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Dynamic response control of structures with horizontal-scissor-jack brace-damper systems

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ABSTRACT

Natural disasters such as earthquakes can cause enormous loss to life and property. To protect life and property, in the design and construction of building structures, it is essential to improve buildings' seismic resistance. This paper proposes a horizontal-scissor-jack brace-damper system for dynamic response control of building structures. The horizontal-scissor-jack brace-damper system increases the energy dissipation of a viscous fluid damper by magnifying relative velocity of the two ends of the damper. To demonstrate the advantages of the proposed system over conventionally adopted damper configurations, the magnification factor of the system is compared with those from six existing configuration alternatives. A five-story shear building is also used to study the effects of the added systems. Results demonstrate that the proposed system gives the highest magnification factor, and under the same damping coefficient of the dampers, when compared to other six damper configurations, the proposed system is the most effective in reducing response displacement and acceleration under given seismic events, both in peak and in root-mean-square responses, because of the increased overall damping by the proposed system. The proposed horizontal-scissor-jack brace-damper system is therefore deemed an effective solution for response control of building structures under dynamic loading.

1. INTRODUCTION

In the modern society, due to the rapid growth of world population, building structures become main places where the people live and work; however, there are natural events that occurred in the past that caused severe damage to building structures and, as a result, terrible losses of human life. In 11th of March, 2011, the earthquake with magnitude of 9.0 took place in approximately 130 km east of Sendai City in Tohoku region of Japan, causing the collapse of at least 3500 buildings and about 16 thousand deaths. It is therefore evident that, to protect property and life of

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human beings, the improvement of the buildings' performance in terms of the earthquake resistance is an essential consideration for the design and construction of building structures in seismically active regions. The ability to provide sufficient dynamic response control is one of the important considerations for the design of building structures.

Among the existing techniques for enhancing seismic resistance of building structures, the use of passive energy dissipation devices is one common approach. Different types of passive energy dissipation systems were developed over the last few decades. Among the existing techniques for enhancing seismic resistance of building structures, the addition of viscous fluid dampers is one common approach. Energy dissipation provided by these dampers results in reduction of the vibration response, which ensures an improved performance of building structures under dynamic loadings. Fluid in the dampers is forced to flow over the small orifices generating absorption of the input energy (Hwang, 2002; Symans et al., 2008). In the aspect of improving the effectiveness of the added viscous fluid dampers for seismic response control, two possible solutions may be proposed. One is to increase the damping coefficient of the dampers, which is often associated with the application of large and expensive dampers; the other is to magnify relative velocity between the two ends of the dampers, which may be achieved by integration of the lever arm mechanism. Due to the potential economical savings that may be obtained via the use of brace-damper systems that lead to higher relative velocity (here referred to as "magnification factor"), in the literature, several different brace-damper configurations were proposed. Typical configurations may include the diagonal type and Chevron type (Fig. 1(a) and (b)), which are perhaps the most commonly applied damper configurations in the construction industry due to their simplicity. The magnification factor for the diagonal braced case is calculated by the cosine of the brace inclination angle, and, for the Chevron braced type, it is always equal to one (Table 1). This means that the relative velocity within the damper as compared to inter-story velocity in the case of the diagonal braced is reduced, and in the case of Chevron braced it remains the same. Therefore, these two approaches are considered "not efficient" and there is a demand for increasing the amplification factor for better structural performance.

To further improve the effectiveness of the added dampers, different configurations such as toggle braced damper systems were developed by Constantinou et al. (2001) (Fig. 1(c), (d), and (e)). In these configurations, upper, reverse and lower toggle geometrical arrangements were proposed, and efficiency of the systems was verified theoretically and by experiments in the investigation (Constantinou et al., 1997). Another configuration for damper allocation considers the integration of the scissor-jack mechanism attached with two ends on the floor slabs (Sigaher and Constantinou, 2003) (Fig. 1(f)). Table 1 shows the formulas used to calculate the magnification factor based on different design parameters for all six damper configurations. It can be seen from Table 1 that the resulting magnification factor depends highly on the inclination of the mechanism. For all six proposed solutions, the value of the magnification factor is found to be within the range up to a maximum of 3.5 (Sigaher and Constantinou, 2003).

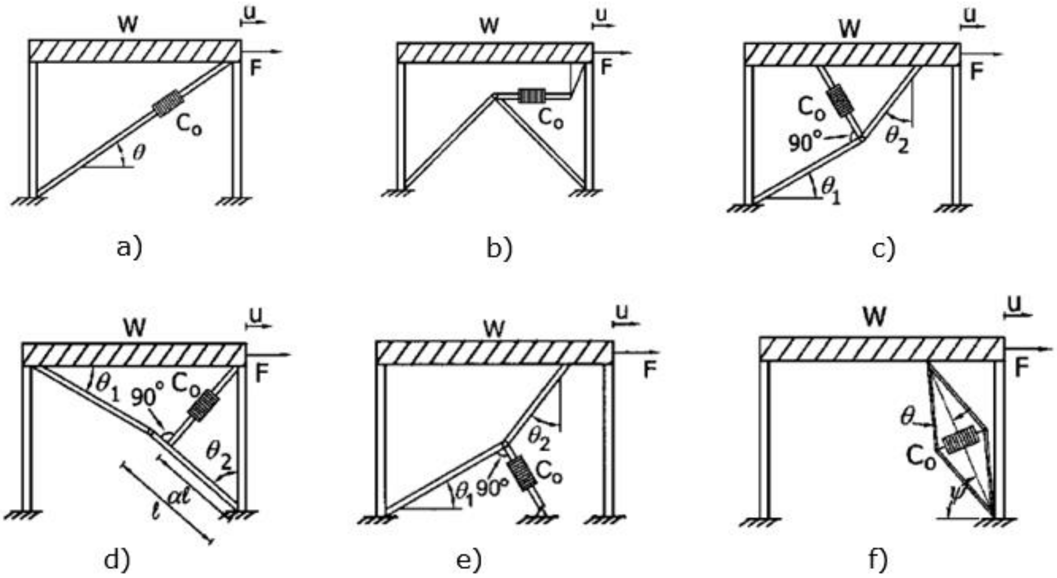


Fig. 1 Various damper configurations: a) Diagonal, b) Chevron, c) Upper toggle, d) Reverse toggle, e) Lower toggle, f) Scissor-jack (Constantinou et al., 2001; Sigaher and Constantinou, 2003).

Table 1 Magnification factors of various damping configurations.

Configuration	Magnification factor, f
Diagonal Brace	$\cos(\theta)$
Chevron Brace	1
Lower Toggle	$\dfrac{\sin(\theta_2)}{\cos(\theta_1+\theta_2)}$
Upper Toggle	$\dfrac{\sin(\theta_2)}{\cos(\theta_1+\theta_2)}+\sin(\theta_1)$
Reverse Toggle	$\dfrac{\alpha\cos(\theta_1)}{\cos(\theta_1+\theta_2)}-\cos(\theta_2)$
Scissor Jack	$\dfrac{\cos(\psi)}{\tan(\theta)}$

A horizontal scissor jack damper configuration derived from conventional scissor jack shown in Fig. 1(f) is proposed in this paper to increase the energy dissipation of the fluid viscous dampers by magnification of the relative movement between two ends of the dampers, with the goal of providing the magnification factor higher than 3.5. To demonstrate the advantages of the proposed system over conventionally adopted damper configurations, the magnification factor of the system is compared with those from six existing configuration alternatives. A five-story building model is also used to study the effects of the added systems by comparing the story displacement and acceleration responses under seismic events. Results demonstrate that the proposed system gives the highest magnification factor, and under the same damping coefficient of the dampers, when compared to other six configurations, the proposed system is the most effective in reducing response displacement and acceleration under given seismic events, both in peak and in root-mean-square responses.

2. HORIZONTAL-SCISSOR-JACK BRACE-DAMPER SYSTEM

2.1 Introduction to Horizontal-Scissor-Jack

In order to increase the magnification factor, in this paper an improvement of the conventional scissor-jack damper configuration is made. It is proposed to position the damper in the horizontal position to provide maximum magnification factor, thus increasing the efficiency of the damper system. For this purpose, the Horizontal-Scissor-Jack (HSJ) brace-damper system is developed and illustrated in Fig. 2. Two Chevron braces, a V and an inverted-V, are rigidly-mounted to the floor and ceiling slabs, respectively, as shown in Fig. 2. The two braces are assumed to be rigid in the horizontal direction, and the top joints (points A and B in Fig. 2) are positioned at the same height so that relative movement of the two joints are consistent with the inter-story drift when the building is subjected to lateral dynamic loadings. Two scissors with scissor legs of equal length are connected to the joints of the Chevron braces by pin connection to allow free rotation of the scissor legs. Scissor legs are assumed to axially rigid so that deformation under axial loading can be neglected. A fluid viscous damper is installed in between the two scissors to form the horizontal-scissor-jack brace-damper configuration.

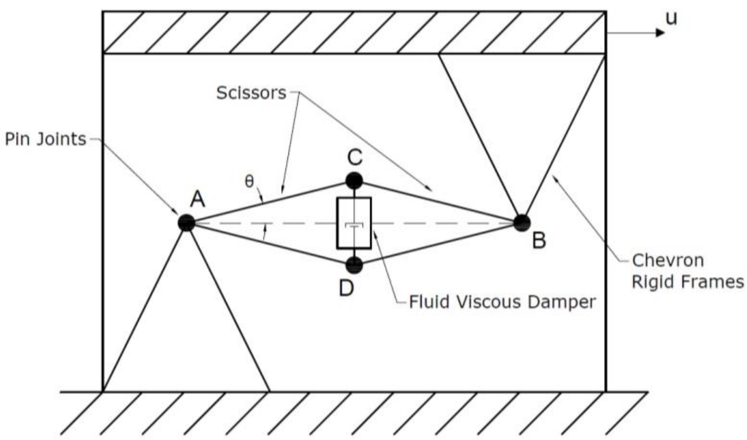


Fig. 2 Horizontal-Scissor-Jack brace-damper system.

2.2 Magnification Factor

The magnification factor for the proposed system can be derived from the analytical model shown in Fig. 2. In this model the distance between points A and B and the distance between points C and D of the damper can be expressed as:

$$\overline{AB} = 2lsin(\theta) \quad (1a)$$
$$\overline{CD} = 2lcos(\theta) \quad (1b)$$

Where l is the length of one leg of a scissor jack and θ is the angle between the leg and the horizontal line joining A and B.

When the single degree of freedom system shown in Fig. 2 is subjected to lateral dynamic loading, the change in the distance $\overline{AB}$ can be considered the same as relative displacement of the upper and lower stories, assuming the two Chevron braces are rigid. Therefore, the two distances after applying dynamic loading can be expressed in terms of the change of the horizontal angle θ inside the scissor-jack, $\Delta\theta$:

$$\overline{AB'} = 2lsin(\theta \pm \Delta\theta) \quad (2a)$$
$$\overline{CD'} = 2lcos(\theta \pm \Delta\theta) \quad (2b)$$

A magnification factor can be defined by relating the relative movement in vertical direction to the inter-story drift in horizontal direction as:

$$f = \frac{\overline{AB}-\overline{AB'}}{\overline{CD'}-\overline{CD}} = \frac{sin(\theta)-sin(\theta \pm \Delta\theta)}{cos(\theta \pm \Delta\theta)-cos(\theta)} \quad (3)$$

Eq. (3) is the full expression of the magnification factor that provides exact result according to the change of the horizontal angle, *Δθ*. If the change of the angle is small, Eq. (3) can be simplified for practical application. In such case, if *Δθ* is small, the following approximations can be applied:

$$\cos(\Delta\theta) = 1 - \frac{(\Delta\theta)^2}{2} \approx 1 \quad (4a)$$
$$\sin(\Delta\theta) = \Delta\theta \quad (4b)$$

Substitute Eq. (4) into Eq. (3) yields a compact form of the magnification factor shown below:

$$f = \cot(\theta) \quad (5)$$

Eq. (5) represents a simplified approach for determination of the magnification factor. To ensure the validity of this expression, results from Eq. (5) by using a wide range of angle θ is compared with those from the full expression (Eq. (3)), assuming the rotation of the scissors, $\Delta\theta$, to be 0.2°. Fig. 3 shows the results of this comparison.

It can be seen from Fig. 3 that, at a relative small rotation of 0.2°, two curves match quite well, indicating that the simplified expression provides satisfactory accuracy as compared to the full expression. It can also be seen from Fig. 3 that magnification factor ranging from 1 to 11 is observed at the angle from 50 to 5 degrees, and with increasing angle a decreasing and diminishing return of the magnification factor is also noted. It is worth noting that there is a rapid growth of magnification factor at the angles below 20 degrees. Comparing with the damper layout conventionally adopted, which provides up to a maximum magnification factor of 3.5 (Sigaher and Constantinou, 2003), the HSJ system at small leg angle can provide a factor larger than 3.5, which is an advantage over the previously proposed damper layouts. Fig. 3 also provides a good basis on how much magnification relative to the inter-story drift can be gained at a given scissor angle.

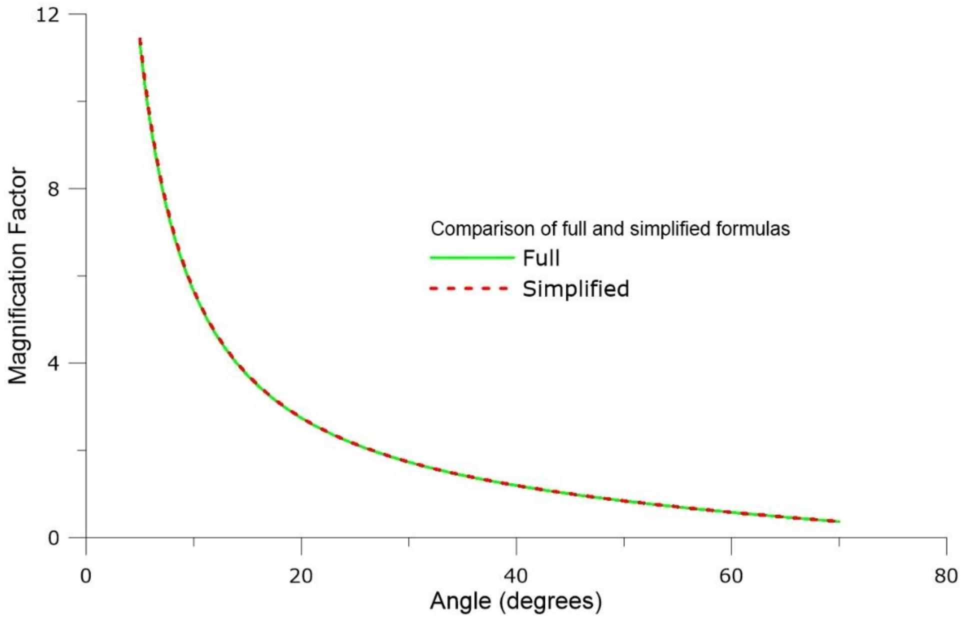


Fig. 3 Comparison of simplified expression with full expression of the magnification factor, assuming 0.2° rotation.

Magnification factor *f* in Eq. (5) represents the cotangent of the horizontal inclination of scissors; therefore, it can be expressed in terms of relationship between distances $\overline{CD}$ to $\overline{AB}$ as:

$$f = \cot(\theta) = \frac{\overline{CD}}{\overline{AB}} \tag{6}$$

Rearranging Eq. (6), the available length for the damper device, $\overline{AB}$, can be obtained based on the desirable magnification factor (*f*) and the allowable scissor-jack width ($\overline{CD}$) as:

$$\overline{AB} = \frac{\overline{CD}}{f} \tag{7}$$

Eq. (7) gives useful information in the selection of proper damper devices for practical application of the HSJ system, as the available space for the dampers is one important limitation in applying the HSJ brace damper system in real building applications.

3. APPLICATION OF THE HSJ SYSTEM TO MULTI-STORY BUILDINGS

To demonstrate the efficiency of the proposed system, the implementation of the HSJ brace-damper system on a five-story building structure shown in Fig. 4 subjected to 1940 El Centro earthquake is modelled. The same fluid viscous dampers but with different damper configurations (the six damper layouts shown in Fig. 1) are also used for comparison of the dampers' effectiveness. The five-story building is assumed to be a shear building with mass lumped at floor level, and the story mass, stiffness, and damping are considered identical for each story. Mass and lateral stiffness of each story are 25000 kg and 51.2 MN/m, respectively. Damping ratio of the building is assumed to be 5%, based on the typical value observed in buildings (Newmark and Hall, 1982). Damping coefficient for the fluid viscous damper is equal to 213 kN.s/m. Table 2 gives properties of the building for later dynamic analysis.

Seven damper configurations with different design parameters and magnification factors shown in Table 3 are used in this case study, with one damper on each of the 5 stories of the structure. In the seven configurations, all dampers used are identical with same damping coefficient, and braces used to support the dampers are assumed to be axially rigid. It should be noted that different design parameters may be used in all the configurations, but the only damper layout that is able to produce magnification factor larger than 3.5 is the HSJ system proposed in this paper.

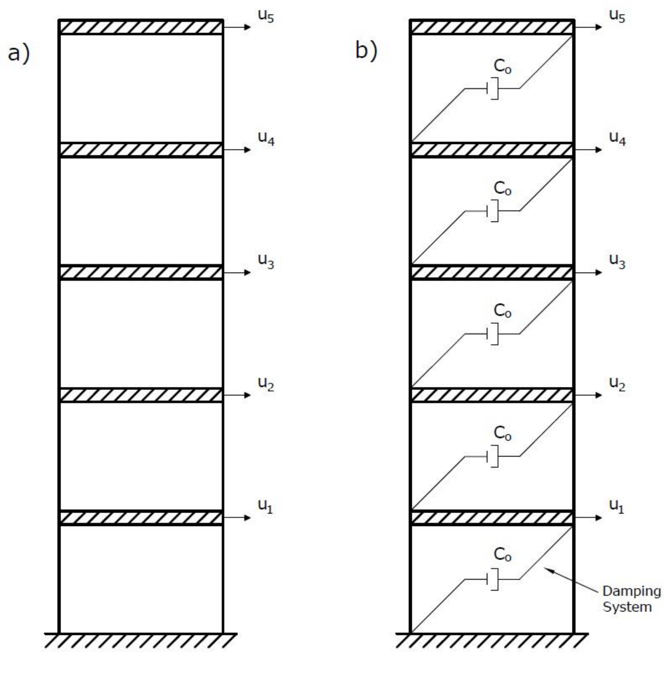


Fig. 4 A five-story structure: a) without dampers, b) with brace-damper systems.

Table 2 Properties of the five-story buiding.

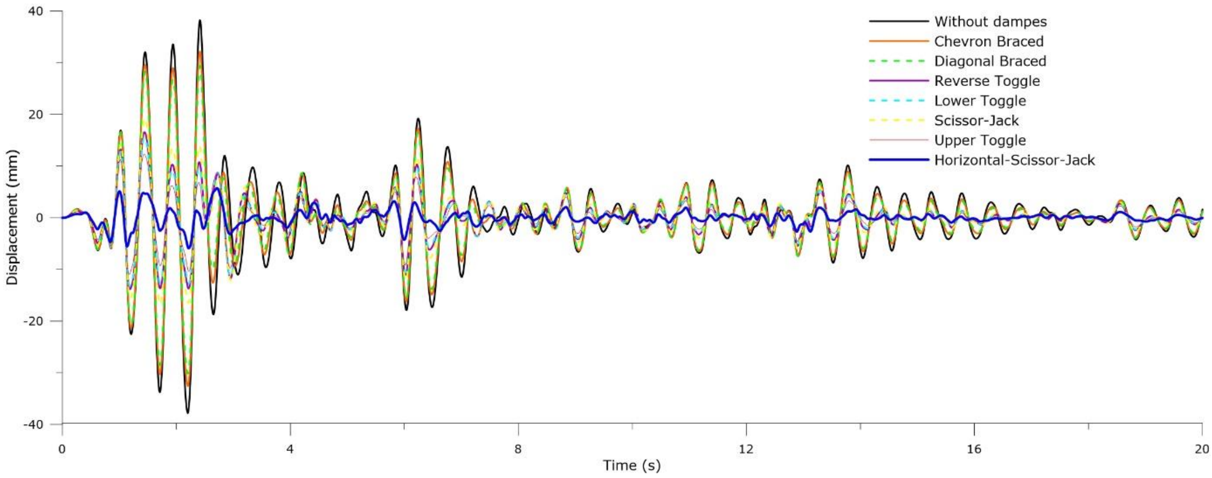
Input	Value
Mass matrix (kg)	$\begin{bmatrix} 25000 & & & & \\ & 25000 & & & \\ & & 25000 & & \\ & & & 25000 & \\ & & & & 25000 \end{bmatrix}$
Stiffness matrix (MN/m)	$\begin{bmatrix} 10.24 & -5.12 & & & \\ -5.12 & 10.24 & -5.12 & & \\ & -5.12 & 10.24 & -5.12 & \\ & & -5.12 & 10.24 & -5.12 \\ & & & -5.12 & 5.12 \end{bmatrix}$
Damping ratio	0.05
Damping coefficient of device (N.s/m)	$2.13*10^5$

Table 3 Parameters and magnification factors for different damper configurations.

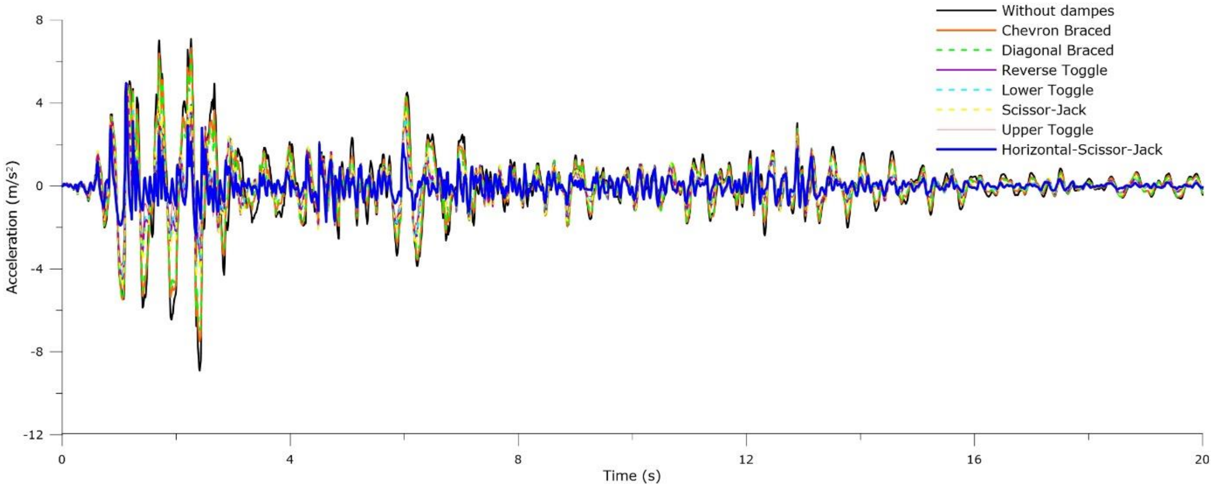
Configuration	Parameters	Magnification factor, f
Diagonal Braced	$\theta = 37°$	0.8
Chevron Braced	-	1
Lower Toggle	$\theta_1 = 31.9°, \theta_2 = 43.2°$	2.662
Upper Toggle	$\theta_1 = 31.9°, \theta_2 = 43.2°$	3.191
Reverse Toggle	$\alpha = 0.7, \theta_1 = 30°, \theta_2 = 49°$	2.521
Scissor-Jack	$\psi = 70°, \theta = 9°$	2.16

Horizontal-scissor-jack	$\theta = 10°$	5.671

Fig. 5 shows the time histories of story displacement and acceleration of the fifth floor of the building under the assigned seismic input excitation. It can be seen from Fig. 5 that, comparing to the six other damper configurations proposed previously in the literature, the HSJ system has the smallest peak and average story displacement and acceleration. This is attributed to the fact that the HSJ system has the largest magnification factor, as can be seen in Table 3. Table 4 shows the peak response displacement and acceleration, while Table 5 shows the root-mean-square response displacement and acceleration of the five story building. It can be seen from both tables that the HSJ system has the largest response reduction in story displacement and acceleration in each story, in both peak and root-mean-square responses, and the proposed HSJ system is proved to reduce significantly the responses of the structure and provide the best performance among all suggested damper configurations under the given seisimc loading.



(a) Displacement



(b) Acceleration

Fig. 5 Story displacement and acceleration histories of the 5th story of the building.

Table 4 Peak displacement and acceleration responses of the builing.

Response	Displacement (mm)					Acceleration (m/s^2)				
Story	1	2	3	4	5	1	2	3	4	5
Without dampers	11.76	21.99	29.92	35.17	38.23	5.17	6.53	7.40	7.57	8.91
Diagonal Braced	10.34	19.19	25.95	30.40	32.58	4.89	5.98	6.54	6.90	7.50
Chevron Braced	9.60	17.78	24.01	28.13	30.15	4.77	5.82	6.10	6.52	6.93
Lower Toggle	4.52	8.60	11.96	14.35	15.59	3.05	4.14	4.65	4.70	4.91
Reverse Toggle	4.77	9.11	12.69	15.25	16.58	3.19	4.16	4.62	4.62	4.91

Upper Toggle	3.68	6.93	9.55	11.39	12.34	2.67	4.01	4.72	4.95	5.00
Scissor-Jack	5.48	10.49	14.69	17.71	19.28	3.58	4.48	4.51	4.63	4.86
Horizontal-Scissor-Jack	1.95	3.52	4.70	5.49	5.89	2.04	3.22	4.07	4.67	4.96

Table 5 Root-mean-square displacement and acceleration responses of the builing.

Response	Displacement (mm)					Acceleration (m/s^2)				
Story	1	2	3	4	5	1	2	3	4	5
Without dampers	2.23	4.28	6.00	7.24	7.89	0.63	0.99	1.23	1.42	1.59
Diagonal Braced	1.93	3.72	5.21	6.29	6.86	0.53	0.85	1.09	1.28	1.41
Chevron Braced	1.81	3.48	4.88	5.89	6.43	0.50	0.81	1.04	1.21	1.33
Lower Toggle	1.00	1.89	2.62	3.13	3.40	0.33	0.54	0.69	0.81	0.86
Reverse Toggle	1.05	1.99	2.76	3.30	3.59	0.33	0.55	0.72	0.83	0.89
Upper Toggle	0.85	1.59	2.18	2.59	2.80	0.29	0.49	0.63	0.72	0.77
Scissor-Jack	1.19	2.27	3.16	3.80	4.13	0.36	0.60	0.77	0.90	0.97
Horizontal-Scissor-Jack	0.44	0.80	1.07	1.25	1.35	0.19	0.33	0.43	0.49	0.52

4. CRITICAL EVALUATION OF THE HSJ SYSTEM

From the results of magnification factor derived from the analytical model of the HSJ system and the simulation of a five-story building with the HSJ systems under a given earthquake excitation, the proposed HSJ system is theoretically proved to be an effective solution for reducing the dynamic responses (e.g. story displacement, acceleration) of building structures. However, for the implementation of the suggested configuration to real structures, it should be evaluated from practical application point of view. First, it is important to recognize that HSJ system can provide better performance at low horizontal leg angles of the scissors, as is evident from Fig. 3 that there is a rapid growth of magnification factor at angles below 20 degrees. However, decrement of the horizontal angle is associated with the reduction of the height available for the installation of the fluid viscous damper. This height limits the use/installation of large damper devices. Hence, it is reasonable to state that practical value of the HSJ systems is limited by the geometry of the system. For example, if the span of the portals in typical building structures is assumed to be 6 meters, then the expected span of the horizontal-scissor-jack may be around 4 meters. Based on Eq. (7), the available height for the damper with target magnification of 5.671 (θ=10°) in the proposed scenario can be calculated to be 0.7 meter. Such space restriction limits the selection and implementation of the fluid viscous dampers that can provide the required damping coefficient and generate necessary damping force at high magnification factors.

Another concern in the application of the HSJ system in practice is the cost. Theoretically, increment of the magnification factor in general benefits the cost savings due to the more efficient operation of the damper devices; however, in the case of the HSJ system, the cost is also associated with the complexity of the brace layout. For instance, for the proposed solution there is a total of eight brace members, i.e. four scissor legs and four braces, and this number of additional braces is the highest among all damper configurations in the case study. Furthermore, the improved performance of structures with HSJ systems is based on the large damper force magnified by the scissor mechanism, therefore, the braces should be stiff enough to transmit the force to the story effectively. Both the number of braces and the requirement for the properties of the braces suggest that there can be additional expenses due to the assembly of such configuration. Hence, further investigation about economic aspect for the application of horizontal-scissor-jack brace-damper system in real structures is needed.

5. CONCLUSIONS

Damping properties of structures is considered to contribute significantly to the reduction of dynamic responses of structures subjected to external loadings. Hence, to improve overall structural performance, an increase of the structures' damping is generally favored, and the implementation of damper devices is considered one of the most suitable options for modification of the energy dissipation for building structures. For a fluid viscous damper, its efficiency depends highly on the relative velocity between the two ends of the damper, thus there is a demand for velocity magnification to improve overall damper's performance in reducing structural responses. For this reason, the horizontal-scissor-jack brace-damper system is proposed. Analytical model and derivation of the magnification factor are developed. Theoretical magnification factor derived from the HSJ system is compared with those from the existing configurations, and the HSJ system provides the highest magnification factor. Results from a five-story building with various damper configurations also reveal that the HSJ system exhibits the best performance in terms of the reduced peak and root-mean-square responses, and is deemed an effective solution for response control of building structures under dynamic loading. It is however important to note that, there are concerns associated with the practical implementation of the HSJ system, e.g. geometrical restrains preventing installation of the large fluid viscous dampers at high magnification factor setting and potential expenses due to its relatively complicated brace assembly. Practical application of the HSJ system in real building structures is therefore worth further investigation.

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