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Simplified design procedure for controlled spine frames with energy-dissipating members

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ABSTRACT

A controlled spine frame system consisting of an elastic moment frame, elastic spine frame and concentrated yielding elements is proposed to ensure continuous usability of buildings in the event of an earthquake exceeding the design level. Prior studies have documented the excellent performance of spine frame structures in preventing both the concentration of damage in soft stories as well as in providing self-centering. The current study develops a simplified design method based on equivalent dual multi-degree-of-freedom and single-degree-of-freedom representations, discussing the effects of damper yield drift, and stiffness ratios between the elastic moment frame, spine frame, and dampers on the structural response. This design method is validated with a parametric study and optimal ranges of the stiffness ratios are provided.

1. Introduction

There is a high probability of large magnitude earthquakes striking major cities in Japan, particularly along the Nankai trough [1,2]. Furthermore, the buildings in these areas may be subjected to multiple events of design level intensity throughout their life. To aid rapid recovery, it is essential to ensure continued usability of buildings, particularly so for public buildings serving as post-disaster shelters or with other critical functions, such as hospitals, schools, and gymnasiums.

Previous studies have proposed and applied various spine systems in both retrofit and new build applications. Z. Qu et al. [3] employed a pivoting spine concept in the seismic retrofitting of a concrete building in Japan. B. Janhunen et al. [4] proposed a seismic retrofit solution by adding a single pivoting concrete spine to the center of a 14-story building to improve the drift pattern and distributed yielding at all levels of the building. M. Eatherton et al. [5,6] carried out a shake table test of an uplifting steel rocking frame system with post-tensioned (PT) strands to provide self-centering, and proposed several design concepts for this system. J. Lai and Mahin [7] examined the Strongback system, which combines aspects of a traditional concentric braced frame with a stiff mast to resist the tendency of damage concentration in a single or a few stories.

A controlled spine frame has been proposed by the authors, as shown in Fig. 1, and applied in the design of a new five-story research center at Tokyo Tech's Suzukakedai campus [8]. This spine frame consists of (1) a stiff braced steel frame (*i.e.*, spine frame), (2) replaceable energy-dissipating members (buckling restrained columns, BRC), and (3) envelope moment-resisting frames. The spine frame prevents the concentration of damage. Unlike the system proposed by M. Eatherton et al. [5,6], the envelope moment frames are designed to remain elastic and reduce residual drifts, providing the self-centering force without resorting to post-tensioning. The input seismic energy is absorbed by BRCs, which feature significant cumulative deformation capacity, and if required can easily be replaced following a large earthquake. This combination of structural elements reduces or effectively eliminates repair cost and downtime.

The spine frames and moment frames offer superior performance in preventing damage concentration and reducing residual deformation. However, the performance in taller structures and the effect of main structural parameters on the seismic performance are unclear. Additionally, an easy and reliable seismic design procedure is urgently required to improve the system efficiency and promote the concept in the industry. In this study, a simplified dual multi-degree-of-freedom (DMD) model was constructed to examine the dynamic characteristics of the spine frame structures. The DMD model proposed in this study is expected to exhibit nonlinear behavior similar to the full model, particularly in terms of the distribution and maximum values of story drift and shear force. Based on this model, the optimal design of the controlled spine frame structure was investigated, and a simple design procedure was proposed based on an equivalent single-degree-of-freedom (SDOF) system. A parametric study with representative design indices was conducted to compare the seismic responses of the DMD and SDOF models. Optimal ranges of key system parameters and the

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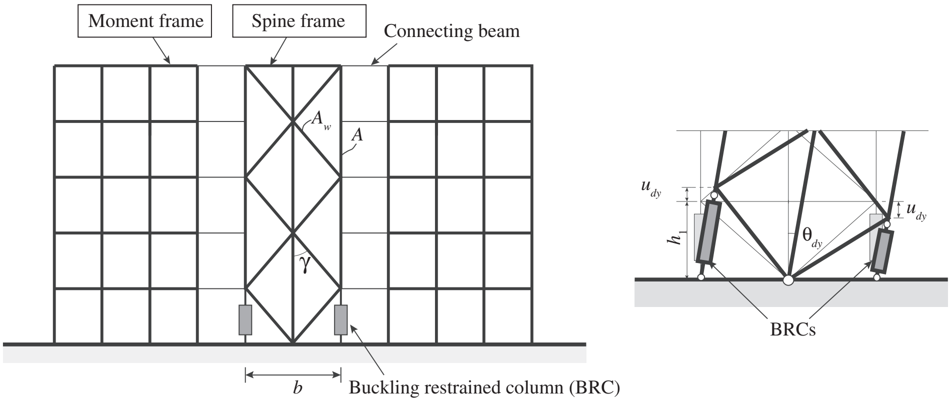


Fig. 1. The concept of a controlled spine frame structure.

applicable scope of the proposed design method was determined.

2. Analytical models for the controlled spine frames

2.1. Benchmark building structures

In order to investigate the effect of the controlled spine system, the three benchmark buildings shown in Fig. 2 were designed as per the Japanese building design codes [9], representing typical office buildings of various heights (5-story, 10-story, and 20-story). The main frames were designed to remain elastic and the damper yield strength taken as 325 MPa. As a simplifying design assumption, for this study the lateral stiffness was set proportional to the story shear, as shown in Fig. 3. However, in general, stiff spine frames provide greater latitude in story stiffness distribution, suppressing soft story formation. Simplified dual multi-degree-of-freedom models of these benchmark structures were used to validate the simplified design methods introduced in the following section.

2.2. Basic concepts and assumptions of the DMD model

A simplified dual multi-degree-of-freedom (DMD) model was constructed to clarify the key characteristics governing the response of the controlled spine frame. The concept of the DMD model used for studying the controlled spine frame is shown in Fig. 4, where the elastic moment frame and controlled spine frame are idealized as two parallel multi-degree-of-freedom (MDOF) models. The moment frame constrains the lateral deformation of the spine frame, with the connecting beams transferring only horizontal force, and it bears the weight of each story, which is represented as lumped masses.

2.3. Simplification of moment frames

The MDOF representation of the moment frame is characterized by a rotational spring representing the total flexural stiffness of the beams at a given story, and a column element representing the stiffness of all columns at a given story. The beam stiffness is conservatively calculated from centerline geometry, and the following points are neglected:

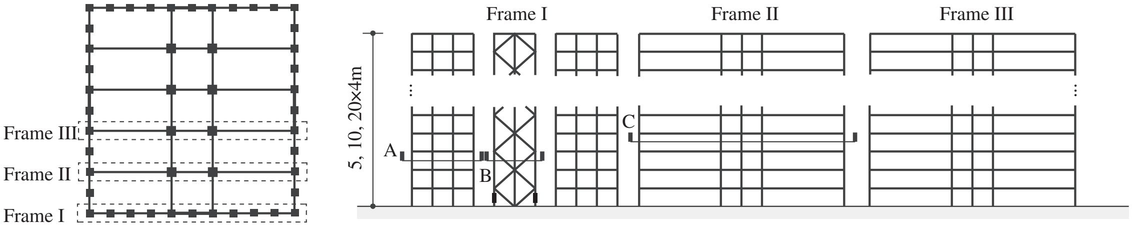
(a) Axial deformation of the beams and columns
(b) Shear deformation of the beams and columns
(c) Panel zone deformation.

This model was initially proposed by M. Nakashima et al. [10]. The original proposal assumed that the rotations of beam-column joints were identical at a given story. In contrast, in this study, it is assumed that the rotations of beam column connections at each story are inversely proportional to the corresponding beam-to-column bending stiffness ratio.

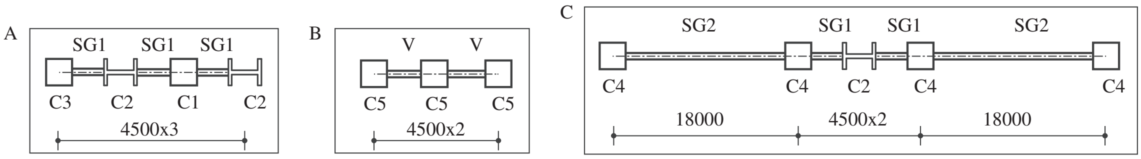
The stiffness of the rotational spring representing beams at the *i*-th story is denoted by K_{bi}, which is calculated by summing the bending moment at each beam-end M_{bij}, and dividing by the average rotation $\overline{\theta}_i$, as expressed in Eq. (1). n_{bi} is the number of beam-end at the *i*-th story.

$$K_{bi} = \sum_{j=1}^{n_{bi}} M_{bij} \Big/ \overline{\theta}_i \tag{1}$$

The columns at the *i*-th story are represented by a 4 × 4 stiffness



a. Plane of the structure of a typical office building b. Benchmark model (consist of three plane frames from the structure in fig a.)



c. Dimension of each frame and section of each structural member

Fig. 2. Benchmark models of the controlled spine frame structures.

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