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Abating Earthquake Effects on Buildings by Active Slip Brace Devices

A hybrid control system for reducing building vibration under a spectrum of earthquake load amplitudes is presented. The hybrid control is accomplished by an energy dissipation device called the active slip brace device (ASBD). The hybrid control system uses the ASBD to regulate the energy dissipation characteristics of the building during its response to earthquakes by utilizing active control principles. The ASBD consists of a Coulomb friction interface with a clamping mechanism on the interface. The clamping force on the friction interface is altered at short time intervals during building vibration. Computer simulations of building response with and without ASBD are compared.

INTRODUCTION

This article describes a hybrid control method using energy dissipation devices installed on building structural lateral load bracing. The energy dissipation device is called the active slip brace device (ASBD). The ASBD is designed to reduce building response to seismic actions and wind. The ASBD is controlled such that the energy dissipation characteristics of the building structure are regulated during vibratory response. Active control principles are utilized to regulate the energy dissipation characteristics.

The ASBD dissipates energy by slipping along a Coulomb friction interface. The load at which this interface slips is controlled by the amount of clamping force applied to the interface. In the example shown in Fig. 1, the ASBD is installed as part of each building lateral load bracing in a chevron arrangement. The ASBD consists of a series of plates with sandwiched friction pads encased by a clamping mechanism. The bracing telescopes in or out during the building's lateral vibrations when the brace force exceeds the friction force generated by the clamping mechanism. The clamping force on the friction interface is monitored and controlled during the building's lateral vibration, which changes the brace force that initiates slip, thus actively altering the dynamic response characteristics of the building. This categorizes buildings with the ASBD as actively controlled structures.

The ASBD concept was first reported by Akbay (1991). The ASBD is the refinement of a passive energy dissipation device described by Giacchetti et al. (1989). Uras and Aktan (1993) described a full scale prototype development of an ASBD. In the prototype development, ASBD was designed for a hypothetical 10-story building located in a high seismicity zone, fabricated, and tested. They reported satisfactory performances of the full scale ASBD, the device response, and its operation. The ASBD design parameters, control algorithm, and their parametric evalua-

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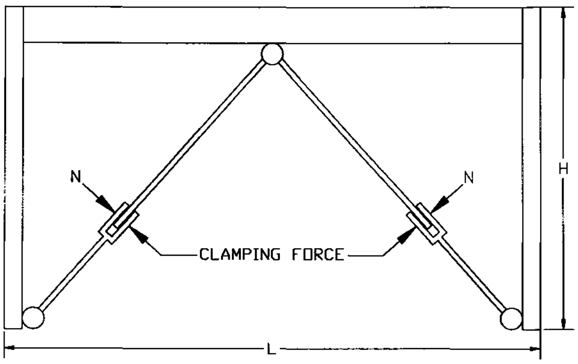

FIGURE 1 Braced building frame with ASBD.

tion on building response under dynamic ground excitations including earthquakes will be described in this article.

In order to explain the ASBD's effect on the seismic response of buildings it is essential to summarize building design and building behavior expectations during earthquakes. Buildings are designed to provide sufficient lateral stiffness for serviceability, and sufficient strength to meet safety requirements under earthquake loads FEMA (1992). The building's structural components are designed to meet the enveloping demands of strength and stiffness. Due to the dynamic nature of the earthquake load, building strength, coupled with stiffness, influences response. Therefore, providing a balance between strength and stiffness becomes very difficult.

Building serviceability requirements are defined as limits on interstory displacements. In the case of dynamic amplification during minor earthquakes, structural viscous damping is assumed to be sufficient to limit interstory displacements. Building strength requirements are based on the load demands created by major earthquakes. Building strength requirements are met not only by providing sufficient strength supply but also by preventing building collapse mechanisms until the deformations are well beyond the elastic deformation limits. The plastification of critical component zones beyond the elastic limit provides solid damping and alters the building's dynamic properties. During earthquakes, this change in dynamic properties will shift the building from the amplification zone. If the building strength is not sufficient, the solid damping capacity will not prevent its collapse. The solid damping capacity of the structure is assumed proportional to the deformation capacity of the building beyond the elastic limit, which is defined as the displacement ductility supply.

Simplified building behavior is depicted in Fig. 2 as an elasto-perfect plastic restoring force–deformation relationship. Figure 2 also shows the three basic building design parameters, namely strength, stiffness, and ductility. The restoring force is the horizontal shear equal to the inertia force at the roof level. In a building with ASBD bracing the building strength is the sum of the strength of each brace times its direction cosine. The strength of each ASBD brace is equal to friction force generated on the interface by the clamping force. The relationships between the design parameters are given below for the building shown in Fig. 1.

$$R_y = \frac{vNL}{\sqrt{\frac{L^2}{4} + H^2}} \tag{1}$$

$$k = \frac{AEL^2}{2\left(H^2 + \frac{L^2}{4}\right)^{3/2}} \tag{2}$$

$$\Delta_y = \frac{R_y}{k} \tag{3}$$

$$\mu_\delta = \frac{\Delta_{max}}{\Delta_y} \tag{4}$$

where R_y is building strength, k is building stiffness, Δ_y is yield displacement, μ_δ is displacement ductility, v is the friction coefficient of the ASBD, N is the clamping force on the friction interface, A is the cross-sectional area of the

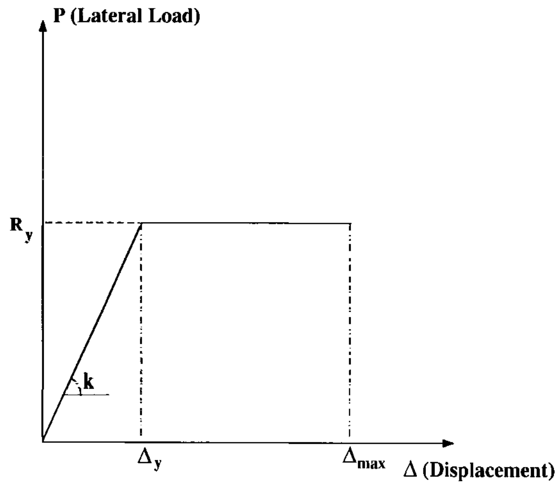

FIGURE 2 Simplified building structure behavior under lateral load.

brace, E is elastic modulus, and L and H are the building span and height shown in Fig. 1.

Changing ASBD brace strength generated by the clamping force alters the building design parameters, i.e., strength, stiffness, and ductility. Thus, during earthquakes adaptive active control is provided by actively changing the friction force generated by the clamping mechanism. The advance achieved by hybrid control is damage control by dissipating vibrational energy in the early stages of building response. The ASBD design parameters and the hybrid control strategy are described in the following sections. The response characteristics of a building with ASBD is presented for various levels of seismic forces.

RESEARCH SIGNIFICANCE

Current research on energy dissipation devices focuses primarily on complementing the damping capacity of buildings. There are very few applications that propose the use of energy dissipaters designed to be operational and to complement structural resistance during the ultimate limit response state of a building (Giacchetti et al., 1989); Pall and Marsh, (1982).

Several active and passive control mechanisms are reported in the literature and proposed for improving building response (Soong, 1990). Passive mechanisms operate using the potential energy generated during the structure's response to supply the control forces. Passive control is designed with only an analytical model of the building and a probabilistic estimate of earthquake excitation. Active control mechanisms operate with actuators using an external energy supply.

The hybrid control application described in this article is the result of a happy marriage between the passive and active methods. The significance of this article and the associated research study (Akbay, 1991) is that a hybrid control concept is demonstrated in a realistic building structure implementation. The control in this application is accomplished by actively altering the energy dissipation characteristics of the building structure during seismic action. Energy dissipation is initiated during the early stages of the seismic action, and actively regulated to minimize the response amplitudes. The ASBD described here requires only a fraction of the power an active control system needs for changing the clamping force on the interface. Adaptive control objectives are also met by being able to change building response parameters without prior knowledge of seismic excitation.

DESIGN PARAMETERS OF ASBD

The design parameters of the ASBD are developed assuming that digital control will be implemented. The maximum axial load capacity of an ASBD member achieved under maximum clamping force (brace strength) is divided into predetermined increments, ΔR. The brace strength or the ASBD capacity under the full clamping force is given in Eq. (1). The two basic design parameters associated with the operation of the ASBD are sampling rate, which defines the count of time increments at which control action is taken as dictated by a particular control algorithm, and the increments of strength that changes the ASBD strength upon demand.

The first design parameter, sampling interval, which is the inverse of the sampling rate (denoted by t_s), is the minimum time between two subsequent actions. The status of the ASBD is monitored at each t_s and a decision is made to decrease or to increase the clamping force. At each t_s the status of the ASBD is either in motion along the friction interface or idle. The t_s parameter is sufficient to study the influence of the frequency characteristics of the ground motion. Furthermore, t_s is expressed in a nondimensional form as a ratio with the fundamental period of the building, T, as t_s/T.

The second design parameters of the ASBD, which is the fixed incremental magnitude of change of brace strength (or slip level load), is normalized as a ratio of the building strength R_y. At each sampling interval (t_s) a decision on the clamping force is made as follows: if the ASBD is in motion along the friction interface, then the brace strength is increased one strength increment (ΔR); if idle, the brace strength is decreased on strength increment (ΔR). As a remainder, the strength increment (ΔR) and sampling interval (t_s) are retained constant throughout the building response.

CONTROL OF BUILDING RESPONSE UNDER GROUND IMPULSE

In this section, the impulsive response characteristics of a one-story building structure braced with ASBD members is investigated and evaluated by comparison to a benchmark building. In these comparisons, both buildings have the same structural design properties, which will be the basis for evaluating ASBD performance. The benchmark building strength is equal to the ASBD building strength that is proportional to the maximum axial load capacity of the ASBD brace under full clamping force, as shown in Eq. (1).

Building Model

The building structural model is a portal frame with X-type structural bracing. The beam and column sections are selected as W12X22 and W12X14, respectively (AISC, 1989). The beam and column members have their strong bending axes in the plane of the frame. The cross-sectional area of the brace members is 0.5 in.^{2} The total weight of the building is 154 kips and its fundamental period is computed as 0.6 s, which is representative of buildings with moderate flexibility resting on firm soils.

The frame's response to its support motion (ground motion) is modeled by a single degree of freedom, which is the horizontal displacement of the free joints. The total mass of the building (400 slug) is distributed as two equal lumped translational masses at free joints. The building strength is computed as 31 kips, which provides a base shear coefficient of 0.2. The base shear coefficient is the ratio of building strength to building weight. The distribution of lateral loads by elastic structural analysis shows that 90% of the strength of the building is supplied by the braces. Both of the braces provide an equal axial load capacity of 14.5 kips.

Building Response

To demonstrate the operation and response characteristics of the ASBD, the building structure is analyzed under an acceleration impulse applied at its base. The finite element analysis code ABAQUS (1989) is used for response calculations. The ASBD members and their control algorithm are modeled using the "User Element" capability of ABAQUS. The impulsive acceleration is taken as a step function of $1.0 \times g$ (where g is the gravitational acceleration) amplitude, and a 0.02-s duration, and applied in the horizontal direction at the base of the building structure. The ground motion pulse is of very short duration and corresponds to one-thirtieth of the initial vibration period of the building structure. The benchmark building exceeds its elastic limit and displays plastification under this impulsive ground acceleration.

Interstory drift time histories of the benchmark and the ASBD building are compared in Fig. 3. Interstory drift is the amount of displacement a story moves in horizontal direction relative to the story below. In case of a single-story building, interstory drift is equal to horizontal roof displacement. The response of the ASBD building is computed for two different strength increments (ΔR) corresponding to $R_y/5$ and $R_y/25$

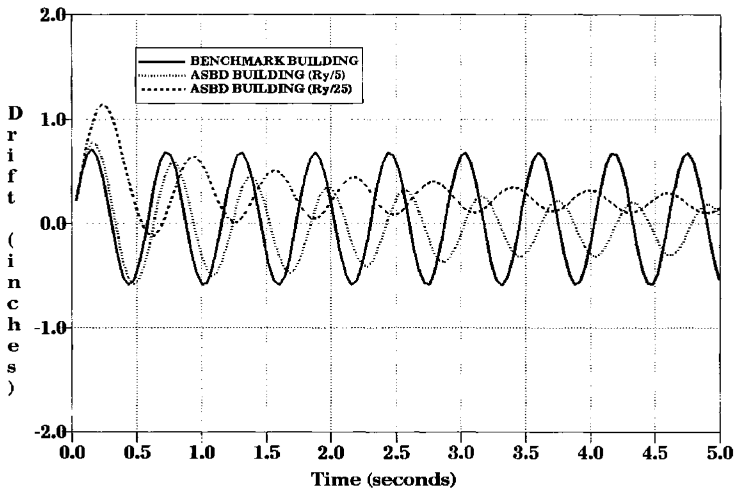

FIGURE 3 Comparison of building interstory drift response under impulsive ground acceleration.

and compared to the benchmark building. The sampling interval (t_s) for this comparison is kept constant at $T/40$, where T is the period of vibration of the ASBD and benchmark buildings.

Under the ground impulse, the benchmark building displacement response achieves a constant steady-state amplitude (Fig. 3), but the ASBD building displacement response exhibits decaying amplitudes. The ASBD building maximum displacement exceeds the benchmark building displacement during the first half-cycle. At every cycle during the later response stages, the ASBD response amplitudes are below the benchmark building. As observed in Fig. 3, increasing strength increment (ΔR) reduces the ASBD building maximum displacement response amplitude, however, it decreases the rate of amplitude decay. The comparisons in Fig. 3 demonstrate the objective in selecting the ASBD design parameters by allowing the increase in the displacement amplitude of the initial cycle as long as damage threshold of the building is not reached. This will maximize the amplitude decay.

The ASBD initial clamping force is set to a value that generates a brace strength equal to one strength increment (ΔR). The ASBD is activated when the brace force exceeds the initial brace strength. When a smaller strength increment (ΔR) is selected, the ASBD is activated sooner. And, because the sampling interval (t_s) is kept constant, displacement during the first cycle will increase. The maximum displacement of the ASBD building will be reduced if the sampling interval (t_s) is reduced while the strength increment (ΔR) is retained constant. This is because the control algorithm used here only allows the ASBD to increase in brace strength by one strength increment (ΔR) after activation.

Energy dissipation achieved by the ASBD increases as the strength increment (ΔR) is decreased and sampling interval (t_s) is increased. By assuring that the energy dissipation is maximized during the early response phase, the amplitude of the consecutive response cycles are reduced. This is demonstrated in Fig. 4 in terms of an equivalent damping coefficient calculated from the amplitude decay of the response time histories shown in Fig. 3. Average damping coefficients shown in Fig. 4 vary between 10 and 25% and correspond, respectively, to the largest and smallest strength increment (ΔR).

Acceleration time histories of the benchmark and ASBD buildings are compared in Fig. 5. Acceleration amplitudes are important because they are proportional to the strength demanded from the building. The comparison shows that the acceleration amplitudes of the ASBD building are all below the benchmark building. Figure 5 also indicates that ASBD acceleration amplitudes decay rapidly with decreasing strength increment (ΔR). The acceleration response comparison in Fig. 5 also shows that the maximum base shear coefficient of the ASBD building is less than the benchmark building.

Brace force versus interstory drift relationships given in Fig. 6 demonstrates the energy dissipation by activating the ASBD. In this figure, the benchmark building remains primarily

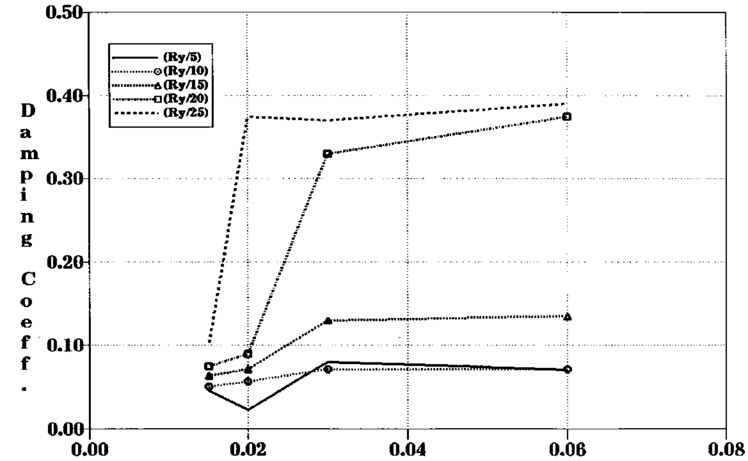

FIGURE 4 Influence of strength increments and sampling interval on ASBD equivalent damping coefficient.

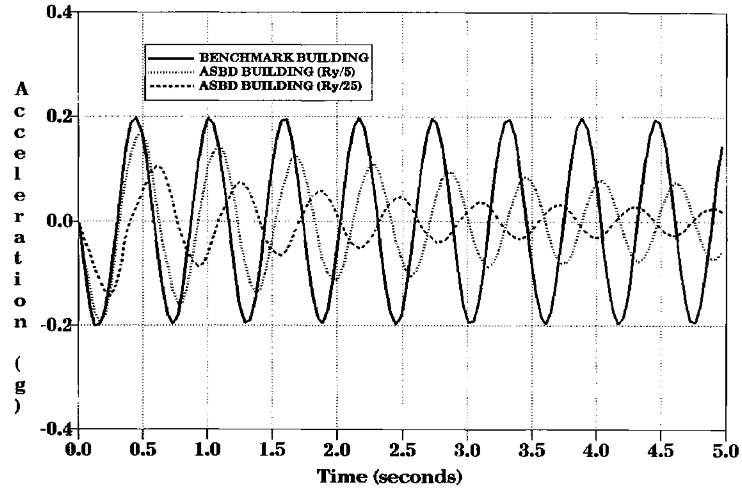

FIGURE 5 Comparison of building acceleration response under impulsive ground acceleration.

elastic near its elastic limit threshold. The ASBD building is controlled with an algorithm such that slippage at the friction interface takes place at different brace axial load levels that changes by changing the brace strength. Figure 6 shows that the ASBD axial load demand is reduced by decreasing strength increment (ΔR).

CONTROL OF BUILDING RESPONSE DURING EARTHQUAKES

The seismic response characteristics of the ASBD are investigated using the same one-story building structure. To demonstrate a realistic simulation a recorded ground motion from the 1952 California earthquake in Kern County is utilized to study the effects of ASBD design parameters.

Earthquake Ground Motion

Moderately flexible buildings have response period range of 0.5s and longer. Ground motion selection is based on the criterion of creating the most unfavorable spectral acceleration demand for buildings resting on firm soil with periods in excess of 0.5 s. The recorded earthquake motion of the 1952 Kern County Taft N21E component is determined as the critical input for the buildings described here. The recorded acceleration time history is 55s of strong motion, with a peak

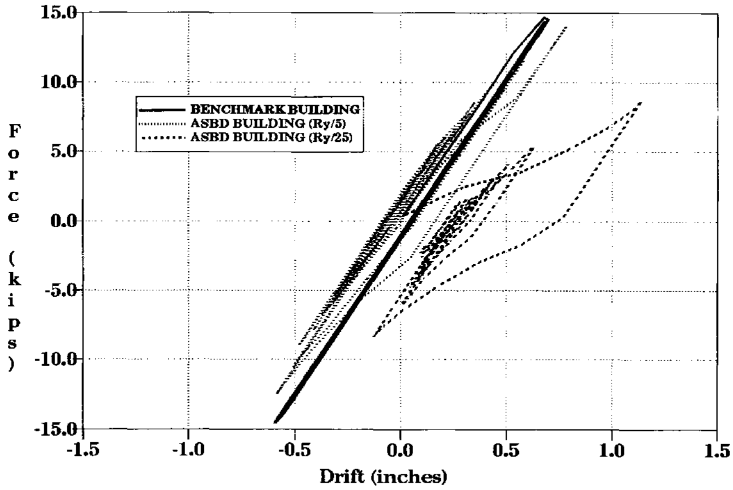

FIGURE 6 Comparison of building brace force under impulsive ground acceleration.

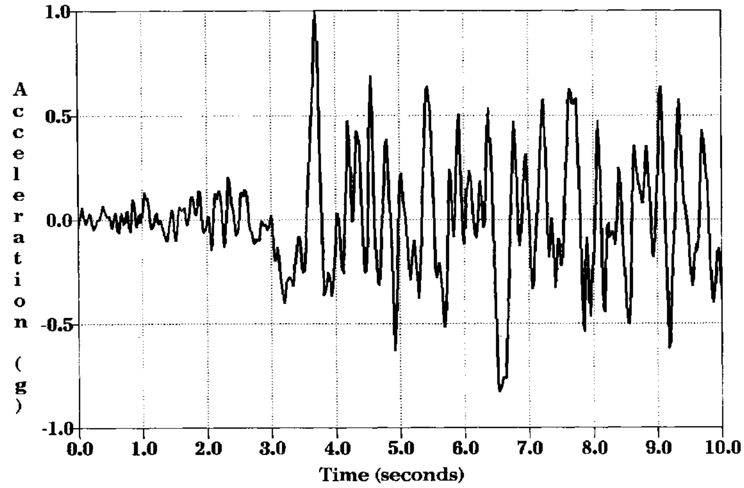

FIGURE 7 Taft earthquake (truncated) acceleration time history.

amplitude of 0.156 × g (where g is gravitational acceleration). For the purposes of the analysis in this article the acceleration record is truncated by retaining only the first 10 of the strong motion record, to reduce the computational effort. The truncated record is shown in Fig. 7. Linear elastic response spectra (LERS) with 2.5% damping of the full and truncated records are plotted in Fig. 8. Comparison of LERS curves shows that the truncated record has spectral effects identical with the full record for a period range up to 5 s. The amplitudes of the truncated strong motion record are also scaled to generate a range of building strength demands between 0.05 and 0.30 × g corresponding to the serviceability and ultimate limit response states.

Building Response to Service Limit State Earthquake

The ASBD and benchmark building structures are subjected to the truncated Taft ground motion scaled at peak amplitudes corresponding to 0.05 and 0.10 × g. The Taft earthquake with 0.10 × g amplitude represents the serviceability limit state of the benchmark building. The interstory drift time histories of the benchmark and ASBD [with a strength increment (ΔR) equal to

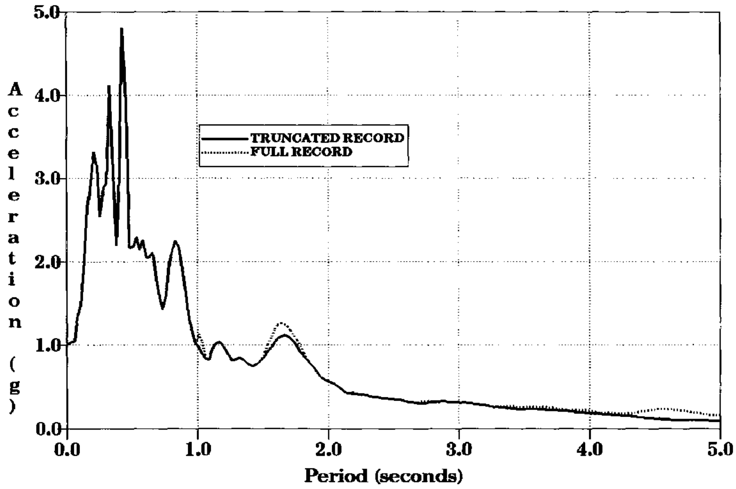

FIGURE 8 Linear elastic response spectra of Taft earthquake (full and truncated records).

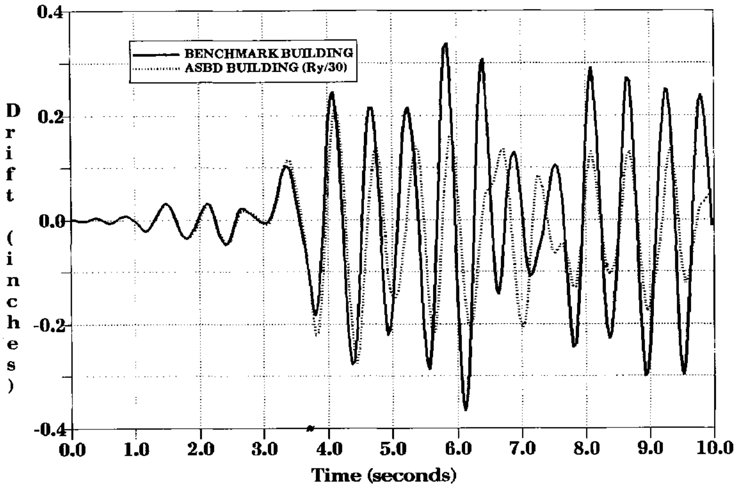

FIGURE 9 Comparison of building interstory drift response under Taft earthquake with 5 × *g* maximum amplitude.

$R_y/30$, and sampling interval (t_s) of 0.015] buildings subjected to a 0.05 × *g* Taft earthquake are compared in Fig. 9. Both building responses coincides until approximately 3.5 s. Up until that time the brace force provided by the initial clamping force is not exceeded and the ASBD is not activated. As soon as the ASBD is activated, the ASBD building displacements momentarily exceed the benchmark building. Later, the ASBD building continually dissipates energy and never allows the buildup of vibrational energy, as observed in the significant reduction of response amplitudes when compared to the benchmark building in Fig. 9. However, it should be emphasized that, similar to other active control schemes, the ASBD will be useless in strong motion earthquakes that consist of only one large pulse.

Building Response to Ultimate Limit State Earthquake

The control strategy of increasing or decreasing the brace strength one increment (ΔR) by changing the clamping force of the ASBD at the end of each sampling interval (t_s) appeared to be very effective in abating the effects of a serviceability limit state earthquake. In the serviceability limit state earthquake, the benchmark building remained elastic and did not dissipate energy. During earthquakes near and at the ultimate limit state, simulations showed that this control strategy is not effective and ASBD building maximum displacement response is greater than the benchmark building (Akbay, 1991). A drift-bounded control algorithm is developed that follows the same decision steps as the service limit state strategy with constant strength increment (ΔR), except that the maximum displacement amplitude is also monitored. A bound is introduced as a limit for the effective range of the constant strength increment (ΔR). Once the displacement bound is reached, the ASBD brace strength is increased to its maximum by applying the maximum clamping force on the friction interface. The maximum brace strength provides the ASBD building structure's enveloping strength. Beyond this displacement bound the ASBD retains its full strength, as in the case of the benchmark building.

The control algorithm of changing the brace strength by one constant strength increment (ΔR) is found effective for interstory drift index (interstory drift index is the ratio of the maximum interstory drift to the story height) below 0.30%. This interstory drift corresponds to the maximum response of the benchmark building subjected to serviceability limit state ground motion. In the response simulation of the ASBD building with drift-bounded control, the strength increment (ΔR) is taken as $R_y/30$, and when the interstory drift index exceeds 0.30% at any time, the brace strength is raised to its maximum by commanding the ASBD to apply the maximum clamping force on the friction interface.

The benchmark and ASBD building displacement responses under the Taft earthquake with 0.30 × *g* maximum amplitude are shown in Fig.

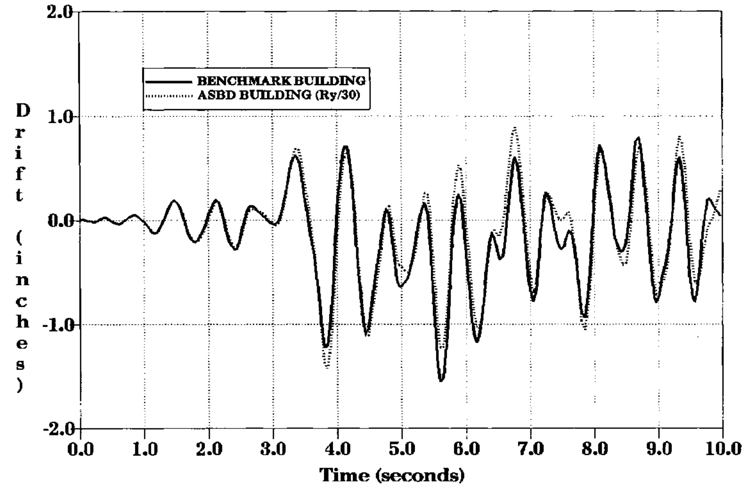

FIGURE 10 Comparison of building interstory drift response under Taft earthquake with 30 × *g* maximum amplitude.

10. Figure 10 shows that the maximum displacement amplitude of the ASBD building is on the same order as that of the benchmark building.

A comparison of the earthquake response envelopes of the ASBD operating based on the drift bounded control algorithm and benchmark buildings under a range of amplitudes are shown in Table 1. Under excitations below or equal to the serviceability limit state corresponding to the 0.05 and 0.10 × *g* amplitude Taft earthquake, the ASBD building response is superior to that of the benchmark building. With increasing maximum amplitude of the Taft earthquake, the benchmark and ASBD building responses merge. Also

Table 1. Response Envelopes of Benchmark and ASBD Buildings Under Different Amplitude Taft Earthquakes

Amplitude (× *g*)	Strength Increment (ΔR)	Sampling Interval t_s (s)	Drift (in.)	IDI (%)	Velocity (in./s)	Acceleration (× *g*)	Brace Force (kips)	Base Shear (kips)
	Benchmark		0.37	0.19	4.35	0.11	8.36	16.98
0.05	$R_y/5$	0.015	0.32	0.16	3.32	0.08	5.89	12.35
		0.020	0.27	0.14	3.10	0.08	5.63	12.35
		0.030	0.26	0.13	3.13	0.07	5.23	10.81
		0.060	0.24	0.12	2.97	0.06	4.54	9.26
	Benchmark		0.68	0.34	7.74	0.20	14.60	30.88
0.10	$R_y/5$	0.015	0.57	0.28	6.33	0.15	10.96	23.16
		0.020	0.60	0.30	6.12	0.15	10.43	23.16
		0.030	0.55	0.28	5.93	0.13	9.22	20.07
		0.060	0.58	0.28	5.25	0.09	5.95	13.90
	Benchmark		0.98	0.49	10.61	0.21	14.60	32.42
0.20	$R_y/5$	0.015	1.17	0.54	10.51	0.20	14.60	30.88
		0.020	0.95	0.48	11.85	0.21	14.60	32.42
		0.030	0.95	0.48	10.56	0.21	14.60	32.42
		0.060	0.97	0.49	10.92	0.21	14.60	32.42
	Benchmark		1.56	0.78	15.30	0.22	14.60	33.97
0.30	$R_y/5$	0.015	1.97	0.99	16.68	0.25	14.60	38.60
		0.020	1.57	0.74	16.25	0.23	14.60	35.51
		0.030	1.52	0.76	15.92	0.23	14.60	35.51
		0.060	1.43	0.72	15.57	0.22	14.60	33.97

Drift: relative roof displacement. IDI: interstory drift index, which is the ratio of drift to story height.

shown in Table 1 are the maximum base shear comparisons. Under earthquakes below or equal to the serviceability limit state the ASBD base shear demand is lower than for the benchmark building. Under earthquakes near ultimate limit state the benchmark building maximum base shear demand approaches the ASBD building.

CONCLUSIONS

A hybrid control procedure based on energy dissipation called the active slip brace device (ASBD) is presented. The hybrid control procedure and the ASBD were developed for controlling structural vibration during earthquakes. The hybrid control monitors and alters the energy dissipation characteristics of a building during its response to earthquakes. A simplified building design incorporating the ASBD is demonstrated under impulsive ground acceleration. The ASBD building is analyzed under two limit state earthquakes to verify its effectiveness. The ASBD is controlled digitally by increasing or decreasing the clamping force on the friction interface, which regulates the brace strength. One control algorithm is used in demonstrating the ASBD building response. In this algorithm the ASBD building strength is divided into equal increments up to the maximum that can be supplied without causing brace buckling or yielding. During the earthquake, if the ASBD friction interface is in motion the building strength is increased one increment by increasing the clamping force on the friction interface. Otherwise, the building strength is reduced by one increment. In the case when building displacements exceed the serviceability threshold, the ASBD building strength is increased to its maximum by applying the maximum clamping force on the friction interface.

The control algorithm is shown to be very effective in improving the building serviceability limit state response to earthquakes. The ASBD building also maintains the effectiveness of an optimally designed benchmark building near ultimate limit state earthquakes. More effective control algorithms for multistory building applications are being studied. As a final note, controllable strength of the ASBD building is a merit to be considered in upgrading seismically deficient flexible buildings resting on firm soils.

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