Seismic performance of base-isolated structures based on the force analogy method

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Summary. Based on the basic theory of force analogy method (FAM), the motion equations of a base-isolated structure were established. Firstly, taken the isolation layer as a separated layer of a structure, a model of the bar system for the base-isolated structure was established based on FAM, which considers bending and shear effects of the rubber isolation bearing at the same time. Then, the motion equations of a base-isolated structure were derived. Dynamic analysis was done for the base-isolated structure and an aseismatic structure separately under the action of an earthquake record and seismic effect of the isolated structure was verified. Finally, compared with the calculation results obtained by SAP2000, the validity of the equations and the effectiveness of the analysis method were proved. This paper provides a new way for the dynamic analysis of base-isolated structures.

Introduction

In order to mitigate the effects of earthquakes on buildings, scholars have carried out a large amount of research on design methods and techniques of aseismatic structure. The isolation is a kind of shock absorption technology and has been applied in engineering widely. Some scholars have carried on the comprehensive research on development of rubber bearing, structure model tests, isolation structures' analysis and theoretical design methods (Zhou F. L 2016; Tang J.X 2002; Zhou X.Y 2013). At present, there are two kinds of calculation models for dynamic analysis of base-isolated structures: One is to consider the overall structure as a single degree of freedom system; the other is to use layer model, which consider the isolation layer and the upper structure separately as a multi-degree of freedom system. The seismic response of upper structure can be obtained when using the second model, and the calculation results are more accurate. The time integral method with variable stiffness is generally adopted as a calculation method. As a new method of nonlinear analysis, the force analogy method (FAM) has been applied in many fields. Wong et al. (2010) applied FAM to calculate a structure with tuned mass dampers (TMD). Qu J.T et al. (2013) studied the location optimization of viscoelastic dampers based on FAM, which expands the application of FAM. So far, the application of FAM in isolation structures has not been studied and layer models are generally adopted to analyze isolation structures. In this paper, a calculation model of a base-isolated structure based on FAM is proposed. The motion equations of an isolation system are established. Finally, the effectiveness of the suggested method is verified.

The establishment of motion equations based on FAM

Compared with ordinary rubber bearings, a lead rubber bearing (LRB) has advantages of large vertical stiffness and good energy dissipation ability. This type of bearing is selected when establishing the calculation model of isolation structures and doing dynamic nonlinear analysis. The force-deformation model of a LRB is expressed by the bilinear model. The analytical model of a base-isolated structure is shown in figure 1 (select a 3-span model for example). The black solid circles show possible positions of plastic hinges on the beam and column ends. m_b and k_b represent the quality and stiffness of the isolation layer. Shear plastic deformation may occur in isolation bearings. The equation of motion for an isolation structure based on FAM can be written by:

$$M_{is}\ddot{Z}(t)+C_{is}\dot{Z}(t)+K_{is}Z'(t)=-M_{is}ea_g(t) \qquad (1)$$

where $Z'(t)$, $\dot{Z}(t)$ and $\ddot{Z}(t)$ are the relative elastic displacement, relative velocity and relative acceleration vectors of an isolation structure; M_{is}, K_{is} and C_{is} denote the mass, stiffness and damping matrices of an isolation structure.

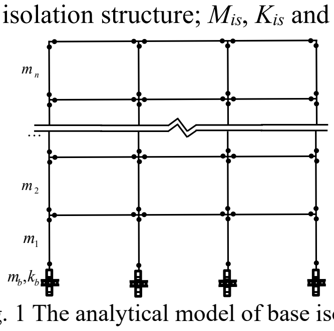
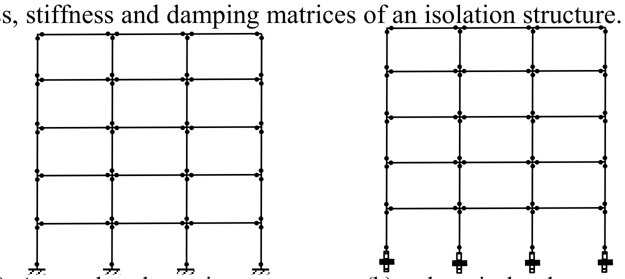


Fig. 1 The analytical model of base isolation structure



(a) An earthquake resistant structure (b) a base-isolated structure

Fig. 2. Two analytical models of structures

Using the static condensation and integrating from 0 to t_k, the energy equation of an isolation structure based on FAM can be obtained:

$$\int_0^{t_k}\ddot{W}_d(t)^T M_{isdd}dW_d+\int_0^{t_k}\dot{Z}_d(t)^T C_{isdd}dZ_d+\int_0^{t_k}Z'_d(t)^T\bar{K}_{is}dZ'_d+\int_0^{t_k}Z'_d(t)^T\bar{K}_{is}dZ''_d=\int_0^{t_k}\ddot{W}_d(t)^T M_{dd}dZ_g \qquad (2)$$

where M_{isdd}、 C_{isdd} and $\bar{K}_{is}$ imply the mass, damping, and stiffness matrix of the base-isolated structure after the static condensation; $\ddot{W}_d(t)=\ddot{Z}_d(t)+\ddot{Z}_g(t)$, $\ddot{W}_d(t)$, $Z_d(t)$, $Z'_d(t)$ and $Z''_d(t)$ are absolute acceleration, relative displacement, relative elastic displacement and relative plastic displacement vectors after the static condensation.

Numerical Analyses

A three-span and five-story steel aseismatic structure is chosen and its analytical model is shown in figure 2 (a). A base isolation structure with the same span and story is established based on FAM (as shown in figure 2 (b)). The isolation layer is set between the upper structure and the foundation. The parameters of the beams and columns of the structures are shown in Table 1. The isolation bearing type for GZY700-140 is chosen. The Friuli, Italy seismic record in 1976 is chosen. The values of peak ground accelerations are scaled to 310 gal and 620 gal respectively.

Table 1. Parameters of the members

Component type		*EI*(Bending stiffness) (kN·m^2)	M_p(The yield strength of plastic hinges) (kN·m)
Columns	Side columns	1.782×10^5	1.302×10^3
	Center columns	3.604×10^5	2.453×10^3
Beams		2.722×10^5	1.131×10^3

Using the magnified Friuli earthquake with scaled peak value 310 gal as the input earthquake ground acceleration to the aseismatic and base isolation structures, dynamic time history analysis are done. The comparison of displacement between the two structures is shown in figure 3. The calculation results indicate that the displacement of isolation layer is bigger than the story drift of the upper structure for an isolation structure. The displacement of isolation layer is 0.092m, accounting for 63% of the displacement of the top story. Energy analyses are done for the aseismic structure and base-isolated structure. The plastic energy dissipation of the two structures are 1080 and 52.3 kN·m respectively. The plastic hinge distribution of the aseismic structure is shown in figure 4 (unit:kN·m). The results indicate that the plastic energy dissipation of the isolation structure decreases 95% than that of the aseismic structure, which is dissipated all by isolation bearings. The upper part of the isolation structure is still in good condition and the isolation layer plays an important role.Using the magnified Friuli earthquake with scaled peak value 620 gal as the input earthquake ground acceleration to the base isolation structures, energy analysis is done. Figure 5 shows the plastic hinge distribution of the isolation structure. The plastic energy dissipation of the isolation layer and upper part are 712.22 and 22.6 kN·m, respectively. The results indicate that most of the input energy is consumed by the damping and isolation bearings.

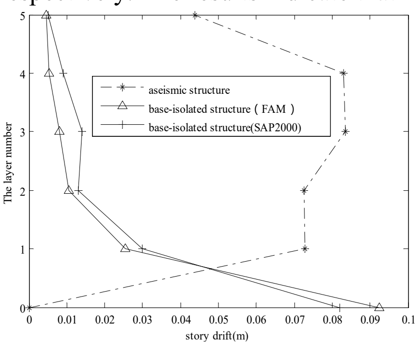


Fig.3 Contrast of displacement for the aseismic structure and isolation structure

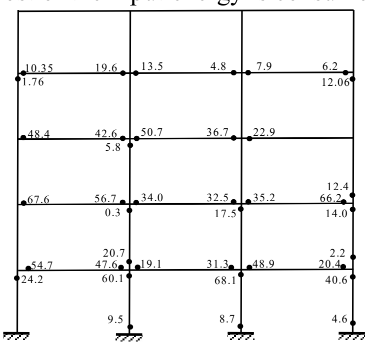


Fig.4 Plastic hinge distribution and PE dissipation of aseismic structure

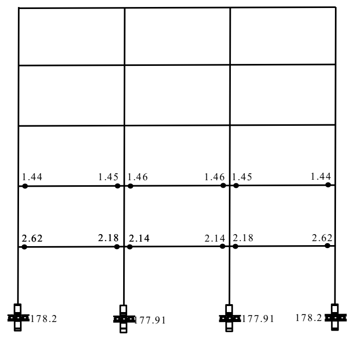


Fig.5. Plastic hinge distribution and PE dissipation of the isolation structure (unit:kN·m)

Conclusions

(1) By comparing the calculation results of FAM and SAP2000, the correctness and effectiveness of the methods and equations proposed in this paper are proven. In addition, the energy analysis of two structures indicates that the plastic energy dissipation of upper structure decreases obviously after the isolation layer is added.

(2) According to the energy equation established in this paper, it can be seen that most of the plastic energy is consumed by damping and isolation bearings and the isolation layer plays an important role.

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