CEE 5464
Structural Dynamics & Earthquake Engineering

Saurabh Patil
Ronit Raj Baishya
Yuhao Li

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1 Acknowledgement

We express our deep gratitude to Dr. Rodrigo Sarlo (and also Instructor Santiago Bertero) for introducing us to various facets of analyzing structures' responses to different kinds of loading, leading to static and dynamic effects. This final project proved to be a combination of lessons learned along the way, strung together to answer the question we had at the beginning of the course: What factors should be considered to limit the damage to buildings due to dynamic loading?

In this report, we will go through different phases covering the design of a base isolator for a structure.

2 Objective

In this project, we will design a miniature base isolation demo. The objective is to design the total mass, stiffness, and damping (m_b, k_b, c_b) of a base isolation system for a single-story building, subject to the design spectrum described below. An effective isolator will result in a maximum moment that is significantly lower than that of the no-isolation case (fixed base). The target reduction in the base moment is shown in Table 1. The challenge is that as you make the isolator more flexible, it will also deform more and could break as well, so we also will place a limit on the maximum allowed deformation.

Requirement	**Limit**
Target reduction in moment	$> 50\%$
Maximum allowable isolator deformation	2 cm

Table 1: Isolator Design parameters

3 Building Description

The building is a 1 story 3D printed model, with dimensions (mm) shown in Figure 1. It carries a 1 kg mass on the roof. It is printed from PLA plastic, which has nominal properties shown in Table 2. This data (link to free vibration response) gives a free vibration response of the building, which may be useful in determining additional parameters about the building.

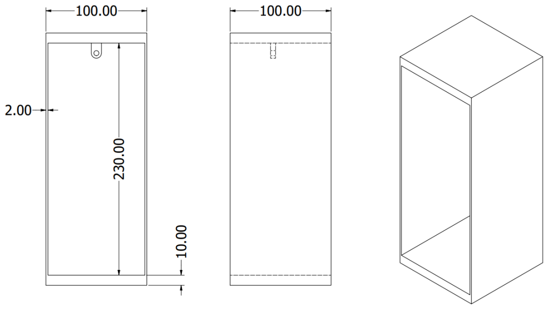

Figure 1: Building dimensions (mm)

Property	**Value**
Elastic Modulus	2.4 GPa
Ultimate strength	50 MPa

Table 2: PLA Plastic Engineering Properties

4 Problem and challenges

The problem is to design a base isolation system for a single-story building with a 1 kg mass on the roof, subject to a given ground motion, such that the maximum moment in the building is significantly reduced. The design should consider the total mass, stiffness, and damping of the base isolator, as well as a limit on the maximum allowable deformation.

1. Ground motion selection: The selection of an appropriate ground motion is crucial for the design of the base isolator. It is important to choose a ground motion that is representative of the seismic hazard at the site and that can be used to validate the design. The availability and quality of ground motion records can also be a challenge. In our case, we are assuming the location of interest is Abeno, Japan.

2. To create an elastic design spectrum that is similar to the chosen ground motion, one may face difficulties. It is important to create a design spectrum that is conservative and provides an approximate representation of the ground motion. This design spectrum can then be utilized to determine the base isolator parameters.

3. Isolator parameter selection: The selection of isolator parameters including mass, stiffness, and damping constant which are critical to the success of the base isolation system. The chosen parameters should provide the desired reduction in the resulting moment while also ensuring that the maximum allowable deformation is not exceeded. The optimization of these parameters can be a complex process.

4. To ensure precise analysis and design of the base isolator, it is essential to model the building accurately. The building is considered a two-degree-of-freedom system, which necessitates performing multiple degrees of freedom analysis. However, determining the accurate values of the structural parameters, including stiffness, mass, and damping ratio, in the two-degree-of-freedom model can be challenging. The precision of the analysis is heavily reliant on accurately determining these parameters.

5 Phase 1: Analyzing the fixed base case

For this assignment, we imported the ground motion time series of the KOBE earthquake (Japan, 1/16/1995, Abeno) from the PEER database and imported it into MATLAB. Acceleration time series in units of g, NPTS = 14000, dt = 0.0100 SEC. We will use this ground motion for validating the design.

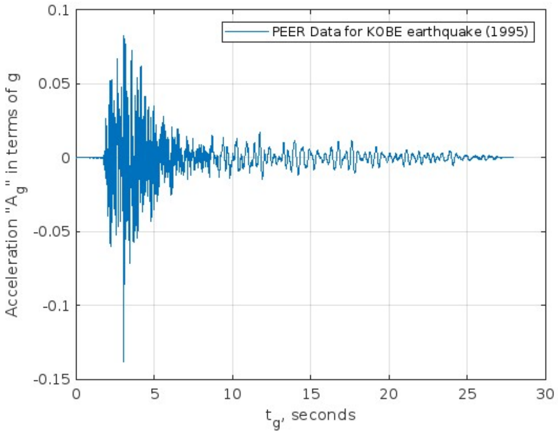

Figure 2: PEER Data for KOBE earthquake

Next, in order to simplify the design process, we define an elastic design spectrum (from Unit 6) that roughly matches your ground motion. We will use it for designing the isolator parameters: m_b, k_b, c_b.

We used the response spectrum function file to come up with the pseudo-acceleration response of the structure.

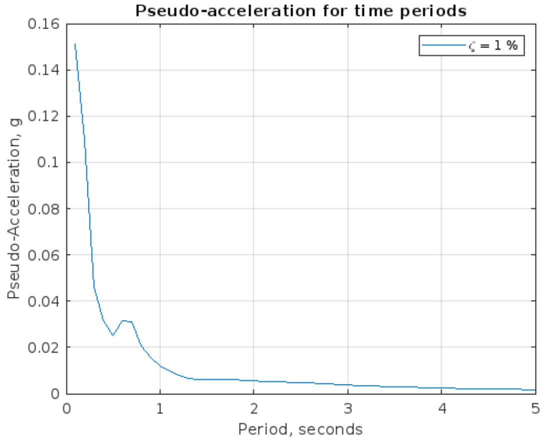

Figure 3: Ground acceleration response

Now within certain limits, we define the parameters - the parameters for managing the function file going through iterations for the design and use the elastic design spectrum function file to come up with the acceleration response.

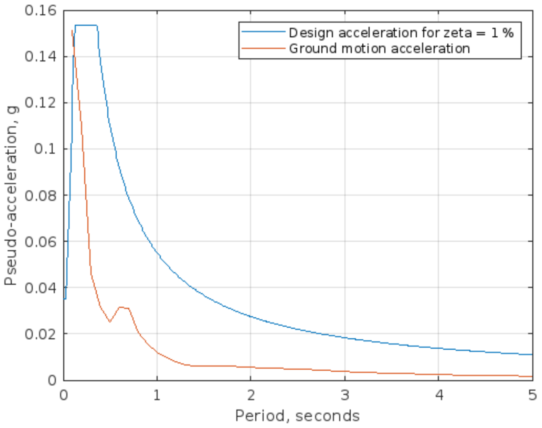

Figure 4: Superimposed response plots for design and ground acceleration

Corresponding to the values obtained from the plot for the free vibration of the structure we get the value for the time period as $'T_n = 0.3422sec'$ and corresponding to that we have the $A = 0.1533g$.

The design moment we got from the calculations is $M(design) = 0.3459N - m$.

Calculation of the maximum moment produced by the ground accelerations of the earthquake $M(actual) = 0.2176N - m$.

Clearly, the structure is well under the safe limit from failure as the maximum moments that can be reached is well over the actual maximum moment.

6 Phase 2: Designing the base isolator

For the design of the base isolator, the moment was decreased. the reduction was based on the reduction targets in Table 1. For simplification, a key assumption was made that the building behavior can be idealized by treating the entire building as a rigid body (except for the isolator). In other words, it will be an SDOF system with stiffness k_b, damping c_b, and mass $m(bldg) + m_b$, where m(bldg) is the mass of the building without isolation. So this phase will consist entirely of SDOF analysis. The limit for moment reduction from table 1 is $> 50\%$.

The design spectrum for the fixed base case and the point corresponding to the building's period was visualized. The pseudo-acceleration of this mode was dropped by the target amount, then using the response spectrum graph a new period was picked which would satisfy this target. k_b and m_b are tweaked until the target period is achieved.

c_b was chosen such that the maximum deflection of the isolator is limited and a deformed design spectrum was used instead of pseudo-acceleration.

This results in a new acceleration value which comes out to be $0.0782g$ which further means the time period new is $0.7sec$.

Assuming the following properties for m_b, k_b, c_b.

$$m_b = 0.75kg$$

$$k_b = 140.99N - m/rad$$

$$c_b = 2.69N - sec/m$$

Again by using the above new parameters, we calculate the acceleration but we would like to know the deformation response this time so we will convert the acceleration response to deformation design spectra.

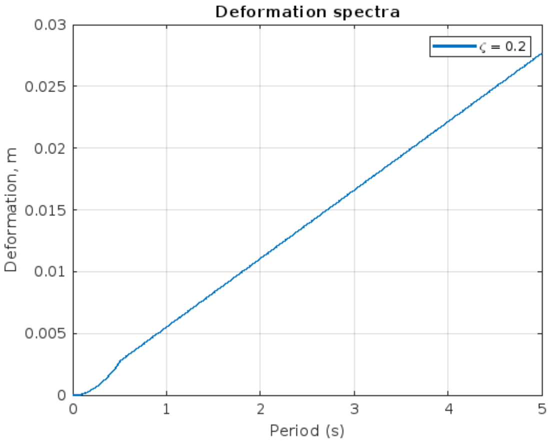

Figure 5: Deformation design spectra

7 Phase 3: Validating the isolator design through MDOF response

As evident from the plot shown above the maximum deflection limit is well within the required limit $(0.4cm < 2cm)$.

In phase 3 the designed values of m_b, k_b, c_b were used to simulate the isolated building response and validate its behavior. An MDOF analysis is required since it is a 2 DOF system now.

Creating the mass, stiffness, and damping matrix we further seek values for mode shapes. For further calculations, we used the Newmark MDOF model, and the resulting displacement through calculations is $0.0927cm$ which is well within the 2cm limit.

At the end of the code we also calculate the modal contribution factors.

The isolator seems to be performing well as the maximum allowable isolator deformation is well under the limit. The actual response of the structure may differ from the design as the assumptions taken may not stand ground in the real world. The analysis here has been idealized such that the whole system is assumed to be rigid instead of flexible.

The following lists how MDOF analysis might end up failing,

1. Insufficient isolator capacity: The base isolator may not have enough capacity to withstand the forces and moments transmitted from the building during an earthquake. This can cause the isolator to fail or the building to experience excessive deformation or displacement.

2. Inaccurate modeling: If the building is not accurately modeled in the MDOF analysis, the isolator design may not be adequate to protect the building from damage. This can occur if the stiffness, mass, or damping properties of the structure are not estimated correctly.
3. Incorrect isolator parameters: The selected isolator parameters, such as stiffness, damping, and mass, may not be appropriate for the building and the ground motion. This can lead to poor performance or failure of the base isolation system.
4. Inadequate detailing: If the details of the base isolator installation are not carefully designed and constructed, it may fail to perform as expected during an earthquake. For example, inadequate anchor bolts or poor connections between the isolator and the building can compromise the performance of the system.

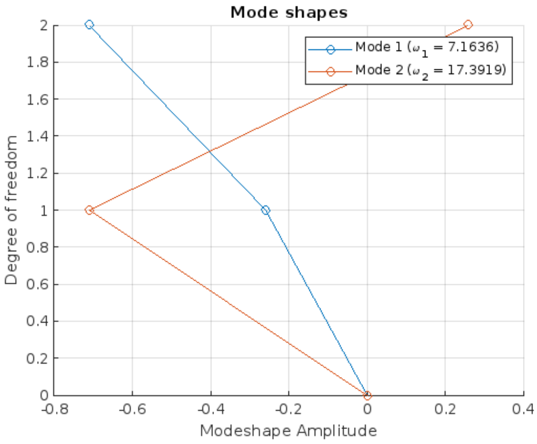

Figure 6: Mode Shapes

8 References

1. Wu. T., *"Design of Base Isolation System of Buildings"*, Master of Engineering 2001 project, Department of Civil and Environmental Engineering, Massachusetts Institution of Technology, 2001
2. Manarbek, S. (n.d.). *"Study of Base Isolation Systems"* - Massachusetts Institute of Technology. https://dspace.mit.edu/handle/1721.1/82820
3. Jalihal, P. and Utku, S., ''Active Control in Passive Base Isolated Buildings Subjected to Low Power Excitations, Computers, and Structures" Vol. 66, pp. 211-224, 1998.
4. Chopra, A. K. (2015). *Dynamics of Structures: Theory and applications to earthquake engineering.* Prentice Hall.