Frictional Slip and Incremental Dynamic Analysis of Plate-rubber Bearing Continuous Girder Bridge by Ambient Temperature in Cold Region

Jiang Hongwei[1,2], Qiao Wei[1,2], Xu Xiaojian[1,2,*]
and Xin Guangtao[1,3]

[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 20 January 2024; Accepted 26 February 2024;
Publication 29 March 2024

Abstract

Special mechanical environment, the environmental temperature or stress transformation easily to the final mechanical properties of the bridge components performance changes. The impact of the cold zone environment on the plate rubber-bearing beams is the object of study, Jining Road refined mechanics finite element analysis of the structural dynamic response study under seismic action. The results show that low temperature leads to bearing friction slip and material parameter changes, which affects the self-oscillation frequency and seismic susceptibility of the bridge. Due to the temperature-induced changes in the material properties and mechanical properties of the bearings, the first principal period of the bridge increases by 3% at high temperature for the EH and decreases by 19% at low temperature for the EL when compared to the first principal period under normal temperature conditions.

European Journal of Computational Mechanics, Vol. 33_1, 51–70.
doi: 10.13052/ejcm2642-2085.3313

Under different extreme temperature conditions, the fundamental period of the bridge is longitudinal, and the effective mode vibration participation mass is more than 90%. The maximum crossover frequency VAL_{max} reaches 75.6 dB. Compared with room temperature, the bearing stress increased by 27.6% to 45.5%. The effect of EL stress change should be considered in the design of bridges in the alpine region.

Keywords: Ambient temperature-stress, plate-rubber bearing, frictional slip, continuous girder bridge, incremental dynamic analysis, seismic vulnerability.

1 Introduction

With the advancement of the strategy of forming a new pattern of Western development in the new era, the construction of transportation infrastructure in Qinghai and Tibet, which are located in seismically active zones and high alpine areas, is progressing rapidly. Due to the large temperature difference between day and night in this region, the ambient temperature easily causes changes in the mechanical properties of bridge structural members [1], which has a non-negligible impact on the seismic performance of bridge structures. At present, scholars at home and abroad for plate-rubber bearing in different ambient temperatures equivalent stiffness, yield force, compressive strength, friction slip performance, and damping characteristics [2, 3] and other parameters carried out a lot of useful research, systematically explore the correlation between the above parameters and ambient temperature. In addition, Wang Li et al. [4], Deng et al. [5], and Du Xinlong et al. [6] analyzed seismic isolation girder bridges at different ambient temperatures by numerical simulation methods. The specification stipulates that when using the vibration isolation device in an environment below 0°C, in addition to seismic analysis and calculation of mechanical properties at room temperature, the vibration isolation device should also be studied Li et al. [7–10] showed that the change in the modulus of elasticity of concrete under the action of temperature is a key factor in the change of the dynamic characteristics of the bridge. The model specifically considers the behavior of concrete under the influence of peripheral pressures (e.g., confining stresses provided by the hoop reinforcement) and temperature. The Mander model provides a way to predict the stress-strain response of concrete under different conditions, which is important for the analysis and design of bridges and other concrete structures. Du Yongfeng et al. [11] measured and theoretical analysis of an ultra-long and complex seismic isolation structure, which showed that the ambient temperature caused by the change in the stiffness of the isolation support The modal frequency of the seismic isolation structure changes; Xu Yongji et al. [12] found that the structural stiffness changes with the change of ambient temperature, resulting in a negative correlation between the self-oscillation frequency of the structure and the change of temperature, and so on. In addition, according to domestic and foreign scholars' investigations and studies on many earthquake damages [13], the earthquake damages that occurred at low temperatures in winter are more serious, and the damage degree of the structure may be related to the influence of temperature. However, at present, there are more investigations related to the mechanical performance parameters of bridge bearings, while there are fewer studies related to the effect of changes in the mechanical parameters of concrete bridge piers on the seismic performance of the structure under the influence of temperature in the cold zone.

The purpose of this study is to investigate in depth the seismic performance of a double-link (3*30 m) continuous concrete box girder with plate rubber bearings under the environment of alpine region. An accurate nonlinear finite element analysis model is established by considering the influence of cold climate on the material properties and the specific material parameters of plate rubber bearing and bridge abutment concrete. On this basis, the seismic sensitivity of the plate rubber bearing is analyzed in depth using the incremental dynamics (I-DA) analysis method, with a view to revealing its mechanical behavior and performance changes under seismic action. The IDA method evaluates the performance of bridges under different seismic levels by gradually increasing the intensity of ground shaking. In this study, the method is effective in modeling the effects of ambient temperature changes on the material properties and seismic response of bridges, but the limitation is that it fails to fully account for the uncertainty of ground shaking and the complexity of nonlinear dynamic response. Nevertheless, the IDA method provides a powerful tool for evaluating the seismic vulnerability of bridges. Ultimately, it will provide scientific basis and practical suggestions for the seismic design of similar bridges in cold regions, and guarantee the safe and stable operation of bridges in extreme environments.

2 Mechanical Calculation Model

This bridge is a continuous girder bridge for Qinghai Province – a highway, adopting double-column type rectangular – piers and pile type foundation joint – bearing platform foundation. The bearing position adopts a plate-type rubber bearing. The bridge site is located in a cold area such as a plateau, where the extreme high and low temperatures are 40°C and −40°C respectively. MAT-civil-software is used to establish a refined M-finite element model of the whole bridge to simulate the lateral-type restrained stiffness of the main girders, bridge-type piers, constrained and unconstrained concrete, main-bars and pile-foundations. The peak friction class slip performance of plate rubber bearings under seismic action is simulated using a bilinear meander model. The results of the study show that extreme temperature and seismic type have a significant effect on the bridge structure, and the effect of a low-temperature environment on the seismic performance of the bridge's main soil needs to be fully considered.

The structural mechanics of the bridge analytical relationship and structural finite element schematic are shown in Figure 1. The pile-soil nonlinear mechanical relationship of the bearing platform and the mechanical model of the plate-rubber bearing are shown in Figure 2. During the modeling process, an accurate geometric model is created based on the actual size and geometry of the bridge, and key components such as abutments, bridge deck system, and plate rubber bearings are considered. In terms of material properties, nonlinear parameters were selected, and key parameters such as modulus of elasticity, Poisson's ratio, and coefficient of thermal expansion of concrete and rubber materials at different temperatures were defined based on experimental data. Finally, by verifying the convergence and accuracy of the model, a finite element model that can reflect the nonlinear behavior of actual bridges at different ambient temperatures can be obtained.

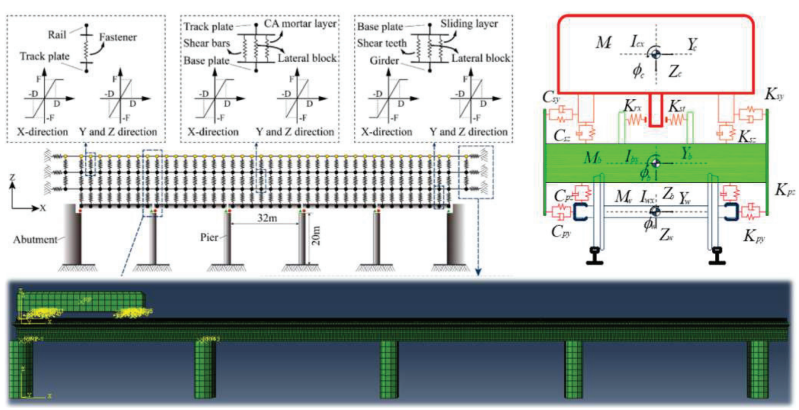

Figure 1 Structural mechanical relationships and finite element models of bridges.

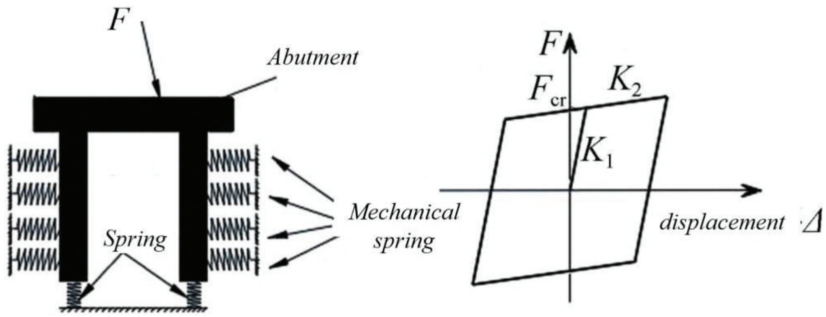

Figure 2 Pile-soil nonlinear mechanical relationship and mechanical modeling of plate-rubber bearing.

The bearing unit is isotropic and flat sliding horizontally, and the shear stiffness K1 of all plate-rubber bearings on a single pier is before the bearing shear reaches the critical sliding force Fe:

$$K_1 = \frac{nG_{\mathrm{d}}A_{\mathrm{r}}}{\sum t} \tag{1}$$

Where: A and Σt are plate-rubber bearing shear area (m^2); n is a single pier on the plate-rubber; the number of bearings. Critical sliding force Fer for the critical bearing sliding support shear force, according to the formula (2) calculation:

$$F_{\mathrm{cr}} = \mu N \tag{2}$$

Where: N is the bearing reaction force; p is the bearing sliding friction coefficient, taken as 0.02 [16]; after the bearing sliding, the bearing shear stiffness K2 is almost 0, and the stiffness ratio after yielding is taken as 0.001 [17].

Bearing unit vertical for compression line elasticity, that is, bearing unit contact reaction force in tension, bearing stiffness is 0; compression, single pier on the plate-rubber bearing total vertical stiffness is:

$$k_{\mathrm{v}} = \frac{nE_{\mathrm{b}}^{\mathrm{c}}A_{\mathrm{r}}}{\sum t} \tag{3}$$

Where: Es, A, and Σt are the vertical compressive-modulus of elasticity of plate-rubber bearing (kPa), shear area (m^2), and the rubber layer sum thickness (m), respectively; n is the number of plate-rubber bearings on a single pier. According to "plate-rubber Bearing for Highway Bridges (JTT4-2019)" [18], the vertical compressive-modulus of elasticity Et and the shape factor S of circular plate-rubber bearing, respectively, are:

$$E_{\mathrm{b}}^{\mathrm{c}} = 5.4 G_{\mathrm{d}} S_{\mathrm{b}}^{2}$$
$$S_{\mathrm{b}} = \frac{d_0}{4t_1} \tag{4}$$

The bearing unit is isotropic and flat sliding horizontally, and before the bearing shear reaches the critical sliding force Fe, the shear stiffness of all plate-rubber bearings on a single pier K!

$$K_1 = \frac{nG_{\mathrm{d}} A_{\mathrm{r}}}{\sum t} \tag{5}$$

A gap unit is used to simulate the collision effects between bridge superstructures and between them and the abutments. The collision unit is simulated using a linear spring model, and the stiffness of the spring is activated when the relative distance between the nodes at the ends of the spring is reduced by an amount greater than the input initial gap.

3 Mechanical Parameter Correction

To study the effect of temperature on the properties of concrete materials, nine 150 mm * 200 mm * 350 mm concrete prismatic specimens were subjected to different temperatures (40°C, 20°C, −40°C).

Under the axial compressive test, the-specimens were grouped as A1–A3. The key mechanical parameters such as concrete strength, modulus of elasticity, and peak strain of each specimen at different CONDs were obtained, as listed in Table 2. The Mander model was used for the mechanical constitutive relationship of concrete, and since the compressive strength of concrete in this model is the compressive strength of the cylinder, it is necessary to multiply the strength of concrete tested in this paper by a correction factor of 0.85. Someone [19] showed that the mechanical properties had little correlation with temperature compared with room temperature (20°C). Eventually, the mechanical properties temperatures are taken as listed in Table 1.

Key Mechanical Parameters for Each group of Specimen as shown in Figure 3, which correspond to 40°C-unrestrained concrete, 40°C-restrained concrete, 20°C-unrestrained concrete, 20°C-restrained concrete, −40°C-unrestrained concrete, −40°C-restrained concrete, and −40°C-restrained concrete for six working conditions, respectively. concrete, −40°C-unrestrained concrete, −40°C-restrained concrete, −40°C-concrete.

Table 1 Key mechanical parameters for each group of specimens

Groups	Temperature T/C°	Strength Class	Peak Stress f/MPa	Peak Strain/u	Modulus of Elasticity/GPA
A1	40	C-40	39.73	3.125	42.55
A2	20	C-40	40.75	3021	43.87
A3	−40	C-40	47.47	1715	49.99

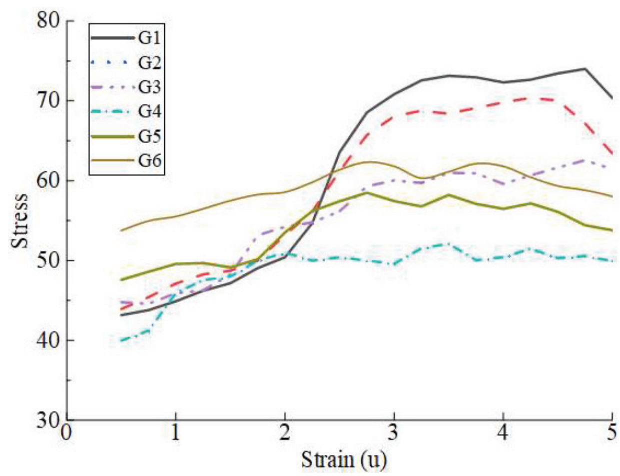

Figure 3 Theoretical stress-strain curve for concrete.

Table 2 Key mechanical parameters for each group of specimens

Groups	40°C	20°C	−40°C
Temperature coefficient γ	0.943 2	1.009 2	1.609 8
Shear modulus g/MPa	0.943 2	1.009 2	1.609 8
compressive-modulus of elasticity E/MPa	618.57	655.82	1 055.74
Vertical stiffness K,/(X106 kN/m)	2.10	2.23	3.59
Initial stiffness Ki/(kN/m)	3 232.88	3 427.56	5517.69
Characteristic strength Fe/kN	82.36	87.32	140.57
Stiffness ratio after yielding r	0.001	0.001	0.001

The shear modulus of the plate-rubber bearing will change with the temperature change. For the relationship between the change of plate-rubber bearing performance with temperature, Zhuang Junsheng [21] conducted mechanical property tests, respectively. Due to the limitation of space, only the mechanical performance GYZ 800 mm–148 mm at different temperatures is listed, as listed in Table 2.

Considering the effect of beam displacement on the spacing of expansion joints caused by extreme temperature in the cold region, the spacing of expansion joints at the end of the beam at room temperature (20°C) is 80 mm as the initial state, and the spacing of expansion joints at extreme-low (EL) temperature (40°C) and extreme-high(EH) temperature (40°C) are calculated to be 111.4 mm and 67.2 mm, respectively. In the test, standardized test methods and procedures were adopted, including sample preparation, temperature control, loading rate setting, etc., all in accordance with relevant standards and specifications. Meanwhile, all the equipment and materials used for the test have been strictly calibrated and inspected to ensure their accuracy and reliability

4 Input of Excitation Force

Selection of suitable seismic waves as excitation is a prerequisite for seismic susceptibility analysis of bridge structures [15], therefore, 10 seismic records with spectral characteristics closer to the response spectrum at the R-bridge were selected as excitation from the database of the U.S. Pacific Earthquake Engineering Research Center. The seismic acceleration response spectra are shown in Figure 4.

For the structural analysis based on IDAM, Peak ground Acceleration (P-GA) is used as the ground shaking intensity parameter, and each seismic wave is amplitude-modulated 10 times, with the peak acceleration increasing by 0.1 g from 0.1 g to 1.0 g, for a total of 100 seismic-waves in total after the adjustment, and the seismic response of the bridge members is calculated by inputting the model along the longitudinal bridge direction. response along the longitudinal direction of the bridge and plot the susceptibility curves. Through the eigenvalue analysis, it is found that under the extreme temperature (40°C, 20°C, −40°C) conditions, the first principal period of the bridge is T1.40 = 2.40 s, T1.20 = 2.33 s and T1.−40 = 1.88 s. Due to the

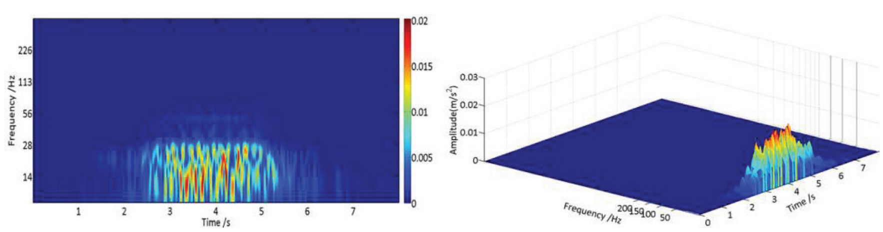

Figure 4 Seismic excitation schematic.

Table 3 Mechanical calculation working conditions

Working Condition	Temperature/°C	Piers	Plate-rubber Bearing
1	Normal-temperature (20)	clogged	clogged
2	Extreme heat (40)	clogged	be
3	Extreme heat (40)	be	be
4	Extreme cold (I-40)	clogged	clogged
5	Extreme cold (I-40)	be	be

temperature-induced changes in the concrete material properties and mechanical properties of the bearings, compared with the first principal period under the ambient conditions, it is increased by 3% in the Case_of extreme-high (EH) temperature, and decreased by 19% in the Case_of extreme-low (EL) temperature, while the first principal period in the Case_of extreme-low (EL) temperature, increased by 3%, and decreased by 19% in the Case_of extreme-low (EL) temperature. Compared with the first main cycle at room temperature, it increases by 3% at extreme-high (EH) temperature and decreases by 19% at extreme-low (EL) temperature, which indicates that the self-resonance period of the structure increases with temperature, i.e., the self-resonance frequency of the structure decreases with the increase of temperature. The fundamental period of the bridge is longitudinal at different extreme temperatures, and the effective modal vibration mode participation mass is more than 90%. Mechanical calculation working conditions are in Table 3.

5 Mechanical Response of Bridges

As can be seen in Figure 5: When bearing, comparing Case_1, Case_3, and Case_5, it can be found that due to the change in ambient temperature caused by changes in the stiffness of the bridge connection in the upper inertia force, making the low-temperature conditions of the pier-top displacement is significantly larger than the normal-temperature and high-temperature conditions; extreme-low (EL) temperature (Case_5) when the pier-top displacement of the maximum increase of 26.8% compared with normal-temperature (Case_1), while extreme-high(EH) temperature (Case_3) when the pier-top displacement of the maximum reduction of 10.4% compared with normal-temperature. In extreme-low (EL) temperature (Case_5), the displacement of the top of the pier increases by 26.8% compared to normal-temperature (Case_1), while in extreme-high(EH) temperature (Case_3), the displacement of the top of the pier decreases by 10.4% compared to normal-temperature.

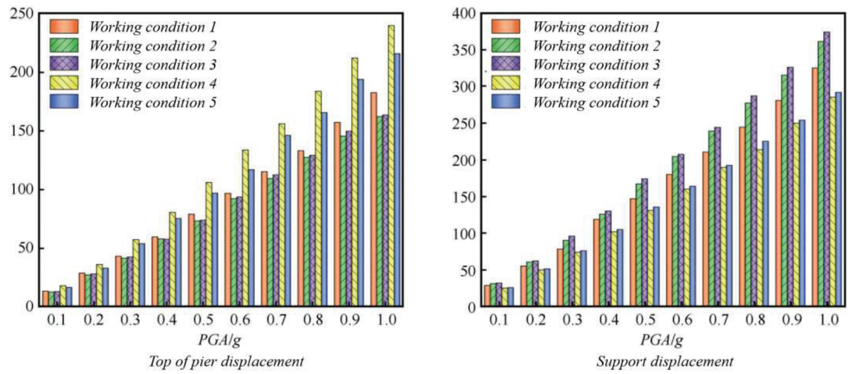

Figure 5 Mechanical response of bridges subjected to seismic excitations.

Similarly, compared with the ambient environment, extreme-high(EH) temperature (Case_3) when the maximum peak displacement of the bearing increased by 19.4%, while in extreme-low (EL) temperature (Case_5) when the maximum reduction of 11.2%, this is due to the rubber bearing shear stiffness with the reduction of temperature and gradually increase, bearing deformation capacity weakened. In the extreme low-temperature environment, comparing Case_4 and Case_5, it can be found that the effect of the low-temperature environment on the performance of the concrete material makes the displacement of the top of the pier in Case_5 decrease by 12.6% compared with Case_4, and the displacement of the bearing in Case_5 increase by 5.4% compared with Case_4. To summarize, the ambient temperature under seismic action is negatively correlated with the displacement of the pier-top, while positively correlated with the peak displacement of the bearing. This result is precisely due to the stiffness-damped mass properties and modal characteristics of the bridge.

Bridge driving excitation based on time-frequency analysis of the dominant frequency band, this paper selected 13 Hz, 23 Hz, 30 Hz, 39 Hz, 57 Hz, and 75 Hz six frequencies, analyzed a single frequency acceleration amplitude in the bridge and the ground isometric out of the spatial distribution of the acceleration response, the results are shown in Figure 6. It can be seen that the amplitude of each frequency with the increase of the measurement point from the spatial location of the load excitation point of action of the overall fluctuation attenuation trend. The bridge structure shows a resonant frequency of 57 Hz. The acceleration amplitude of the ground measurement point 30 m away from the bridge abutment increases slowly at multiple single frequencies.

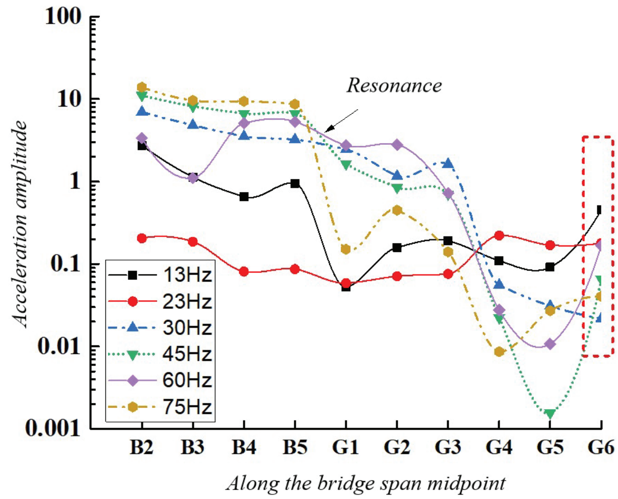

Figure 6 Acceleration responses with exciting forces.

In addition, after analyzing the vibration after the coupled excitation, it can be seen that the vibration response at different ground locations shows a more consistent frequency, and this condition is reflected in the acceleration peaks around 63–100 Hz. The crossover frequency VALmax of the ground measurement points g_1, g_2, g_3, g_4, g_5, and g6 are 75.6 dB (80 Hz), 73.3 dB (63 Hz), 70.0 dB (63 Hz), 50.2 dB (80 Hz), 51.3 dB (100 Hz) and 55.5 B (100 Hz) in Figure 7.

6 Effect of Temperature Forces on Bridge Susceptibility

Hwang et al. [22] defined the damage of bridges as five states, which are: based on the deformation damage criterion, the damage states and damage indexes of bridge abutments and plate-rubber bearings at different temperatures under seismic action are defined sequentially. and then the displacement ductility ratio of abutments can be calculated based on the plastic hinge theory. According to the above specification content, while referring to the literature [25–27], the ratio $\mu 2$ of the allowable relative displacement of each limit state support to the relative displacement at shear strain y $=$ 100% is used to determine its corresponding 4 damage states, i.e.:

$$\mu_z = \frac{\delta_z}{\delta_1} \tag{6}$$

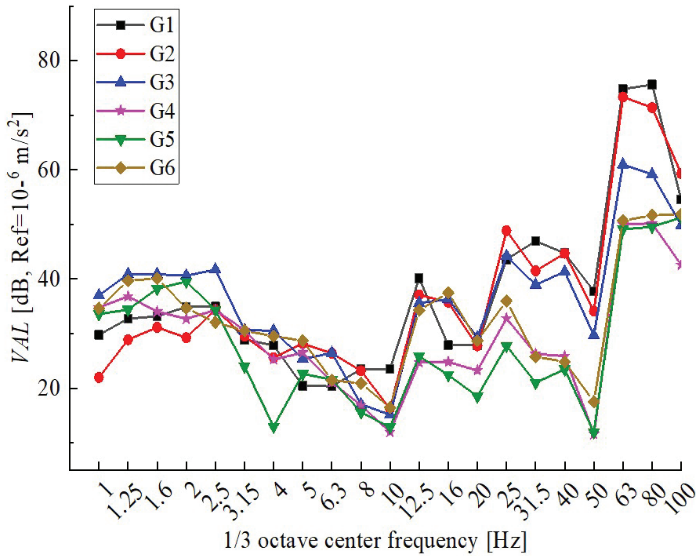

Figure 7 Z-weighted crossover frequency levels of bridges with exciting forces.

According to the definition of the bearing damage state obtained support at $-40°$C when the damage index; through the support in the high-temperature displacement response calculation found that the support in 40°C displacement value compared to room temperature increased by 19.4%, so according to the definition of the bearing damage state, the support in 40°C when the damage index.

PgA is selected as the ground shaking intensity parameter, and it is assumed that the relationship between the mean structural seismic response a and PgA obeys an exponential relationship, and the following relationship exists:

$$\ln \tilde{\mu}_{\mathrm{d}} = a + b \ln(PGA) \tag{7}$$

As can be seen from Figure 8, the seismic damage of the bridge system at extreme-low (EL) temperature is generally greater than that at room temperature and extreme-high (EH) temperature. When the effects of extreme temperature on the concrete material properties and bearing stiffness of the bridge abutment are also considered, under the E1 seismic action, from slight damage to complete damage, the damage probability of the bridge at extreme-high (EH) temperature (Case_3) decreases by 6.7%, 16.9%, 22.2%, and 20.0%, respectively, compared with that of room temperature (Case_1); whereas, under the E2 seismic-action, the damage probability of the bridge

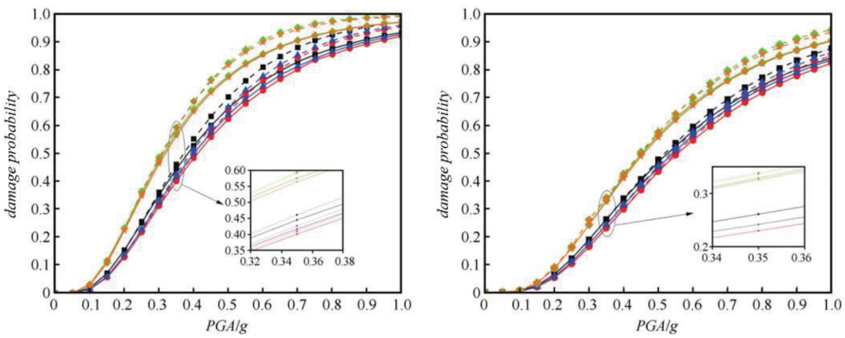

Figure 8 Damage probability for different temperature conditions.

at extreme-low (EL) temperature (Case_5) increases by 2.6%, 8.0%, 27.2%, and 26.8%, respectively, compared with that at room temperature. increased by 2.6%, 8.5%, 27.5%, and 26.8%, respectively, compared with the normal temperature. When only considering the effect of extreme temperature on the mechanical properties of rubber bearings, under the action of the E2 earthquake, comparing Case_1, Case_2 and Case_4, it can be found that the damage probability of the bridge system in completely damaged state under the action of Case_2 is reduced by 12.0% compared with Case_1, and the damage probability of the bridge system in severely damaged state under the action of Case_4 is increased by 29.2% compared with Case_1. Under extreme-low (EL) temperature conditions, comparing Case_4 and Case_5, it can be found that the damage probability of slight damage and moderate damage of the bridge under Case_5 is increased by 10.4% and 14.3% respectively, i.e., the damage probability of the bridge will be underestimated by 14.3% according to the structural design of the Code [2, 25]; since the effects of Case_4 and Case_5 on the bridge abutment in the state of severe and complete damage are more significant than that of the bearing, the difference in the effects on the bridge system under Case_4 is more significant than that of the bearing. Because the difference between the effects of Case_4 and Case_5 on the bridge abutments in the severe and complete damage states is more significant than that of the bearings, the damage probability of the bridge system in the severe and complete damage states under Case_4 is greater than that of Case_5, with a maximum increase of 3.5% and 1.3%, respectively. The application of bridge dynamic damage studies at different temperatures is promising, especially in extreme climates and complex engineering environments. However, the bottleneck lies in the uncertainty of material properties with temperature and the complex dynamic response mechanisms. It is recommended to strengthen interdisciplinary cooperation to study the temperature dependence of material properties, develop advanced monitoring and assessment techniques, and consider the dynamic behavior of bridges under multi-factor coupling to promote research progress and applications in this field.

7 Conclusion and Discussion

Special mechanical environment, the environmental temperature or stress transformation easily to the final mechanical properties of the bridge components performance changes. In this paper, the cold zone environment on the plate rubber-bearing beam is the object of study, Jining Road refined mechanics finite element analysis under the seismic action of the structure dynamic response study. The results show that:

(1) Low temperature leads to bearing friction slip and material parameter changes, which affects the self-oscillation frequency and seismic susceptibility of the bridge. The first principal cycles of the bridges are T1.40 = 2.40 s, T1.20 = 2.33 s, and T1-40=1.88 s. Due to the temperature-induced changes in material properties and mechanical properties of the bearings, the EH increases by 3% at high temperatures and decreases by 19% at low temperatures of the EL when compared with the first principal cycle at room temperature conditions.
(2) Under different extreme temperature conditions, the basic cycle of the bridge is longitudinal, and the effective mode vibration participation mass is more than 90%. The amplitude of each frequency under the coupled excitation shows a fluctuating attenuation trend with the increase of the spatial position of the measurement point from the load excitation point, and the maximum crossover frequency VALmax reaches 75.6 dB.
(3) Compared with room temperature, the bearing stresses in the extreme mechanical environment increased by 27.5% to 45.0%. The effect of EL stress change needs to be considered in the design of bridges in alpine regions.

The limitations of the results in this paper for practical applications are mainly in the simplified treatment of ground vibration uncertainty and the complexity of nonlinear dynamic response. In addition, the selection and calibration of model parameters may also have an impact on the accuracy of the results. In order to improve these findings, future studies may consider adopting more advanced ground shaking models to capture the uncertainty of ground shaking more comprehensively, as well as introducing more refined bridge models to simulate the nonlinear dynamic response of bridges more accurately. In addition, the reliability and applicability of the results can also be improved by comparing and validating them with other research methods and experimental data. These improvements will help to more accurately assess the seismic susceptibility of bridges at different ambient temperatures and provide a more scientific basis for the seismic design of bridges.

References

[1] Chen Bo, Zheng Jin, Wang Jianping. State-of-the-art of the temperature effects of bridges[J]. State-of-the-art of the temperature effects of bridges[J].
[2] Zhang R J, Li A Q. Experimental study on temperature dependence of mechanical properties of scaled high-performance rubber bearings[J]. Composites Part B: Engineering, 2020, 190:107932.
[3] Li Yue, Ji Mengwei, Li Chong. Influence of environmental temperature on the frictional sliding performance of plate-rubber bearings[J]. China Earthquake Engineering Journal, 2021, 43(3):672–678.
[4] Wang Li, Yu Lusong, Liu Shizhong, et al. Influence of extreme temperature on seismic response of continuous girder bridges in alpine and high-intensity zone[J]. Bridge Construction, 2022, 52(2):89–96.
[5] Deng PR, Gan ZP, Hayashikawa T, et al. Seismic response of highway viaducts equipped with lead-rubber bearings under low temperatures [J]. Engineering Structures, 2020, 209:110008.
[6] Du Xinlong, Yu Lusong, Wang Li, et al. Study on the influence of extreme temperature on seismic response of continuous girder bridge with laminated rubber bearing[J]. Journal of Safety Science and Technology, 2022, 18(10):210–215.
[7] Ministry of Transport of the People's Republic of China. Specifications for seismic design of highway bridges: JTg/T 2231-01-2020[S]. Beijing: China Communications Press, 2020.
[8] Xie Jian, Li Xiaomei, Wu Honghai. Experimental study on axial compression performance of concrete confined by stirrups at cryogenic temperatures [J]. Engineering Mechanics, 2014, 31(S1):103–108.
[9] Li Xiang, Xie Jian, Wu Honghai. Experimental research on the constitutive relationship of concrete in a cryogenic environment[J]. Engineering Mechanics, 2014, 31(Suppl01):195–200.

[10] Wang Li, Liu Shizhong, Ding Wanpeng, et al. Dynamic characterization of a new type of corrugated steel web combined box girder considering time-varying temperature effects[J]. Vibration and Shock, 2021, 40(4):58–65.
[11] Du Yongfeng, Zheng Wenzhi, Li Wanrun, et al. Temperature correlation study of static-dynamic characteristics of ultra-long complex foundation isolated structures[J]. Engineering Mechanics, 2017, 34(7):69–78.
[12] Xu Yongji, Zhu Sanfan, Zong Zhouhong. Experimental study on the effect of ambient temperature on the dynamic characteristics of bridge structures[J]. Earthquake Engineering and Engineering Vibration, 2007, 27(6):119–123.
[13] Billah A M, Todorov B. Effects of subfreezing temperature on the seismic response of lead rubber bearing isolated bridge[J]. Soil Dynamics and Earthquake Engineering, 2019, 126:105814.
[14] Li Yue, Li Chong, Li Xi. Influence of plate-rubber bearing slip on seismic performance of small and medium span girder bridges under earthquake[J]. Journal of Civil Engineering, 2014, 47(Suppl 1):124–129.
[15] Du Xiu-Li, Han Qiang. Seismic analysis and seismic protection of bridge structures [M]. Beijing: Science Press, 2019.
[16] Li Chong, Wang Kehai, Hui Yingxin, et al. Seismic Response Analysis of Continuous Girder Bridge with plate-rubber Bearing Considering Frictional Slip[J]. China Journal of Highway, 2016, 29(3):73–81.
[17] Li JZ, Tang H. Research on transverse seismic design of small and medium span plate-rubber bearing girder bridges. Journal of Civil Engineering, 2016, 49(11):69–78.
[18] Ministry of Transportation and Communications of the People's Republic of China. plate-rubber bearings for highway bridges: JT/T4-2019 [S]. Beijing: people's transportation press, 2019.
[19] Xie Jian, Han Xiaodan, Pei Jiaming, et al. Experimental study on mechanical properties of steel reinforcement bars under ultra-low temperature environment[J]. Industrial Building, 2015, 45(1):126–129, 172.
[20] Mander J B, Priestley M J N, Park R. Observed stress-strain behavior of confined concrete [J]. Journal of Structural Engineering, 1988, 114(8):1827–1849.
[21] Zhuang Junsheng. Bridge bearings [M].4 ed. Beijing: China Railway Press, 2015.
[22] Hwang H, Liu Jingbo, Analysis of structural vulnerability of reinforced concrete bridges under earthquake[J]. Journal of Civil Engineering, 2004, 37(6):47–51.

[23] Shirato M, Fukui J, Unjoh S, et al. Japanese seismic design specifications for highway bridges [M]. Singapore: World Scientific Publishing, 2014.
[24] Navadeh, N., Goroshko, I. O., Zhuk, Y. A., Fallah, A. S. Approximate Mode-Based Simulation of Composite Wind Turbine Blade Vibrations Using a Simplified Beam Model. European Journal of Computational Mechanics, 2019, 28, 307–324.
[25] Ministry of Transportation and Communications of the People's Republic of China. Rules for evaluation of seismic performance of highway bridges: JTg/T 2231-02-2021 [S]. Beijing: People's Transportation Press, 2021.
[26] Li Lifeng, Wu Wenpeng, Huang Jiamei, et al. Study on the susceptibility of medium-span RC continuous girder bridge system under earthquake[J]. Journal of Civil Engineering, 2012, 45(10):152–160.
[27] Preumont, A., Marneffe, B. de, Rodrigues, G., Nasser, H., Deraemaeker, A. Dynamics and Control in Precision Mechanics. European Journal of Computational Mechanics, 2008, 17, 597–611.

Biographies

Jiang Hongwei received the Master's degree from Beijing Municipal Engineering Research Institute. 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.

Qiao Wei received the Master's degree from Chang'an 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 bridge and tunnel inspection, maintenance and reinforcement.

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.