Research Article

Effect of Material Characteristics of High Damping Rubber Bearings on Aseismic Behaviors of a Two-Span Simply Supported Beam Bridge

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Received 14 June 2020; Revised 25 August 2020; Accepted 14 September 2020; Published 23 September 2020

Academic Editor: Michael Aizenshtein

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There are a large number of damping materials in high-damping rubber (HDR) bearings, so the HDR bearings have the characteristics of both common rubber bearings and damping measures and show good aseismic effect. In this paper, the time-history dynamic analysis method is used to study the seismic effects of HDR bearings on the aseismic behaviors of two-span simply supported beam bridge under Northridge earthquake by changing the damping characteristics of the bearings. It is found that, with increasing damping of the bearings, both the horizontal shear and the displacement of the HDR bearings decrease, and the seismic energy dissipates through both the yield deformation and damping of the bearings. Although the girder and bearings have smaller displacement, when the HDR bearings with larger damping, the seismic responses, including displacement of pier top, shear force of pier bottom, and bending moment of pier bottom, are hardly affected by the change of the damping of the bearings. The HDR bearings with higher damping and yield characteristics separate and dissipate the seismic energy transmitted to the superstructure of the bridge and have better seismic effect on the structure in an earthquake.

1. Introduction

High-damping rubber is made by adding graphite, etc. to ordinary rubber in order to improve its viscoelasticity and overall damping properties [1], dissipate seismic energy to a certain extent, and thereby reduce the seismic response of the structure and extend the structural period. Thus, HDR is widely used in bridge structures [2–5].

It widely recognized that the mechanical properties of high-damping rubber materials are relatively complex and the stress-strain relationship of high-damping rubber materials is approximately linear in the case of small strain, but nonlinear in the case of large strain [6, 7]. The coupling of damping property and nonlinear material property makes the seismic performance of the HDR bearing under the action of the earthquake more complicated. To find out the effects of the damping and yield characteristics of HDR bearings on the aseismic behaviors of bridge structures, many researchers have studied the effects for different bridge structures.

The aseismic behaviors of HDR bearings, including their stiffness, damping, and seismic grade, are mainly studied by numerical simulation and shaking table test [8–11]. Erkus et al. [12] modeled a bridge as a linear two-degree-of-freedom system, and the seismic response of pier and high damper bearings are studied. The result shows that the seismic responses of pier do not decrease continually with the increase in bearing damping, and the pattern of responses is more obvious under the Kobe and Northridge earthquakes. Cardone et al. [13] compared the seismic performance of viscous dampers, high-damping rubber bearings, and their combinations, and the studies indicate that HDR bearings and damper with damping ratios ranging from 10% to 25% make the displacement of the bridge
structure reach a preliminary range based on the Displacement-Based Design (DBD) procedure. Many research
studies the seismic response of continuous beam bridge
supported on HDR bearings with experimental and ana-
lytical method. The study shows that the isolation effect
of the HDR bearing is obvious under the action of small
earthquakes, but the bridge structure will be nonlinear under
the action of large earthquakes, and the isolation charac-
teristic of the bearing is undefined [8, 12–15]. Alam et al.
[16, 17] found that under the action of high intensity
earthquake, the bridge with isolation design would have
excessive displacement and the residual deformation could
not be recovered. As the bridge enters into the nonlinear
situation, the influence of the isolation system on the
structural behavior needs further studies. Dezfuli and
Shahria Alam [18] analyzed the seismic effect of HDRBs and
SMA-HDRBs with a high aspect ratio for a three-span
continuous steel girder bridge, and the result reveals that the
HDRB and SMA-HDRB can reduce the girder acceleration
to approaching 50% by energy dissipation. Losanno et al.
[19] analyzed the seismic response of a continuous beam
bridge with different isolation bearings, including simply
supported, lead rubber bearings (LRBs), HDRB with 10% damping, and rubber isolators with 70% supplemental
damping ratio. The results reveal that HDRBs represents a
very effective solution for mitigating the displacement of
bridge and shear force in the piers base under near-fault
ground motions. Hassan [20] has carried out the parametric
study on the effect of accidental eccentricity and damping
ratio on the accuracy of isolating bearing displacement
expression. The results showed that the bearing displacement
without damping estimations improved by 7–33%
compared to the bearing with the damping ratio, which may
promote the use of isolation bearings as a seismic hazard
mitigation solution. These studies provide references for the
aseismic behavior of HDR bearings in terms of methodol-
gy, mechanism analysis, numerical model, etc [21, 22].
However, the HDR bearings not only yield but also consume
seismic energy through damping under the action of the
earthquake. The aseismic behaviors of HDR bearings with
both damping and yield characteristics, especially their coupled aseismic behaviors under the action of the earth-
quake, are seldom studied. Therefore, the research on the
effects of the material characteristics of HDR bearings on
their aseismic behaviors is beneficial to understanding the
seismic theory of HDR bearings and thereby ensures that the
bridge structure will not be seriously damaged under the
action of a strong earthquake.

Therefore, the finite element method was used to study
the effects of HDR bearings with different dampings on the
aseismic behaviors of two-span simply supported beam
bridge by coupling their damping and yield characteristics.
The energy consumption, displacement, and mechanics characteristic of bearings were emphatically analyzed, and
the dynamic information, such as displacement of girder,
displacement of pier top, bending moment of pier bottom,
and shear force, that affects the aseismic behaviors of the
bridge were analyzed in this paper. This study not only
enriches the theoretical cognition of HDR material but also
analyzes the effects of the bearings with different dampings
on the mechanical properties of the bridge and thereby
provides reasonable suggestions for selection of HDR
bearings in practical projects.

2. Mechanical Characteristics of HDR Bearings

The equivalent bilinear model was used to characterize the
hysteresis curve of HDR bearings under dynamic action
[23]. This model is also used in the finite element model of
bearings in this paper. The parameters and their relative
relations in the bilinear restoring force model are shown in
Figure 1.

\[ X = \text{shear displacement of bearing}, \quad X_y = \text{the yield displacement}, \quad Q = \text{the shear force caused by bearing displacement}, \quad Q_y = \text{the horizontal yield force}, \quad K_1 = \text{the pre-yield stiffness}, \quad K_2 = \text{the post-yield stiffness}, \quad K_h = \text{the equivalent stiffness}, \quad Q_d = \text{the damping force at the intersection of the hysteretic curve and the vertical axis} \]

Each parameter in the bilinear restoring force hysteretic
curve is calculated according to the formula below: the pre-
yield stiffness \( K_1 = G_1 A_0 / T_{e1} \), the post-yield stiffness \( K_2 = G_2 A_0 / T_{e2} \), the horizontal yield force \( Q_y = G_1 (\gamma - \gamma_0) \cdot Q_{e0} \), and the yield displacement \( X_y = Q_y / K_1 \), where \( A_0 \) is the plane area of the rubber inside
the bearing; \( G_1 \) is the shear modulus at initial horizontal
stiffness; \( G_2 \) is the shear modulus at horizontal stiffness after
yield; \( T_{e1} \) is the total thickness of rubber layer; \( Q_{e0} \) is the
damping force at the intersection of the hysteretic curve and
the vertical axis; and \( G(\gamma) \) is the shear modulus of rubber
bearings as the shear strain is \( \gamma \); \( G_1 (\gamma) = a_0 + a_1 \gamma + a_2 \gamma^2 + a_3 \gamma^3 + a_4 \gamma^4 \) and \( G_2 (\gamma) = b_0 + b_1 \gamma + b_2 \gamma^2 + b_3 \gamma^3 + b_4 \gamma^4 \); in
polynomials, the \( a_i = a_0, \ldots, a_4 \), \( b_i = b_0, \ldots, b_4 \) are obtained from a large number of statistical tests of the rubber
materials.

3. Model, Algorithm, and Case Setting

3.1. Physical Model of Bridge Structure.

In this paper, a two-span simply supported beam bridge with the span of
2 \times 30 m was studied, and the double-column piers with the
height of 8 m and the diameter of 1.6 m are shown in
Figure 2(a) [25, 26]. The pier tops were connected by a 1.7 m
high capping beam. The designed deformation of the ex-
pansion joint is 160 mm. The girder of the bridge consists of
five small box girders, which has the total width of 16.75 m
and the height of 1.6 m, as shown in Figure 2(b).

3.2. Parameters and Case Setting of Bearings.

In this paper, the aseismic performance of HDR bearings with different
dampings for the bridge was studied, in order to study the
effects of the damping characteristics of the bearings on
the seismic response of the structure. The HDR bearings are
selected mainly based on their axial bearing capacity. The
bearings yield when their horizontal seismic load exceeds the
horizontal yield force and have pre-yield stiffness and post-
yield stiffness. All the parameters of the equivalent bilinear
model used as the mathematical model for HDR bearings are
shown in Table 1.
The damping coefficients of the HDR bearing, \( c_b \), is evaluated by the damping ratio, \( \xi_b \), which is expressed as \( c_b = \xi_b \times 2M\omega \), where \( M \) is the mass of the isolation structure (the total mass of the superstructure of the bridge is approximately \( 820 \) t); \( \omega \) is the natural circular frequency of the isolation bridge with HDR bearings \([23, 27]\). The damping ratio of the HDR bearings in practical engineering varies from 10% to 17% (according to the Chinese codes JTT 842-2012) \([28, 29]\). The circular frequency of the isolation bridge decreases from 4.63 rad/s to 1.78 rad/s as the damping ratio of HDR bearings increase \([20, 30]\). Therefore, the damping coefficient \( c_b \) of a single HDR bearing ranges from 19.47 to 86.04, and the damping coefficients of 20, 40, 60, and 80 kN·s/m were selected for each HDR bridge bearing in our study.

### Table 1: Parameters of high-damping rubber bearings.

| Bearing size (mm) | 370 \times 420 \times 158 |
|-------------------|---------------------------|
| Bearing force (kN)| 1521                      |
| Tolerable displacement (mm) | 176 |
| Horizontal yield force (kN) | 74 |
| Vertical stiffness (kN/m) | 934000 |
| Pre-yield stiffness (kN/m) | 9250 |
| Post-yield stiffness (kN/m) | 1420 |

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#### 3.3. Finite Element Model of Bridge.

The nonlinear finite element program MIDAS was used to model the bridge structure \([31]\). Figure 3 shows quite clearly the numerical model of the bridge, and the girder and deck elements are neglected to display. In the three-dimensional model of the bridge structure, the girder, piers, and cap beams of the bridge were simulated by elastic linear beam-column elements based on the lumped mass system and the small discrete segment method. Fixed constraints are applied at the base of the piers, and the soil-structure-interaction effect were neglected \([30, 32]\). The bearings were simulated using the bilinear elastic plastic elements model, which can simulate their equivalent horizontal stiffness, pre-yield stiffness, post-yield stiffness, yield force, damping coefficients, etc., in the finite element program \([33, 34]\). The compression strength of concrete used in the model for girder and piers was 50 MPa and 40 MPa, respectively. The model had a total of 191 nodes, 48 nonlinear beam-column elements, 159 elastic linear beam-column elements, and 15 bilinear elastic plastic spring elements, respectively.

#### 3.4. Loading Protocol.

In order to analyze the seismic response of bridge structures under the action of the earthquake, the bridge model was subjected to ground motion in transverse and lateral directions. The ground motion is the 1994 Northridge earthquake recorded by New Hall Fire Station and characterized by the near-fault effect, as shown in Figure 4. The peak acceleration of the earthquakes is 0.59 g \([26]\).
4. Verification and Experimental Research

Verification of the mathematical model is the key of simulation research [35, 36]. The shaking table test in reference is analyzed by numerical simulation in this paper [26]. The scale model of two-span simply supported bridge model for shake-table tests was shown in Figure 5(a), with the scale of 1/4 to the prototype bridge. All the pier columns are 2 m height and have the diameter of 0.4 m. The bearings of the bridge are circular laminated-rubber bearings with the dimensions of $D600 \times 130$ mm, which is used to support the girder. The Northridge earthquake, the same as the numerical analysis, has been used to analyze the seismic response of the bridge in shaking table test. It can be seen from Figures 6(a)–6(e) that the bearings yield under the action of the earthquake, and the bridge generally has greater seismic response in the longitudinal direction than in the lateral direction. The hysteretic curves have very high coincidence degree at the bearing damping of 0 kN·s/m, 20 kN·s/m, 40 kN·s/m, 60 kN·s/m, and 80 kN·s/m, respectively. It can be seen from Figures 6(a)–6(e) that the bearings yield under the action of the earthquake, and the bridge generally has greater seismic response in the longitudinal direction than in the lateral direction. The hysteretic curves have very high coincidence degree at the bearing damping of 0 kN·s/m, indicating that the seismic response of the HDR bearings is not weakened under the action of the earthquake. With increasing bearing damping, the area surrounded by the hysteretic curves gradually decreases, and the curves of the hysteretic loops gradually change slowly, showing that both the horizontal shear force and displacement of the bearings decrease, and the bearings deform slowly under the action of the earthquake.

The maximum horizontal shear force, displacement, and total energy consumption value of the bearings under the action of Northridge earthquake at different dampings are shown in Table 2. The data in the table shows that, with increasing damping, all the seismic responses of the bearings decrease under the action of the earthquake. The maximum horizontal shear force, displacement, and deformation energy consumption at the damping of 80 kN·s/m are about 80%, 85%, and 65% of that at the damping of 0 kN·s/m, respectively. With increasing damping of the bearings, their deformation energy consumption decreases. The decreased deformation energy is consumed by the damping force of the bearings. The seismic energy consumption by the damping of the HDR bearings with damping coefficient of 80 kN·s/m is close to 50% of the deformation energy consumption.
5.2. Seismic Response of Bridge. The responses of the bridge structure under the action of earthquake are also affected by the aseismic behavior of the bearings and the change of the damping. Figure 7 shows the displacement of the girder and piers of the bridge structure under the action of earthquake at different dampings of HDR bearings. As shown in Figure 7(a), with the increase of the bearing damping, the displacement of the girder decreases; the displacement of the
girder in the longitudinal and lateral directions at the bearing damping of 80 kN·s/m is 81% and 76% of that at the bearing damping of 0 kN·s/m, showing that the increase of the bearing damping can effectively reduce the seismic impact on the superstructure of the bridge. The displacement of the girder in the longitudinal direction of the bridge is almost 1.2 times that in the lateral direction, indicating that more attention should be paid to the longitudinal seismic response of double-column simple supported beam bridge under the action of earthquake. When the damping coefficient of the HDR bearings is 0 kN·s/m and 20 kN·s/m, the longitudinal displacement of the girder is larger and exceeds the design deformation of the expansion joint (16 cm). As shown in Figure 7(b), with the increase of the bearing damping, the displacement of the pier top in the longitudinal and lateral directions of the bridge hardly changes, indicating that the change of the bearing damping has a small effect on the seismic response of the substructure. The longitudinal displacement of the pier top is almost 3.6 times that in the lateral direction, meaning that the piers have differences between the displacements in the longitudinal and lateral directions of the bridge under the action of earthquake mainly due to the fact that the double-column piers have larger lateral stiffness. In summary, the increase of HDR bearing damping will reduce the displacement of the girder of the bridge structure under the action of the earthquake, but has a small effect on the displacement of the pier top. Figure 8 shows the bending moment and shear force of the pier bottom of the bridge structure under the action of Northridge earthquake at different dampings of HDR bearings. With the increase of bearing damping, the bending moment of the pier bottom in the longitudinal and lateral directions of the bridge hardly changes; the difference in the bending moment of the pier bottom in the longitudinal and lateral directions of the bridge at the bearing damping between 80 kN·s/m and 0 kN·s/m is less than 1%, and the bending moment of the pier bottom in the lateral direction of the bridge is about 2.1 times that in the longitudinal direction, as shown in Figure 8(a). With the increase of bearing damping, the shear force of the pier bottom in the lateral and longitudinal directions of the bridge increases and decreases slightly, respectively. The difference in it at the bearing damping between 80 kN·s/m and 0 kN·s/m is less than 2%, as shown in Figure 8(b). The above analysis shows that the change of bearing damping has a small effect on the seismic response of the substructure mainly because the HDR bearings isolate the relative vibration between the superstructure and substructure through their deformation in the earthquake, but hardly weakens the seismic response transmitted to the substructure.

| Seismic responses                      | Direction | 0 kN·s/m | 20 kN·s/m | 40 kN·s/m | 60 kN·s/m | 80 kN·s/m |
|----------------------------------------|-----------|----------|-----------|-----------|-----------|-----------|
| Shear force (kN)                       |           |          |           |           |           |           |
| Longitudinal                           | 293       | 281      | 271       | 264       | 257       |           |
| Transverse                             | 258       | 244      | 234       | 226       | 221       |           |
| Displacement (cm)                      |           |          |           |           |           |           |
| Longitudinal                           | 16.19     | 15.30    | 14.45     | 13.68     | 12.94     |           |
| Transverse                             | 13.78     | 12.74    | 11.85     | 11.08     | 10.40     |           |
| Energy dissipation by deformation (kJ) |           |          |           |           |           |           |
| Longitudinal                           | 27574     | 24681    | 22296     | 20235     | 18443     |           |
| Transverse                             | 20580     | 17832    | 15595     | 13846     | 12457     |           |
| Energy dissipation by damping (kJ)     |           |          |           |           |           |           |
| Longitudinal                           | —         | 2893     | 5278      | 7339      | 9131      |           |
| Transverse                             | —         | 2748     | 4983      | 6734      | 8123      |           |

**Figure 7:** Displacement of bridge in different directions with the variation of effective damping: (a) displacement of girder; (b) displacement of pier top.
6. Conclusions

(1) The HDR bearings with larger damping have better isolation effect, leading to smaller seismic response of the superstructure of the bridge. However, the change of bearing damping has less effect on the seismic response of the substructure of the bridge. The seismic responses of the bridge structure in the longitudinal direction with double-column piers are larger than that in the lateral direction.

(2) The HDR bearings have good isolation performance and energy dissipation effect under the action of earthquakes. With the increase of bearing damping, the horizontal shear force and displacement of the HDR bearings decrease.

(3) When the damping coefficient of the HDR bearings is 0 kN·s/m and 20 kN·s/m, the longitudinal displacement of the girder exceeds the design deformation of the expansion joint (16 cm). It means that the bridge may collide under the action of the earthquake. Therefore, the seismic measures are suggested to be used to limit the excessive relative displacement between the bridge substructure and superstructures.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Shaanxi Natural Science Foundation (Grant no. 2018JQ5073) and Fundamental Research Funds for the Central Universities (Grant no. CHD300102210517).

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