New seismic stabilization technology for retrofits and new construction

By Jeff Yoders

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Recent earthquakes and ongoing research have demonstrated that modern buildings constructed according to design procedures perform well when subjected to seismic loading. However, many older and historic structures have performed poorly during earthquake events. Since 2008, Kit Miyamoto, Ph.D., F.ASCE, CEO and president of West Sacramento, Calif.-based Miyamoto International Earthquake and Structural Engineers and Global Risk Miyamoto, has studied and collected data on earthquakes in Japan; New Zealand; Haiti; L'Aquila, Italy; and Sichuan, China. Miyamoto has brought the technologies his firm uses for seismic retrofits and new buildings in California to Haiti and other quake-stricken areas around the globe. Fluid viscous dampers (FVDs), one of the technologies explored in this article, are currently being used by Miyamoto and the Pan American Development Foundation in new residential housing in Haiti. Many of the technologies in this article were pioneered and tried for the first time by Miyamoto's firm.

Fluid viscous and fluid viscoelastic dampers

Miyamoto International Earthquake and Structural Engineers evaluated the seismic performance of a reinforced concrete building built in 1910 in Stockton, Calif. The Hotel Stockton, a historic landmark, was torsionally irregular and composed of a six-story segment and an adjoining two-story portion. Prior to its $18 million rehabilitation and seismic retrofit it would not have withstood the level of earthquake shaking expected at the site for two reasons. First, the original design used a weak lateral force resisting system at the first story. Second, the concrete column reinforcement had poor and inadequate seismic detailing. A detailed mathematical model of the building was prepared and the structure was analyzed using nonlinear static and dynamic procedures which showed it would not survive a substantial earthquake. The main objective was to provide collapse-prevention performance for the 500-year return event. The seismic retrofit was comprehensive and included using nonlinear fluid viscoelastic dampers (FVEDs) among other remedies.

FVEDs and FVDs provide an efficient and robust alternative for seismic retrofit of nonductile concrete structures. Conventional retrofits of historic buildings are often costly and could obscure the valuable architectural features of these landmarks. In contrast, viscous dampers provide structural engineers with a non-invasive option. They enhance building performance with minimal alteration to building layout (Miyamoto et al, 2007).

The first story of Hotel Stockton is 5.5 meters tall and the remaining floors have a story height of 3.1 meters each. The building consists of 15 bays in the east-west (E-W) direction and five bays in the north-south (N-S) direction; each bay measures 6.1 meters. Reinforced concrete columns, beams, and shear walls compose the gravity and lateral load resisting system.

The major weaknesses of the building were a soft first story and the torsional response of the building. The retrofit would limit the earthquake response of the structure to linear elastic behavior, limiting the maximum E-W and N-S components of the second-floor displacement to 22 mm and 36 mm, respectively. The seismic deficiencies and selected retrofit strategies were:

- Large torsional response due to asymmetric mass distribution — Add FVEDs to provide damping and additional stiffness to the weak parts of the building.
- Soft story response of first floor and large seismic demand — Use FVDs at the first floor level.
- Inadequate transverse confinement and longitudinal reinforcement splice length — Wrap first story columns, at the plastic hinge regions, with fiber-reinforced polymer (FRP) composites.
- Inadequate redundancy of gravity load columns — Add steel columns adjacent to

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Learning Objectives

After reading this article, you should know the following:

- How and when to specify nonlinear fluid viscous dampers (FVDs) and fluid viscoelastic dampers (FVEDs) for seismic retrofits.
- How to use performance-based design and a system of steel special moment resisting frames (SMRFs) with FVDs for seismic compliance in a new building in a seismic zone.
- How to use a tuned mass damper to reduce seismic load in an existing structure to achieve code compliance.

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existing columns for FVD braces.

- Lack of redundancy in resisting shear force at upper floors in the transverse direction — Add wood shearwalls for upper six floors of the building.

Using FVEDs and FVDs reduces story drifts and demand on existing members without substantially increasing demand on columns and foundation components. For the Hotel Stockton, FVDs were placed to optimize their efficacy without blocking architecturally sensitive areas.

FVDs were originally developed for the defense and aerospace industries. They are activated by the transfer of incompressible silicone fluids between chambers at opposite ends of the unit through small orifices. During earthquakes, the unit becomes active and the seismic input energy is used to heat the fluid and is thus dissipated. FVDs have been extensively researched (Constantinou and Symons, 1992) and implemented in many upgrades such as this.

Following is the equation for computing force-velocity relation of an FVD:

$$F = C\,sgn(\dot{u})|\dot{u}|^{\alpha}$$

where

- F = damper force,
- C = damping constant,
- sgn = sign function
- $\dot{u}$ = damper velocity, and
- α = velocity exponent,

An FVED consists of a combination of springs and dashpots acting in parallel that can add dynamic stiffness and supplemental damping to the lateral load resisting system. FVEDs are a combination of FVDs and polyurethane elastomers in parallel. The retrofit of Hotel Stockton was the first application of FVEDs in structural engineering for seismic protection. They had been used extensively in aerospace. Urethane elastomers provide consistent mechanical properties through a wide range of temperature application, are flame resistant, and exhibit no deterioration of their mechanical properties from static stress if protected from ultraviolet light.

The force-displacement ratio for an FVED is:

$$F = Ku + C\,sgn(\dot{u}\,|\dot{u}|^{\alpha}$$

where u is damper displacement, K is an elastic constant, and the other variables are the same as defined above.

Table 1 shows the pertinent properties for both types of dampers.

As a result of the retrofit, the Hotel Stockton's story drift ratios were reduced from 1.9 percent and 2.3 percent, respectively, to 0.3 percent and 0.4 percent in the E-W and N-S directions after the dampers were added. The maximum x and y compo-


The Hotel Stockton, built in 1910, was torsionally irregular and composed of a six-story segment and an adjoining two-story portion.

nents of displacement at the second floor are 14 mm and 22 mm, respectively, and are now well within the threshold limits and significantly less than the non-retrofitted displacements of 90 mm and 120 mm.

Performance-based design and SMRFs

Performance-based design and a system of steel special moment resisting frames (SMRFs) with FVDs were used as part of the seismic design of a new, five-story, 123,000-square-meter, $26 million medical office building completed in northern California in 2009. It is one of the first structures in the United States to apply 2005 ASCE/SEI 7 procedure to design with FVDs. In accordance with ASCE 7, the steel frames were sized and designed with strength requirements of code-level forces. The FVDs were used to control displacement. Site-specific response spectra and spectrum-compatible time histories, synthesized for 500- and 2,500-year return events, were used for nonlinear response history analysis. The building's lateral loading system is composed of the SMRFs, using ductile and laboratory-tested beam-to-beam connections, and FVDs. The SMRFs were designed to provide strength requirements and the drift limitations of the structure were met by the FVDs. Performance-based design was used to optimize design (Miyamoto and Gilani, 2008).

ASTM Grade 50 SMRFs and FVDs are used for seismic design. The beam-to-beam column connections for SMRFs use the ductile slotted-web beam design. The application of FVDs for seismic design of steel SMRFs is one of the recommended practices of the SAC Joint Venture and has been implemented successfully by Miyamoto International in new construction and seismic rehabilitation (FEMA, 2000; Miyamoto, et al, 2007). Slotted-web connections are proprietary products developed to ensure ductile flexure behavior away from the face of the connection. The webs are slotted to make sure the flanges carry normal stresses; the shear force and part of the bending moment is resisted by the web. This eliminates the triaxial state of stress, common

Table 1

Device	No.	DBE Capacity, kN	C, kN-sec/m	α	K,kN/mm
FVD	16	930	35	.5	0
FVED	4	1330	45	.5	50

Steel columns were added adjacent to existing columns for FVD braces on the first floor of the Hotel Stockton.

The 1959 Theme Building at Los Angeles International Airport is composed of a reinforced concrete annular core and four steel arches placed at 90-degree orientations.

to pre-Northridge connections. The separation of beam flanges and web eliminated lateral torsional buckling.

Forty nonlinear FVDs composed of 10 units in the N-S and E-W directions for the first two floors were used in this project. The FVDs were arranged in a chevron configuration along the bays; the equivalent dampening ratio of the FVDs was approximately 35 percent of critical.

A computer program was used to prepare a 3D parametric model of the building. The steel beams and columns were all modeled using the beam-column element. Nominal spans and member sizes as defined in AISC 2005 and as specified in the contract plans were used in the analysis. In this performance-based design model, the bases of all columns were modeled as pinned to represent the expected boundary condition. A similar model without the FVDs was prepared to simulate the conventional design model. Fixed column base boundary conditions were used in the conventional design model.

Site-specific response spectra for the design basis earthquake (DBE) and the maximum considered earthquake (MCE) — 500-year and 2,500-year return events, respectively — were developed. Since the steel members were sized using conventional code design procedures. (CBC, 2001), the FVDs were sized to control story drift. Two performance levels were considered, in accordance with ASCE 7 recommendations:

1) DBE — ensure all steel members of the SMRF remain elastic and limit story drifts to 1 percent; and

2) MCE — limit the demand-capacity ratios for all SMRF members to 1.5 or less.

Analysis showed that the performance-based design had a superior seismic performance to that of a traditionally designed structure. The expense of FVDs was offset entirely by the reduction in cost of steel members and the foundation. ASCE/SEI 7-05 provisions are readily applicable to seismic design. Performance-based design using FVDs is superior to conventional design and the demand on both structural and non-structural components is reduced. FVDs provide non-intrusive and reliable costs for seismic design. The FVD force demand is controlled by using nonlinear damping properties. These forces are out-of-face with elastic forces and they do not increase demand on members.

Seismic retrofit using a mass damper

The 1959 Theme Building at Los Angeles International Airport is composed of a reinforced concrete annular core and four steel arches placed at 90-degree orientations. Miyamoto International used performance-based engineering to assess the performance of the building's concrete core. A detailed mathematical model of the structure was analyzed using site-specific acceleration histories. This analysis showed the concrete core had insufficient flexural and shear capacity to resist seismic loading. A retrofit strategy of increasing the core capacity and lowering demand was undertaken for the iconic building. The focus of that strategy was a tuned mass damper placed at the roof of the structure to reduce seismic demand. Additional strengthening for flexure and shear were also incorporated into the design.

Both conventional and innovative seismic retrofits were investigated. The conventional retrofit of the building consisted of adding a layer of concrete to the outside core of the structure to increase flexural and shear capacity of the core. The innovative retrofit consisted of adding a tuned mass damper (TMD) to the top of the core. The TMD option was selected because it was less expensive, protected the building's architectural features, and minimized building closure (Miyamoto, et al 2010).

The addition of the TMD altered the fundamental mode of the concrete core by introducing two modes. In one, the TMD is in-phase with the concrete core; in the other mode, the TMD motion is out-of-phase with the concrete core. As a result, most of the seismic motion is taken up by the TMD and reducing drifts and seismic demand of the concrete core. A high-damped TMD with a mass ratio (defined as mass of TMD to the concrete core) of 20 percent was selected. This large mass corresponds to 25 percent of the mass in the fundamental mode and was selected to get approximately 30- to 40-percent reduction in the responses. The retrofitted structure met its performance goal and there was moderate to high confidence of satisfactory performance in a major earthquake

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Jeff Yoders is a freelance editor and writer. For five years, he covered IT, CAD, and building information modeling (BIM) as senior associate editor of *Building Design + Construction*. He's a chair at-large of the Associated General Contractors of America's BIM Forum and has won four American Society of Business Publications Editors awards.

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1. The Hotel Stockton was found to have inadequate earthquake protection because:

a) It was tortionally irregular

b) It comprises a six-story structure and an adjoining two-story structure

c) The original design used a weak lateral force resisting system

d) The concrete column reinforcement had poor and inadequate seismic detailing

e) All of the above

2. At Hotel Stockton, to mitigate lack of redundancy in resisting shear force at upper floors in the transverse direction, the Miyamoto team decided to:

a) Add SMRFs

b) Add wood shearwalls for the upper six floors of the building.

c) Use FVDs at the first floor level.

d) Wrap first story columns, at the plastic hinge regions, with fiber-reinforced polymer composites.

3. Using FVEDs and FVDs:

a) Reduces story drifts and demand on existing members without substantially increasing demand on columns and foundation components

b) Is more expensive than conventional retrofits

c) Requires replacement of hydraulic fluids once a year

d) Is only for experimental buildings

4. FVDs are activated by:

a) An earthquake, tsunami, or meteorite

b) The transfer of incompressible silicone fluids between chambers at opposite ends of the unit through small orifices.

c) An internal spark that starts heating them up

d) Voice commands

5. FVEDs are:

a) FVDs with glue in their mixture

b) FVDs that stretch

c) A combination of FVDs and polyurethane elastomers in parallel

d) A combination of FVDs and SMRFs

6. Urethane elastomers provide:

a) Consistent mechanical properties through a wide range of temperature application

b) Flame resistance, and exhibit no deterioration of their mechanical properties from static stress if protected from ultraviolet light

c) A high risk of breakdown after time

d) a and c

e) a and b

7. SMRFs are a system of steel special moment resisting frames.

a) True

b) False

8. Slotted-web connections are proprietary products designed to:

a) Make sure the flanges carry normal stresses

b) Ensure ductile flexure behavior away from the face of the connection

c) Ensure the shear force of and part of the bending moment is resisted by the web

d) Provide structural engineers with a non-invasive option.

9. The 1959 Theme Building at Los Angeles International Airport had a concrete core that had insufficient flexural and shear capacity to resist seismic loading.

a) True

b) False

10. A tuned mass damper:

a) Is tuned to the structure so its damping works in two different modes

b) Needs to be synced with its structure

c) Works for unconventional buildings

d) Should only be used as a last resort

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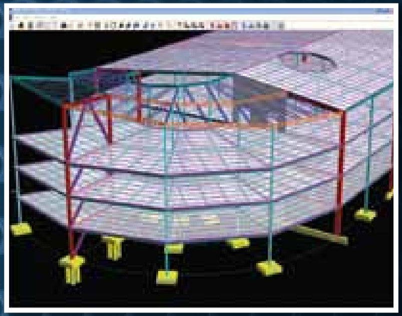

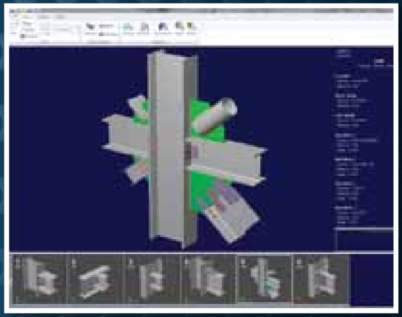

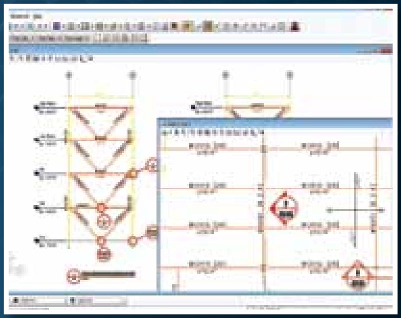

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