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Test and analysis of bridge vibration isolation

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ABSTRACT: A earthquake simulation test of a bridge model was made.In the test three kinds of bridge bearings were used, they were lead–rubber bearing, rubber bearing and hinge–rolling bearing.The dynamic responses of the bridge model, such as acceleration, relative displacement and strain, were directly measured and recorded by a computer to show the vibration isolation effect of lead–rubber bearings and rubber bearings.A simple analytical method of the dynamic responses for vibration isolation of the bridge with lead–rubber bearings is also provided in this paper.

1 INTRODUCTION

The earthquake attacks on a bridge can be isolated by isolation devices between bridge decks and piers. The flexible isolation devices can change the resonant frequency of the bridge, and reduce the dynamic responses of the bridge because the isolation devices have high damping supplied by the deformation of lead or mild steel. The lead–rubber bearing was found to be the most appropriate device to isolate bridge structures from earthquakes because it has the advantages of simplicity, cheapness and the functions of enough vertical support, lateral flexibility and energy absorbtion. This technique was already used in New Zealand, U.S.A. and Japan.

In China, the bearings in most of simple beam bridges are hinge–rolling bearings. This traditional design is high in economic cost and material consumption.Recent years rubber bearings were also used in bridge design.So, a dynamic test is needed to study earthquake resistance capability of a bridge using lead–rubber bearings and rubber bearings.A analytical method is also in demand to meet the need of the isolated bridge design in future.

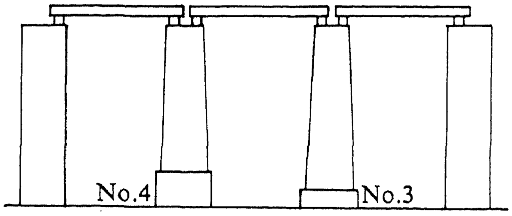

Figure 1. The bridge model

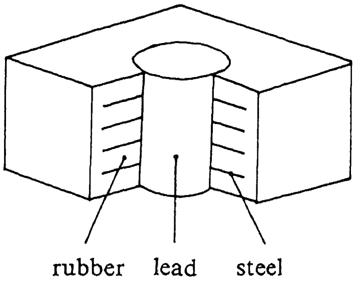

Figure 2. A lead–rubber bearing

2 DYNAMIC TEST OF A BRIDGE MODEL

The bridge model has three spaces, and the two piers, No. 3 and No. 4, are emphasized, as shown in Figure 1. Each spaces is 136cm in length. The height of pier No. 3 is 237cm and No.4 is 181cm.The piers are made of reinforced concrete. The beams are made of steel and each one is 134cm in length and 51.4kg in weight.The bridge model was tested on an earthquake simulation table which was 5m in length and width respectively. The model was tested in the direction of horizon and the direction same with the bridge model.

There were three different size rubber bearings, as shown in Table 1.There are some steel plates between laminated rubber to increase the ability of vertical support of the rubber bearing.The lead–rubber bearings (shown in Figure 2) of three different sizes were converted from rubber bearings by casting lead down the central holes made ahead.The volumn of the plug was a little bigger than that of the hole, so the lead plug was locked with the steel plates and extruded for a little into the layers of rubber. Thus, when the lead–rubber bearing was deformed horizontally, the lead insert was forced by interlocking steel plates to deform its whole volumn in pure shear.The bearings were bound to beams and piers by glue.

The dynamic test was carried out under 7 conditions, as shown in Table 1 . The input acceleration is El Centro Earthquake NS. Under each condition, four or five times of tests were made with different input peaks from 0. 2g to 0. 8g. The structural responses of acceleration, relative displacement and strain were recorded by a computer.

3 THE ANALYTICAL METHOD

A simplified isolated bridge structure is shown in Figure 3. The experimental model is a distribution structure. In oder to simplify analytical method, each pier is separated from the structure and discreted into a system with definite DOF, as shown in Figure 4. The mass of beam is connected with the top of pier by lead–rubber bearing. Therefore, the whole bridge structure which is isolated by lead–rubber bearings can be simplified into some systems of n+1 DOF, where n is the number of DOF of one pier.

When divided the pier into n parts of the same height, the mass matrix of n+1 DOF system can be presented by:

$$[M] = diag(m_1,\ m_2,\ \dots,\ m_n,\ m_b) \tag{1}$$

where m_1, m_2, ..., $m_{n-1}$is respectively the half of total mass of the two parts of the pier which neighbor to each mass piont. $m_n$is the half of the mass of the nth part. $m_b$is the half of the mass of the two beams which were supported by this pier.

The lead–rubber bearing is considered as a nonlinear element. The restoring force model of a lead–rubber bearing is taken as bilinear, as shown in Figure 5. $k_{b1}$is the elastic stiffness, $k_{b2}$is the yield stiffness and $k_{b3}$is the restoring stiffness. $R_T$is the shear yield force.

The stiffness of a rubber bearing k_{br}can be given as

$$k_{br} = G \cdot A / h \tag{2}$$

in which G represents the shear modulus of the rubber bearing, A donates the shear area of the rubber bearing and h is the height of the rubber bearing.

The restoring force parameters of the lead–rubber bearing which is the same size with the rubber bearing referred in Equation(2) can be determined by:

$$k_{b2} = k_{br} \tag{3}$$

$$k_{b1} = 10k_{br} \tag{4}$$

$$k_{b3} = 10k_{br} \tag{5}$$

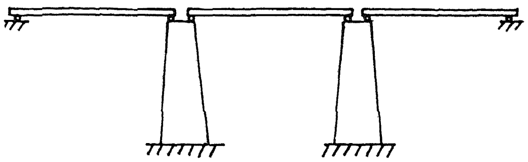

Figure 3. The simplified bridge modell

The shear yield force of the lead–rubber bearing R_T can be given by:

$$R_T = \sigma \cdot A' \tag{6}$$

where σ represents the shear yield stress of lead (about 10MPa), A' donates the shear area of the lead plug.

In order to simplified analytical method, we assume that the deformation of pier is linear. The stiffness matrix of the n DOF pier can be given as:

$$[k] = \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ k_{n1} & k_{n2} & \cdots & k_{nn} \end{bmatrix} \tag{7}$$

Considering the deformation of the pier is bending one and the deformation of the lead–rubber bearing is shearing, the combinated stiffness matrix of the n+1 DOF system shown in Figure 4 can be presented as:

$$[K_i] = \begin{bmatrix} k_{11} & \cdots & k_{1(n-1)} & k_{1n} & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ k_{(n-1)1} & \cdots & k_{(n-1)(n-1)} & k_{(n-1)n} & 0 \\ k_{n1} & \cdots & k_{n(n-1)} & k_{nn} + k_{bi} & -k_{bi} \\ 0 & \cdots & 0 & -k_{bi} & k_{bi} \end{bmatrix} \tag{8}$$

where i = 1, 2, 3, represents the elastic, yield or restoring state of the lead–rubber bearing.

The structure damp is taken as Rayleigh Damp, it is given by:

$$[C] = a[M] + b[K_2] \tag{9}$$

where [M] represents the mass matrix and $[K_2]$ donates the elastic stiffness matrix of the n+1 DOF system.

Coefficient a and b are determined by

$$\xi_i = \frac{a + b\omega_i^2}{2\omega_i} \qquad (i = 1,\ 2) \tag{10}$$

where ω_1 and ω_2 are the first and second vibration angle frequency of the n+1 DOF system.

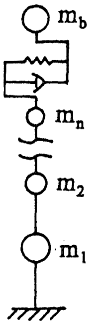

Figure 4. The system of n+1 DOF

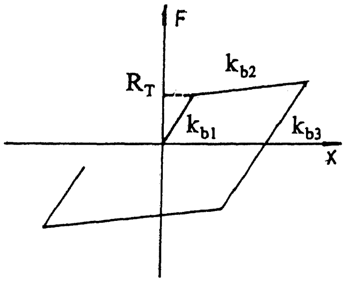

Figure 5. The restoring force model of lead–rubber bearing

ξ_1 and ξ_2 are the first and second mode damping rate.

At time t, the motion equation of the system is

$$[M][\ddot{X}]_t + [C][\dot{X}]_t + [K][X]_t = [F]_t \tag{11}$$

Using the assumption of Willson–θ method and the incremental equation, we can calculate the displacement and velocity of the system at time t+△t, $[X]_{t+\triangle t}$ and $[\dot{X}]_{t+\triangle t}$. Substitue both of them into the motion equation at time t+△t, we can obtain the system acceleration at time t+△t

$$[\ddot{X}]_{t+\Delta t} = [M]^{-1}([F]_{t+\Delta t} - [C][\dot{X}]_{t+\Delta t} - [K][X]_{t+\Delta t}) \tag{12}$$

In the dynamic analysis of the bridge structure isolated by lead–rubber bearings, the nonlinear system stiffness matrix is changeable. So in each steps of calculation, it is necessary to determine the state of the system, therefore to adopt the system stiffness matrix $[K_1]$, $[K_2]$ or $[K_3]$.

4 RESULTS

Some important results can be obtained from the dynamic test of the bridge model and the dynamic analysis of bridge structures.

4.1 The effect of vibration isolation of lead–rubber bearings

Normalized results of the 4th test in condition 5 and the 5th test in condition 7 are taken for comparing the responses of model structure. It can be seen from the data of acceleration and strain of the bridge model that the earthquake resistance effect is excellent when the bridge is isolated by lead–rubber bearings.

The three measured accelerations of beams are obviously reduced, the maximum one is reduced by 50.1 percent, the minimum one is also reduced by 38.6 percent. The maximum decreasement of strain is by 51.7 percent and the minimum one is reduced by 17.1 percent. Except a relative displacement increasement of 50.5 percent, the others are reduced by 58.5 percent, 18.1 percent and 8.9 percent.

Using lead–rubber bearings as isolation device to isolate bridge from earthquake can decrease the dynamic responses of bridge structure, enhance the earthquake resistant capability of the bridge.

4.2 The effect of rubber bearing on the aseismatic capability of the bridge structure

Comparing the experimental data of the bridge model using rubber bearings with those using hinge–rolling bearing, we found that rubber bearings have no contribution to the earthquake resistance capability of the model structure.

The data of acceleration for rubber bearing is greater than those for hinge–rolling bearing. The data of strain at the base of piers have some increasement obviously.

Using rubber bearings as the isolation device on the bridge model did not devote to earthquake resistance capability. The reason is the small horizontal stiffness and little damping(about 1 percent). Although rubber bearings can change the natural frequency of bridge structure, it can not dissipate the movement energy of the bridge caused by earthquake.

4.3 The effect of parameters of lead–rubber bearings on the capability of vibration isolation.

Normalized results of test 4, 5, 6 are taken to compare the structural responses to study the effect of parameters of lead–rubber bearings on vibration isolation.

Comparing the experimental data, the responses of the 4th test in condition 5 is smaller than the other conditions, in particular the response of strain. So it can be seen that the parameter of lead–rubber bearing can greatly affect the responses of isolated bridges. The dynamic responses of a bridge structure can be reduced effectively when the bridge is isolated by the

Table 1. Test conditions

condition	bearing*	square (cm × cm)	height (cm)	diameter of lead (cm)
1	R	3×3	2.8	
2	R	5×5	4.2	
3	R	5×5	2.8	
4	L–R	3×3	2.8	0.5
5	L–R	5×5	4.2	0.5
6	L–R	5×5	2.8	0.5
7	H–R			

* R: Rubber bearing L–R: Lead–rubber bearing H–R: Hinge–rolling bearing

lead–rubber bearings of suitable parameters.

4.4 The result of the dynamic analysis

With the help of a computer, the dynamic reponses of the bridge model isolated by the lead–rubber bearings, which is 4. 2cm in height, 5cm in length and width respectively and whose lead plug is 0. 5cm in diameter, is calculated by using the simplified analytical method discussed above. It is found that the calculating data are agreeable with the exprímental data, the maximum error is less than 20 percent. The analytical method is simple and accurate enough, it is suitable to be used in engineering design of bridges.

5 CONCLUSION

Rubber bearings can not be used alone as the isolation device to isolate bridges from earthquake because rubber bearings have no high damping to absorb energy. On the contrary, lead–rubber bearings are suitable to be used as the isolation device to protect bridge structures from earthquake because of the advantages of vertical support, lateral flexibility and energy absorbtion. It can greatly decrease the seismic responses of beams and piers, relative displacement between beams and piers and strain of piers. Lead–rubber bearings can enhance the capability of earthquake resistance of bridge and reduce the economic cost and material consumption. It has great economic and social benefit adopting the technique of isolation to the bridges in the seismically active area.

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