Engineering Structures 56 (2013) 431–442

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Seismic performance of steel structures with seesaw energy dissipation system using fluid viscous dampers

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ARTICLE INFO

Article history:
Received 3 July 2012
Revised 8 April 2013
Accepted 9 May 2013

Keywords:
Passive control
Seesaw mechanism
Earthquake engineering
Energy dissipation
Fluid viscous dampers
Seismic protection

ABSTRACT

This paper presents a new vibration control system based on a seesaw mechanism with fluid viscous dampers. The proposed vibration control system comprises three parts: brace, seesaw, and fluid viscous dampers (FVDs). In this system, only tensile force appears in bracing members. Consequently, the brace buckling problem is negligible. This benefit is useful for steel rods for bracing members. By introducing pre-tension in rods, long steel rods are applicable for bracing between the seesaw members and the moment frame connections over several stories. The relation between the frame displacement and the damper deformation is first derived in consideration of the rod deformation. Simplified analysis models of seesaw energy dissipation system are developed based on this relation. Subsequently, seismic response analyses are conducted for three-story and six-story steel moment frames with and without dampers. In addition to the proposed system, a diagonal-brace-FVD system and a chevron-brace-FVD system are analyzed for comparison. Parameter analyses of rod stiffness and damping coefficient are conducted for the six-story frame. The maximum story drift angle and response of the top floor displacement are discussed. Results show a high capability of seesaw energy dissipation system for improving the structural response.

1. Introduction

For the last few decades, energy dissipation systems have been used increasingly in new and retrofit construction to dissipate earthquake-induced energy into structures [1]. Various energy dissipation systems have been developed such as friction dampers, metallic dampers, viscoelastic dampers, and fluid viscous dampers. Such energy dissipation systems absorb seismic energy and enhance the seismic performance of structures by modifying the dynamic characteristics of a structure [2]. Several references have described the design and implementation of passive control in seismic protection [3–6].

Displacement-dependent passive dampers increase the lateral stiffness of the structure and provide energy dissipation through sliding friction or metallic yielding. During mild or moderate ground motion, however, the seismic energy is not dissipated, although the stiffness increases. Under large ground motions, the seismic performance is improved because of the added energy dissipation and the force-limiting characteristics of the damper [7]. Some researchers have investigated displacement-dependent dampers such as various friction devices [8–11], buckling-restrained braces [12,13], and U-shaped steel dampers [14,15].

The salient benefits of velocity-dependent dampers such as fluid viscous dampers (FVDs) and viscoelastic dampers (VEDs) are energy dissipation for all levels of vibration and flexibility in application. VEDs have been investigated extensively as passive dampers [16–21]. VEDs are comprised of some layers of viscoelastic material bonded with steel plates. The energy input to structures is absorbed through shear deformation of the viscoelastic material. Fluid viscous dampers (FVDs) consist of a cylinder and a stainless steel piston. The cylinder is filled with incompressible silicone fluid that has stable properties over a wide range of operating temperatures. Dampers are activated by the transfer, through small orifices, of silicone fluids between chambers at opposite ends of the unit [22]. FVDs can also be used in innovative configurations that amplify the velocity across the device, including toggle brace systems, scissor–jack systems, amplifying brace systems, and lever arm systems [1,23–25].

This study investigates passive vibration control system based on a seesaw mechanism using fluid viscous dampers (FVDs). In the proposed seesaw energy dissipation system (SEDS), only tension force is generated in bracing members. The brace buckling need not be considered. This paper first presents the relation between the frame displacement and the damper deformation obtained by considering the rod deformation. Based on this relation, simplified analysis models of seesaw energy dissipation system have been developed. Then, seismic response analyses are

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http://dx.doi.org/10.1016/j.engstruct.2013.05.015

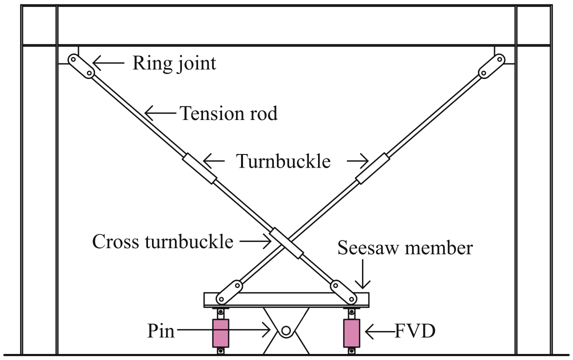

Fig. 1. Proposed vibration control system.

conducted for three-story and six-story steel moment frames with and without dampers. In addition to the proposed system, the diagonal-brace-FVD system and the chevron-brace-FVD system are analyzed for comparison. Parameter analyses of rod stiffness and damping coefficient are conducted for the six-story frame. The maximum story drift angle, response of top floor displacement, base shear force, and peak acceleration are discussed. Results demonstrate the capability of seesaw energy dissipation system for improving structural response effectively.

2. Seesaw energy dissipation system (SEDS)

2.1. Fluid viscous dampers

Fluid viscous dampers (FVDs) include a piston head with orifices contained in a damper-housing filled with fluid, which is mostly a compound of silicone or a similar type of oil. Energy is dissipated in the damper as the piston rod moves through the fluid and forces the fluid to flow through the orifices in the piston head [26]. The force F_D in a FVD is calculated as

$$F_D = Cv^{\vartheta}, \tag{1}$$

where F_D denotes the damper force, C represents the damping coefficient, v stands for the relative velocity between the ends of the damper, and ϑ signifies an exponent that controls the shape of the force velocity relation. The typical values of ϑ are between 0.5 and 2.0. FVDs with $\vartheta > 1$ are generally not used in seismic design applications. Those with $\vartheta < 1$ are called nonlinear FVDs [27]. For high-velocity applications, nonlinear FVDs are used to avoid exceeding the device force capacity. In these nonlinear FVDs, the force is a fractional power law of the velocity [28]. Those with $\vartheta = 1$ are called linear FVDs, in which the damper force is proportional to the relative velocity. This study adopts linear FVDs.

2.2. Seesaw-brace systems

Kang and Tagawa proposed a vibration control system with long rods and seesaw mechanism [29,30]. Fig. 1 portrays the proposed vibration control system comprising a Brace, Seesaw, and FVDs. A couple of FVDs are installed in the seesaw member, which is pin-supported. The brace members comprise two tension rods, turnbuckles, and a cross-turnbuckle. Tension rods intersect from the edge of the seesaw member. By introducing pre-tension in rods, only tensile force appears in bracing members. Accordingly, the brace buckling problem is negligible, and steel rods are applicable as bracing between the seesaw member and the moment frame connections over some stories. When the frame deforms under a lateral load, the FVDs dissipate energy via movement of the piston through a highly viscous fluid. When the lateral load direction reverses, tensile axial force is generated immediately in the opposite rod. This behavior is based on the seesaw mechanism characteristics.

One benefit of this system is that it enables the long steel rods to be used as bracing between the seesaw member and the moment frame connections over some stories, as shown in Fig. 8d. Accordingly, one damping device mounted on ground level can control the frame vibration instead of mounting the damping device on every floor level. This advantage has been confirmed using an analytical approach [29,30].

3. Formulation of SEDS

3.1. Damper deformation

To consider rod deformation as shown in Fig. 2, the horizontal displacement δ of the frame is expressed as

$$\delta = \delta_r + \delta_b, \tag{2}$$

where δ_r signifies the horizontal displacement of the frame attributable to damper deformation, and where δ_b stands for the horizontal displacement of the frame attributable to rod deformation.

The relation between the damper deformation (δ_D) and horizontal displacement (δ) of the frame has been obtained as [30]

$$\delta_D = \left(1 - \frac{\xi}{\cos\alpha}\right)\frac{\cos\alpha\cos\beta}{\sin(\alpha+\beta)}\delta, \tag{3}$$

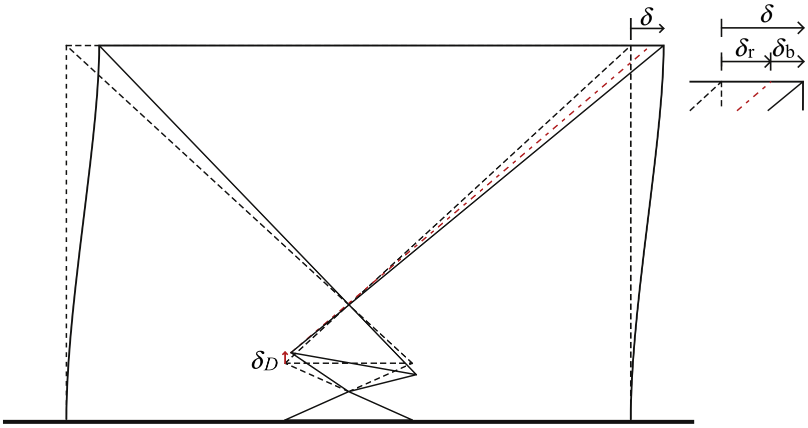

Fig. 2. Analysis of SEDS movement.