z. Machine learning-based processing of unbalanced data sets for computer algorithms[J]. Open Computer Science, 2023, 13(1).

[31] Fabio G S M E L D M. ENRICH: Multi-purposE dataset for beNchmaRking In Computer vision and pHotogrammetry[J]. ISPRS Journal of Photogrammetry and Remote Sensing, 2023, 19884–98.

[32] Yemin Y L W Y L W Z T K. A Digital Timing-Mismatch Calibration Technique for Time-Interleaved ADCs Based on a Coordinate Rotational Digital Computer Algorithm[J]. Electronics, 2023, 12(6):1319–1319.

Biographies

Xu XiaoJian received the Master's degree from Beijing University of Technology. Now, he works in Zhongzi Highway Maintenance & Test Technology Co., Ltd, under the jurisdiction of China Highway Engineering Consulting Corporation. His research field is bridge and tunnel inspection, maintenance and reinforcement.

Xin GuangTao received the Master's degree from Beijing University of Technology. Now, he works in CHECC DATA Co., Ltd, under the jurisdiction of China Highway Engineering Consulting Corporation. His research field is Structural Engineering and Transportation Informatization.

Zhao Jian received the Bachelor degree from Yanshan University. Now, he works in Zhongzi Highway Maintenance & Test Technology Co., Ltd, under the jurisdiction of China Highway Engineering Consulting Corporation. His research field is Steel structure and bridge structure.

Chen Yu received the Master's degree from Northeast Forestry University. Now, he works in Zhongzi Highway Maintenance & Test Technology Co., Ltd, under the jurisdiction of China Highway Engineering Consulting Corporation. His research field is Steel structure and bridge structure.