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Seismic response of building frames with flexible base optimized for reverse rocking response

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ABSTRACT

A reverse rocking response is investigated for a steel frame that has flexible base. The mechanism of response reduction is first investigated using a simple flexible base model consisting of truss elements. It is demonstrated that the roof displacement is reduced by the dominant second mode, in which the base rotates in the opposite direction to the upper frame. Seismic responses of the frame can be further reduced by installing viscous dampers at the support. A topology optimization approach is next presented for design of flexible base structure consisting of frame elements. It is shown that the cross-sectional properties and nodal locations are successfully optimized using a nonlinear programming approach to generate a flexible base.

1. Introduction

The approaches to reduction of seismic responses of building frames are classified into (a) *seismic design*: stiff design of the structural members so as to resist the seismic load within the allowable small deformation, (b) *base isolation*: reduction of the seismic input energy by increasing the natural period, and (c) *passive vibration control*: dissipation of seismic energy utilizing plastic deformation, viscosity, and/or inertia. In this paper, we present a new approach that is not categorized into any of the above three approaches.

The basic principle of seismic design of a building frame does not allow uplift of the column-base, because it may lead to a damage to the foundation as well as an unexpectedly large deformation of the frame during a severe earthquake. However, it is possible to utilize a rocking system, allowing uplift of the column base, to reduce deformation of the upper frame through energy dissipation at the column base as well as the increase of potential energy of the upper frame due to overturning moment [1–7]. A rocking system also reduces the input energy by increasing the natural period of the frame during uplift. Seismic responses can also be reduced utilizing a soft first story [8–10], partial uplift of each column base [11], and base isolation with rocking device [12,13]. On the other hand, a flexible structure such as a compliant mechanism [14–16], which utilizes flexibility of structural elements, can also be used for devices for seismic response reduction such as base isolation [17,18] and tuned mass damper [19,20]. A flexible structure enables large deformation and stores elastic strain energy through deformation.

Optimization of frames and trusses under seismic excitation has been extensively studied since 1970s. In the early stage, the responses were evaluated using a response spectrum approach [21,22]. If a single mode dominates in the seismic response, then reduction of seismic response is closely related to mode control. In the field of mechanical engineering, several optimization approaches have been developed for specifying the mode shape [23,24].

Recently, large deformation under long-period ground motion has become a critical issue for design of building frames. It is not always safe to utilize a base-isolation system, because it increases the first natural period and the structure may have large deformation under long-period motion. Therefore, a new seismic design approach that does not rely on increase of natural period is desired to be investigated.

Reduction of roof displacement and acceleration is important to mitigate damage of nonstructural components and to improve serviceability in upper stories of a building frame during earthquake. Todorovska [25] proposed a rocking system with inclined rubber bearing. Zhang [26,27] investigated a simple base model with inclined columns. However, in these papers, the parameters such as the nodal locations and cross-sectional properties are not optimized, and the relation between stiffnesses of the upper and base

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structures are not discussed in detail. Rocking mechanisms can also be used for bridge piers [28,29].

In this paper, we first investigate a reverse rocking response of a steel frame that has a flexible base. The mechanism of response reduction is investigated using a simple flexible base model consisting of truss elements. We next propose a new flexible structure that can reduce the roof displacement of a building frame utilizing rocking response. Topology optimization is carried out for a base model consisting of frame elements. It is shown that the cross-sectional properties and nodal locations are successfully optimized to generate a flexible base using a nonlinear programming approach.

2. Overview of flexible base for reverse rocking of building frame

We first demonstrate the effectiveness of reverse rocking response for reduction of roof displacement using a simple flexible base model as shown in Fig. 1, which is to be attached below the ground level of a plane frame. This structure can also be regarded as a soft first story. However, for the consistency of notation throughout the paper, we call this *flexible base*, and the beam between nodes 5 and 6 at the ground level is called *base beam*.

Fig. 2 illustrates the deformation of the base and upper frame subjected to horizontal loads, where the frame is simply represented by a column. Owing to the flexibility of the base, the frame with flexible base has a *reverse rocking response* as shown in Fig. 2(a); i.e., the base beam rotates in the opposite direction to the drift of frame to reduce the displacement of the roof. By contrast, if the frame has a stiff base, the base beam rotates slightly in the same direction as the frame as shown in Fig. 2(b). This way, the roof displacement against horizontal loads can be reduced utilizing a flexible base.

In the following, each member is indicated by the two nodes at its two ends; e.g., the member connecting nodes 1 and 2 is denoted by 'member 1-2'. The flexible base in Fig. 1 consists of six truss members and one stiff base beam (member 5-6). The truss members 1-5, 2-5, 3-6, and 4-6 are stiff enough, and horizontal truss members 1-2 and 3-4, which are called *thin members*, have small stiffness to realize a flexible base. Note that a thin member can actually be manufactured as a spring. The horizontal vibration of the upper frame leads to horizontal displacement of the roller supports 2 and 3; hence, the shape of dominant mode against horizontal excitation becomes different from that of the conventional model with a stiff base.

3. Design response spectrum and method of seismic response evaluation

The design acceleration response spectrum is specified according to the Notification 1461 of Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), Japan, corresponding to the performance level of operational limit for the Design Based on Calculation of Response and Limit State, which is similar to the capacity spectrum approach. The amplification factor for the ground of second rank in Notification 1457 of MLIT is used. The response acceleration spectra for the damping factor $h = 0.02$, 0.05, and 0.10 are plotted in Fig. 3.

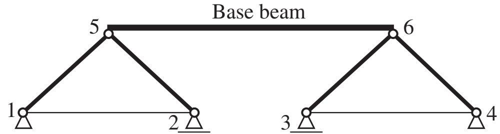

Fig. 1. A simple flexible base model.

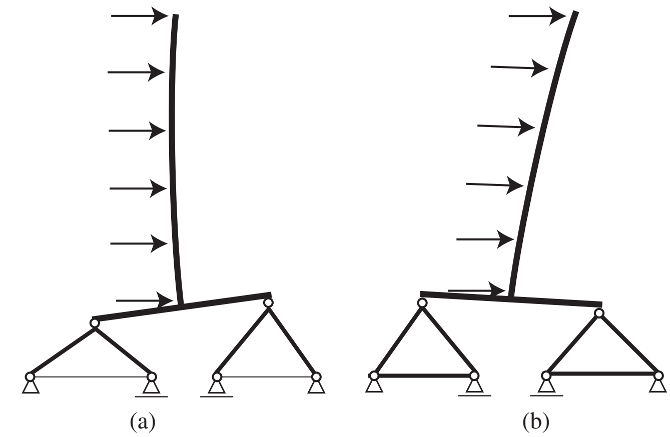

Fig. 2. Deformation of a frame model subjected to horizontal loads: (a) flexible base, (b) stiff base.

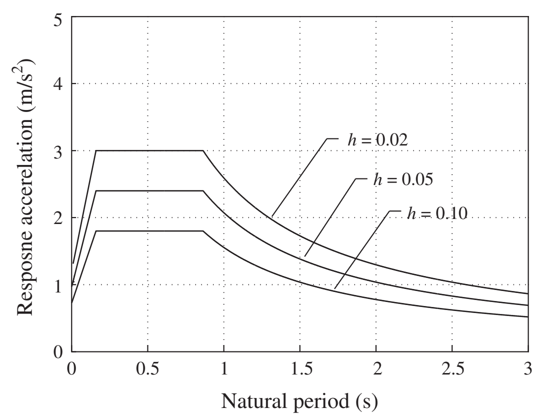

Fig. 3. Design acceleration response spectra for damping factors 0.02, 0.05, and 0.10.

In the following examples of a frame supported by the truss model in Sections 4.2 and 4.3 and optimization process of the frame model in Section 5, the mean-maximum displacements against seismic excitations are evaluated using the square-root-of-sum-of-squares (SRSS) method. The pseudo-displacement response spectrum $S_{Di} = S_D(T_i, h_i)$ corresponding to the period T_i and damping factor h_i of the ith mode is defined from the acceleration response spectrum $S_A(T_i, h_i)$ as $S_{Di} = S_A(T_i, h_i)/(\omega_i)^2$, where ω_i is the ith natural circular frequency. The mean-maximum response u_j of the jth displacement component is evaluated by:

$$u_j = \sqrt{\sum_{i=1}^{s} (\beta_i \phi_j^i S_{Di})^2} \quad (1)$$

where β_i is the ith participation factor, ϕ_j^i is the jth component of the ith mode, and the lowest s modes are incorporated for response evaluation. Note that geometrical nonlinearity is not considered, because rotations of the base and upper frame are sufficiently small.

Ten ground motions compatible to the design acceleration response spectrum are generated for investigation of time-history responses. The duration of each motion is 20 s., and the time increment is 0.01 s. A standard approach of superposition of sinusoidal waves is used [30,31]. The phase of each discretized frequency component is defined using the phase spectrum of the El Centro EW ground motion, because it is important to use the sequence of phases of a recorded ground motion rather than generating it randomly [32]. Suppose the seismic ground motion is generated using K sinusoidal waves. The phase φ_i the ith frequency