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DEVELOPMENT AND APPLICATION OF ISOLATION BEARING ELEMENT CONSIDERING BI-DIRECATIONAL COUPLED INTERACTION

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Base isolation technology, which introduces isolated bearings between the top of foundation and upper structure, is regarded as an effective method to reduce seismic energy absorbed by the upper structure. Lead rubber bearing (LRB), that is, a representative seismic isolation device, has been widely used in isolated structural systems. An isolation bearing element for simulating the behavior of LRB was developed with the user element subroutine (UEL) feature of ABAQUS, which was further introduced into seismic analysis of the base-isolated structure with LRB. The Bouc-Wen bi-directional coupled restoring force model was adopted in the developed element to describe the nonlinear hysteric characteristics for LRB in the lateral direction. Meanwhile, the strength differences of LRB in the vertical direction were also included in the element. The accuracy of the isolation bearing element was verified by close agreement between numerically predicted hysteresis curves and experimental counterparts. Moreover, the nonlinear earthquake responses of a four-story reinforced concrete structure isolated by LRB with and without the bi-directional coupled interaction of bearing restoring forces were separately explored, and it was revealed that the bi-directional coupled interaction had considerable effects on the seismic responses of the isolated buildings. Once these coupled interaction effects were not taken into account, the displacement of LRB was underestimated while the bearing capacity would be over-predicted, which had a detrimental effect on the design of isolated buildings.

Keywords: Bouc-Wen model, Lead rubber bearing, Base isolation, Seismic analysis, Seismic capability.

1 INTRODUCTION

Base isolation has been taken as a favorable design method for earthquake resistant design of structural systems and sensitive instruments. Protecting structural systems against severe earthquake events can be achieved by isolating them from the ground rather than the conventional techniques by strengthening the structural members. Therefore, the seismic deformation of the structural system can be transferred into the isolation device, which provides an effective solution for the performance objectives of superstructures.

The existing recorded earthquake accelerograms indicate that the horizontal ground motion is basically multi-dimensional. The buildings in Japan are usually designed in each horizontal direction, while the multi-directional excitation effect is considered in both China and America. It has to be noted that the restoring force characteristics of rubber bearings subjected to bi-directional loading can be significantly different from those obtained under unidirectional loading. For example, the equivalent stiffness was reduced by bi-directional loading, resulting in an increase in the shear deformation. The bi-directional coupling effects were observed in a series of earthquake shaking tests on isolated bridges and isolated buildings (Yamamoto *et al.* 2009). For the design of the base isolation system, it is important to accurately determine the force versus displacement constitutive model of the base isolation bearing. Thus, nonlinear seismic analysis of the base isolation system can be used to acquire the structure and bearing seismic demands.

The objective of this paper is to demonstrate that the bi-directional coupled interaction of restoring force model cannot be neglected. The Bouc-Wen bi-directional coupled restoring force model was introduced into the developed element to describe the nonlinear hysteric characteristics for LRB in the lateral direction (Casciati 1989). An isolation bearing element for simulating the behavior of LRB was developed with the user element subroutine (UEL) feature of ABAQUS, which was further introduced into the seismic analysis of the base-isolated structure with LRB. The seismic response of the bi-directional coupling model of the isolation bearing system under simultaneous bi-directional excitation is further compared with that which is obtained by uncoupled modeling.

2 FINITE ELEMENT MODELING PROCEDURE

2.1 Element Formulation

The biaxial coupled and uncoupled restoring force models were implemented with the user element subroutine (UEL) feature of ABAQUS. The physical model of LRB is simplified as a two-node, six degrees-of-freedom discrete element. The macro bearing element is efficient in seismic dynamic analysis of large-scale structure. The lateral shear behavior and axial strength differences of LRB are idealized as three pairs of axial springs as shown in Figure 1. The nonlinearity in shear behavior of LRB is condensed into the coupled or uncoupled restoring force model in the axial springs.

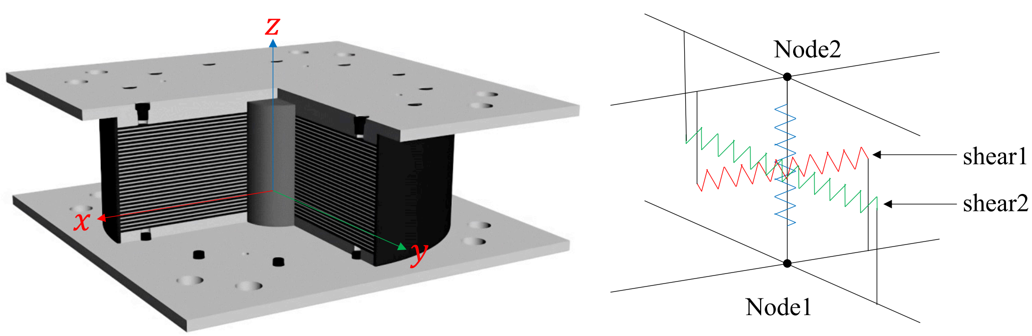


Figure 1. Isolation bearing element of LRB.

2.2 Biaxial Hysteretic Restoring Force Model

Based on smoothed plasticity, the Bouc-Wen model has been extensively used to describe components and devices with hysteretic behavior such as LRB (Wen 1976, Park *et al.* 1986). In the Bouc-Wen model, the restoring force vector may be expressed as seen in Eq. (1)

$$\begin{Bmatrix} q_x \\ q_y \end{Bmatrix} = \alpha[K]\begin{Bmatrix} u_x \\ u_y \end{Bmatrix} + (1-\alpha)[K]\begin{Bmatrix} Z_x \\ Z_y \end{Bmatrix} \tag{1}$$

in which q_x and q_y are the lateral resistances in the x- and y-direction, respectively. $[K]$=initial stiffness matrix, α = post-yielding stiffness ratio, Z_x and Z_y represent the hysteretic components of the restoring forces. Meanwhile, the independent unidirectional Bouc-Wen model is adopted for comparison. In this uncoupled model, Z_x and Z_y satisfy the differential equation given in Eq. (2)

$$\begin{Bmatrix} \dot{Z}_x \\ \dot{Z}_y \end{Bmatrix} = A \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} - \beta \begin{Bmatrix} |\dot{u}_x Z_x| Z_x^{\eta-1} \\ |\dot{u}_y Z_y| Z_y^{\eta-1} \end{Bmatrix} - \gamma \begin{Bmatrix} \dot{u}_x Z_x^{\eta} \\ \dot{u}_y Z_y^{\eta} \end{Bmatrix} \tag{2}$$

in which η is the exponent of the non-linear hardening component.

For the coupled hysteretic restoring force model, the modified bi-directional Bouc-Wen model proposed by Casciati (1989) is utilized. In view of the combined action of loading in two directions, the hysteretic variable is assumed to be an interaction curve in the form as seen in Eq. (3)

$$\phi = (Z_x)^2 + (Z_y)^2 \tag{3}$$

where ϕ is the interaction curve between lateral resistances of the LRB $\phi = 1$ when yielding is reached. For the case with no interaction, the yielding in a particular direction is independent to the yielding in the orthogonal direction. In this model, Z_x and Z_y satisfy the differential equations given in Eq. (4) and Eq. (5):

$$u_y \begin{Bmatrix} \dot{Z}_x \\ \dot{Z}_y \end{Bmatrix} = \left(A[I] - \chi \begin{bmatrix} Z_x^2 & Z_x Z_y \\ Z_x Z_y & Z_y^2 \end{bmatrix} \right) \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} \tag{4}$$

and

$$\chi = \|Z\|^{\eta-2} \left[\gamma + \beta sign(\dot{u}_x Z_x + \dot{u}_y Z_y) \right] \tag{5}$$

in which u_y is the yield displacement, sign() is the sign function, and *[I]* is the second-order identity matrix. In this study, the values of model's parameters are taken as $A = 1$, $\eta = 2$, $\gamma = \beta = 0.5$.

2.3 Validation of the Isolation Element Implementation

The test results of LRBs under bi-lateral displacement histories were reported by Huang *et al.* (2000), which included the bi-directional interaction performances of bearings. The shear modulus of rubber G was 0.55MPa, the characteristic strength Q_d was 6.786kN, and the initial post-elastic stiffness $K_{d,0}$ was 0.1775kN/mm. As shown in Figure 2, the box displacement orbit (100% shear strain) in the horizontal plane was employed in this displacement-control testing.

The comparisons between experimental and numerical responses of the bearings are shown in Figure 3 and Figure 4. It can be seen that that the restoring force model without interaction fails to capture the observed force reduction effect of the bi-directional coupled behavior. With fixed horizontal displacement in the x direction (100% shear strain), the corresponding resisting force of coupled model in the x direction decreases due to the loading along the y direction (from point 1 to point 2 in Figure 2). However, they were independent of each other. The simulation responses predicted by the bearing element with the coupled restoring force model are in close agreement with both the experimental interaction curve and the hysteresis loops in slight residual errors. Therefore, the developed element can effectively characterize the bi-directional coupled behavior of LRBs under bi-lateral static excitation.

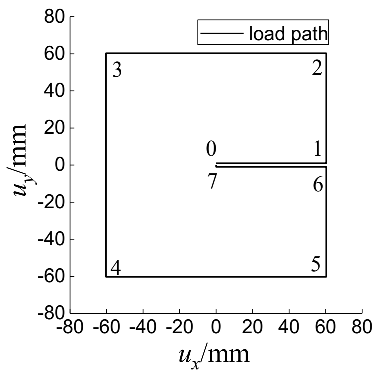


Figure 2. The box displacement orbit for tests.

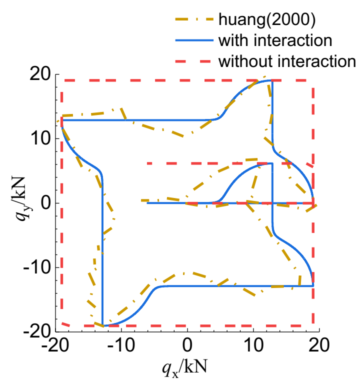
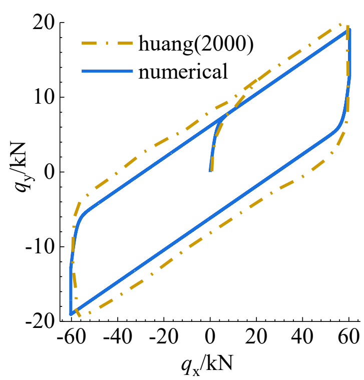
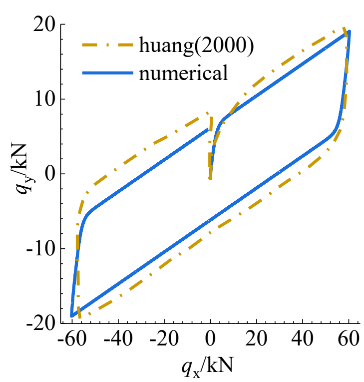


Figure 3. Interaction curves of resisting force

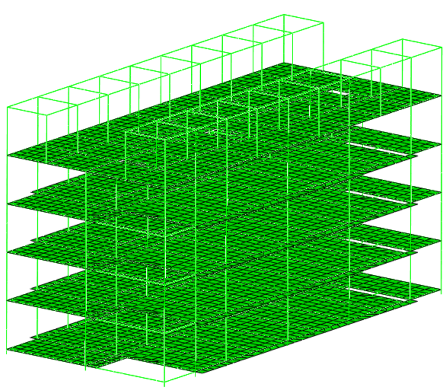


(a) *X* direction

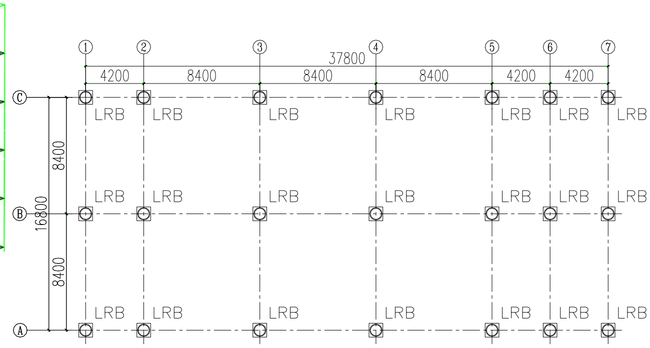


(b) *Y* direction

Figure 4. Comparison of experimental and numerical results of the hysteretic loops.



(a) Finite element model



(b) Typical layout of the structure

Figure 5. The structure of the isolated building.

3 TIME HISTORY ANALYSIS OF A FRAME STRUCTURE

3.1 Structural Modeling

Nonlinear dynamic elastic-plastic analysis of a four-story reinforced concrete structure with LRBs was conducted to further verify the bearing element. The developed finite element model and typical plane of the isolated building are presented in Figure 5. The bearings were in a radius of 450 mm, the characteristic strength was equal to 146.6kN, and the initial elastic stiffness was set as 22.6kN/mm, and the post-yielding stiffness was taken as 1.656kN/mm.

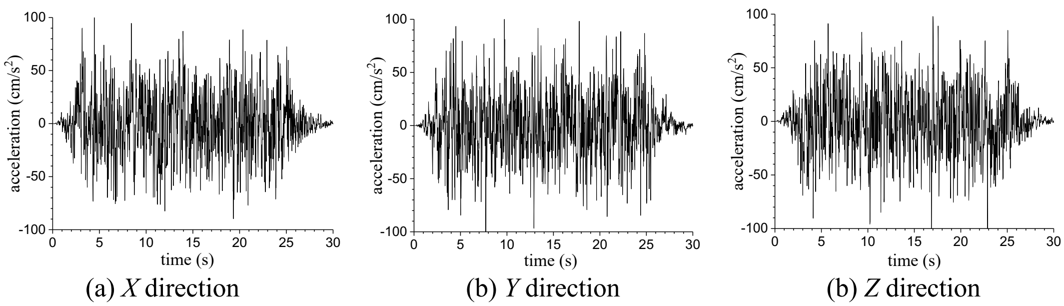


Figure 6. Time history components.

3.2 Seismic Response Under Earthquake Excitation

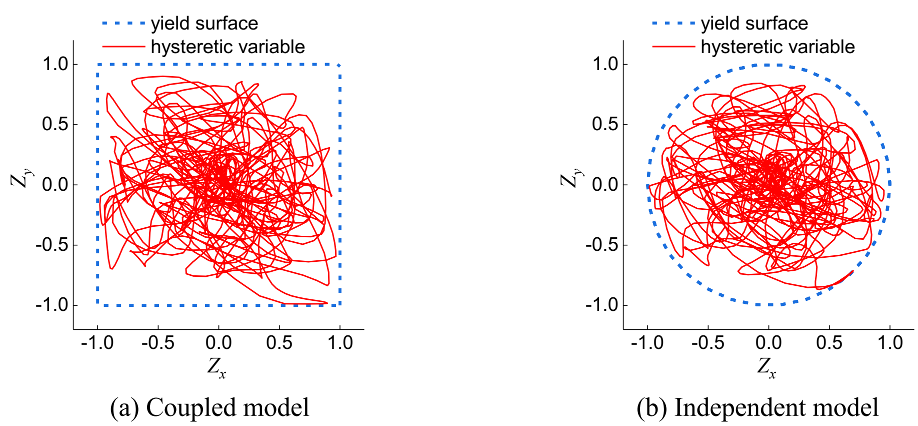


Figure 7. The locus of coupled and uncoupled hysteretic variable Z .

The loci of coupled and uncoupled hysteretic variable are plotted in Figure 7. Figure 7a shows that the hysteretic variable Z was bounded by a square yield surface in the independent unidirectional model, while the plot of the hysteretic variable Z in coupled restoring force model illustrates that the bi-directional coupled response of bearings is coupled through a circular yield surface as shown in Eq. (3) (see Figure 7b). Moreover, as shown in Figure 8, the maximum forces in the X direction of both models were basically the same, yet the maximum force of uncoupled model was overestimated by about 20% in the Y direction. The energy absorbed by the bearing was also overestimated. It can be concluded that the unidirectional model resulted in overestimated bearing capacities of LRBs, which can be attributed to the fact that the interaction effect between the lateral restoring forces has not been taken into account.

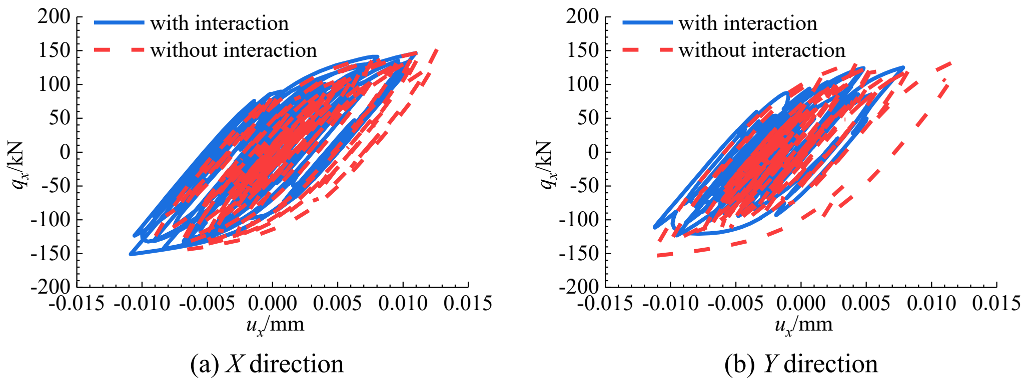


Figure 8. Comparison of the hysteretic loops of coupled and uncoupled model.

4 CONCLUSIONS

In this study, a bearing element for LRBs was developed by using ABAQUS. The established element—a 2-node, 6-degrees-of-freedom macro element—has numerous advantages, such as the convenience in implementation and high computational efficiency. The coupled effect of restoring forces of LRB under static loading and earthquake excitation was studied. In view of the comparison between the coupled model and the uncoupled one, the bi-directional interaction of restoring force is found to have a negligible influence on the response of isolation building. The obtained conclusions are as follows:

(1) The adopted coupled restoring force model can be used to predict the bi-lateral interaction behavior of bearings and agree well with the existing test results.

(2) The peak bearing restoring forces can be overestimated if the interaction effects are neglected under earthquake excitation.

(3) A restoring force model that is defined by uncoupled behavior in two orthogonal directions would not be adopted to acquire shear behavior of LRBs.

It is focused on bi-lateral interaction of LRB in this paper without consideration of degrading effect. To further study, degrading models of Bouc-wen type is one of the feasible options.

Acknowledgments

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