A Partial View of Japanese Post-Kobe Seismic Design and Construction Practices

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ABSTRACT

Lessons learned from the 1995 Kobe earthquake have considerably accelerated Japanese research and motivated substantial advances in Japanese seismic design and construction practices. The severity of seismic hazards has been realized, leading to a significant increase in the applications of new technologies to full-scale structures. This paper presents a partial view of post-Kobe design and construction practices adopted in Japan. Described issues include the revision of the Japanese seismic design code, reinforced concrete structures, steel structures, steel-encased reinforced concrete structures, wood structures, and innovative applications of seismic isolation and passive control systems. Recent progress in the diagnosis of seismic resistance and retrofitting of existing buildings is also reported.

INTRODUCTION

The January 17th, 1995, Hyogoken-Nanbu (Kobe) earthquake was the most destructive earthquake in modern Japanese history causing significant economic impact and great loss of life. Over 6,000 people were confirmed dead, 26,000 people were injured, and more than 100,000 buildings were damaged beyond repair, making more than 300,000 people homeless immediately after the shaking [1,2]. The estimated direct damage costs surpassed ten trillion yen.

With a ruptured fault running very close to the downtown of Kobe City, very large ground motions were recorded in these areas, particularly in the Shindo (the earthquake intensity scale adopted in Japan) 7 region where the earthquake intensity was rated in the range of IX to XII on the modified Mercalli scale. Kobe is an old city whose urban development dates back over 50 years. The city, therefore, contained a large stock of engineered buildings more than 30 years old, constructed of non-ductile material details and vulnerable to earthquake destruction. As a result of low seismic resistance and large ground motion intensity, many old buildings nearly or completely collapsed [3]. A clear contrast in damage levels and patterns was observed between the old and new vintages of buildings as shown in Fig. 1. The Architectural Institute of Japan (AIJ) conducted a thorough review of the damage to buildings from the Kobe earthquake and published a reconnaissance report series consisting of thirteen volumes with over 6,000 pages [4].

New buildings were not exempt from damage [4]. This damage is understandable because Japanese modern seismic design code allows

Fig. 1 Difference in damage sustained by old and new buildings in the 1995 Kobe earthquake

partial structural damage in the event of large earthquakes. Furthermore, the ground shaking in some regions was significantly larger than that considered in the seismic design code. These observations have accelerated research and have led to substantial evolution in Japanese design and construction practices. After the Kobe earthquake, numerous efforts have been made to address the source of unexpected structural damage and to provide structural systems with enhanced safety and functionality. This paper presents a partial view of post-Kobe seismic design and construction practices adopted in Japan. Issues addressed herein are the revision of the Japanese seismic design code, reinforced concrete (RC) structures, steel structures, steel encased reinforced concrete (SRC) structures, wood structures, and innovative applications of seismic isolation and passive energy dissipation systems. The progress of the diagnosis of seismic damage and retrofitting of existing buildings in Japan is also noted.

JAPANESE SEISMIC DESIGN

In 1950, the first post-World War II Building Standard Law (BSL) was enforced. The law and associated regulations were revised a few times. The seismic design code was overhauled in 1981, and a two-level design concept was introduced. In this design, the structure should remain elastic in small to moderate earthquakes (called Level 1 design), while it can sustain some yielding and plastification in some structural members in a large earthquake (called Level 2 design). In terms of the performance-based design that has received significant attention in recent years, Level 1 design corresponds to “no or very limited damage” to ensure continuing occupancy, and Level 2 design corresponds to “collapse prevention” to ensure life safety. The design seismic forces are a function of location (in terms of seismicity), soil condition, and building height. The standard base-shear coefficients are 0.2 for Level 1 and 1.0 for Level 2. The corresponding values of design peak ground accelerations are 0.3 ~ 0.4g for Level 2 design and are reduced to one-fifth for Level 1 design. In Level 2, a force reduction factor is introduced to allow for the trade-off between the structural strength and ductility. The strength required for the most ductile category of buildings is reduced to 0.25 for steel and 0.3 for RC from the unreduced base-shear coefficient of 1.0. This seismic design had been implemented for about fifteen years at the time of the Kobe earthquake, and its adequacy was seriously tested. To expedite knowledge about the Japanese design code, it is worthwhile to compare the code to other base-line seismic codes. A comparison between the Uniform Building Code (UBC) in the U.S. [5] and the Japanese seismic design code (BSL) is presented by Tada, *et al*. [6].

Peer review is rather common in Japan. Design of all high-rise buildings over 60m and all buildings into which nonstandard structural materials and elements are incorporated, such as base-isolated buildings, has to be approved by a peer-review panel organized by a government authority called Building Center of Japan (BCJ). Two reviewers assigned by the BCJ review each design project. Most of the reviewers are from academia to avoid conflicts of interest, and the duration of a peer review is one to two months in most cases. In peer-reviewed design, various design provisions stipulated in the BSL need not be fulfilled if the adequacy of the design is agreed upon between the reviewers and designers. Peer-reviewed design commonly involves consideration of site-specific ground motions, nonlinear pushover analyses to assess the strength and deformation capacity, and nonlinear time-history analyses to examine expected maximum story drifts.

GROUND MOTION RECORDS

Large ground motions were recorded in the Kobe earthquake. Figure 2 shows the pseudo-acceleration response spectra (5% critical damping) obtained from two of the most severe motions recorded at the Japan Meteorological Agency (JMA) and the JR Takatori (JRT) Station. Both records were for the fault-normal direction. Also plotted for comparison is the response spectrum corresponding to a fault-normal ground motion recorded near the epicenter at TCU084 Station in the 1999 Chi-Chi Earthquake. The very large acceleration responses depicted in Fig. 2 imply that even modern buildings designed in accordance with the present Japanese seismic design code might suffer fatal damage in such large shaking.

Figure 3 is a map of Kobe and its vicinities, and the areas painted black are the "Shindo 7" most strongly shaken regions. The regions scatter in a narrow band, extending approximately in the east-west direction. They are located between the foot of the Rokko Mountains on the north and the seashore of Seto Inland Sea on the south. Extensive aftershock observations were conducted immediately after the Kobe earthquake, and many analytical studies were presented by seismologists to interpret the mechanisms responsible for very strong ground motions and for the narrow-banded regions of strongest shaking. Forward directivity combined with the basin edge effects, i.e., the constructive interference of direct S-waves with basin-induced diffracted waves, have been found most attributable to the mechanisms [7~10].

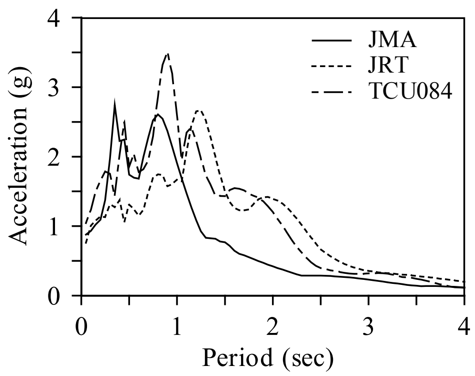


Fig. 2 Pseudo-acceleration response spectra of recorded ground motions in the 1995 Kobe earthquake (JMA and JRT) and 1999 Chi-Chi earthquake (TCU084)

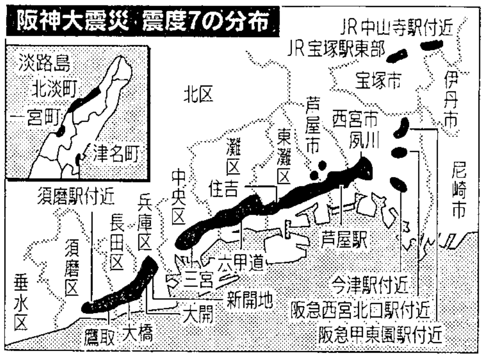


Fig. 3 Distribution of Shindo 7 regions in Kobe and vicinity

It was unfortunate that few ground motions were recorded in the strongly shaken regions, because at that time the Kobe area was not well equipped with a dense array of strong-motion seismographs. In fact, only a dozen stations provided notably strong ground motion records. This number is much smaller than the few hundred ground motion records obtained from the 1999 Chi-Chi earthquake. To gather valuable seismological data about future earthquakes, the National Research Institute for Earth Science and Disaster Prevention has established a strong-motion seismograph network named "K-net" with more than 1,000 stations, and a high sensitivity seismograph network named "KiK-net" with about 650 stations deployed throughout Japan [11]. A national project to establish seismic hazard maps that cover the entire Japan is also underway [12].

SEISMIC DESIGN CODE

As introduced earlier, the Japanese BSL adopted a two-level seismic design in 1981. The

1981 BSL is rather prescriptive and somewhat inconsistent in defining the representative ground motion with respect to different soil conditions. Moreover, the application of this code encounters some difficulties in the design of buildings with seismic isolation or structural control systems. As a response to these shortcomings, the building code was revised in 2000 to be more "performance-based." Two limit states, life safety and damage limitation, are specified in the 2000 BSL. The former is aimed at protecting human lives by preventing partial or complete collapse of the structure under expectedly large earthquakes (return period of approximately 500 years). The latter intends to limit structural damage under moderate earthquakes (return period of approximately 50 years) so that the structural system would not lose any of the performance intended in the original design even after such earthquakes.

The two limit-states are commensurate with the two levels stipulated in the 1981 BSL but are distinguished because of two new features. First, the design acceleration response spectra are given at the engineering bedrock to allow an explicit consideration of site-dependent soil conditions and soil-structure interaction effects. In the 1981 BSL, earthquake effects were stipulated as the design base shear. Second, both strengths and deformations of the structure are explicitly considered. In the 1981 BSL, a calculation was made only for the strength required for an expected ductility, while the ductility capacity to be possessed by the structure was given prescriptively as functions of various member provisions. In the evaluation of strength and deformation demands, the 2000 BSL recommends the use of the capacity spectrum method in which seismic demands and structural capacities are compared through an equivalent single-degree-of-freedom (SDOF) system and the representative site-dependent response spectra. According to these two features, the 2000 BSL advantageously facilitates flexible structural design and encourages the development of new construction materials, structural elements, and construction technologies. The Ministry of Land, Infrastructure and Transport has the authority to revise and update the BSL and associated regulations, and a government-affiliated agency called the Building Research Institute (BRI) is in charge of providing the technical background of the law and associated regulations. The outline of the 2000 BSL is reported by Midorikawa, *et al*. [13], who work for the BRI.

REINFORCED CONCRETE BUILDINGS

During the Kobe earthquake, many RC buildings underwent weak-story failures at the first story or higher [4]. Those that exhibited mid-story failures were old RC or combined RC/SRC buildings designed and constructed by obsolete seismic design codes. Inadequate strength distribution along the height and poor detailing of reinforcement, among other causes, were found to be responsible for such failures. In general, newer RC buildings designed in accordance with the latest seismic design code (the 1981 BSL) showed satisfactory performance for the levels of ground motions experienced in the Kobe earthquake.

Exceptions were the RC buildings having weak first stories. Because of the scarcity of land, many office and apartment buildings use the first story as parking space, which results in the termination of lateral resisting walls in the second floor level. Similar soft-story mechanisms and damage to RC buildings were also observed in the 1999 Chi-Chi earthquake [14]. The 1981 BSL explicitly considered the distribution of lateral stiffness along the height and required overstrength by up to 50% for stories having smaller stiffness. The damage to newer RC buildings with weak first stories revealed the inadequacy of the code. In response to this serious damage, associated code provisions were amended within one year after the earthquake, and strength requirements for the first story columns of such buildings were raised by up to 100%. The new provisions, however, have been found so stringent as to nearly deny the design and construction of such buildings, and practical design alternatives are being sought. Details of the damage and post-earthquake considerations about the design of RC buildings having weak first stories are presented by Yoshimura [15].

STEEL BUILDINGS

Steel is a very popular structural material in Japan. Figure 4 indicates the market shares of building construction (in terms of the constructed floor area) according to the structural material. Wood is the most popular, being used primarily for houses. Steel is ranked second and is significantly more popular than RC. Most old steel buildings built after the early 1960s consist of hot-rolled wide-flange steel beams and columns [16]. It was in the early 1980s that Japanese steel construction moved toward a newer building system consisting of cold-formed steel tube columns and wide-flange steel beams. Due to the difference in seismic provisions and construction technologies adopted in old and new steel buildings, a clear contrast in the severity of damage became evident in the Kobe earthquake. Many collapsed structures were old buildings having two to five stories, while no new buildings experienced such a collapse [4].

Inspections after the earthquake raised serious concerns regarding unexpected damage found in some new steel buildings, including brittle fractures at welded beam-to-column moment connections, severe buckling and connection failures at diagonal braces, and damage to anchor bolts. Among these, the damage to beam-to-column connections was very similar to that extensively found in the 1994 U.S. Northridge earthquake. This finding accelerated research collaboration between Japan and the U.S. in the mid to late 1990s. Although the damage location was the same, sources of damage were found to differ significantly between Japan and the U.S. in various aspects, including materials, design, fabrication, and inspection. As a result of these differences, practical solutions adopted to overcome the problems are also different. The U.S. strengthens the quality requirements for welding and adopts design details that can reduce stresses induced in the connection such as the reduced beam section (RBS) [17].

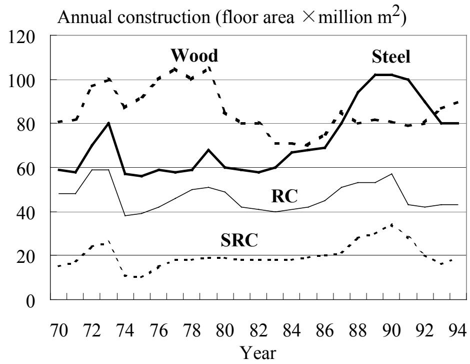


Fig. 4 Comparison of structural materials used in building construction

Japan places more emphasis on material toughness and connection details to mitigate stress concentrations at welds such as the no-weld-access-hole connection.

To gain insight into Japanese steel design practice, it is useful to examine the Japanese code in comparison to other base-line seismic codes. Comparison between the U.S. Load and Resistance Factor Design (LRFD) recommended by the American Institute for Steel Construction (AISC) [18] and the Japanese Building Standard Law (BSL) and its associated provisions is presented by Tada, *et al*. [6], wherein strength and ductility requirements are the primary topics discussed. Details on similarities and differences in the post-earthquake designs as well as the damage sources are documented in Refs. [16] and [19], and connection designs that reflect the post-Kobe research efforts are found in Ref. [20].

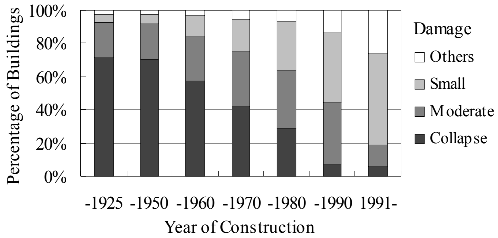
STEEL REINFORCED CONCRETE BUILDINGS

Since the mid 1950s, SRC has been used extensively in Japan for the construction of relatively large buildings (Fig. 4). A popular construction type is structural steel encased in reinforced concrete. The encased steel was made by built-up open sections in early constructions and was later changed to hot-rolled wide-flange steel in the early 1960s. Quite a few old SRC buildings constructed in the 1960s and early 1970s suffered damage including mid-story collapses. On many occasions, the collapsed story was supported by columns in which a SRC cross-section was converted into a RC cross-section. An abrupt change in column strength was considered to be responsible for such mid-story collapses. As with newer RC buildings, newer SRC buildings designed and constructed in accordance with the present seismic code exhibited satisfactory performance. It is notable that the superposed strength method has been used for design of SRC buildings for many decades. In this method, the SRC strength is given as the sum of the strengths of the RC and steel portions calculated separately [21].

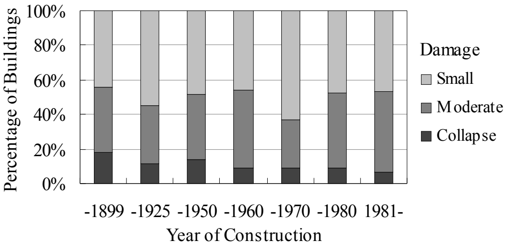
To achieve superior seismic performance, the use of concrete-filled steel tube (CFT) columns with wide-flange steel beams would be a promising alternative. CFT technology has been in development in Japan for over 40 years. Since about 1970, the CFT framing system has been used in the Japanese construction, particularly for medium- to high-rise buildings. The Japanese design provisions for CFT framing systems were first established in 1967 by the Architectural Institute of Japan (AIJ), adopting the superposed strength method for the strength evaluation. Based on extensive research conducted in 1990s, the AIJ standard was considerably revised in 2001 [22]. Details of the design recommendations, recent research findings, and construction trends of the CFT framing system in Japan are summarized by Morino and Tsuda [23].

WOOD BUILDINGS

Wood structures have gained the largest market share of Japanese building construction (Fig. 4). Most wood structures are used for houses. The collapse of houses during the Kobe earthquake that occurred at 5:46 am was found to be the cause of nearly 90% of the total number of deaths [24]. Figure 5(a) [25] shows the statistics of damaged wood structures in Ashiya City with respect to the year of construction. A strong correlation between the damage level and the construction year can be observed. Older



(a) 1995 Kobe earthquake



(b) 2000 Tottoriken-Seibu earthquake

Fig. 5 Distribution of damage to wood houses with respect to year of construction [25]

structures were far more susceptible to structural collapse as a result of the traditional Japanese construction practice of having rather heavy roofs (serving to protect against typhoons), large openings in the first story with very few and low shear-resistant partitions, weak connections between the residences and foundations, and poor structural integrity using the connections made by tenons and mortises rather than nails or other efficient connectors. Many old structural members were also weakened by wood rot.

Design provisions for wood houses were updated a few times from the 1960s to the 1980s [4]. Although the present provisions still do not require detailed structural calculation of the strength and ductility, they do adopt the concept of “wall ratio,” defined as the amount of lateral load-resisting elements such as braces with respect to the unit floor area, and stipulate the minimum wall ratios to ensure a sufficient structural strength. Due to the significant evolution in design and construction practices in the past few decades, it was common to see relatively new houses standing nearly intact among old houses that had collapsed (Fig. 1). It was agreed upon from the Kobe wood damage that the current design provisions for wood houses are adequate as long as the construction quality is assured. It was also notable that the so-called "industrialized houses" whose design and construction methods were reviewed and authorized by building authorities performed satisfactorily during the Kobe earthquake.

Because of the strong correlation between the damage level and year of construction in the Kobe earthquake, the distribution of houses with respect to the year of construction has frequently been used in the assessment of the earthquake vulnerability of towns, cities, and other local municipalities. The two significant earthquakes that hit the western part of Japan after the Kobe earthquake, i.e., the 2000 Tottoriken-Seibu and 2001 Geiyo earthquakes, however, provided different observations about the correlation between the damage and year of construction of wood houses.

As shown in Fig. 5(b) [25], the damage level is nearly constant with respect to the age in the 2000 Tottoriken-Seibu earthquake. This revealed that construction of wood houses is affected by various localities, particularly in country regions where traditional, elaborate wood construction prevails.

APPLICATION OF BASE-ISOLATION SYSTEMS

The technique of seismic isolation was adopted in Japan in the early 1980s. The first base-isolated building was completed in 1983. In the pre-Kobe period, seismic isolation technology was in the experimental stage, and its application to large-scale structures was still limited. Two base-isolated buildings, the West Japan Postal Savings Computer Center, conceived as the world's largest base-isolated building at that time, and Matsumura-Gumi Research Laboratory, were shaken during the Kobe earthquake. Both buildings exhibited satisfactory performance during the Kobe earthquake, although located outside the most strongly shaken regions [26]. The serious loss of life and economic loss disclosed in the 1995 event apparently led society to seek an alternative damage control strategy. This has considerably accelerated seismic isolation construction from about ten buildings per year in the 1985 ~ 1994 period to more than 150 buildings per year thereafter (based on the information provided in Ref. [27]). The trend of applications of seismic isolation is depicted in Fig. 6, wherein the cumulative number of seismically isolated buildings is plotted against the year of construction approval.

Seismic isolation has become common for building structures. Commonly used isolators in Japan are natural rubber bearings, high-damping rubber bearings, lead rubber bearings, and sliding bearings. A combination of different types of isolators is often adopted to achieve satisfactory stiffness of the isolation system. Supplemental dampers (mostly viscous or metallic-yielding dampers) are also added into the isolation system to reduce the relative displacement demanded of the isolated superstructure. Design of seismically isolated buildings involves nonlinear time-history analyses with an explicit consideration of local site conditions in the selection of input ground motions. As mentioned earlier, peer review is mandated for the design of these buildings.

In the post-Kobe period, the development of seismic isolation technologies has been quite extensive. Particularly notable are various efforts toward the implementation of seismic base-isolation to larger and taller buildings. As shown in Fig. 7, the floor area of base-isolated buildings has increased significantly in recent years. The main vehicles of these efforts are the construction and device supplying industries.

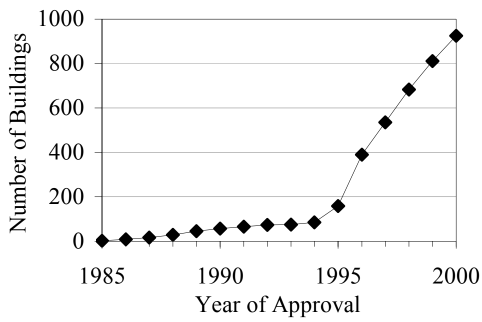


Fig. 6 Cumulative number of seismically isolated buildings approved until 2000

This indicates that the design and construction of seismic base-isolated buildings have arrived at a mature stage in Japan. A recent trend in the design of seismic base-isolation is the reduction of lateral shear and acceleration exerted into the superstructure, as evidenced in Fig. 8, in which the distribution of design base-shear coefficients is plotted with respect to the year. This reduction can be achieved by increasing the natural period, and various developments have been made along this line. One such development is presented by Higashino, *et al*. [28].

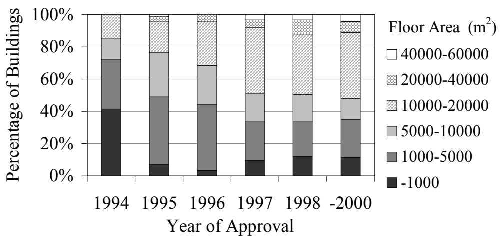


Fig. 7 Floor area of base-isolated buildings approved until 2000

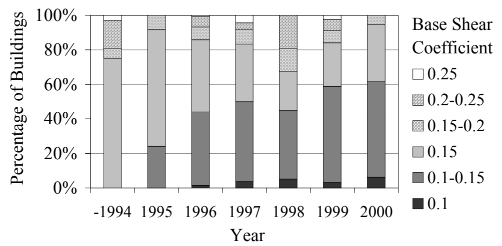


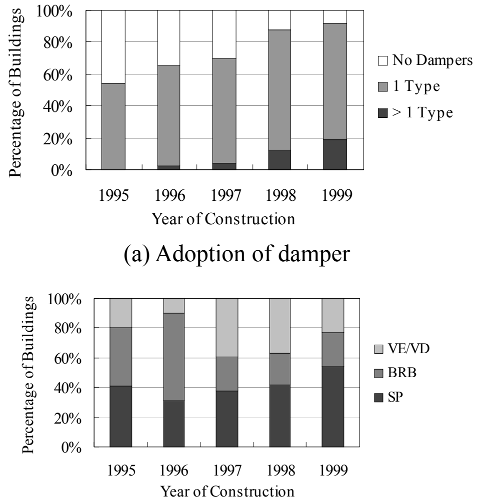
Fig. 8 Base shear coefficients used in design of base-isolated buildings adopted until 2000

APPLICATION OF PASSIVE CONTROL SYSTEMS

The concept of passive structural control for seismic-resistant structures was introduced in Japan in 1968 when slitted RC walls were adopted as energy absorbers in the Kasumigaseki Building in Tokyo, the first high-rise building in Japan [29]. Structural control developed further with the use of more efficient types of dampers, such as metallic-yielding, friction, viscoelastic, and viscous dampers. Research and development flourished from the mid-1980s to the early 1990s, when Japan's economy was booming. Real implementation of design and construction using the dampers also started around that period, with most of the applications in high-rise buildings.

Since the 1995 Kobe seismic event, passive control applications have been increasingly used. Figure 9(a) shows the statistics of high-rise steel/CFT buildings constructed with passive control systems. Almost all post-Kobe high-rise buildings were equipped with passive control systems to reduce seismic demands on primary structural members as well as overall structural responses. The great majority of passively controlled steel buildings constructed have metallic-yielding dampers, followed by viscoelastic shear dampers, viscous dampers, and friction dampers [27]. The market share of dampers adopted in the late 1990s is presented in Fig. 9(b). A combination of different types of damper is also frequently found. In recent years, the buckling-restrained brace and the shear panel damper have been the most popular devices in practice. The major advantages of these devices are stable hysteresis behavior under large deformation, flexible adjustability of strength and stiffness, reasonable cost, less maintenance required, and temperature independency. Some applications of the passive control system are presented by Tanaka, *et al*. [30]. The paper introduces outlines of individual applications and discusses design thinking and a process by which to arrive at the adoption of a particular passive control system among various alternatives.

There is no doubt that the 1995 Kobe event was a trigger for the significant increase in the application of seismic-base isolation and passive structural control. It should be noted, however, that this event alone was not sufficient to promote this trend. The prerequisite is the maturity of the associated design, construction, operation, and maintenance environment, including experienced designers who are comfortable with these new technologies, solid manufacturing industry that can provide the necessary devices in quantity and at



(a) Adoption of damper

(b) Type of damper (VE = viscoelastic dampers, VD = viscous dampers, BRB = buckling-restrained braces, SP = shear panel type)

Fig. 9 Implementation of passive control systems in high-rise steel/CFT buildings

reasonable cost, and skilled constructors who can incorporate the devices into the building systems with the required precision. The peer-review process described earlier also contributed significantly to the application and dissemination of such new technologies.

AWARENESS OF FUTURE EARTHQUAKES

Many issues have been addressed thus far with regard to post-Kobe design and construction practices. The most important issue that has not been mentioned is the issue of structural retrofitting of seismically vulnerable buildings. There is no question about the critical need for seismic retrofit throughout Japan. The seismic resistance diagnosis and rehabilitation in Japan are now in progress. Of 114,399 publicly owned pre-1981 buildings (those designed and constructed with obsolete seismic codes), 30% have been evaluated [31]. This means that 70% have not been checked for seismic safety. It was found that 71% of the evaluated buildings were considered unsafe, and among these unsafe buildings 34% have been rehabilitated. It should be noted that the buildings considered here are those owned and managed by prefectures and local municipalities. If private buildings are taken into account, the percentage of retrofitted buildings would become considerably smaller.

In view of these statistics, many point out that seismic retrofit is rather slow. Reasons for the slow progress include lack of criteria to suggest the level of structural retrofitting with respect to the remaining life of the building and lack of systematic rules to define the sequence of rehabilitation for numerous buildings [31]. In addition, the structural retrofitting business is still rather small and unsystematic, leading to higher costs. Further, structural retrofitting has not been compulsory in Japan and thus has to depend solely on individual decisions. With all of these difficulties put aside, we shall continue in our efforts to encourage society to inspect and rehabilitate all old buildings and provide them with adequate margin of safety against future destructive earthquakes.

CONCLUSIONS

A review of the Japanese seismic design and construction practices adopted after the 1995 Kobe earthquake has been presented in this paper. Important post-Kobe progress can be summarized briefly as follows: (1) the Japanese seismic design code has been revised toward more performance-based engineering; (2) various design provisions for RC, steel, and SRC buildings have been reinforced to prevent structural damage observed in the Kobe earthquake; (3) seismic isolation and passive control of buildings have arrived at the mature stage as applications have been increasing substantially; and (4) seismic diagnosis and retrofitting are in progress, but achievement of the ultimate goal is still some distance away.

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