Study on Base Isolated Structure with Variable Oil Damper

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ABSTRACT

To mitigate base displacement in structural seismic isolation for large input level earthquake while performing well for moderate input level earthquakes, variable oil damper (VOD) has been proposed and small-scaled model has been developed. The basic idea of this VOD consists of enhancing damper force by tunable internal mechanism (without computer or power supply) when base displacement overreaches limit value (set length). Using the seismic simulator to provide the input motion, the mechanical properties of the VOD model were identified. Experimental studies showed that damper force increased as base displacement exceeds damper's set length. Numerical model of VOD is employed to investigate effect of the VOD parameters on behavior of a real eight story building in different input ground motions. Results of analytical study demonstrated effectiveness of VOD to decrease base displacement while maximum acceleration, shear and interstory displacement of superstructure are slightly increased.

KEYWORDS: Base Isolation, Base Displacement, Damping, Seismic Response, Variable Oil Damper

1. INTRODUCTION

Conventional approach to earthquake protection of buildings seeks to design structures with sufficient strength and ductility capacity to dissipate energy through inelastic deformation. In contrast, base isolation, as a design alternative for earthquake damage mitigation, tries to control level of transmitted ground motions to the superstructure. Seismic base isolation, providing flexibility and energy dissipation mechanism, decreases earthquake-induced interstory drift and absolute acceleration of superstructure at the expense of large displacement of the isolation level.

Near fault earthquake excitations, at the presence of long-period large-velocity pulses, have strong impact on seismic isolation systems and can lead to large displacement demand (Hall *et al.*, 1995; Jangid and Kelly, 2001). It is a common practice to incorporate nonlinear energy dissipation systems within the isolated level in order to reduce base displacement. Although, implementation of supplementary passive damping can mitigate isolator displacement in the fundamental mode, but it may have counter effect of raising floor acceleration and interstory drift through increasing response in the higher modes (Kelly, 1999). Comparing with viscous damping, adding hysteresis damping might impose adverse effect on superstructure, mainly because of larger amplification of higher mode contribution (Politopoulos, 2008).

A variable oil damper (hereinafter referred to as VOD) has been proposed and small-scaled model has been developed at Tohoku University. The VOD enhance performance and reliability of base-isolated systems by providing sufficient linear damping to mitigate transmitted force into the superstructure at more frequent moderate earthquakes while inducing higher level of energy dissipation to limit isolation deformation for severe events. The basic idea is to provide functionality for the isolation system at frequent moderate level of excitation and displacement control at rare extreme condition. In this study, mechanism and behavior of the VOD is described in different stages, numerical model of the VOD is presented, adequacy of the numerical analysis is verified by shaking table test and influence of incorporating such a damper within the base isolation system of an 8-story building is investigated analytically under near-field ground motions.

2. VARIABLE OIL DAMPER

The small-scaled prototype damper, shown in Figure 1, weights 73.5 *N* and had a fully compressed length of 900 *mm*, a housing diameter of 40 *mm*, a stroke of ±135 *mm*, and a maximum output force of 2.9 *kN*.

2.1. VOD Mechanism

Behavior of the VOD is regulated by an internal mechanism which is independent of sensor, monitoring and power supply.

The configuration of the VOD, as depicted typically in Figure 2, consists of a fluid damper combined with a bypass loop which is connected to two pilot-cylinders. The bypass loop has a fixed orifice and a variable orifice that is adjusted by a control valve. A pointer is installed on piston rod of the damper. The pilot-cylinders, made up of a cylinder with 10 *mm* diameter and a piston with maximum stroke of 30 *mm*, are fastened with appropriate distance from initial position of the pointer, hereafter referred to as set length, on drive sleeve which is fixed to hydraulic cylinder. As soon as damper displacement exceeds set length, the pointer dislocates piston of the pilot-cylinder. Consequently, spring is compressed proportional to volume of fluid discharged from the pilot-cylinder and additional force is imposed on the control valve in the bypass loop, thus variable orifice is obstructed. Then, position of pilot-cylinder's piston remains constant resulting in steady pressure on the control valve.

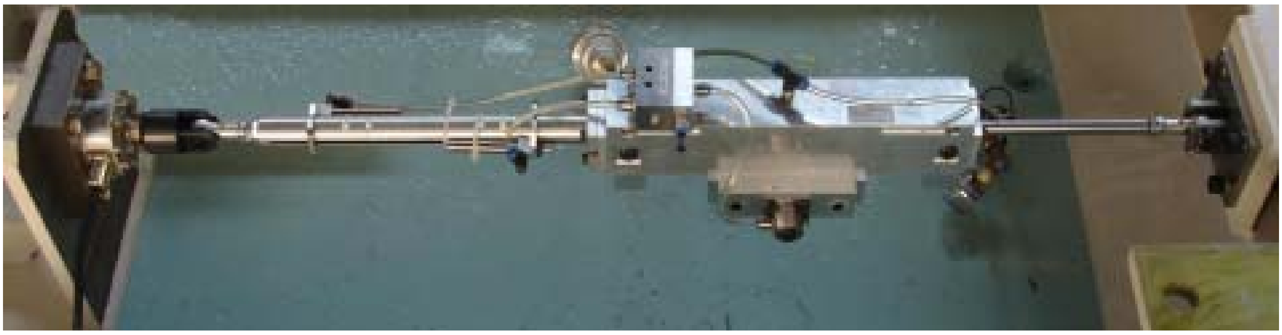


Figure 1. Photograph of variable oil damper (VOD)

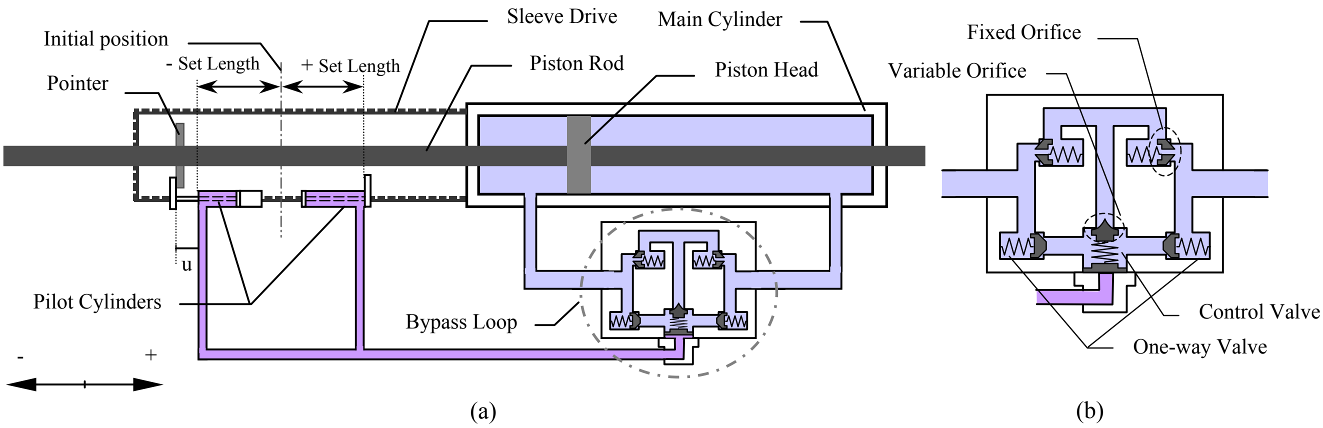


Figure 2. Variable Oil Damper: (a) Schematic diagram of VOD; and (b) Bypass loop detail

The difference of the pressure across the piston head results in damping force and the damper response depends on the configuration of orifices. Therefore, behavior of the VOD includes two stages: normal and nonlinear mode. In normal stage as shown in Figure 3, output force of the damper is generated by passing fluid through both of variable and fixed orifices. In nonlinear condition as represented in Figure 4, till internal hydraulic pressure overcomes interaction of spring and control valve, damper response is mainly due to fluid flow across fixed orifice.

2.2. VOD Numerical Model

The damper response in different stages, derived from fluid dynamics principles, is expressed by simple equations. In normal mode, both of the orifices are open and damper forced is proportional to relative velocity of the damper rod respective to the damper cylinder, v, as

$$F_d = c_d v \tag{1}$$

where c_d is linear damping coefficient. Linear viscous behavior, even though fluid can flow across both orifices, is mainly due to variable orifice effect. When variable orifice is obstructed in nonlinear mode, damper force is given by following equation

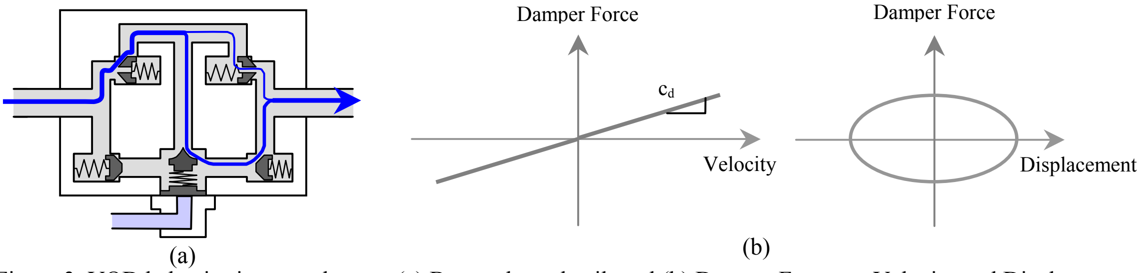


Figure 3. VOD behavior in normal stage: (a) Bypass loop detail; and (b) Damper Force vs. Velocity and Displacement

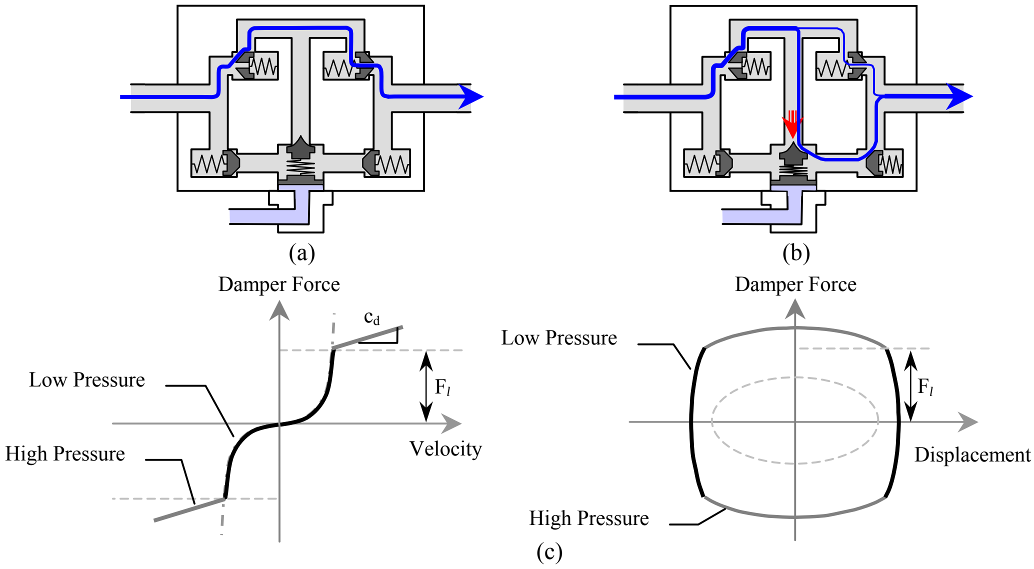


Figure 4. VOD behavior in nonlinear stage: (a) Bypass loop detail in low pressure; (b) Bypass loop detail in high pressure; and (c) Damper Force vs. Velocity and Displacement

$$F_d = a\,\mathrm{sgn}(v)v^2 \tag{2}$$

where a is damping constant and sgn represents signum function. When internal pressure of the damper surpasses spring-valve interaction which is equivalent to a limiting force for nonlinear behavior, additional damper force can be found by applying Equation (1). The limiting force can be determined by

$$F_l = bk_s u \tag{3}$$

where k_s represents stiffness of the spring in control valve, u denotes dislocation of the pilot-cylinder's piston, and b is non-dimensional parameter, which depends on the damper physical properties such as area of pilot piston, main piston, and variable orifice. The ideal mathematical models for the VOD simulation in normal and nonlinear stages are illustrated in Figures 3 and 4 respectively.

It is clear that smaller set length, correlated to further dislocation of the pilot-cylinder's piston, leads to higher limiting force in nonlinear phase and thus energy dissipation capacity is enhanced. The limiting force restriction on damper response in nonlinear phase has the advantage that squared-velocity range, which undesirably can impose excessive damping force as Equation 2, is switched to linear behavior in higher velocity range. Dynamic properties of prototype damper are identified through harmonic loading test. By utilizing sinusoidal motion, parameters of the damper model are calibrated and used in this study as: c_d=1.6 kN.s/m, a=229 kN.s^2/m^2, b=2.92 and k_s=16.8 kN/m in equations (1) to (3).

3. VERIFICATION OF ANALYTICAL SIMULATION

Shaking table test on base isolated system incorporating VOD is carried out to investigate performance of VOD and assess validity of the analytical model. For experimental study according to maximum base displacement , the base isolated system is subjected to two scaled earthquake records: the EW component of Harbor Office record of Hachinohe 1968

Earthquake (far-field excitation) scaled 38% and the NS component of JMA record of Kobe 1995 Earthquake (near-field ground motion) scaled 57%.

3.1. Test Setup

Test model is a single story structure which consists of two parallel and similar one-bay frames with removable bracing in excitation direction, as depicted in Figure 5, and overall dimensions of the frame are 1.43×1.75 *m* in plan and 1.55 *m* in height. Additional mass is introduced on the floor of the model. The frame is fixed on the base which is mounted on roller bearings to produce isolator system. Spring and the VOD are incorporated within isolation system to provide stiffness and damping respectively. Instruments are used to measure absolute acceleration of floor, base, and input motion; relative displacement of floor respect to base and base respect to shaking table; and damper force. Analytical models of the isolation system is developed and calibrated through system identification tests. Dynamic properties are identified through quasi-static loading, free vibration, harmonically forced vibration, and white noise excitation.

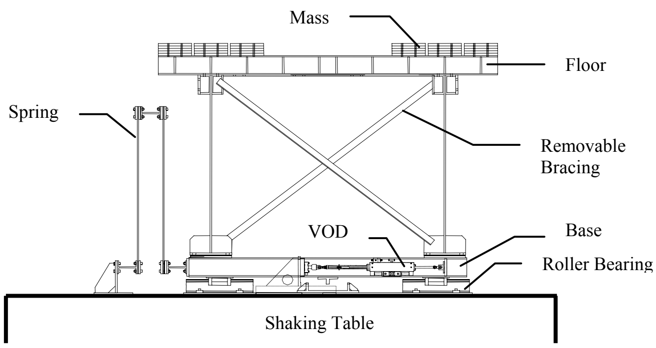


Figure 5. Details of model structure mounted on isolated base

3.2. Simulation Model

Lumped-mass models with mass of 0.67 *ton* for the base and 2.13 *ton* for the floor is utilized to simulate response of the model structure. The simulation model of bare frame (without bracing) is illustrated graphically in Figure 6 as a two degree of freedom (2-DOF) system. The fixed bare-frame with 280.6 *kN/m* lateral stiffness has a natural period of 0.55 *s* and 1.15% damping ratio. The spring stiffness is estimated to be 11.25 *kN/m* and thus natural period of base-isolated system is 3.13 *s*. It is found that performance of the roller bearing is equivalent to a 30 *N* friction force and the isolation system has 0.3 *kN.s/m* equivalent viscous damping. The mathematical model of base-isolated steel frame relies on following assumptions. The steel superstructure remains elastic during excitation and its damping is in the form of equivalent viscous dashpot. The restoring force of the spring is considered to be linear. The friction force of the roller bearing and damping coefficient of the isolation system is constant throughout the motion (independent of sliding velocity). The friction force can be represented adequately by elasto-plastic model with relatively large stiffness. These assumptions lead to mathematical model of isolated steel frame. The equation of motion can be solved in the incremental form by employing Newmark-β constant-acceleration method (β=¼).

$m = 2.13\ t$	Floor mass
$k = 280.6\ kN/m$	Frame stiffness
$m_b = 0.67\ t$	Base mass
$k_b = 11.25\ kN/m$	Base stiffness
$c_b = 0.3\ kN.s/m$	Isolation system equivalent damping
$f_b = 30\ N$	Roller bearing friction

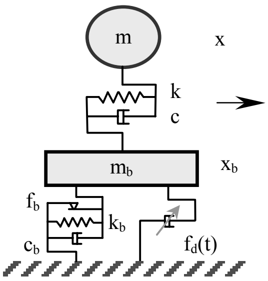


Figure 6. Schematic diagram of simulation model

3.3. Results

A series of tests are performed with different set length values, which is relative distance of pilot-cylinder respect to initial position of the pointer as denoted in Figure 2, while base isolated system is subjected to two scaled ground motions. In addition to normal damper test, in which damper responses as a linear viscous dashpot, for isolated system under Kobe earthquake set length is 65, 55, or 45 *mm* and under Hachinohe excitation set length is 70, 60, or 50 *mm*. To facilitate evaluation of the VOD influence on base-isolation response experimentally, only one pilot-cylinder is installed on negative direction with appropriate set length and thus similar condition is considered in simulation model. Comparison of experimental results and corresponding analytical simulation of the 2-DOF system subjected to scaled Kobe ground motion are shown in Figure 7 for 45 *mm* set length case. Analytical model predicts adequately experimental response of the damper incorporated in base isolated system. Similar trend can be observed in other cases of the experimental study and corresponding analytical simulation.

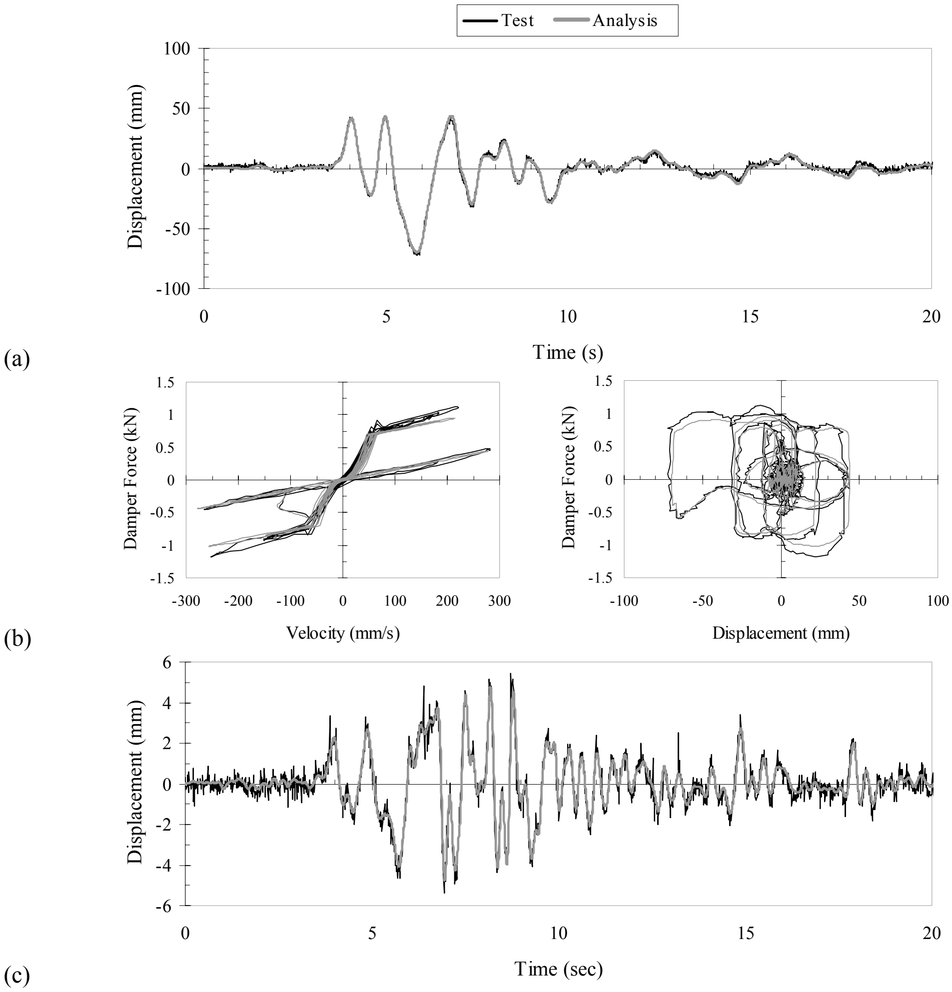


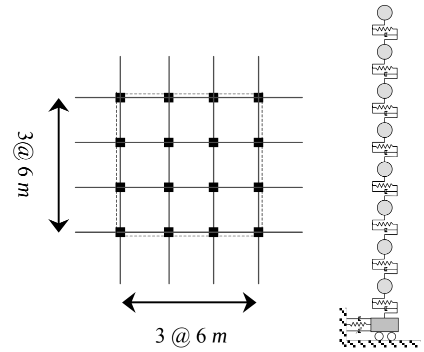
Figure 7. Comparison of experimental and analytical simulation results of 2-DOF system subjected to scaled Kobe earthquake when set = 45 *mm*: (a) Base displacement time history; (b) Damper force vs. Velocity and Displacement; and (c) Relative displacement of floor respect to base time history.

4. ANALYTICAL STUDY ON VOD APPLICATION

Performance of the VOD incorporated within base isolation system is evaluated through analytical study. To understand influence of the VOD, response of a full-scale isolated building is investigated utilizing lumped-mass, shear-building model in different ground motions.

4.1. Analytical Model Properties

The superstructure, as shown in figure 8, is considered to be an 8 story reinforced concrete building with 3×3 bays in plan, each measuring 6 *m* × 6 *m*, and identical story height of 4 *m*. By estimating that uniform mass per unit area for all stories is 1.23 t/m^2, mass of each floor would be 400 *t* approximately. Ratio of base raft mass respect to story mass is assumed to be two, thus total mass of superstructure is around 4000 *t*. To include effect of lower stories cumulative bending deformation on upper level in shear spring model, it is assumed that lateral stiffness distribution through height of structure varies linearly from k_1 at first story to $k_1/3$ at top story. Utilizing empirical formula (IBC2000) for estimating fundamental period of fixed-base building (T_s = 0.656 *s*), leads to find stiffness of superstructure (k_1 = 1423.2 *MN/m*). Stiffness proportional damping of 3 % is applied to the superstructure model. It is considered that isolation system provide sufficient stiffness to obtain period of 3 *s* according to rigid response of superstructure. The VOD is implemented within isolation system such that in normal stage, behaving as a linear damper, damping ratio is 20 %.



m = 400 *t*	Floor mass
T_s = 0.656 *s*	Fixed base period
k_1 = 1423.2 *MN/m*	First floor stiffness
h_s = 3 %	Damping ratio
m_b = 800 *t*	Base mass
m_t = 4000 *t*	Total mass
T_b = 3.0 *s*	Base isolated period
k_b = 17.5 *MN/m*	Base stiffness
h_d = 20 %	VOD damping ratio in normal stage
cd = 3.35 *MN.s/m*	VOD linear damping coefficient

Figure 8. Base isolated 8 story building

Behavior of the VOD in normal and nonlinear modes can be defined by three parameters which are c_d linear damping coefficient, *a* nonlinear stage damping constant and F_l nonlinear stage limiting force. Linear mode damping coefficient is considered 20% of critical damping for base isolation system. Nonlinear stage limiting force, as denoted in Figure 4 to be directly related to amount of energy dissipation in nonlinear stage, is proportional to stiffness of spring in control valve, thus easily can be adjusted by replacing appropriate spring. To simplify results of this study, limiting force is represented by percentage of total weight regardless of corresponding damper properties. Limiting force involves superposing effect of the two pilot-cylinders on both directions. It is assumed that ratio of linear damping coefficient and nonlinear damping constant for prototype damper and VOD within isolation system of RC building is identical; consequently damping constant for nonlinear stage can be determined.

To investigate performance of building isolated system with VOD through numerical simulation, two near-field ground motions considered for the study are: (1) NS component of JMA Record from Kobe 1995earthquake and (2) the Northridge 1994 earthquake recorded at Sylmar station.

4.2. Results

Base displacement, base shear and damper force are response quantities of interest for the base isolation system incorporating VOD and for superstructure height wise distribution of root-mean-square absolute acceleration and maximum drift are presented. Results of base-isolated building incorporating VOD with nonlinear stage limiting force equivalent to 4 percent of total weight subjected to Kobe excitation are shown in Figure 9, while damper response is linear (set length is larger than maximum base displacement = 265 *mm*) or nonlinear (set length = 150 *mm*). When maximum displacement of base displacement exceeds pre-adjusted set length, damper response switches from linear mode into nonlinear stage; therefore energy dissipation capacity is enhanced and consequently base displacement is mitigated at the expense of higher superstructure imparted acceleration. For instance, through selecting 150 *mm* set length, 13.8% reduction of maximum base displacement is achieved by means of 35.7% larger damper force, while base shear is increased 8.6%.

Comparison of VOD and equivalent linear damping, defined as damping ratio that renders maximum base displacement identical to the VOD, is presented in Figure 10. Response of aforementioned base-isolated building subjected to Sylmar earthquake, where VOD has nonlinear limiting force equals to 6% of total weight, includes results of linear VOD (set length is larger than maximum base displacement = 449 *mm*), nonlinear VOD (set length = 300 *mm*) and equivalent damping ratio (total damping ratio = 29%). Introducing 300 *mm* set length into VOD or implementing 29% linear damping ratio within isolation system leads to 13.9% reduction of maximum base displacement. Equivalent linear damping requires 14.7% higher maximum damper force, while transmitted base shear is relatively 9.0% less.

5. CONCLUSIONS

In this study, new damper is proposed and fabricated to mitigate base displacement in isolation system. Performance of the small-scaled VOD is investigated experimentally and analytical model is developed to simulate response of the VOD. A series of shaking table test are conducted on base isolated system incorporating VOD to evaluate analytical model. By employing the numerical model of VOD, response of base-isolated 8-story building incorporating VOD is investigated. This study leads to following points:

- Damper behavior in two stages is considered in analytical model.
- Results of shaking table test of 2-DOF systems with VOD and corresponding analytical model conforms reasonably well, thus analytical model can be employed for assessment of VOD response.
- The VOD can reduce base displacement through enhancing energy dissipation capacity when displacement exceeds set length at the expense of higher force imposed on superstructure.
- Performance of VOD within isolation system of 8-story building depends on nonlinear stage limiting force and set length value.
- The VOD can mitigate maximum displacement with lower damper force respect to equivalent linear damping system with slightly higher transmitted force.

Adequate performance of the VOD within base isolated system to mitigate base displacement, even for near-fault excitation, when maximum displacement overreaches pre-designed value, set length, leads to employ the VOD as a safety device subjected to extreme event that can cause crucial base displacement beyond design displacement. The VOD can be implemented in isolation level to provide linear dashpot behavior under frequent moderate earthquake and as displacement control device at extreme event by enhancing energy dissipation capacity through nonlinear response.

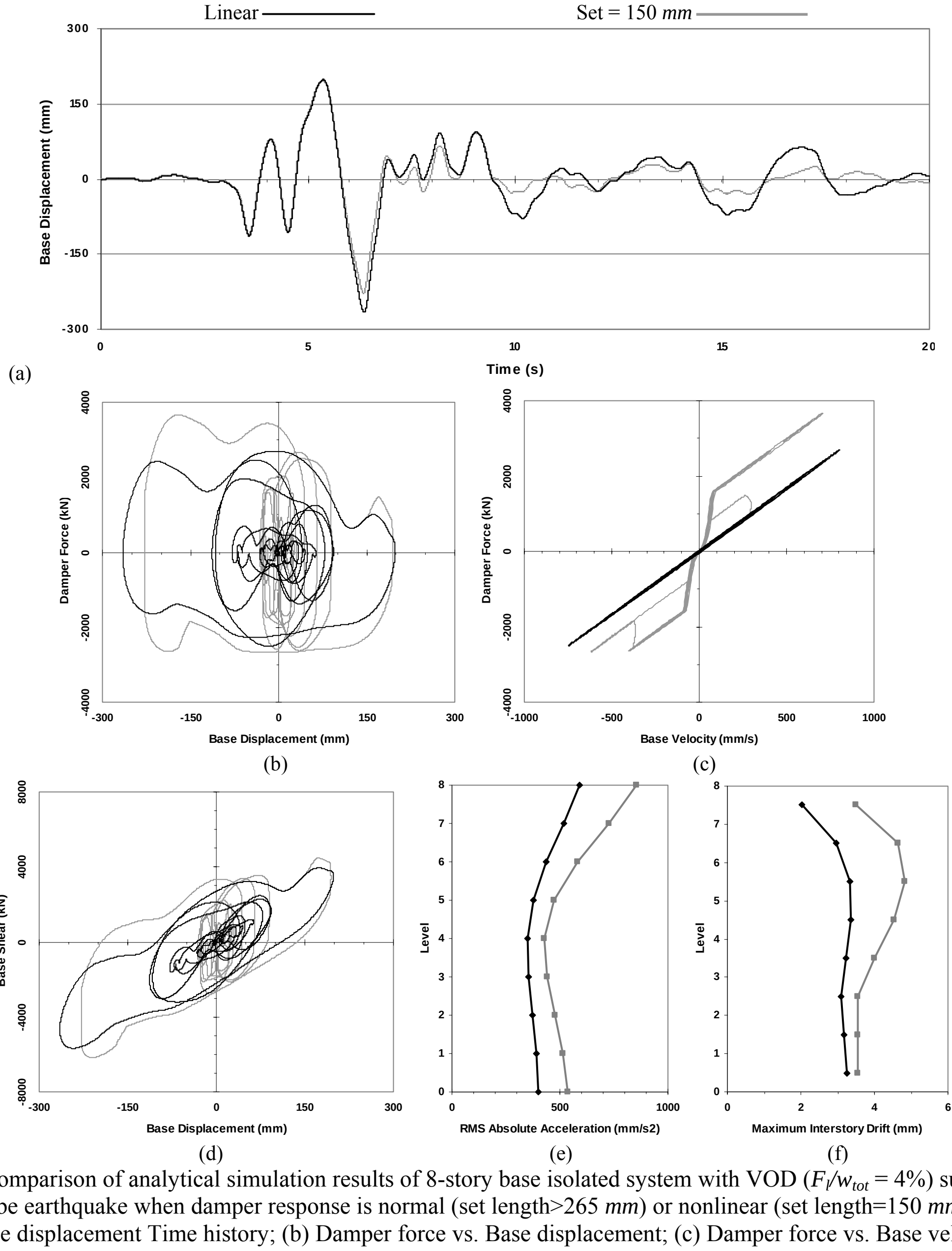


Figure 9. Comparison of analytical simulation results of 8-story base isolated system with VOD (F_l/w_{tot} = 4%) subjected to Kobe earthquake when damper response is normal (set length>265 *mm*) or nonlinear (set length=150 *mm*):
(a) Base displacement Time history; (b) Damper force vs. Base displacement; (c) Damper force vs. Base velocity;
(d) Base shear vs. Base displacement; (e) RMS absolute acceleration distribution; and (f) Maximum interstory drift distribution

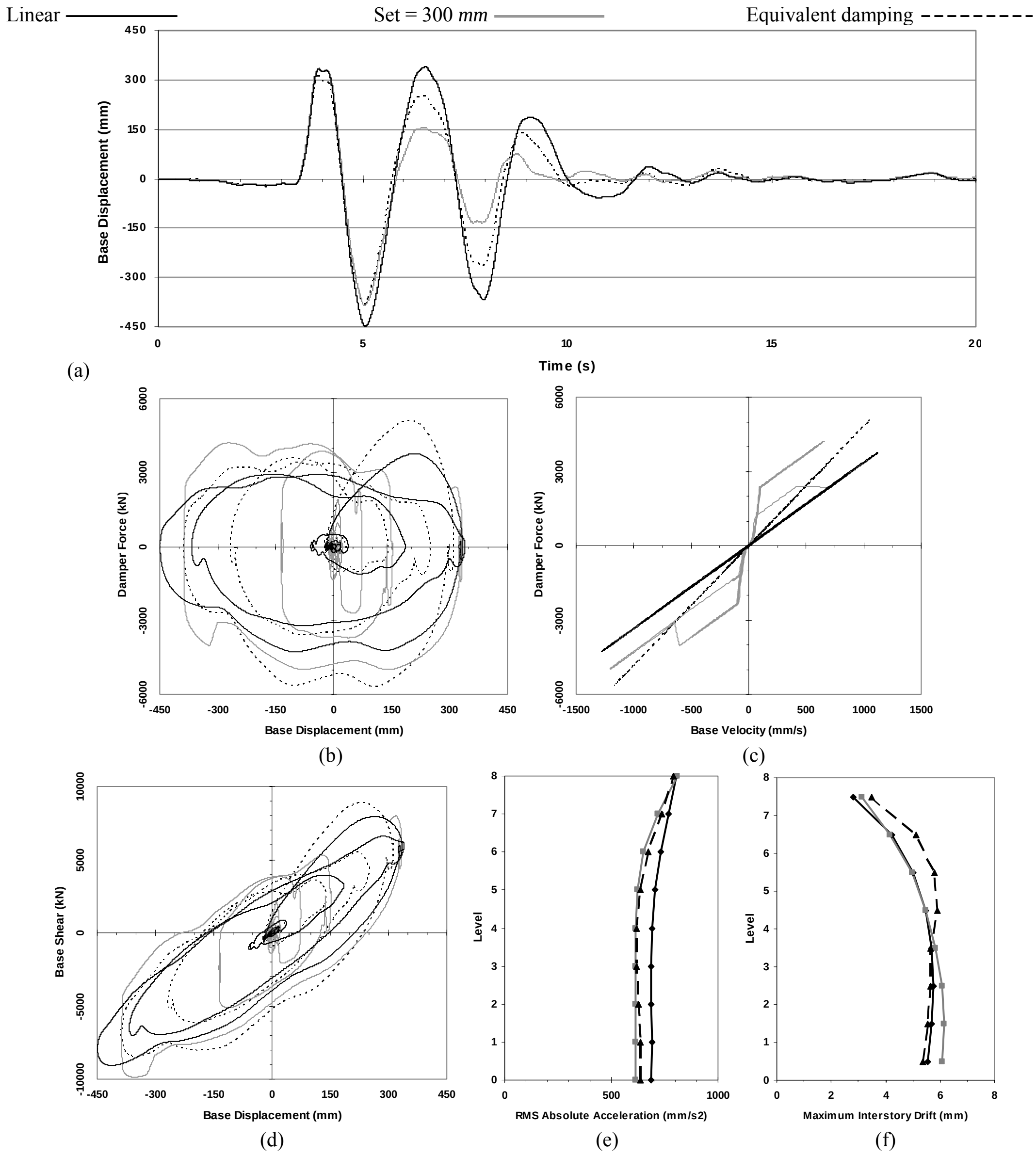


Figure 10. Comparison of response of 8-story base isolated system with VOD (F_l/w_{tot} = 6%) subjected to Sylmar earthquake when damper response is normal (set length>449 *mm*) or nonlinear (set length=300 *mm*) and equivalent linear damping: (a) Base displacement Time history; (b) Damper force vs. Base displacement; (c) Damper force vs. Base velocity; (d) Base shear vs. Base displacement; (e) RMS absolute acceleration distribution; and (f) Maximum interstory drift distribution

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