Japan Architectural Review Open Access

Architectural Institute of Japan

Review Paper

Recent research and development of structural control in Japan

Yoshiki Ikeda[1] **Masashi Yamamoto**[2] **Takeshi Furuhashi**[3] **and Haruhiko Kurino**[4]

[1]Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan; [2]Earthquake Engineering Department, Research and Development Institute, Takenaka Corporation, Inzai, Chiba, Japan; [3]College of Science and Technology, Nihon University, Tokyo, Japan; [4]Architectural Design Division, Kajima Corporation, Tokyo, Japan

Correspondence
Yoshiki Ikeda, Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan.
Email: ikeda.yoshiki.6r@kyoto-u.ac.jp

Funding information
No funding information is provided.

Received December 21, 2018; Accepted February 12, 2019

doi: 10.1002/2475-8876.12081

Abstract

In Japan, structural control is widely recognized as a fundamental technology for exceeding the performance limitations of conventional earthquake/wind-resistant buildings. Over the last three decades, research and development (R & D) has been implemented in construction, mechanical industries, and universities. Additionally, many types of control strategies have been proposed through theoretical, experimental, and numerical investigations. In comparison with other countries, Japan has successfully and rapidly developed remarkable engineering applications for actual buildings using advanced structural control technologies, because Japanese construction companies promote R & D in cooperation with mechanical industries, structural design offices, and universities. This review paper introduces the recent structural control advances in Japan. The state-of-the-art report is based on papers published by the Architectural Institute of Japan, the Proceedings of the 16th World Conference on Earthquake Engineering, articles published in a structural engineering magazine, the special theme sessions at the 7th World Conference on Structural Control and Monitoring, and other relevant information. The key research directions are the simplification of control laws and mechanical devices, high performance with either little or no energy supply, device magnification, use of structural frames and substructures, new materials, adaptability, and cautious uses serving various purposes.

Keywords
large earthquake, new damper, practical applications, seismic retrofitting, structural control

1. Introduction

The concept of structural control was internationally proposed for civil engineering structures in 1972.[1] According to this proposal, structures counter earthquake/wind excitations not only through their structural members but also through the control systems, which means that civil engineering and mechanical engineering technologies must be integrated. Until the late 1980s, structural control practically meant active control, and its fundamental dynamic properties were understood theoretically and experimentally from a civil engineering viewpoint.[2] By the mid-1980s, information science was becoming widespread in society and structural control re-emerged as a solution to extremely complex seismic motions and their inherent uncertainty, which make it impossible to guarantee structural safety through conventional design methods.[3]

The practical application of active and semiactive control began in 1989, when an active mass damper (AMD) system was first applied to an actual 10-story office building in Tokyo.[4] In 2001, the journal of *Earthquake Engineering & Structural Dynamics* published a special issue on the practical applications of active and semi-active structural control systems to actual civil engineering structures.[5] A review paper has presented a list of 31 practical applications in Japan, from 1989 to 1998. In 2003, the *Journal of Structural Engineering* also published a special issue on structural control,[6] which listed 40 applications of active and semi-active control in buildings (36 in Japan, 2 in Taiwan, 1 in China, and 1 in Korea) from 1989 to 2002, and 10 applications of active control applied to bridges (all in Japan). For all bridges introduced, AMDs were installed only under their constructions. The applied active control included the AMD, active tuned mass damper, and active gyroscopic stabilizer. The applied semi-active control included a variable-stiffness system, variable-orifice damper, controllable-fluid (electrorheological fluid or magnetorheological fluid), damper, and semi-active tuned mass damper. The application list was revised by introducing 52 actively controlled buildings and 17 semi-actively controlled buildings in Japan.[7] The effectiveness of active control was also reported as the equivalent damping ratios in the first horizontal vibration modes,[7] because AMDs and their derivatives had been installed to many buildings.

The 1995 Kobe Earthquake marked the beginning of a new research phase wherein buildings could be controlled semi-actively, even under large earthquakes. Nowadays, structural control including passive control is an indispensable consideration for high- and middle-rise buildings and towers and helps improve living comfort and structural safety. However, performance improvement is rather difficult using conventional earthquake-resistant design. After the 2011 Great Tohoku Earthquake, the effectiveness of passive control was reported as the equivalent damping ratios in the first modes using the recorded measurements of the seismic structural responses.[8] In the future, structural control should consider long-period and long-duration ground motions with large amplitudes. This aspect of earthquake events emphasizes the amount of vibration energy absorbed from a structure using control devices, and stimulates the research and development (R & D) of structural control. Since 2011, structural control has also been expected to contribute to the seismic retrofitting of many old buildings.

By introducing newly developed dampers, this paper outlines the recent progress of structural control in Japan to identify recent R & D trends in the field of building engineering. The information is mainly based on national papers published by the Architectural Institute of Japan (AIJ), the Proceedings of the 16th World Conference on Earthquake Engineering, Japanese articles published in a structural engineering magazine, and papers presented at the special theme sessions on structural control during the 7th World Conference on Structural Control and Monitoring (7WCSCM) 2018. This review paper describes the differences between the advanced processes implemented by Japan and other countries. Additionally, the key directions of future research are summarized.

2. Recently developed damper for structural control

Recently developed dampers for structural control have been previously summarized in a literature review,[9] which was conducted in 2017 for dampers investigated and developed both in Japan and abroad.

2.1 Dampers developed in Japan

Using a search system managed by AIJ, a survey was conducted for all AIJ papers published at national level since 2013. The retrieval keywords were “damper” and “development,” and returned a search result of 104 papers as of 15 March 2017. From these papers, experimental tests with large-scale damper specimens (damper force more than 100 kN) were extracted from 46 technical papers considering 11 types of dampers. Table 1 lists the dampers along with their development concepts. From a search viewpoint, some of the retrieved concepts may be different to what the developers had intended.

These dampers were developed with consideration to the following concepts: small size and high capacity, high durability, seismic retrofitting, earthquakes ranging from small to large, easily adjustable characteristics, and high-performance efficiency. The concepts of “small size and high capacity” and “high-performance efficiency” were introduced by recognizing that the current structural control performance of dampers may be insufficient according to some expectations. Generally, the space available for installing dampers is severely limited by architectural design requirements. This limitation expects the device developers to deliver dampers with compactness and higher efficiency. The concept of “high durability” is intended to improve metallic dampers for long-period and long-duration earthquakes occurring in subduction zones such as the 2011 Great Tohoku Earthquake. The concept of seismic retrofitting has been proposed to guarantee the safety of old buildings during predicted earthquakes with larger intensity. The “from small to large earthquake” concept relates to the fact that the metallic dampers installed on buildings in the Tokyo metropolitan area did not perform well during the 2011 Tohoku Earthquake. In this area, the earthquake ground motion was as large as the design earthquake load estimated for a 50-year return period. Another aspect of the high durability concept is that developers would like to make the metallic dampers more effective, even under relatively smaller excitations, by reducing their yielding displacements. In Japan, many recent development concepts were motivated by lessons learned from the 2011 Tohoku Earthquake.

Table 1. Recently developed dampers in Japan

No.	Name	Development concept[a]
1	High capacity oil damper[10,21]	Small size and high capacity
2	Inertia with acceleration mechanism[11]	Small size and high capacity
3	High capacity buckling restrained brace with triple core plates[12]	Small size and high capacity
4	Shear panel damper with concave shape[13]	High durability
5	Hysteretic damper using stainless steel[14]	High durability
6	Hysteretic damper using Fe-Mn-Si-based alloy[15]	High durability
7	Variable-friction-force slip damper[16]	Seismic retrofit
8	Oil damper with visco-elastic material[17]	Seismic retrofit
9	Friction damper with multi-stage friction force[18]	From small to large earthquake
10	Friction damper using ring springs[19]	Easily adjustable characteristics
11	Semi-active oil damper with energy recovery system[20,22]	High-performance efficiency

[a] The development concepts are considered according to the corresponding papers and may be different to the developers' intentions.

2.2 Dampers developed outside of Japan

A similar survey was conducted in the Proceedings of the 16th World Conference on Earthquake Engineering. First, interesting papers were chosen according to their titles, which were used as a selection criterion; another criterion was whether the papers described damper development. Next, the selected papers were investigated individually, and the papers describing a certain feasibility level according to the results of experimental tests were extracted. The extracted papers include dampers developed in the 1990s, such as triangular added damping and stiffness,[29,30] because it is important to know which dampers have been used to date.

Table 2 shows seven types of dampers along with the authors' countries and the development concepts. These dampers have been investigated and developed either in earthquake prone countries or countries that export control devices to earthquake prone countries. Because metallic/friction dampers

Table 2. Recently developed dampers outside of Japan

No.[a]	Name	Country[b]	Development concept[c]
12	Mega Pall friction damper[23]	Canada	Small size and high capacity
13	Buckling inhibited metal shear panel[24]	Italy	High durability
14	Crescent shaped brace[25]	Italy	High durability and fail safe
15	Compression-free brace[26]	Thailand	Seismic retrofit
16	Prestressed lead extrusion damper[27]	Turkey	Low cost and toughness
17	Friction spring damper[28]	Germany/ USA	Toughness
18	Triangular added damping and stiffness (TADAS)[29,30]	Chile	Low cost and crack prevention for reinforced concrete

[a]Numbering is continued from Table 1. [b]The country of corresponding paper authors. [c]The development concepts are considered according to the corresponding papers and may be different to the developers' intention.

are easy to design and handle while maintaining economic efficiency, only metallic/friction dampers, and not viscous dampers or oil dampers, are listed. Unlike the situation in Japan, the development was not motivated from any specific earthquake event. A paper discussing the friction spring damper mentions the 2010 and 2011 Christchurch earthquake events[28]; however, these events did not motivate development. The development concepts for dampers No. 12 to 15 are the same as those in Japan. Japanese structural engineers find it interesting that the development concept for dampers No. 16 and 18 is low-cost, because Japanese developers have always been concerned with the fact that a low-cost concept is not clearly mentioned in the Japanese literature.

3. Seismic retrofitting for high-rise buildings

In Japan, the necessity of seismic retrofitting for existing buildings has been increasing, not only because of the need to repair existing non-conformed buildings, but also as a response to long-period and long-duration ground motions.[31,32] Additionally, there exists a need of ensuring safety when responding to the increasing intensity of predicted earthquakes. The methods of seismic retrofitting for existing buildings can be categorized into three types: conventional earthquake-resistant deign method, seismic isolation method, and structural control method. With regard to the investigation of retrofitting to high-rise buildings, it may be difficult to apply either the conventional design method or the seismic isolation method. The structures are tall and of a large scale with relatively longer natural periods, which naturally leads to the application of the retrofitting method to structural control. However, traditional structural control methods should be modified in retrofitting applications.

This section considers instances of seismically retrofitted high-rise buildings by surveying open literature and information provided by the members of the AIJ Subcommittee with regard to structural control. Retrofitting is reported from the viewpoint of applied technologies, their dynamic characteristics, and the set-up performance objectives, among other considerations.

3.1 Case studies of seismically retrofitted high-rise buildings

The literature search was conducted using the following resources: the Kenchiku Gijyutsu magazine (in Japanese), whose target audience is mainly structural engineers, and which has published 1014 articles under the term "Technical View" over an 8-year period from January 2009 to December 2016. Amongst these articles, 50 of them use the "structural control" key word. Five articles and four instances introduce seismic retrofitting for high-rise buildings using structural control technologies (Cases 1, 3, 4, and 7 listed in Table 3). Cases 2, 5, and 6 have been added to the table by the AIJ subcommittee members, because these retrofitting applications have not been published. Therefore, Table 3 lists seven instances. The cases are numbered in the order by which the retrofitting works commenced. Table 4 shows the systems proposed for seismic retrofitting using structural control, which have been reported in articles under the term "Technical View." The difference from Table 3 is that these proposals have not been implemented in actual applications.

3.2 Analysis of instances and proposed systems

The instances and proposed systems listed in Tables 3 and 4 were analyzed according to four viewpoints: (i) terms of retrofitting work, (ii) structural control device, (iii) objectives, and (iv) effect of retrofitting.

Terms of retrofitting work

The retrofitting in Cases 1 and 2 was completed before the 2011 Great Tohoku Earthquake and was carried out with consideration to the long-period and long-duration ground motions observed during the 2003 Tokachi-oki Earthquake. Cases 3 to 7 were completed after the 2011 Great Tohoku Earthquake. Both systems listed in Table 4 were proposed subsequently.

Structural control device

Cases 4 and 7 listed in Table 3, and the two systems listed in Table 4, include the installation of large-size tuned mass dampers (TMDs). These new TMD systems are effective against large earthquakes with various device modifications, because traditional small-size TMDs are effective only against small/medium earthquakes. The TMD in Case 4 has a weight of 1800 tons and oil dampers with ±2 m strokes. The weight of the TMD in Case 7 is 1400 tons and is supported with double laminated rubber bearings and linear sliders. The TMD in System No. 1 listed in Table 4 is a multistage TMD with a stroke of ±4 m. The TMD in System No. 2 uses an inverted pendulum mechanism to obtain compactness, adjustability in a period, and a fail-safe mechanism.

The other Cases used oil dampers. Cases 3 and 6 installed rotational-inertia dampers and oil dampers. The devices combining rotational-inertia dampers and an oil damper are three times more effective in comparison with conventional oil dampers. Additionally, they enable the concentrated installation of control devices. Case 1 used oil dampers with an axial force restriction mechanism, which solves the problem regarding the increase in the axial forces of the columns by applying seismic retrofitting to high-rise buildings. Case 2 used high-efficiency oil dampers. Case 5 applied both efficient oil dampers and elasto-plastic steel dampers. The total number of dampers was 666. These high-efficiency oil dampers have energy recovery systems and are two times more effective than conventional oil dampers.

Table 3. Seismically retrofitted high-rise steel buildings using structural control

Case no.	1	2	3	4	5	6	7
Building name	C	P	S	M	S60	D	N
Story above ground	54	52	24	55	60	15 with 152 m high steel tower on top	53
Working term	August 2008–July 2009	February 2009–September 2009	April 2012–August 2012	August 2013–April 2015	March 2014–August 2016	December 2014–October 2015	January 2015–September 2016
Control device	288 oil dampers with axial force restriction mechanism	48 high-efficiency oil dampers	28 rotational-inertia damper and oil damper units	Large-size TMDs and high-efficiency oil dampers	252 high-efficiency oil dampers and 414 steel elasto-plastic dampers	24 rotational-inertia dampers, oil dampers, and buckling-restraint steel dampers	Two TMDs
Target excitation	Long-period and long-duration earthquake	Long-period and long-duration earthquake	Predicted more severe earthquake	Long-period and long-duration earthquake	Long-period and long-duration earthquake	Predicted severe local earthquake	Long-period and long-duration earthquake
Characteristics	Damper mechanism to restrict additional axial force to existing columns	Dampers installed only on 24th floor	Three times as efficient as conventional dampers	TMD on roof Weight: 1800t; Stroke: ±2 m	Total of 666 dampers	Inertia and oil dampers installed from 1st to 3rd floor; steel dampers installed from 6th to 9th floor	Two 700t TMDs on top floor
Retrofitting effectiveness	Reduce peak structural response by 10% under large earthquakes; secure business continuity after large earthquake; additional damping ratio based on measurement: 0.6% in longitudinal direction and 1.2% in lateral direction	Reduce peak structural response by 25% and shorten response time under Tohoku Earthquake (based on measurement and simulation)	Secure safety under large earthquakes twice as severe as the 1923 Kanto Earthquake	Reduce structural response and shorten response time under long-period earthquakes	Reduce structural response and girder fatigue under long-period earthquakes.	Secure safety under predicted local earthquakes more severe than existing criterion	Reduce structural response and shorten response time under long-period earthquakes

Objectives

Cases 1, 2, 4, 5, and 7 mention that the retrofitting objectives are countermeasures to long-period and long-duration ground motions. The scope of Cases 3 and 6 was to ensure increased safety against larger predicted earthquakes, in comparison with the existing criterion. In any case, the building seems to be safe according to the existing criterion and improved performance is expected. The objectives of System No. 1 are also countermeasures to long-period and long-duration ground motions. The objectives of System No. 2 are not described clearly.

Effect of retrofitting

The assertion of retrofitting effectiveness seems to be expressed delicately in Japan, owing to the difficulty faced by structural engineers in clearly explaining the effectiveness of retrofitting under large earthquakes to building owners, building tenants, and other stakeholders. This is because an earthquake will always produce extremely complex seismic motions with inherent uncertainties. The retrofitting effectiveness for long-period and long-duration ground motions can be described as follows: (i) the seismic structural response under a large earthquake is certainly reduced, and the duration time is shortened; and (ii) business continuity is ensured immediately after a large earthquake. Effectiveness with regard to severe earthquakes means that structural safety is ensured more effectively in comparison with the existing criterion.

After the 2011 Tohoku Earthquake, structural control became a significant technology in application studies on seismic retrofitting for high-rise buildings in Japan. The technology has been realized by various modifications applied to traditional structural control devices, which means that new or revised control systems have been introduced. However, it is somewhat difficult for structural engineers to explain the effectiveness of seismic retrofitting to the public from the viewpoint of economic efficiency.

4. Review of papers submitted to 7WCSCM

The WCSCM is one of the representative international conferences regarding structural control technology. In July 2018, the

Table 4. Proposed seismic retrofitting systems in high-rise buildings using structural control

System no.	1	2
System name	T-M damper	Pair mass-damper
Structure of objective building	Steel	
Control device	Multi-stage TMD	TMD with inverted pendulum mechanism
Target excitation	Long-period and long-duration earthquake	Not indicated
Characteristics	Multistage TMD on top floor Stroke:±4 m	TMD on top floor; its mechanics provide the building with compactness and adjustability

7WCSCM provided the latest significant information following the survey of Sections 2 and 5. Approximately 400 papers were presented at the conference, of which approximately 1/3 was relevant to structural control research, while the remaining 2/3 was concerned with structural monitoring research. The special theme sessions titled "Application, Research, and Design on Structural Control in Japan" were held in cooperation with the AIJ subcommittee and received 28 paper submissions. This section introduces various studies that seem to include useful information, which was not mentioned in Sections 2 and 5.

Efforts to simplify and rationalize control devices and control laws are ongoing.[33,34] One study[33] combined a friction damper with four tensile brace members. The brace sections of the brace-integrated dampers may become larger, owing to demands for brace buckling resistance, which is a major obstacle when applied to buildings with limited space. In the proposed system, only the tension axial force always acts on the brace member, owing to the geometric non-linearity; therefore, it is possible to use the brace element of a smaller cross section. Another study[34] investigated a design method using rotational inertial mass dampers, which is a relatively new passive type of control device, as introduced in Section 2.[11] Unlike conventional dampers, which can exert only a resistive force that depends on the displacement or velocity, the rotational inertial mass damper can exert a resistance force according to the relative acceleration between the nodes where the device is installed, and can thus be applied to mode control. This study proposed a simple design method that attempts to eliminate the modal amplitude in the higher modes of the target structure using a rotational inertial mass damper.

Research has also been conducted on a control system using structures other than the main structure. One study[35] has analytically investigated the possibility of enhancing the control effect of the TMD installed onto the main structure by connecting the adjacent structure and the TMD with a rotational inertial mass damper. This study pointed out that, by properly adjusting the mass ratio and frequency ratio, it is possible to efficiently reduce the responses of the two structures in comparison with the conventional viscous damper connection.

Various studies have aimed at careful control that serves various purposes and the automatic adjustment of the control device.[36] The dynamic characteristics of an actual base-isolated building using a semi-active oil damper, whose damping coefficient is controlled using Linear Quadratic Gaussian control theory, were identified based on the observations recorded during the 2011 Tohoku Earthquake. Then, the control parameters were updated to minimize the damage probability evaluated by the fragility curves obtained by many response analyses using the updated structural model.

The final consideration is related to seismic retrofitting. Although the retrofitting device for high-rise buildings was reviewed in Section 5, one study[37] has presented another retrofit example applied to the steel-truss structure of Tokyo Tower. In parallel with the reinforcement of the steel member, several original horizontal members were replaced with oil dampers. Although the employed device is a conventional oil damper, the study proposed an effective method of controlling the whipping behavior of a tower-like structure, where bending vibration was problematic.

5. Future directions of structural control

The challenges with regard to the structural control of buildings are that the objective structures are larger, and that the external forces acting on them are both severe and highly uncertain. In the aftermath of the 2011 Tohoku Earthquake, emphasis was placed on structural control research with regard to long-period and long-duration ground motions with large amplitudes, particularly for large-scale/tall buildings. This section summarizes the challenging research directions over approximately 20 years after the publication of previous special issues.[5,6] These directions are based on many existing applications and the recent R & D trends in Japan.

5.1 Simplification and improvement of control laws/devices

The simplification of control laws/devices is a key consideration for large-scale and long-term structures, which makes maintenance easier. Since their early practical applications, AMDs have not worked on state feedback control but rather on output feedback control. Although earlier semi-active control continuously changes the damping forces by adjusting the valve openings through which confined oil flows,[38] it was followed by a simplified on-off-switching oil damper[39] which finally led to a new passive oil damper with high performance equal to that of the simplified semi-active damper.[40] The simplification considers that the Maxwell model constrains its force-displacement hysteresis loop within a certain limited area through its stiffness values. A decentralized autonomous system in the semi-active on-off-switching damper is also considered as a simplification and improvement of the control law.[39]

5.2 High performance with small or no energy supply (improved passive control)

Early R & D identified the direction toward achieving highly efficient control that can produce large control forces with a small energy supply, and semi-active control was developed as a response. The examples are passive oil dampers with capability equal to that of semi-active oil dampers or kinetic energy-recovery systems.[40] This improvement updates passive control based on the deep understanding of mechanical devices. High-performance dampers require that traditional mechanical devices should remove backlash, and this removal results in structural control under small-scale excitations.

5.3 Device magnification for large damping force

In an actual building, the installation spaces for control devices are limited and this limitation often becomes more severe for large earthquakes and seismic retrofitting work. When a damper is installed in a structural frame, its width and length are restricted by the width of columns and the frame span, respectively. For a standard high-rise building, 2000-2500 kN may encounter the limitation of a damper. This space limitation expects each damper to raise its maximum loading force in a new development. A typical device magnification can be seen in the development of oil dampers. In the 1990s, the maximum damping force was 1000 kN per damper for passive or semi-active control. Since 1993, a 25-story office building has had 1000 kN passive oil dampers.[41] The dampers produce 10-20 equivalent damping ratios in the lower three vibration modes of each horizontal direction. The maximum force was raised to approximately 1500 kN in the year 2000, and further raised to approximately 2000 kN in 2004. The other approach is a multi-unit oil damper wherein plural oil dampers are arranged in series. The multi-unit damper provides a solution to large earthquakes, mega-structures, and the intensive installation of devices. A 6000 kN passive oil damper has been developed by integrating three 2000 kN oil dampers.[42] As shown in Cases 4 and 7 listed in Table 3, device magnification was found in the applications of large-size TMDs with an increase in the accompanying damper capacity to aseismic retrofitting. Directions (2) and (3) provide automatic solutions to severe and highly uncertain earthquakes.

5.4 Effective use of structural frames and substructures

Under the same excitation, control effectiveness depends mainly on the scales and total number of control devices. To obtain heavy auxiliary masses, various AMD systems have employed ice thermal storage tanks and a heliport on the roof floors.[43] Additionally, a TMD system has employed a garden floor with viscous dampers.[44] These examples indicate device magnification. For dampers responding to relative displacement/velocity, the effective use of structural frames and substructures are additional solutions to the production of extremely large damping forces. Multi-story parking structures within or adjacent to high-rise condominiums are often used as substructures, and hysteresis/oil dampers are installed between them as joint damper systems.

5.5 New materials for hysteresis dampers in passive control

The development of dampers employing new metallic materials is one of the future directions for passive control using hysteretic devices. Stainless steel is one such new metallic material. The advantages of stainless steel are the high tensile strength, high breaking elongation, good aesthetics, and good recyclability. Performance tests have been conducted on 150 mm-square-shear-panel specimens whose materials were SUS304 (austenitic stainless steel), SUS329 (austenitic-ferritic stainless steel), and SS400 (common steel).[14] The test results confirmed that the stainless steel specimens had stable hysteretic loops and higher strength in comparison with the common steel specimens. Additionally, the SUS304 specimen exhibited strain hardening. A new Fe-Mn-Si based alloy,[15] which is a type of shape memory alloy, is another example. The new Fe-15Mn-10Cr-8Ni-4Si (FMS) alloy realized a low Mn composition to apply an electric furnace process and produce materials with a large size. The fatigue durability of the FMS alloy was confirmed by material tests as approximately ten times larger than that of LY225 (low-yield-strength steel). Using this new material, the dampers were designed as a shear panel. The results of performance tests conducted on the damper revealed that the hysteresis loop under the design basis earthquake was stable, even for the third loading.

5.6 Adaptability and careful uses serving various purposes

A control system that is appropriate to each structure can achieve very high vibration control effectiveness. Adaptability and tuning are key considerations in structural control research. These concepts are linked to adaptive control and optimization for removing uncertainty and obtaining robustness. Base isolation with a semi-active damper is an example of adaptability.[36,48] After many types of control devices had been proposed, careful use serving various purposes became more prominent in structural control design. Additionally, device combinations attracted a growing amount of interest in practical applications.[49] Combined uses are categorized as (i) active, semi-active, and passive control; (ii) passive control for small vibration and passive control for large vibration; (iii) structural control and base isolation; and (iv) passive control using complex dampers for small and large vibration. A complex damper is defined as a device with multiple functions, such as the integration of a visco-elastic damper and a hysteresis damper.[50]

5.7 Aseismic retrofitting

As described in Section 5, after the 2011 Great Tohoku Earthquake, there was an increased amount of interest in seismic retrofitting work applied to already constructed high-rise buildings.

6. Conclusion

This paper reports on state-of-the-art methods for structural control in Japan by reviewing recently published papers and articles in the field of structural engineering. The 1995 Kobe earthquake and the 2011 Tohoku Earthquake initiated new R & D phases with regard to the structural control of buildings. The key research directions are the simplification of control laws and mechanical devices, high performance with either little or no energy supply, device magnification, uses of the structural frame and substructure, new materials, adaptability, and careful uses serving various purposes.

Disclosure

The authors declare no conflict of interest.

References

1 Yao JTP. Concept of structural control, Journal of the Structural Division, ASCE 1972; 98(ST7), pp. 1567-1574.

2 Yang JN, Soong TT. Recent advances in active control of civil engineering structures, Probabilistic Engineering Mechanics 1988; 3(4), pp. 179-188.

3 Kobori T. State-of-the art report: Active seismic response control, Proceedings of the 9th World Conference on Earthquake Engineering 1988; VIII, pp. 435-446.

4 Kobori T, Koshika N, Yamada K, Ikeda Y. Seismic-response-controlled structure with active mass driver system, Earthquake Engineering & Structural Dynamics 1991; 20(2), pp. 133-166.

5 Caughey TK, Kobori T (editors). Special issue: Practical applications of active and semi-active structural control systems to actual civil engineering structures, Earthquake Engineering & Structural Dynamics 2001; 30(11), pp. 1561-1743.

6 Spencer BF Jr, Nagarajaiah S (ed.). Special issue: structural control, Journal of Structural Engineering, ASCE 2003, 129(7), pp. 843-997.

7 Ikeda Y. Active and semi-active vibration control of buildings in Japan—Practical applications and verification. Structural Control & Health Monitoring 2009; 16(7-8), pp. 703-723.

8 Ikeda Y. The aspects of structural control before and after the 2011 Great Tohoku Earthquake, Panel Discussion on the State-of-the art of Structural Control and Preparation for Coming Earthquakes 2013; AIJ Annual Meeting,

pp. 15-24. https://www.aij.or.jp/jpn/pdf/taikaidoc/2013/taikai/13.pdf (in Japanese).

9 Yamamoto M. Recently developed dampers for structural control, Panel Discussion on Current Situation and Future Perspective of Technologies of Seismic Isolation and Structural Control - Staring a Large-amplitude Earthquake 2017, AIJ Annual Meeting, pp. 45-58 (in Japanese).

10 Minewaki S, et al. A real scale performance test of a high capacity oil damper, AIJ Journal of Technology and Design 2016; 52, pp. 881-884 (in Japanese).

11 Matsui K, Isoda K, Okamoto M. Development of inertia mass damper with acceleration mechanism (part 7): result of vibration experiment, Summaries of Technical Papers of Annual Meeting AIJ 2014; Structures-II, pp. 781-784 (in Japanese).

12 Tateishi T, et al. Development of buckling restrained brace with triple core plates (part 1): mechanical performance of small-scale specimen, Summaries of Technical Papers of Annual Meeting AIJ 2016; Structures-II, pp. 791-792 (in Japanese).

13 Natori S, Kubota M, et al. Study on the shear panel damper in the shape of concave type lens for seismic response control structure (part 1): outline of the lens type shear panel damper, Summaries of Technical Papers of Annual Meeting AIJ 2014. Structures-II, pp. 851-864 (in Japanese).

14 Kudo T, Kuratomi Y, Inada T. Development of high-performance hysteretic devices using stainless steel (part 1): performance verification by experimental work under cyclic horizontal load, AIJ Kyushu Chapter architectural research meeting 2014; pp. 277-280 (in Japanese).

15 Umemura K, et al. Development of seismic damper using Fe-Mn-Si-based alloy and its application to the super high-rise building (part 3): design and basic performance of the new seismic damper, Summaries of Technical Papers of Annual Meeting AIJ 2016; Structures-II, pp. 105-106 (in Japanese).

16 Sano T, et al. Development of variable damping force friction slip damper (Part 3): elemental test and full-scale test of advanced damper, Summaries of Technical Papers of Annual Meeting AIJ 2013; Structures-II, pp. 857-858 in Japanese.

17 Yokoyama A, Takahashi O, Asano Y. Development of new oil damper for architectural vibration control and experimental research on structural characterization, Summaries of Technical Papers of Annual Meeting AIJ, Structures-II 2016; pp. 145-146 (in Japanese).

18 Utsumi Y, et al. Development of friction slip dampers using high-tension bolts (part 16): performance confirmation full scale test of friction slip damper with multi-step sliding loads, Summaries of Technical Papers of Annual Meeting AIJ 2013, Structures-II, pp. 1041-1046 (in Japanese).

19 Sato T, et al. Study of friction damper using ring spring (part 5): applied to wooden framed structure, Summaries of Technical Papers of Annual Meeting AIJ 2015; Structures-II, pp. 731-732 (in Japanese).

20 Kurino H, Fukuda R. Enhancement of energy dissipation capacity of oil damper by introducing energy recovery system, AIJ Journal of Structural and Construction Engineering 2016; 722, pp. 713-723 (in Japanese).

21 Kushima S, et al. Structural planning for 189-meter-tall damped building with irregularly-shaped plan and elevation, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

22 Fukuda R, Kurino H. Highly efficient semi-active oil damper for structural control with energy recovery system, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

23 Pall A. The making of mega Pall friction dampers for Torre Cuarzo office tower in Mexico City, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

24 Brando G, De Matteis G. Buckling inhabited metal shear panels: A new damper based on the development of the BRB concept in the 2D space, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

25 Dib A, et al. Experiments on crescent shaped brace—a new simple hysteretic bracing device, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

26 Thammarak P, et al. Development, and testing of cam-grip type, compression-free energy dissipative brace, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

27 Soydan C, et al. Determination of the characteristics of a new prestressed lead extrusion damper, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

28 Jahnel L, Cole E. Design approach for friction spring dampers in steel framed buildings. Experiences from Christchurch, NZ, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

29 Zemp R, et al. Design, testing and implementation of TADAS devices in three RC buildings with shear walls and coupling beams, Proceedings of the 16th World Conference on Earthquake Engineering, 2017.

30 Tsai KC, et al. Design of steel triangular plate energy absorbers for seismic-resistant construction. *Earthquake Spectra*. 1993;**9**(3):505-528.

31 Kasai K, Pu WC, Wada A. Response of passively-controlled tall buildings in Tokyo during 2011 Great East Japan Earthquake. Proceedings of the 15th World Conference on Earthquake Engineering, 2012.

32 Furuhashi T. Seismic Retrofitting of High-rise Buildings, Panel Discussion on Current Situation and Future Perspective of Technologies of Seismic Isolation and Structural Control—Staring a Large-amplitude Earthquake 2017; AIJ Annual Meeting, pp. 37-44 (in Japanese).

33 Hirata H, et al. Seismic control system of tensile brace and friction damper combination, Proceedings of the 7th World Conference on Structural Control and Monitoring, 2018.

34 Han W, et al. A study on simple design method of hybrid control system about mode control system and oil-damper, Proceedings of the 7th World Conference on Structural Control and Monitoring, 2018.

35 Maruo J, et al. Analytical study on response reduction effect by tuned mass damper with amplifier mechanism, Proceedings of the 7th World Conference on Structural Control and Monitoring, 2018.

36 Kohiyama M, et al. Update of control parameters of semi-actively controlled base-isolated building, Proceedings of the 7th World Conference on Structural Control and Monitoring, 2018.

37 Kashimoto N, et al. Application of structural control to seismic retrofit of Tokyo Tower, Proceedings of the 7th World Conference on Structural Control and Monitoring, 2018.

38 Kurata N, Kobori T, Takahashi M, Niwa N, Midorikawa H. Actual seismic response-controlled building with semi-active damper system. *Earthquake Eng Struct Dynam*. 1999;**28**(11):1427-1447.

39 Kurino H, et al. Switching oil damper with built-in controller for structural control, Journal of Structural Engineering 2003; ASCE, 129(7), pp. 895-904.

40 Kurino H, et al. Switching oil damper with automatic valve operation system for structural control. Proceedings of the 4th World Conference on Structural Control and Monitoring, Paper No. 217, 2006.

41 Niwa N, et al. Passive seismic response controlled high-rise building with high damping device, Earthquake Engineering & Structural Dynamics 1995, 24(5), pp. 655-671.

42 Yamamoto M, et al. Development of high-capacity oil damper for structural control of tall buildings, Proceedings of the 7th World Conference on Structural Control and Monitoring, 2018.

43 Yamamoto M, et al. Practical applications of active mass dampers with hydraulic actuator, Earthquake Engineering & Structural Dynamics, 2001; 30(11), pp. 1697-1717.

44 Ishizuka K, et al. Design of seismic control using roof garden as mass damper, Summaries of Technical Papers of Annual Meeting AIJ, 2001; Structures-II, pp. 451-454 (in Japanese).

45 Furuki T, Katagihara K, Utsumi Y. Design of high-rise building with joint damper for visco-elastic materials, Summaries of Technical Papers of Annual Meeting AIJ 1998; Structures-II, pp. 857-858 (in Japanese).

46 Nishimura K, et al. Response performance of high-rise reinforced concrete building using coupled vibration control structure (part 1): outline of structural system and plan, Summaries of Technical Papers of Annual Meeting AIJ 2008; Structures-IV, pp. 859-860 (in Japanese).

47 Akita S, et al. Earthquake responses for an existing high-rise building by connecting with its high-rise extension using viscous dampers (part 2): the example applied to the real buildings, Summaries of Technical Papers of Annual Meeting AIJ 2009; Structures-II, pp. 451-452 (in Japanese).

48 AIJ. References and practical applications, Proceedings of Symposium on "Past and future of active structural control of building structure" 2002; pp. 192-193 (in Japanese).

49 AIJ. Intelligible guide to structural control, 2014 (in Japanese).

50 Yamamoto M, Sone T. Damping systems that are effective over a wide range of displacement amplitudes using metallic yielding component and viscoelastic damper in series, Earthquake Engineering & Structural Dynamics, 2014; 43(14), pp. 2097-2114.

How to cite this article: Ikeda Y, Yamamoto M, Furuhashi T, Kurino H. Recent research and development of structural control in Japan. *Jpn Archit Rev*. 2019;2:219–225. https://doi.org/10.1002/2475-8876.12081