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RESPONSE CONTROL SYSTEMS IN THE UNITED STATES AND LESSONS LEARNED FROM THE TOHOKU EARTHQUAKE

Andrew W. TAYLOR[1]

[1]Associate, KPFF Consulting Engineers, Seattle, USA, andrew.taylor@kpff.com

ABSTRACT: During the last 15 years earthquake response control systems have been widely adopted in Japan. In contrast, in the United States the total number of commercial and residential buildings with response control systems is probably less than 250. The Great East Japan (Tohoku) earthquake provided a unique opportunity to study the behavior of these systems. Key observations about the performance of response control systems are summarized, and possible implications of these observations for future applications of response control systems in the United States are described.

Key Words: Great East Japan Earthquake, Tohoku, response control system, seismic isolation, supplemental damping, earthquake reconnaissance

INTRODUCTION

During the last 15 years earthquake response control systems (seismic isolation, supplemental damping) have been widely adopted in Japan. According to the Japan Society of Seismic Isolation, there are over 2600 commercial and residential buildings, and over 3800 single-family homes in Japan with seismic isolation systems, and over 950 buildings with supplemental damping systems (JSSI 2012). In contrast, in the United States the total number of commercial and residential buildings, including single family homes, with earthquake response control systems is probably less than 250.

An overview is presented of the state of application of response control systems for buildings in the United States. This situation is compared with applications of response control systems in Japan. Not only are there fewer buildings with response control systems in the United States, but there are also fewer types of systems in use. Possible explanations for these differences are proposed.

Because of the prevalence of response control systems in Japan, the Great East Japan Earthquake provided a unique opportunity to study the behavior of these systems when subjected to high-amplitude, long-duration ground shaking. Many response control systems in the Sendai and Tokyo areas were activated by the earthquake. The author was fortunate to participate in the earthquake reconnaissance team of the Structural Engineers Association of Washington (SEAW), and the U.S-Japan reconnaissance team coordinated by the Earthquake Engineering Research Institute (EERI) and the Architectural Institute of Japan (AIJ) during late May and early June, 2011. Key observations about the performance of response control systems are summarized, and possible implications of these observations for future applications of response control systems in the United States are described.

RESPONSE CONTROL SYSTEMS IN THE UNITED STATES

Response control systems fall into two broad classes: supplemental damping systems and seismic isolation systems. Of course, seismic isolation systems often incorporate supplemental damping devices, and there are many other forms of mixed or hybrid response control systems, but for the purposes of discussion, we will separate response control systems into these two groups.

In the United States there is no official register or centralized database of buildings with response control systems. This is because buildings with response control systems are not regulated by any single government agency. Instead, building permits for structures with response control systems are issued by the local authority having jurisdiction in the area where the building is constructed, such as the Building Department of a city or county. Because no central database of response control projects exists, estimates and discussion presented here are based on the author's own experience with response control systems in the United States.

Supplemental Damping in the United States

In the United States the primary method of providing supplement damping in building superstructures is oil dampers, also known as fluid viscous dampers (FVDs). While some oil dampers used in buildings have been of the linear type (i.e., dampers with a linear proportional relationship between velocity and force), there has been a trend in the United States towards use of nonlinear oil dampers in buildings (i.e. oil dampers with damping exponents less than 1.0).

The most common configuration of oil dampers in the United States is the "V" or "chevron" arrangement, where two diagonal braces form a vertical frame in the shape of a "V" or an "A". The top of the "V" or the base of the "A" is attached to a beam or girder, while the tip is not. An oil damper (or pair of oil dampers) is positioned at the tip so that one end of the damper is attached to the tip and the other end to the adjacent beam or girder. In this way, the displacement created by inter-story drift between adjacent floors of the building is imposed on the piston of the damper. Another less common configuration is to position an oil damper in line with a diagonal brace, so that distortion of the building frame causes shortening and lengthening of the brace, and imposes displacements on the damper piston.

A few high-rise buildings have incorporated oil dampers in mechanisms known as "scissor braces". The principal advantage of a scissor brace is that the scissor mechanism magnifies inter-story drift, which imposes sufficient displacement on the damper piston to generate useful damping forces. Thus, scissor braces are intended primarily to control day-to-day, small-amplitude wind movements of building frames, rather than large-amplitude earthquake response.

Very few examples exist of other types damping systems for control of seismic response of buildings in the United States. In the 1970s a few buildings were constructed that incorporated visco-elastic material dampers (VE dampers) into rigid braces, but these dampers were mainly intended for control of wind motions. VE dampers have not been used in United States buildings in recent years, and there is currently no producer of VE dampers for building structure applications in the United States. About eight building projects in the United States have incorporated friction dampers for control of seismic response. The friction dampers are typically placed in-line with bracing elements, so that compression and tension induced in the braces during an earthquake will cause relative motion between the friction elements. Passive tuned mass damper (TMD) systems have been used in a few tall buildings in the United States to control wind motions, but no applications of TMDs have been explicitly developed for control of seismic motions in tall buildings. For one recent project, the seismic retrofit of the Theme Building structure at Los Angeles International Airport, a TMD will be used to control earthquake demands on the structure. To the author's knowledge, no active building control systems are currently in use in the United States for earthquake response control.

The first project to incorporate viscous wall dampers (VWD) is currently under construction in the United States. This is a 15-story hospital in San Francisco, California, which is scheduled to be completed in 2012.

Buckling Restrained Braced Frames

Buckling Restrained Braced Frames (BRBFs), also known as “Unbonded Brace” frames have become increasingly popular in the United States. Currently there are approximately 300 buildings in the United States that incorporate BRBFs.

In the United States, BRBFs are not considered supplemental damping systems. Rather, they are treated as a special form of a steel braced frame (ASCE 7-10, 2010). BRBF systems are usually designed without time-history analysis, or explicit consideration of damping properties. Instead, the contribution of the yielding BRBF braces to structural control is recognized by assigning a high response modification coefficient R equal to 8. Other steel braced frames that are specially detailed for seismic resistance, so-called “Special Concentrically Braced Frames”, are assigned a response modification coefficient R equal to 6. Because seismic design forces in the United States building code are proportional to the inverse of the response modification coefficient R, this means that buildings with BRBFs may be designed for earthquake forces that are 25 percent lower than buildings with steel Special Concentrically Braced frames. The building code in the United States assigns a response modification coefficient R equal to 8 for steel Eccentrically Braced Frames (EBFs). Because EBF and BRBF systems have the same response modification coefficient R equal to 8, BRBFs are sometimes substituted for EBFs during the design process.

Seismic Isolation in the United States

In the United States the predominant systems used for seismic isolation are rubber bearings, flat sliding bearings, and a sliding seismic isolation system, known as the Friction Pendulum (FP) System, which has a sliding surface in the shape of a spherical dish and a low-friction articulated slider.

Rubber Bearings

The most common type of rubber bearing in the United States is the lead-core rubber bearing (LRB). This is followed in popularity by high-damping rubber bearings (HDR) and natural rubber bearings (NRB). A common rubber isolation system configuration consists of LRBs around the perimeter of the building, with NRBs at interior support locations. When HDR bearings are used for an isolation system, usually all bearings in the system are HDR bearings.

There are at least five instances of NRB and HDR isolation systems that also incorporate oil dampers (fluid viscous dampers) in parallel with the isolation system to provide additional damping as shown in Figure 1. This type of hybrid system is most common when an isolated building is located within a few kilometers of an active fault. Sites near a fault may be subject to ground motions with strong velocity pulses, a phenomenon sometimes referred to as “near fault effects”. Isolation system response to such velocity pulses can be effectively controlled with oil dampers, because the resisting force developed by the damper is related to the magnitude of velocity.

Fig. 1 Oil damper in combination with high damping rubber seismic isolation bearings, Arrowhead Regional Medical Center, San Bernardino County, California

Flat Sliding Bearings

Flat sliding bearings often consist of a polytetrafluoroethelyne (PTFE) disc backed by a rubber layer, which is set into a circular depression in a steel plate. The PTFE disc slides against a polished stainless steel surface. This configuration is sometimes referred to as a "pot bearing" because the circular depression forms a "pot" that contains the rubber disc and prevents it from shifting. The rubber backing layer promotes uniform distribution of bearing stress because it allows the PTFE disc to adjust to slight inclinations or irregularities of the structural element supported by the bearing.

Flat sliding bearings may also consist of a PTFE disc or sheet bonded to, or set into a depression in, the top steel surface of a laminated steel/rubber bearing, but this arrangement is less common.

In the United States isolation systems sometimes consist of flat sliding bearings in combination with rubber bearings. The flat sliding bearings support vertical loads, and provide additional damping through friction, but do not add to the effective stiffness of the isolation system. This can be advantageous when it is desired to minimize the effective stiffness of the isolation system. Also, when the displacement demands on an isolation system are large, the stability of rubber isolation bearings under high axial loads may be a limiting factor. By concentrating the effective elastic stiffness of the isolation system into a few large-diameter rubber bearings, rather than distributing the stiffness among a greater number of small-diameter rubber bearings, the large-diameter bearings can accommodate larger displacements without stability concerns. Finally, there is an economic advantage to substituting sliding bearings for rubber bearings, since sliding bearings are usually less expensive than rubber bearings.

Friction Pendulum Bearings

Friction pendulum (FP) bearings are used in about 20 to 25 percent of seismically isolated building projects in the United States. Most FP bearings used to date have been the "single" FP type, consisting of a single articulated slider in a single concave dish. A few recent building projects have incorporated "triple" FP isolators, which consist of an articulated slider captured between top and bottom concave dishes, which are in turn captured between another outer set of top and bottom concave dishes.

At least two projects in the United States have been constructed with FP isolation systems that also incorporate oil dampers as a means of providing additional damping. Both of these projects are located near active earthquake faults, and an important function of the oil dampers is to control isolation system response to potential velocity pulses in near-fault ground motions.

Other Isolation Systems

Two projects in the United States have incorporated seismic ball bearing (SBB) isolation systems. SBB bearings consist of hardened steel ball bearings, approximately 50 mm (2 inches) in diameter, which are placed between two flat, hardened steel plates. Each ball supports a rated load of approximately 15 kN (3,300 pounds). While this system provides a very low resistance to lateral movement (with an effective coefficient of rolling friction of about 0.0025), re-centering stiffness and damping must also be provided to control maximum displacements. This is accomplished with lead rubber bearings (LRB) positioned near the perimeter of the isolated structure.

Two townhomes in the Los Angeles area have been isolated with isolation systems consisting of steel springs and viscous dashpots, and one home in Oakland, California has been isolated with a system of flexible steel pipe piles in combination with oil dampers.

Type Distribution of Isolation Systems

The approximate distribution of isolation system types in the United States is shown in Table 1. This distribution is based on the author's database of approximately 65 seismic isolation projects. The database is a representative sample, but not an exhaustive list, of isolation projects, so the data presented in Table 1 are estimates. In Table 1, projects designated LRB typically also include NRBs or flat sliding bearings as part of the isolation system. Projects labeled HDR usually have only HDR bearings in the isolation systems, and in some cases the HDR bearings are supplemented with oil dampers. One project, designated NRB, includes oil dampers as part of the isolation system. Most projects with FP bearings incorporate only FP bearings, although a few FP systems also include supplemental oil dampers. Of the total projects in the database, about 13 percent include oil dampers in parallel with the isolation bearings.

Table 1 Approximate distribution of seismic isolation system types for buildings in the United States

Isolation System Class	Isolation System Type	Percentage of Total Projects
Rubber	Lead Rubber Bearings (LRB)	45%
	High Damping Rubber Bearings (HDR)	25%
	Natural Rubber Bearings (NRB)	2%
Sliding	Friction Pendulum System (FP)	22%
Other	Other Types	6%
	Total	100 %

OBSERVATIONS AFTER THE GREAT EAST JAPAN EARTHQUAKE

Following the Great East Japan Earthquake, the author was a member of the U.S.-Japan study team for response control systems, organized by the Earthquake Engineering Research Institute (EERI) and the Architectural Institute of Japan (AIJ). The other team members were Kazuhiko Kasai, Professor, CUEE, Tokyo Institute of Technology (TIT); Geoff Bomba, Forell/Elsesser Engineers, San Francisco; Kazuhiro Matsuda, Assistant Professor, CUEE, TIT; Wuchuan Pu, Researcher, CUEE, TIT; and Troy Morgan, Assistant Professor, CUEE, TIT. From June 1 to 6, 2011 the team visited 17 buildings with protective systems in the Sendai area, and in the Tokyo metropolitan area. Of these buildings, 6 incorporated supplemental damping systems, and 11 incorporated seismic isolation systems.

Below is a summary, prepared by the EERI/AIJ team, of observations made at three buildings with supplemental damping systems and four buildings with seismic isolation systems. These observations were originally described in a report prepared for the EERI newsletter, which has not yet been published. Here, the original observations have been abbreviated because of space limitations. The reader is referred to the future EERI newsletter for the complete summary of observations.

Buildings with Supplemental Damping Systems

7-Story Building in Sendai City: Tohoku Institute of Technology Building B10

Building B10 on the campus of the Tohoku Institute of Technology was constructed in 2003. It is seven stories tall, and the lateral force resisting system consists of steel moment resisting frames. The height of the first level is 8 m (26.25 feet) and the height of all other levels is 3.8 m (12.5 feet). At each floor level there are four oil dampers in each principal direction (a total of eight dampers per floor). The dampers are installed at the tips of “V” braces. Figure 2 shows one of the oil dampers at the second level. The damper assembly includes a displacement snubber frame (gray in Figure 2) that limited the stroke of each damper to 12 mm. During the earthquake the displacement limit of some dampers was exceeded. This caused yielding of some dampers and the snubber assembly. At the first story one snubber assembly in the east-west (longitudinal) direction failed completely.

Building B10 was instrumented with accelerometers. However, the data acquisition system was damaged during the March 11 main shock, so no data was recorded during that event. Because data had been recorded during smaller events both before and after the March 11 main shock, it was determined that the fundamental period of the building had increased from 1.2 to 1.3 seconds as the result of damage sustained to one first floor damper frame during the main shock. No damage, or only minimal damage, was sustained by the moment frames and damper frames at floors above the first floor. Building B10 was re-opened one month after the earthquake, while repairs were being carried out on the first floor damper frame that had been damaged.

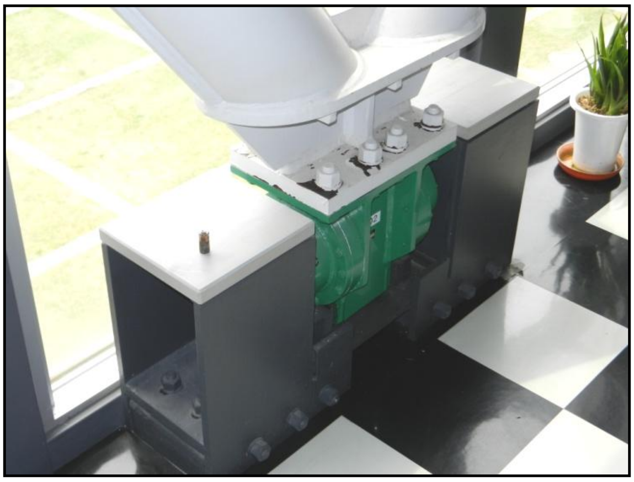

Fig. 2 Oil damper and snubber assembly at Tohoku Institute of Technology Building B10, second floor

In a previous event, the 2003 Miyagi earthquake, a peak ground acceleration of 101 cm/sec^2 was recorded at the site and the peak acceleration at the roof of Building B10 were 159 cm/sec^2. This demonstrated successful control of amplification of ground motions over the height of this building during this relatively small event. By comparison, similar surrounding structures without damping systems exhibited significant amplification of accelerations over the building height: measured roof accelerations at these nearby buildings were 290 cm/sec^2 and 459 cm/sec^2 during the same event.

8-Story Building in Sendai City: Tohoku Institute of Technology Building B5

Near Building B10 at Tohoku Institute of Technology is Building B5, which was constructed in 1971. The later force resisting system consists of a nonductile concrete frame, combined with concrete walls in the transverse (north-south) direction. The building was damaged in the 1978 Miyagi-ken Oki earthquake. The building was subsequently repaired using a retrofit scheme that consisted of steel cross brace frames at the exterior of the building, in the longitudinal (east-west) direction (Figure 3). These exterior frames contain yielding elements that were intended to dissipate energy during a major earthquake. In 2005 the need for additional earthquake protection was identified. At that time additional chevron braces with oil dampers were added within certain exterior concrete frame bays, and critical concrete columns were strengthened with fiber wrapping.

Fig. 3 Exterior steel frame for seismic strengthening of Building B5 at Tohoku Institute of Technology

During the earthquake, the peak ground acceleration at the base of three buildings surrounding Building B5 were 336 to 354 cm/sec^2 and the peak acceleration measured at the upper floor of Building B5 was 820 cm/sec^2. Interior spaces suffered severe nonstructural damage, including loss of ceiling light fixtures and toppling of bookshelves. Some of the exterior steel braces yielded at the reduced flange sections as intended, but some of the braces also buckled outwards, resulting in distorted gusset plates at the intersections of cross braces. The damage that was visible at the time of the team visit included the distorted gusset plates, and cracked interior shear walls. The interaction between the 1978 exterior steel frames and the 2005 oil dampers was not clear, but it appeared that the oil dampers were activated only after yielding and distortion of the exterior steel frames had occurred.

54-Story Retrofitted Building in Tokyo: Shinjuku Center Building

In Japan, there is a significant number of high-rise buildings that employ either base isolation or supplemental damping systems. In the United States, we have not typically applied seismic isolation to high-rise buildings, and we have applied damping systems to only a limited number of high-rise buildings. Some vintage high-rise structures in Tokyo were designed without consideration of long period ground motions. Since 2000, Japanese codes have required design for velocity response spectrum values of 80 cm/s up to a period of 10 seconds, whereas in previous codes this requirement did not exist. Prior to 2000, three ground motions were primarily used for design of high-rise structures (El Centro, Taft, and Hachinohe). These ground motions have much smaller peak ground velocity values for periods above 3 seconds than current code requirements.

The team visited the 54-story Shinjuku Center in Tokyo. It was constructed in 1979, and its total height is 223 m. The first natural periods of the structure are 5.2 and 6.2 seconds in two perpendicular directions. In 2009 the building was retrofitted from the 15th to 39th floor with 288 oil dampers that were configured to exhibit a form of deformation dependency, in addition to velocity dependency (Figure 4). Taisei Corporation developed this damper for the purpose of reinforcing existing high-rise buildings against long period motions. The theory of the deformation-dependent damper is to reduce the damping force at the instant when the frame deformation comes close to its maximum value. As a result, engineers determined that no reinforcement of the surrounding columns, girders, and foundations were required for the retrofit. The effects of the dampers were calculated to have reduced the maximum accelerations by 30 percent and roof displacement by 22 percent during the earthquake. Acceleration data is not available at this time; however, shaking in the structure during the earthquake lasted 10 minutes without any reported structural or nonstructural damage.

Fig. 4 Retrofit damper at 54-story Shinjuku Center Building

Buildings with Seismic Isolation Systems

18-Story Building in Sendai City: Sendai MT Building

This 18-story office building in Sendai City was constructed in 1999, and is supported on a combination of 26 rubber bearings and 10 flat sliding PTFE bearings.

Fig. 5 Sendai MT Building

During the earthquake the maximum displacement of the isolation system was approximately 23 cm, as shown by a scratch plate (Figure 6). The peak ground acceleration recorded below the isolation level was 311 cm/sec^2. Accelerometers in the superstructure indicated that peak floor accelerations were in the range of one-half to two-thirds of the peak ground acceleration over all 18 stories.

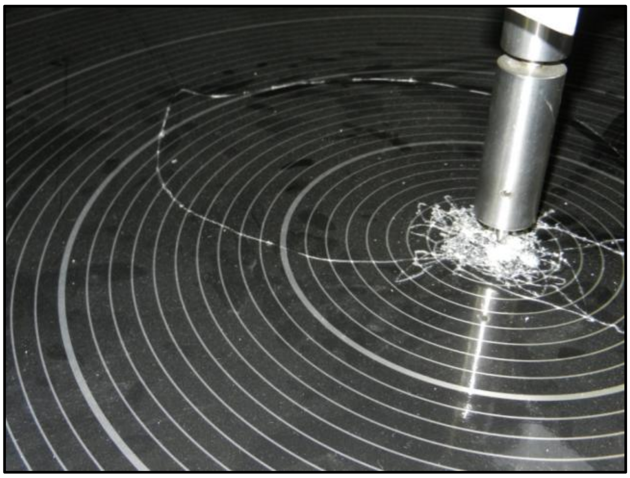

Fig. 6 Scratch plate indicating maximum isolation system displacement of 23 cm

The MT building experienced no structural damage, and was fully occupiable following the earthquake. Minor non-structural damage occurred at some joints covering the isolation gaps at the building base, but this damage was repairable and did not affect the functionality of the building.

26-Story Building in Tokyo: Yozemi Tower

This high-rise building in central Tokyo incorporates a seismic isolation system combined with a semi-active damping system at the base isolation level. The building has 26 stories above grade, and

3 stories below grade. The isolation level is between the 1st and 2nd stories of the basement so that the total height of the isolated structure is 27 stories.

The isolation system consists of 49 bearings, a combination of 25 rubber bearings and 24 flat sliding PTFE bearings. The isolation damping system includes 12 semi-actively controlled oil dampers, and 12 passive oil dampers. The semi-active dampers may be switched between two damping coefficients, depending on the structural control requirements. Accelerometers and displacement meters within the building provide feedback to the control system, which switches the damping coefficient of the semi-active dampers to optimize structural response. In addition, the lateral force resisting system of the upper floors of the building incorporates viscoelastic (VE) material dampers. The VE dampers improve not only the seismic response of the structure, but also control wind-induced accelerations, to improve occupant comfort. The maximum observed isolation system displacement in the earthquake was approximately 10 cm. There was no reported structural or non-structural damage, and the building remained fully functional after the earthquake.

Fig. 7 Yozemi Tower, in the Shinjuku area of Tokyo

20-Story Building in Yokohama City: Tokyo Institute of Technology Building J2

This 20 story base-isolated building is located on the Suzukakedai campus of the Tokyo Institute of Technology. The isolation system includes 16 rubber bearings, acting in parallel with 14 yielding metal dampers and two oil (hydraulic) dampers.

Fig. 8 Building J2 at the Tokyo Institute of Technology

The plan dimensions of the building are approximately 46 by 18 meters, and the height is approximately 91 meters. Thus, the aspect ratio (height/width) of the building in one direction is approximately 5, which creates the potential for uplift occurring at rubber bearings during strong ground shaking. To counteract this effect, certain bearings are outfitted with Belleville spring washers (conical spring washers) on the mounting bolts, so that if uplift occurs at those bearings, the springs will allow limited uplift to occur without inducing large tensile strains within the rubber. The effects of potential uplift were considered in the dynamic analysis and design of the structure.

During the earthquake the maximum measured radial displacement of the isolation system was approximately 12.5 cm (9.5 cm in the NE-SW direction). It is not known at this time whether uplift occurred at any of the rubber bearings during this event. The peak ground acceleration measured below the isolation plane was 69.0 cm/sec^2 in the NE-SW direction. At the first level above the isolation plane, the maximum acceleration in the NE-SW direction was 69.6 cm/sec^2. The maximum acceleration at the 20th floor in the NE-SW direction was 116.2 cm/sec^2. Comparing the peak ground acceleration and the peak acceleration at the 20th floor, it can be seen that the isolation system was highly effective at minimizing amplification of ground motions over the height of the building.

6-Story Building in Tokyo: Shimizu Institute of Technology Main Building

The Shimizu Institute of Technology is a research campus for the Shimizu Corporation. Located on this campus are three base-isolated buildings: The Safety & Security Center building which incorporates a unique core-suspended isolation system; the Wind Tunnel Testing Facility is constructed on a seismic isolation system that is partially submerged in water – the "Partially-Floating Structural System" – in order to take advantage of buoyancy to improve the seismic performance of the isolation system; and the six-story Main Building which is isolated on six 1.1 m diameter lead-core rubber bearings. The Main Building is of particular interest because during the Tohoku Earthquake a monitoring system captured live video of the seismic isolation system in operation (see http://www.shimz.co.jp/english/theme/earthquake/effect.html).

Fig. 9 Main Building at the Shimizu Institute of Technology

During the earthquake the maximum displacement of the isolation system was approximately 9 cm. The peak ground acceleration was 132 cm/sec^2, and at the second floor, just above the isolation system, the peak acceleration was 69 cm/sec^2. There was virtually no dynamic amplification over the height of the building, as at the 6th (top) floor the peak acceleration was 72 cm/sec^2. There was no reported structural or nonstructural damage in the main building during the Tohoku earthquake.

LESSONS LEARNED FROM THE GREAT EAST JAPAN EARTHQUAKE

Comparing the Implementation of Response Control Systems in Japan and the United States

In Japan many more buildings have been constructed with seismic response control systems than in the United States. The total number of seismically isolated buildings in the United States is about 125 or less, and there is approximately an equal number of buildings with supplemental seismic damping systems (not including approximately 300 buildings with BRBF systems). This contrasts sharply with the number of buildings with response control systems in Japan: over 2,600 commercial and multifamily residential buildings, and over 3,800 single family homes have base isolation systems, and over 950 buildings have supplemental damping systems (JSSI 2012).

Besides having a larger total number of buildings with response control systems than the United States, Japan has also developed and implemented more different *types* of response control systems than the United States. There are several reasons for this difference. First, because the number of projects with response control systems is much greater in Japan, there are more opportunities in Japan to implement a wider range of response control devices. Second, there are more manufacturers of response control devices in Japan. This promotes a climate of innovation and development of diverse approaches to response control. Third, in Japan research and development of response control systems is carried out not only at universities (as in the United States), but also within the large research centers associated with Japan's major construction companies. This leads to development of diverse approaches to seismic response control, and to direct implementation of innovative ideas on projects constructed by the major construction companies.

Observed Performance of Response Control Systems

The reported performance of buildings with supplemental damping systems was generally very good, demonstrating that these systems were effective at reducing structural and nonstructural damage in buildings. One exception was the B5 Building at Tohoku Institute of Technology, which incorporated a mixed system of a rigid external braced frames and internal oil dampers. While the structure itself was not seriously damaged, accelerations within the building were high, resulting in damage to building contents. The retrofit configuration for this building was unusual, and it is possible that the rigid external steel frames resulted in the high recorded accelerations at upper stories. Building B10 at the Tohoku Institute of Technology performed well, with no reported non-structural or structural frame damage. Due to the limited displacement capacity (stroke) of the oil dampers, however, some damage to the damping system occurred. This highlights the importance of providing sufficient displacement capacity in supplemental damping systems. The 54-story Shinjuku Center Building in Tokyo, which had been retrofitted with oil dampers, responded well in the earthquake. Although the building swayed for more than 10 minutes, there were no reports of structural or non-structural damage.

The reported performance of buildings with seismic isolation systems was also generally good. All seismically isolated buildings visited by the EERI/AIJ team had responded to the Great East Japan Earthquake as expected, and there were no reports of structural or non-structural damage in these buildings. In a few cases the team observed minor damage to moat covers and joint covers around seismically isolated buildings, but this damage was not consequential and easily repairable. Damage to moat and joint covers does serve as a reminder, though, that there should be close coordination between the structural engineer, who understands the expected motions of the isolated structure, and architect, who generally is responsible for the detailed design of moat and joint covers.

The behavior of the three high-rise base-isolated structures visited by the team was especially interesting: the 18-story MT Building, the 27-story Yozemi Tower, and the 20-story J2 Building. These buildings exhibited isolator displacements of 23 cm, 10 cm, and 12.5 cm, respectively. The successful performance of these buildings in a long-duration earthquake with ground motions containing strong long-period components demonstrates that it is feasible to implement seismic isolation systems in high-rise structures.

Lessons Learned

Building owners, engineers, and public officials can learn much from the observed performance of response control systems in the Great East Japan Earthquake, and the potential advantages of implementing these systems more widely in the United States.

This event has confirmed that response control systems provide excellent earthquake protection for both structural and non-structural elements of buildings. In both Japan and the United States a high percentage of the economic loss from earthquakes is the result of damage to nonstructural components and building contents. Response control systems can effectively reduce these economic losses.

Japan has been quick to implement lessons learned from past earthquakes, and has widely adopted response control technologies as a means of reducing earthquake losses. In the Great East Japan Earthquake buildings with response control systems experienced minimal, if any, economic losses. Buildings with response control systems are relatively uncommon in the United States, however, possibly because damaging earthquakes are less frequent in the United States. The United States can learn from Japan's experience, and minimize future economic losses, by more readily adopting response control technologies.

The successful performance of several high-rise base-isolated buildings in the Great East Japan Earthquake demonstrates that it is feasible to implement seismic isolation systems in tall structures. This provides opportunities for protecting a broader range of structures in both Japan and the United States.

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