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Enhancing the teaching of seismic isolation using additive manufacturing

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ABSTRACT

This paper provides a complementary study to two previous papers by Virgin (2017a,b). In those papers, 3D printing was used to provide hands-on experience for students studying structural analysis and structural dynamics, respectively. In this paper, the application of 3D printing is extended to investigate advanced seismic design strategies, namely seismic isolation. This paper describes the use of 3D printing to fabricate pendulum-type isolation bearings under parametric variation. Both sliding and rolling mechanisms are modeled, designed, fabricated and tested, and the influence of bearing geometry (radius) and damping (friction versus rolling resistance) on dynamic characteristics and isolation performance is explored.

1. Introduction

Seismic isolation is a practical strategy for earthquake-resistant design whereby a flexible interface is introduced between the structure and its foundation [3,4]. This has the result of lengthening the fundamental period of the structure, thus reducing the sustained accelerations in this mode and the earthquake-induced forces in the structure. Additive manufacturing (or 3D printing) offers compelling pedagogical opportunities in the context of learning seismic isolation. Pendulum-type isolators of simple geometry enable students to easily design, print, and test the isolation systems to verify isolation principles. The capabilities of 3D printing will allow for varied designs at a lower cost compared to full-scale modeling. Varying the component geometries (e.g., curvature of the isolator) would allow for comparative studies that can be easily repeated, therefore allowing the student the opportunity to observe and compare theoretical calculations to empirical data. This paper provides a complementary study to previous papers by Virgin addressing structural analysis [1] and structural dynamics [2].

1.1. Basic theory of seismic isolation

In active seismic areas, buildings and their contents are susceptible to harmful vibrations from earthquake ground motions, posing a threat to the structural integrity of buildings and damage to sensitive equipment. Consider the fixed-base building shown in Fig. 1(a), which has lumped mass m, damping coefficient c, and lateral stiffness k. The natural period of the fixed-base structure is given by

$$T_\mathrm{f} = \frac{2\pi}{\omega_\mathrm{f}} \quad \text{where} \quad \omega_\mathrm{f} = \sqrt{\frac{k}{m}} \tag{1}$$

The natural period calculated from this equation, together with the damping ratio $\zeta_\mathrm{f} = c/(2\sqrt{km})$, is used to determine the pseudo-acceleration and hence earthquake-induced forces in the structure from elastic design spectra (Fig. 2). The fundamental period of low- to medium-rise buildings is commonly in the range of periods where earthquake energy is strongest, giving rise to large spectral accelerations. These accelerations can be reduced if the structure is designed to be more flexible (longer period), but this approach may be neither feasible nor practical [5]. The necessary flexibility can be achieved by *base isolation*. Base isolation provides an alternative to the standard, fixed-base design of structures and may be cost efficient for new buildings in highly active seismic locations [6].

Consider the same m-c-k structure from before but now mounted on a base slab of mass m_b supported by isolation bearings (Fig. 1(b)). The isolation system has lateral stiffness k_b and damping coefficient c_b. The period of the isolation system, assuming the building to be rigid, is given by

$$T_\mathrm{b} = \frac{2\pi}{\omega_\mathrm{b}} \quad \text{where} \quad \omega_\mathrm{b} = \sqrt{\frac{k_\mathrm{b}}{m + m_\mathrm{b}}} \tag{2}$$

The base isolation period T_b must be much longer than the fixed-base period T_f in order to be effective in reducing the spectral accelerations and as a result the forces in the building. The two-degree-of-freedom system that defines the isolated structure (Fig. 1(b)) has two natural periods (T_1,T_2) that are close to, but do not exactly match, the fixed-base period T_f and isolation period T_b. The periods of the coupled system are given by

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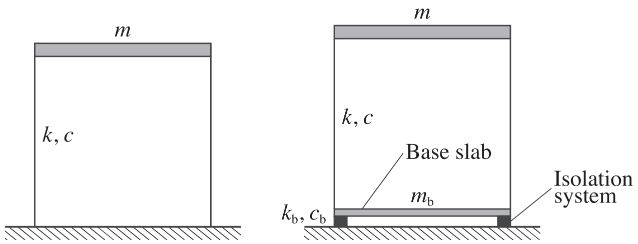

(a) Fixed-base structure (b) Isolated structure

Fig. 1. Conceptual idealization of fixed-base (a) and isolated (b) structures.

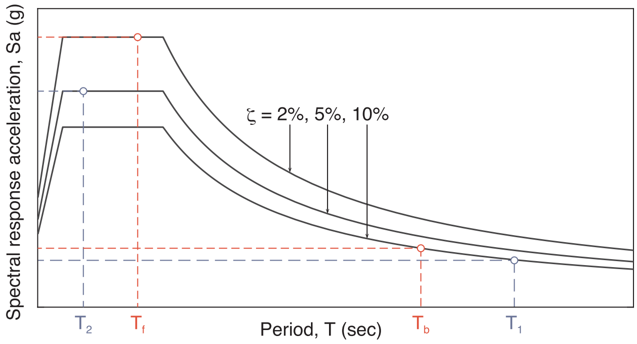

Fig. 2. Elastic design spectra.

$$T_1 = \frac{2\pi}{\omega_1} \quad \text{and} \quad T_2 = \frac{2\pi}{\omega_2} \tag{3}$$

where the natural frequencies are found from the following equation [7]:

$$\omega_{1,2}^2 = \frac{1}{2(1-\gamma)}[\omega_b^2 + \omega_f^2 \mp \sqrt{(\omega_b^2-\omega_f^2)^2 + 4\gamma\omega_b^2\omega_f^2}] \tag{4}$$

in which the mass ratio γ is defined as

$$\gamma = \frac{m}{m + m_b} \tag{5}$$

Fig. 3 shows the influence of γ and the period ratio on the coupled system's modal periods.

The first mode is called the *isolation mode* because the isolation system undergoes deformations but the structure behaves as essentially rigid. The second mode is called the *structural mode* because the it involves deformation of the structure as well as the isolation system. While the structural mode's pseudo-acceleration may be large (Fig. 2), this mode is essentially not excited [6] and contributes little to the earthquake-induced forces in the structure. The earthquake-induced forces are dominated by the fundamental (isolation) mode, which has low pseudo-accelerations (Fig. 2). Further, these forces are carried by the isolation bearings because the isolation mode involves deformations primarily in the isolation system. Hence the primary benefit of base isolation is the lengthening of the fundamental period, reducing earthquake-induced forces in the building. A secondary benefit of base isolation is the reduction in structural response through the damping in the isolation system [7].

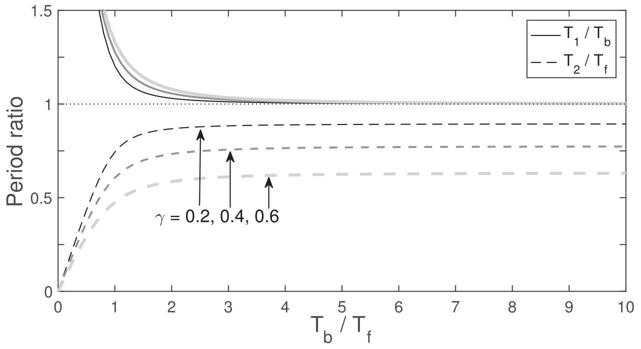

Fig. 3. Effect of mass ratio γ and uncoupled period ratio T_b/T_f on the coupled system's natural periods T_1 and T_2.

1.2. Seismic isolation in practice

In practice, two types of isolation systems are commonly used. The first type involves the use of a flexible layer between the base of the structure and its foundation. The most common system of this type is laminated rubber bearings (LRB). These are short, cylindrical bearings with alternating layers of steel plates and hard rubber to remain vertically stiff yet horizontally flexible [8]. The addition of damping is readily incorporated through mechanical dampers such as hydraulic dampers, steel dampers, or a lead core [9].

The second type entails placing a pendulum mechanism between the foundation and the base of the structure. The most common system of this type is the *friction pendulum bearing* that operates through a sliding mechanism [10,11]. The sliding interface provides enough friction to withstand strong winds and small earthquakes, while having a low coefficient of friction to dissipate shear forces created from large earthquakes. The sliding displacement is limited by curved sliding surfaces that provide a restoring force to return the bearing to its equilibrium position. In particular, the friction pendulum sliding bearing employs spherical sliding surfaces that slide relative to each other when the ground motion overcomes the static friction. When sliding occurs along the spherical surfaces, the building raises slightly resulting in gravitational restoring forces. Another type of pendulum bearing is the *rolling pendulum bearing*, which operates under the same gravitational restoring action [12]. These systems tend to have much less damping then their sliding counterparts due to the rolling resistance being much less than friction in sliding bearings [13]. For the purpose of this study, the isolation systems of interest are limited to rolling and sliding systems.

2. 3D printing of seismic isolation bearings

3D printing has increasingly been used as a teaching and research tool in mechanical engineering [14], revolutionizing the prototyping of mechanical components such as gears. More recently, 3D printing has been used to teach linear structural analysis [1] and structural dynamics [2] in the context of civil engineering. Thus, 3D printing has the capabilities of being used to teach base isolation, merging efforts from across mechanical and civil engineering disciplines. We shall focus attention on planar, pendulum-type isolation bearings supporting a single-degree-of-freedom planar frame structure. Two mechanisms are considered for the isolation bearings: sliding and rolling. These mechanisms were chosen partly to facilitate 3D printing, but also due to their ubiquity in practice. We shall focus attention on relatively simple geometries, as discussed in the following section, to obtain linear force-displacement relationships, but more complex geometries are discussed later.

2.1. Isolation bearing design and fabrication

In this study, we consider two typical pendulum-type isolation bearings: friction pendulum (FP) bearings and rolling pendulum (RP) bearings. Fig. 4 shows the design for the FP bearing, which was modeled after a common design in practice [15]. The bearing is comprised of a bottom plate with circular sliding surface of radius R that is attached to the ground, an upper plate that supports the structure, and an articulated slider that transfers the load between the sliding surface and the upper plate. Fig. 5 shows the design for the RP bearing, which is comprised of lower and upper rolling surfaces (both of radius R) and a