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PRELIMINARY STUDY OF OPTIMAL PLACEMENT OF VISCOUS DAMPERS IN BUILDINGS

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ABSTRACT

Although earthquake-resistant design with supplemental viscous damping has increased in use, there is not a consensus on the best way to optimise the placement of dampers within structures. Limited research has been conducted on the optimisation of viscous dampers. The rate-dependencies of nonlinear viscous dampers have been observed with physical behavioural testing, and basic analytical models prove to overestimate the energy dissipation potential of these devices. A preliminary optimisation scenario is presented for a baseline building with linear viscous dampers. The stiffness inversely-proportional damping technique proves to be the most effective at reducing interstory drifts for this preliminary scenario, while the Simplified Sequential Search Algorithm is slightly less effective than the stiffness inversely-proportional damping technique and more effective than a uniform damper placement technique at reducing interstory drifts. Future work will incorporate the application of various optimisation techniques with nonlinear viscous dampers to determine effective and easily applied optimisation placement methods.

Introduction

Supplemental energy dissipation with passive devices for earthquake resistant design has become a successful alternative or enhancement to conventional seismic structural design. The advantage of supplemental energy dissipation is the ease of installation of passive devices and the potential for structural retrofit solutions not requiring expensive reconstruction. The viscous device, a type of passive device that dissipates energy by shearing of a viscous fluid or deformation of a viscoelastic material, has had the quickest rate of implementation in structures, as compared to other passive devices. Viscous dissipative devices are well known for their high energy dissipation potential compared to their size. However, there are no guidelines or a general consensus for optimising the placement of viscous dampers within buildings. The configuration of the devices within the building may depend on rules of thumb or common practices. These methods cannot be assured to be optimal or cost-efficient.

Numerous techniques for placing dampers in buildings have been proposed, many of

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which apply to the placement of linear viscous dampers. The future aim of this research is to investigate these proposed placement techniques with two different nonlinear viscous dampers to determine effective and easily applicable means of optimising the placement of dampers in a baseline building. Because most nonlinear viscous dampers have rate dependent properties, physical testing is used to validate the analytical model of the dampers. The thrust of this paper is two-fold: to present the initial nonlinear viscous device testing and characterisation and to present a preliminary analysis of an optimised damper placement with linear dampers using the Simplified Sequential Search Algorithm, one of the most recently proposed methods for placing dampers.

Viscous Devices' Behaviour

The optimisation of device placement may depend on the mechanical behaviour and potential rate-dependent characteristics of the device. Hence, investigating the behaviour of different types of nonlinear viscous devices provides a basis for understanding the potential effects of nonlinear dampers on optimised placement schemes. Physical behavioural testing of the devices provides validation of the constitutive equations and an accurate representation of the device behaviour. Descriptions of the viscous devices and the test rigs, test results and preliminary analytical models, and generalised conclusions about the devices are presented. Two viscous dampers were acquired from different manufacturers: a fluid spring damper and a fluid viscous damper. Both devices were of small capacity, and it is likely that larger scaled versions would be installed in full-size buildings for supplementary seismic energy dissipation.

Fluid Spring Damper

The fluid spring device, also referred to as an elastomeric spring damper or spring-damper pressurized-fluid viscous damper, dissipates energy by viscous deformation of a pressurized compressible silicone-based fluid, which is forced to flow between the piston head and inner casing (Fig. 1). The fluid spring damper is nonlinear and has a viscous component (C) and a stiffness component (k); its resistive force (F_e) is proportional to the sum of displacement ($x(t)$) and exponential velocity ($\dot{x}(t)$), where alpha (α) is the exponential value (Eq. 1).

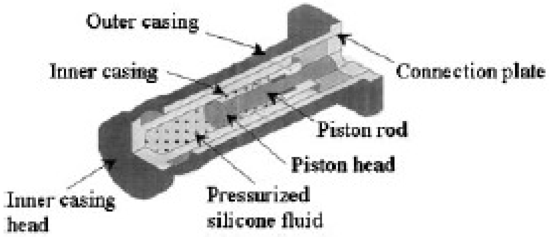

Figure 1. Fluid spring damper (Molina et al. 2004).

$$F_e = k\,x(t) + C\,\mathrm{sgn}(\dot{x}(t))\left|\dot{x}(t)\right|^{\alpha} \tag{1}$$

The fluid spring damper can only operate in compression; therefore, installation of these devices in buildings must incorporate two equal and opposite viscous devices along the same line of action. The maximum force of the fluid spring damper was approximately 20 kN, and the stroke was ± 10mm. Previous testing on similar devices has been conducted by Pekcan et al. (1995), Sorace and Terenzi (2001), Molina et al. (2004), and Blakeborough (2004). The testing rig was designed to apply a purely axial load along the centre line of the fluid spring dampers (Figs. 2, 3). A linear encoder attached to the centre reaction plate measured the displacements, and a thermal couple measured temperature changes during testing.

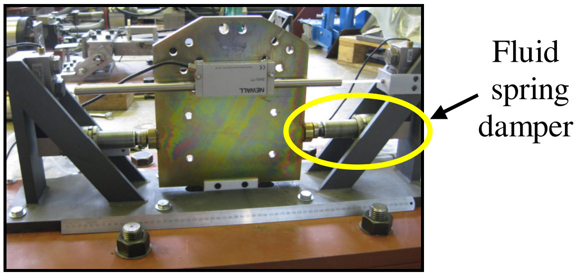

Figure 2. Fluid spring damper.

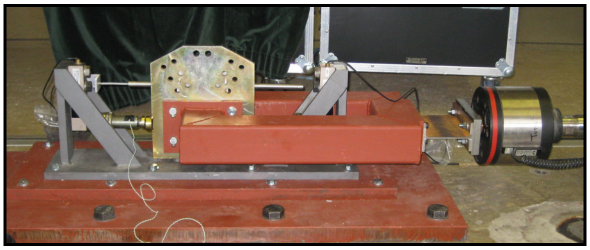

Figure 3. Fluid spring damper test rig.

Fluid Viscous Damper

The second viscous damper tested was the nonlinear fluid viscous damper, which dissipates energy through the deformation and shearing of viscous fluids by fluid orificing. An example of a viscous device is shown in Fig. 4, whereby the piston moving through the compartments forces the silicone-based viscous fluid through the piston orifices, shearing the fluid and dissipating energy. The acquired fluid viscous device was expected to have only a velocity-dependent component ($\dot{x}(t)$) and no apparent stiffness, as represented by its constitutive equation (Eq.2). The viscous damping coefficient (C) and exponential alpha (α) represent the same properties as for the fluid spring damper.

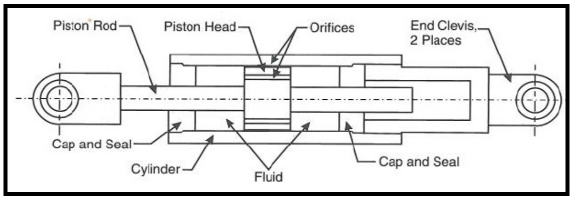

Figure 4. Orificed fluid viscous damper (Hanson and Soong 2001).

$$F_{\mathrm{f}} = C\,\mathrm{sgn}(\dot{x}(t))\left|\dot{x}(t)\right|^{\alpha} \tag{2}$$

Fluid viscous devices are categorised as nonlinear and linear, depending on the exponential value alpha. Nonlinear fluid viscous devices, with an alpha value less than 1.0, have a greater energy dissipation potential than linear devices. The manufacturer's information designated the acquired fluid viscous device as nonlinear with a value of 0.15 for alpha and 5.1 kN-sec/mm for the viscous damping coefficient 'C'. The maximum force of the fluid viscous damper was approximately 13.1 kN, and the stroke was ±60mm. The test rig utilised a small reaction anchor and a clamp attachment for the linear encoder reader (Figs. 5, 6). The thermal couple was also employed for the fluid viscous device testing.

Figure 5. Fluid viscous device.

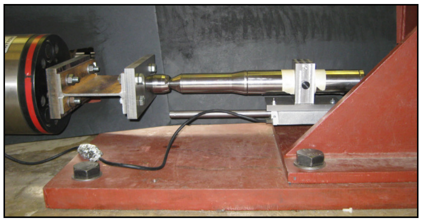

Figure 6. Fluid viscous device test rig.

Test Results and Analytical Models

The behavioural testing was conducted with a series of dynamic cyclic tests over the range of the viscous devices' capacities. Attention was given to monitoring the device temperature to avoid overheating (following manufacturer specifications and prEN15129, (CEN/TC 2008)). In addition, observations were made about the physical behaviour of the devices, noting any unforeseen movement, misalignment, or potential operation or maintenance concerns. The analytical models for the devices were estimated based on the general constitutive equations for each device (Figs. 7, 8).

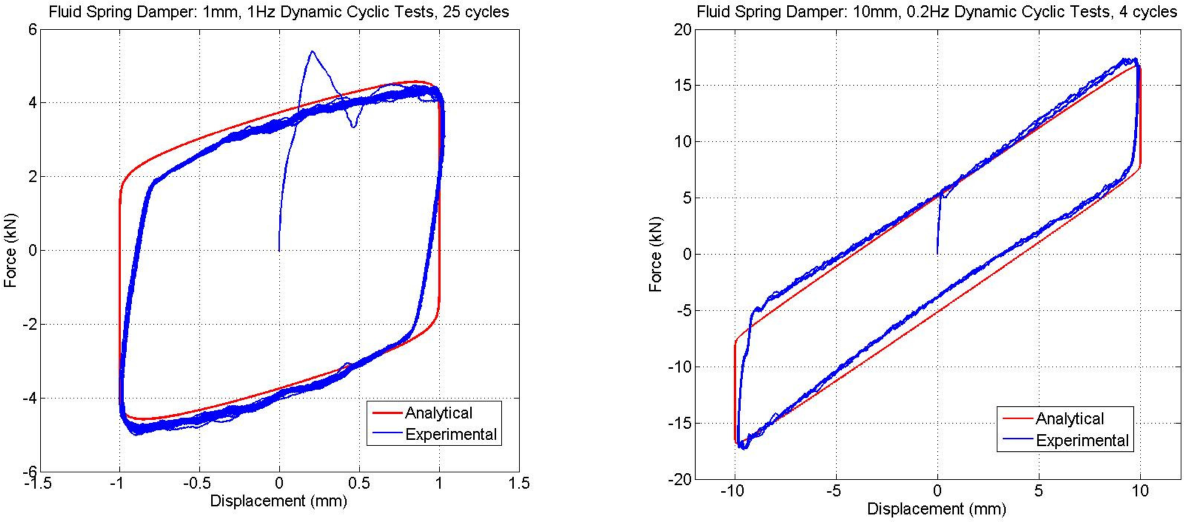

Figure 7. Comparison of experimental and analytical models of the fluid spring damper.

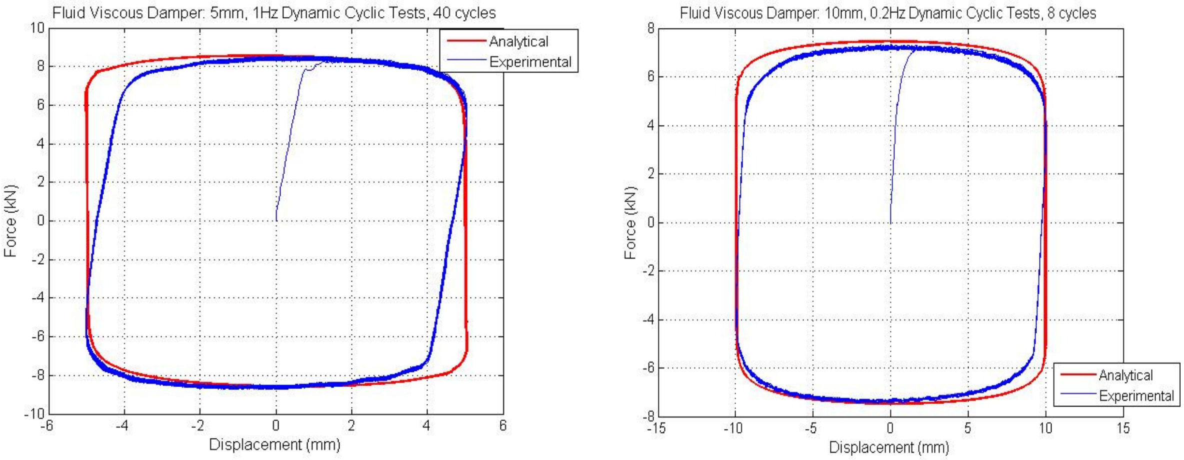

Figure 8. Comparison of experimental and analytical models of the fluid viscous damper.

In the case of the fluid spring damper, a rough estimate of the analytical model was created by using the general constitutive equation (Eq. 1) and visually fitting the curve by iteratively changing the stiffness coefficient, viscous damping coefficient, and exponential alpha value (Table 1). In the case of the fluid viscous damper, the constitutive equation and coefficients provided by the manufacturer were used (Eq. 2). The results are not final analytical models but merely preliminary estimates of the basic analytical models that do not consider device-specific nonlinear effects and irregularities.

Table 1. Preliminary analytical model parameters.

	Dynamic Cyclic Test	Stiffness K (kN/mm)	Viscous Damping Coefficient C (kN-sec/mm)	Exponent α
Fluid Spring Damper	1mm, 1 Hz	1.30	3.0	0.13
Fluid Spring Damper	10mm, 0.2 Hz	1.23	4.5	0.05
Fluid Viscous Damper	5mm, 1 Hz	0	5.1	0.15
Fluid Viscous Damper	10 mm, 1 Hz	0	5.1	0.15

General Conclusions

The general analytical models of the devices are not adequate to represent their true behaviour. The models overestimate the energy dissipation potential of both devices, and the slight tilt of the hysteresis curves for both devices may indicate stress relaxation and creep in the devices' behaviour. As proposed by the Anti-seismic Devices Standard (prEN15129) (CEN/TC 2008), a Maxwell model of a spring and dashpot in series may best model the fluid viscous damper, and it is expected that the addition of a spring in series for the fluid spring damper may improve the analytical model. In addition, the visual fitting of the fluid spring damper model shows that its properties, such as the exponent alpha, the viscous damping coefficient, and stiffness, may be frequency-dependent. Finally, temperature effects were noted during testing. In particular, a frictional resistance or slight stiffness was apparent in the fluid viscous device prior to warming-up. This phenomenon diminished after a few cycles of testing. The preliminary investigation of the behaviour of these two viscous devices has confirmed the existence of rate-dependent and temperature-dependent properties in these particular devices and the necessity to verify physically the constitutive behaviour of the devices. Development of refined analytical models is needed. The analytical models will be critical in numerically modelling a building with realistic nonlinear fluid spring and fluid viscous dampers.

Preliminary Optimisation Case

Manufacturers and engineers may employ various methods for placing dampers in buildings for seismic-resistance. These include the uniform distribution of dampers throughout the building, a uniform distribution of same-size dampers that is then iteratively reduced until an acceptable performance and cost-effective solution is achieved (recommended technique of a damper manufacturer), distributing dampers primarily on one floor (i.e. base of the building), or a damping that is proportional to lateral floor stiffness. Although these methods have been successfully employed, these placement techniques may lead to uneconomical scenarios with multiple damper sizes and cannot be ensured to be the optimal or cost-effective solution. Various optimisation placement techniques have been proposed in engineering journals in the past fifteen years; however, there is still not a consensus on the best way to place dampers within a structure. Of the few manufacturers specialising in viscous dampers, the president of one of the companies suggested that the next innovative research area for passive damping would be generalised solutions for the placement of dampers within various building types.

A review of current building guidelines and standards revealed that although passive dissipative systems are generally referenced, no guidelines or recommendations for placement provisions are presented. *FEMA 356 – Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (2000) (superseded by ASCE 41) includes a section devoted to seismic design or retrofit with general dissipative devices but does not address placement configurations. *ASCE*-7-05 (2006) addresses similar issues of *FEMA 356*, with the main focus on different analysis techniques for damped structural systems. The *International Building Code* (IBC) (2006) only addresses seismic isolation systems. *Eurocode 8. Design of Structures for Earthquake Resistance: General Rules* (BS EN 1998-1:2004) discusses base isolation but does not mention passive damping while *Eurocode 8. Design of Structures for Earthquake Resistance: Part 3: Assessment and Retrofitting of Buildings* (BS EN 1998-3:2005) very briefly mentions passive damping as a potential retrofit option via base isolation or dissipative bracing. The Anti-seismic Devices Standard (prEN15129) presents acceptable methods for testing and modelling dampers but not the incorporation of dampers in structures (CEN/TC 2008). Finally, Liu et al. (2005) suggests that the effective damping technique presented in FEMA 356 and FEMA 368 cannot ensure optimal performance of the structure.

The focus of this section is to present a preliminary optimisation case using an optimisation technique proposed in literature, one general placement technique, and an adaptation of a general technique. A brief description of the optimisation placement technique, the scenario for retrofitting a baseline building, and the results of the optimisation technique as compared to general placement techniques are presented. Linear viscous dampers were chosen for the building retrofit for two reasons: application of many of the optimisation techniques has only been successfully implemented for linear dampers and a linear viscous damper represents the simplest type of damper to employ for a preliminary optimisation case.

Application of the Simplified Sequential Search Algorithm

Lopez-Garcia (2001) proposes the Simplified Sequential Search Algorithm (SSSA), which is an adaption of the Sequential Search Algorithm (SSA) (Zhang and Soong 1992). The overall objective of the method is to sequentially place dampers where their maximum effectiveness will be achieved. An advantage of this placement technique is its simplicity and ability to be employed without complex computational algorithms. Like the SSA method, the SSSA method assumes that dampers are the same size or multiples of that size. To apply this optimisation technique, it is necessary to know the structural properties of the building (lateral stiffness, floor masses, fundamental period, and damper inclination). The variable is the required total damping per floor (distribution of the total viscous damping). Optimal location indices (γ_i) determine where the damper's effect will be maximised (Eq. 3). The optimal location index is dependent on the sum of the interstory drift (δ_i) and interstory velocity ($\dot{\delta}_i$), respectively multiplied by the alpha coefficients (α_1, α_2). For the case of a purely linear fluid viscous damper, the first alpha value is zero, as the device adds no stiffness, and the second alpha equals one, as the device's impact is solely proportional to velocity. Therefore, the optimal location index for a linear fluid viscous damper is proportional to the maximum interstory velocity.

$$\gamma_i = \alpha_1 \delta_i + \alpha_2 \dot{\delta}_i \tag{3}$$

The procedure for applying the SSSA technique is as follows:
(1) Create a modal model or three-dimensional model of the building.
(2) Choose the desired performance objective (i.e. increased effective damping ratio)
(3) Use the modal strain energy method (Zhang and Soong 1992) to calculate the total added damping coefficient required to achieve the desired performance objective.
(4) Approximate realistic damper sizes and estimate the number necessary to achieve the required added damping.
(5) Apply the ground motion to the building.
(6) Place the first damper where its effect is maximised (see optimal location indices).
(7) Re-apply the ground motion record and determined the next optimal location.
(8) Repeat steps 6-7 until all dampers have been placed.

However, there are numerous limitations of this optimisation technique. The SSSA assumes that the response of the structure is linear, a reasonable assumption in the case of a building retrofit with dampers. It also assumes that the first modal shape is a straight line, implying equivalent first mode interstory drifts. The SSSA technique is dependent on the ground motion applied, unlike its counterpart, the SSA technique, which uses a stochastic representation of ground motions. Therefore, to produce a true optimised configuration, the SSSA technique must be applied for various ground motions. In addition, successful applications of the SSSA technique are restricted to linear viscous dampers and modal models.

Preliminary Optimised Building Scenario

For investigating the optimisation techniques, a Eurocode-compliant building was designed as a baseline structure for a retrofit with viscous devices. The following section presents details of the baseline building, the applied ground motion, and the retrofit of the building with dampers to achieve a desired performance objective. The SSSA technique, uniform distribution technique, and stiffness inversely-proportional damping were applied.

Baseline Building and Ground Motion

The baseline building was an eight-story, steel moment-resisting frame building with 0.15m concrete floor slabs. The building was designed according to the Eurocode. SAP2000 was used for structural member design and analysis, and the building was designed for a peak ground acceleration of 4 m/s^2. The inherent structural damping was represented by 2% Rayleigh damping. The three-dimensional model, masses and approximate stiffness per floor are presented (Fig. 9). The fundamental period of the building was 0.99 seconds. The N-S El Centro Imperial Valley 1940 ground motion record was used because of its long duration and acceptance as a standard ground motion reference. For future work, multiple ground motions should be considered to definitively conclude the effectiveness of the SSSA optimisation configuration, as the technique is inherently dependent on the applied ground motion. Since the SSSA technique assumes a linear response of the building, it was necessary to use a scaled ground motion that resulted in a linear response of the retrofitted building. It was concluded that a 50%-scaled El Centro N-S ground motion (0.15g) would prompt a linear response of the building. This was justified by ensuring that the design value of the maximum, elastic roof displacement was similar to the maximum roof displacement of the 50% El Centro earthquake.

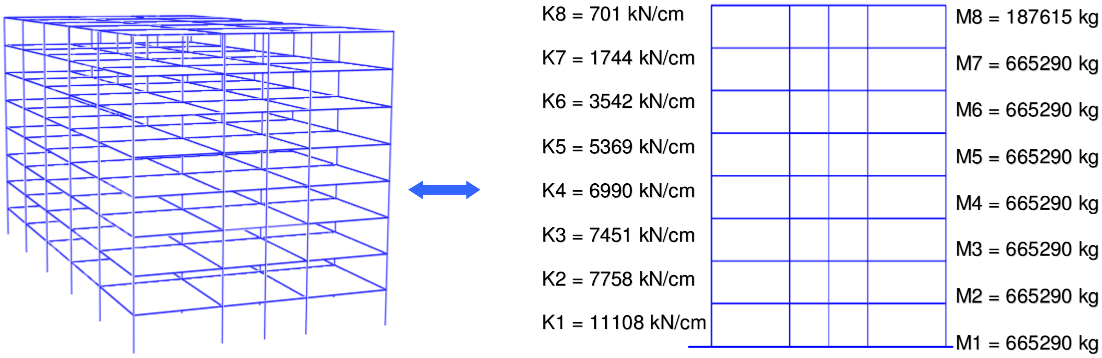

Figure 9. Baseline building - floor masses and stiffnesses.

Dissipative Device Retrofit

The objective was to apply a building retrofit with linear viscous devices to achieve an increased total damping ratio of 7%. Since the inherent structural damping was 2%, the additional viscous damping was designed to add 5% effective damping to the structure. It is acknowledged that this level of damping may be too low to be realistic; however, it is a similar value to those used in SSSA examples (Lopez-Garcia 2001) and was used in this preliminary case as an instructive example of the effects of added viscous dampers. Application of the SSSA technique and the modal strain energy equation for linear viscous dampers determined that the necessary additional viscous damping to meet the performance objective was 1100 kN-sec/cm. This was achieved by the addition of eight linear viscous dampers, each with a viscous damping coefficient of 138 kN-sec/cm. To avoid torsional effects, the dampers where placed symmetrically in each floor, two dampers with viscous coefficients of 69 kN-sec/cm in the centre bays. ABAQUS was employed to model the building with the damper retrofit, and it was chosen because of its wide range of options for damper modelling. Using the SSSA procedure, dampers were applied sequentially at the floors where there was a maximum floor interstory velocity. Linear time history was used to analyse the building performance after the addition of each damper pair per floor.

The stiffness inversely-proportional damping (SIPD) technique was selected to investigate an adaptation of a common placement technique (stiffness-proportional damping). The SIPD technique distributes damping per floor that is inversely proportional to the lateral floor stiffness. The uniform distribution technique applies an equal quantity of damping for every floor. For this preliminary scenario, both general placement schemes use the same total viscous damping, 1100 kN-sec/cm, used for the SSSA technique.

Test Results and Discussion

The final configuration using the SSSA technique was eight dampers, placed sequentially on floors 8-7-7-6-6-6-2-2 (Table 2). The building was also retrofitted using the uniform distribution and SIPD placement schemes. Finally, these placement configurations were compared to the original building without dampers. An informative performance building performance indicator is interstory drift, as it denotes the levels deflection that will be imposed on the structural members. Fig. 10 presents the building performance as a time history of the sum of the peak interstory drifts of all floors. The ground motion is applied from 10 to 50 seconds. Fig. 11 presents the distribution of peak interstory drifts.

Table 2. Total added damping in the form of linear viscous dampers.

Floor	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
SSSA *Added Damping (kN-sec/cm)*	138	276	414	0	0	0	276	0
SIPD (Stiffness Inversely-Proportional Damping) *Added Damping (kN-sec/cm)*	274	191	184	172	132	87	43	17
Uniform Distribution *Added Damping (kN-sec/cm)*	138	138	138	138	138	138	138	138

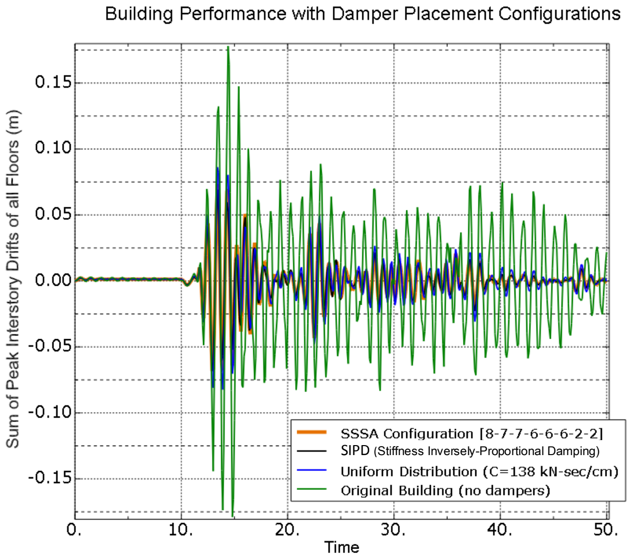

Figure 10. Sum of peak interstory drifts
- building under 50% El Centro.

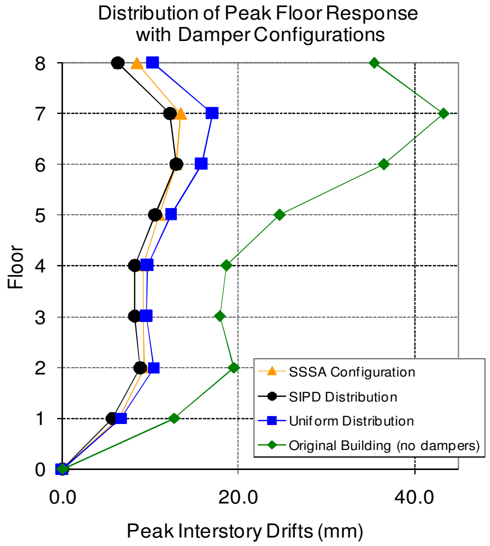

Figure 11. Floor peak interstory drifts
- building under 50% El Centro.

The results of the peak interstory drifts show that the SIPD configuration was the most effective at reducing the seismic interstory drift. The SIPD technique was marginally more effective than the SSSA technique for floors 1-6 and most effective for floors 7 and 8, while the SSSA technique was slightly more effective at reducing peak interstory drifts than the uniform distribution for floors 1-5 and particularly most effective for floors 6, 7, and 8. All three placement techniques greatly reduced interstory drifts and improved the overall distribution of interstory drifts along the building height. As opposed to the increasing interstory drifts with height as seen in the original, undamped building, the placement techniques yielded a smaller distribution of interstory drift values along the building height, approaching a uniform spread of interstory drifts. It is suggested that the large difference in the stiffnesses of floors 7 and 8 and small magnitude of the stiffnesses in these floors may explain why the SIPD technique was most effective at reducing interstory drifts, particularly on floors 7 and 8. Both the uniform placement and SIPD techniques were simple and time-efficient to implement. Finally, a limitation of this application of the SSSA method is the restricted number of dampers used (equivalent to the number of stories). Additional research by Lopez-Garcia and Soong (2002) suggests that optimal number of dampers should be greater than or equal to 1.5 – 2 times the number of stories. Further work is needed to investigate the SSSA technique's effectiveness for an optimal number of dampers.

Conclusions

Based on a preliminary investigation of the SSSA optimisation technique with linear viscous dampers, it can be concluded that the SSSA technique is not as effective as the stiffness inversely-proportional damping technique and slightly more effective than the uniform distribution technique at reducing interstory drifts for this scenario. This conclusion is limited by this specific building scenario, ground motion, and quantity of dampers, and additional analysis of the SSSA technique for different ground motions, various building performance objectives, building designs, and varied number of dampers is necessary to make a definitive conclusion about its effectiveness compared to general placement schemes. The behavioural testing of the viscous devices confirmed the well-known existence of rate-dependent and temperature-dependent properties. More importantly, it was instructive to observe through preliminary testing and simple analytical models that refined numerical models are needed to avoid exaggerating the energy dissipation potential and neglecting rate-dependent behaviour of the devices. Future work will encompass improved nonlinear modelling of the fluid spring damper and fluid viscous damper, incorporation of nonlinear models into various optimisation techniques, and validation of the nonlinear models and optimisation techniques using real-time hybrid testing.

Acknowledgements

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