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Advanced Structural Technologies For High-Rise Buildings in Japan

Masayoshi Nakai

This paper reviews the development and current status of seismic design for high-rise buildings in earthquake-prone Japan. Additionally, it briefly describes two important areas of wind-resistant design for high-rise buildings in typhoon-prone areas of Japan. Third, through the example of three recently completed high-rise buildings, Japan's advanced structural technologies are explored, focusing mainly on structural frameworks, high-strength materials and response-control damping systems.

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After completing the master course at Graduate School of Engineering, Kyoto University, Nakai joined Takenaka Corporation in 1984 and has been in charge of advanced structures such as large space structures, base isolation and vibration control. Notable works include the Fukuoka Dome, Odate Jukai Dome, Sapporo Dome and Kaohsiung Stadium (Taiwan). In 2004, Nakai received three major Japanese awards for the structural design of an iconic base-isolated building, Prada Aoyama. Nakai leads Takenaka's Advanced Structural Engineering division and is responsible for structural scheme design, expert support for design/construction teams and R&D activities relevant to special structures including supertall buildings. In 2013, he received a PhD in engineering from Kyoto University.

Progression of Seismic Design In Japan's High-Rises

In 1924, one year after the Great Kanto Earthquake that devastated Tokyo, Professor Toshikata Sano (1880–1956) added to the Urban Building Law a new requirement: the static horizontal seismic factor should be set as 0.1 or more. Ten years later, Professor Ryo Tanabashi (1907–1974) published an article in July 1934 stating that the seismic resistance of a structure cannot be adequately assessed simply by providing ample strength against a static horizontal force. Tanabashi contended that the seismic impact should be expressed using the energy squared by the maximum ground velocity, and that the resisting capacity of a structure should be assessed by using the strain energy absorbed by the structure itself.

Tanabashi's confidence in this formulation was underscored when, in March of the same year, he suggested that research should be started on the construction in Japan of high-rise buildings like those seen in New York.

In an article published in April 1963, Tanabashi insisted that high-rise buildings should be possible in Japan in light of the following examples.

Given that seismic motion works on small and large structures with identical amplitudes, a flower vase might fall over in an earthquake, but a large high-rise building would not, Tanabashi argued, even if both objects were proportionally identical. Put another way, contrary to small boats, large ships are resistant to capsizing in rough seas.

Around the same time, Professor Kiyoshi Muto (1903–1989) promoted research on a high-rise building at Tokyo Station. While his effort in this case was not rewarded, the Hotel New Otani (see Figure 1) was completed in Tokyo in 1964 with a building height surpassing 45 meters. In 1968, the Kasumigaseki Building (see Figure 2), designed by Muto, at 156 meters and 36 stories in height, was completed as Japan's first high-rise building to surpass 100 meters. On every story of the building frame, precast concrete walls with many vertical slits were incorporated in order to maintain their initial structural stiffness while absorbing energy during a strong earthquake. Accordingly, it can be said that the concept of passively controlled structures was already being applied at the initial stage of high-rise building in Japan.

Figure 1. Hotel New Otani, Tokyo. © Rs1421. Source: Wikipedia

Introduction of Advanced Seismic Design

Entering the 1970s, most high-rise buildings were constructed using a seismic design method that relied on the plastic rotation capacity of steel-frame beam ends to provide energy absorption. However, several structural designers believed such designs would leave these buildings with residual deformations in frames subjected to large plastic deformation, thereby making post-quake restoration difficult. In response to this, the concept of damage-controlled design began to grow (see Figure 3).

In Japan, following the implementation of the New Seismic Design Codes in June 1981, extensive research has been conducted on seismic-isolation structures.

The Northridge Earthquake of January 1994, Los Angeles, and the Great Hanshin Earthquake of January 1995, Kobe, caused fracture phenomena in many steel-structure beam-ends, resulting in considerable concern about the feasibility of restoring damaged buildings.

In 1995 a seismic-isolation structure was put into practical use that adopted energy-absorption members such as steel and lead dampers, and also employed laminated rubber bearings as elastic supporting members. Since then, another concept has been increasingly applied, whereby the beam-column frames of high-rise buildings bear vertical loads in a manner similar to the laminated rubber bearings in seismic-isolation structures. This design produces mainly elastic behavior during an earthquake, so that the seismic energy is absorbed by the energy-absorbing members incorporated in the framing of each floor. In Japan, many kinds of passive damping devices, such as hysteretic dampers using standard steel or low-yield-strength steel, oil dampers, viscous wall dampers, friction dampers, visco-elastic dampers, and so on, have been developed over four decades. With respect to most recent high-rise buildings in Japan, several types of damping devices are combined and arranged in highly integrated ways within their structural frameworks, in order to optimally control and reduce the building vibration due to seismic or wind load. It can be said that this a uniquely Japanese innovation and represents an advanced approach for the structural design of high-rise buildings.

Enhanced Seismic Resistance

In addition to the seismic designs mentioned above, the seismic safety of high-rise steel structures is steadily being enhanced due to following factors: higher strength and sufficient ductility of steel materials, the provision of upper and lower limits for yield stresses, progress in welding technology, and the adoption of haunches to prevent the plasticization of beam-end welds. Another contributing factor is the utilization of column members with sufficient stiffness and strength, made possible by the use of concrete-filled tubular (CFT) steel columns.

Figure 2. Kasumigaseki Building, Tokyo. © Joe Jones. Source: Wikipedia

In addition, remarkable progress in computer-aided structural analysis technology has made it possible to use a dynamic response analysis that can accurately predict the dynamic behavior of columns, beams, shear walls, and various dampers. This, in turn, has resulted in the construction of high-rise buildings with complex framing.

> “Damping devices are combined and arranged in a highly integrated way within their structural frameworks, in order to optimally control and reduce seismic- and wind-induced building vibration.”

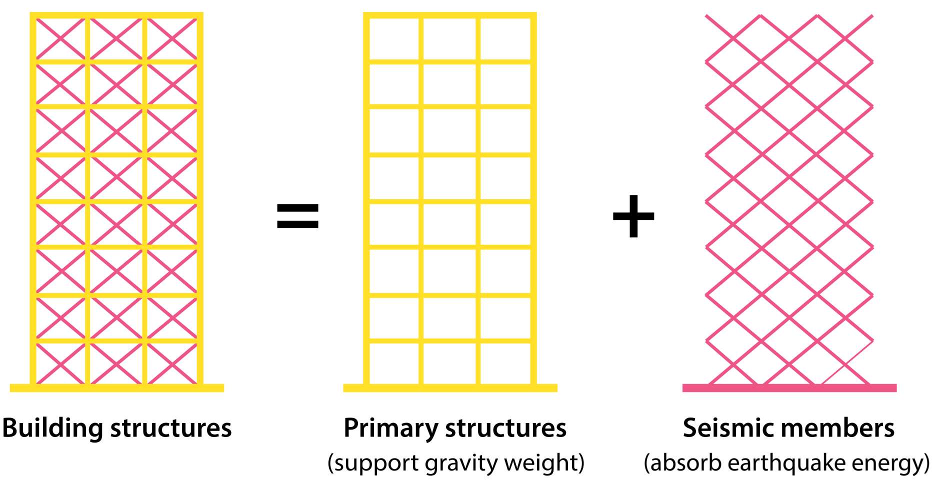


Figure 3. Damage-controlled design.

> “An important task in the building plan was the resolution of how to build safe structural framing with no structural hindrances in the large space provided between the ‘Otemachi Forest’ and the subway concourse below.”

Wind-Resistant Design Of Japan’s High-Rise Buildings

In Japan, very strong seismic excitations such as the Great East Japan Earthquake on March 11, 2011 (Moment magnitude = 9.0, Maximum recorded ground acceleration 2,933 cm/s^2) have to be considered in building design. Japan also has very strong typhoons, such as Typhoon Maemi, which recorded a maximum peak 3-second gust exceeding 90 m/s at Miyakojima Island on September 10 and 11, 2003 (Cao et al.2009).

Figure 4. Toranomon Hills, Tokyo. © Hidenori Karasaki

Extensive Damping Requirements

Completely opposite design criteria apply to buildings for seismic and wind actions, and very high levels of both seismic and wind action have to be considered in Japan. To resist seismic actions, buildings should be designed as lightweight and flexible, but for wind actions, buildings should be massive and rigid. However, in general, the dominant external design load is seismic for the majority of tall buildings (those that are 200 meters high and shorter). Given that seismic loads dominate their design, they are relatively lightweight and flexible, thus making them vulnerable to wind. Consequently, the habitability of buildings subjected to vibrations induced by daily wind is inevitably an important issue in Japan. Since the early 1970s, unique and significant development has been made in Japan, not only for structural performance against external actions, but also for the evaluation of habitability during building vibrations.

Based on these studies, several relevant recommendations and guidelines were issued and have been utilized by designers.

Guidelines for the Evaluation of Habitability During Building Vibration published by the Architectural Institute of Japan (2004) has been commonly used for checking the livability or comfort performance of tall buildings during daily winds. To satisfy target criteria for building habitability, application of damping devices is one of the feasible solutions, and many tall buildings in Japan have been equipped with auxiliary damping devices.

Incidentally, crosswind response due to periodic Karman vortex shedding generally predominates over along-wind or torsional responses for tall or supertall buildings. Therefore, aerodynamic means to prevent the formation of Karman vortices, to reduce their intensity and periodicity, and to minimize the spatial correlation of shed vortices along the vertical axis are useful. Recently, many tall and supertall buildings with unconventional configurations have been constructed around the world. One reason for their curious and complicated configurations is that doing so presents advantageous aerodynamic characteristics, especially for the crosswind component.

Environmental Assessment

One of the most important issues presented by tall buildings is the environmental problem induced by their height, especially the wind conditions at the pedestrian level. A mixture of low-, medium-, and high-rise buildings is a characteristic feature of the landscape of Japanese cities, and the effects of constructing a tall building on environmental conditions in the surrounding area can be very significant. Thus, an environmental assessment of pedestrian-level winds is necessary for tall building construction.

For this, the Environmental Effects Assessment Municipal Bylaw (EEAMB) has been enforced by the Metropolis of Tokyo. The EEAMB requires a wind environmental assessment based on an appropriately conducted wind tunnel study or CFD analysis for buildings higher than 100 meters, with a total floor area of over 100,000 square meters.

The EEAMB also recommends two authorized assessment methods for wind environmental evaluations. More interestingly, full-scale measurements of pedestrian-level winds should be conducted one year before and after construction in order to validate the assessment made in the design stage. In any event, various potential environmental problems, including the pedestrian-level wind environment, should

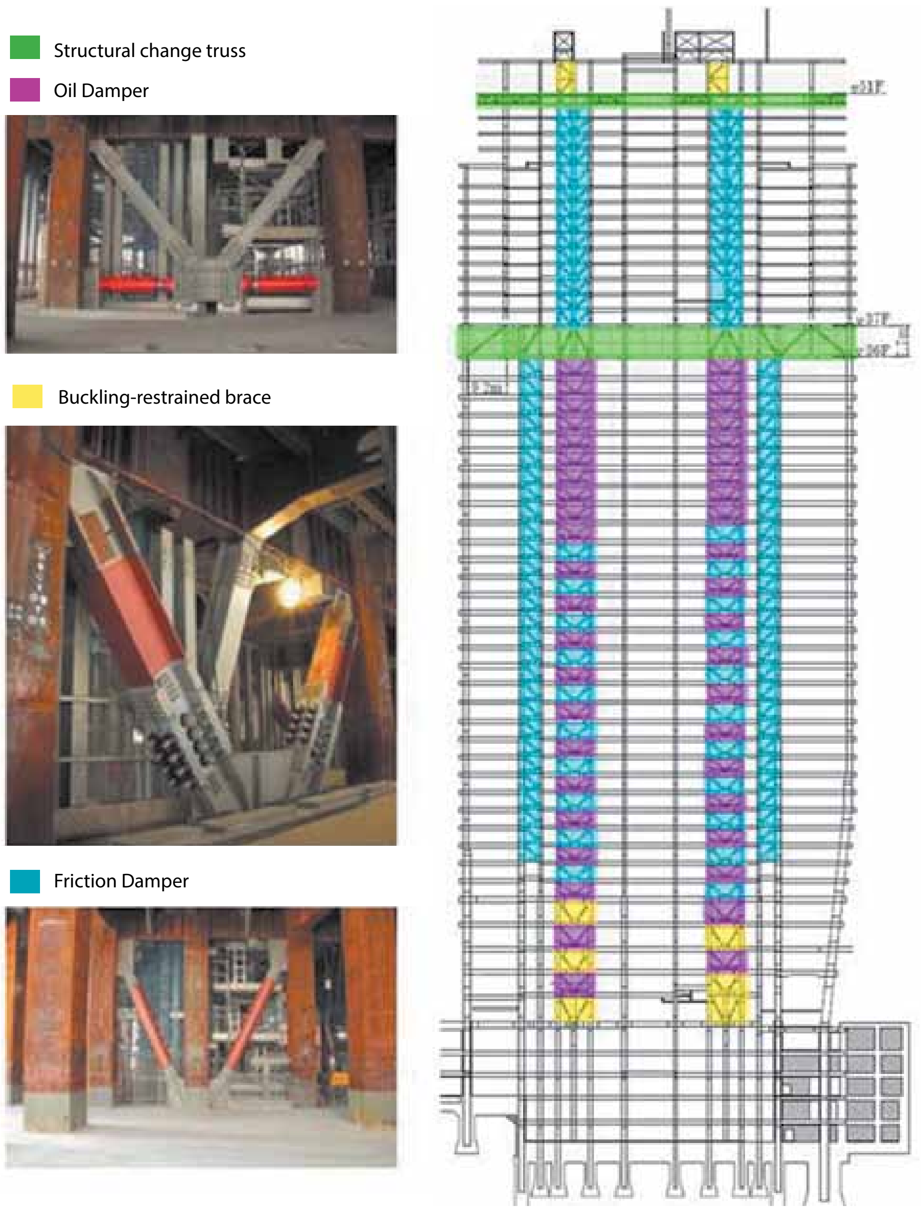


Figure 5. Toranomon Hills response-control devices.

be considered as important issues for tall or supertall building construction in urban areas.

Structural Technologies in Recent Japanese High-Rise Buildings

Toranomon Hills: Building Over a Highway

Toranomon Hills is a large-scale urban redevelopment project in the Toranomon area of Tokyo. A notable feature of this project is that Loop Road No. 2 crosses east to west through the development site and under a 255.5-meter-high building (see Figure 4).

This building was erected on a site of about 17,000 square meters, has 52 floors above ground and five below ground, and has a total floor area of about 244,000 square meters. As a mixed-use building, the parking garage takes up the sub-grade floors, shops and a conference facility occupy floors 1 to 5 of the lower level, and offices fill floors 6 to 35 of the medium-rise section. Beyond this, the 36th floor is exclusively reserved for use as a space truss that supports a different arrangement of columns on the 37th floor and above. In the high-rise section, residential facilities are located from the 37th to the 46th floors, while a hotel occupies the 47th floor and above.

Outline of building structure

The above-ground section of the building is mainly a rigid steel frame structure (using CFT columns) with response-control devices attached (Hitomi et al. 2014).

The underground section is a mixed structure comprising steel framing, steel frame-reinforced concrete, and reinforced concrete. The platform over the Loop Road tunnel consists of one meter-thick precast slabs.

Because the inverted construction method was adopted in order to reduce the construction term, cast-in-place piles were used to form a piled-raft foundation, in which the piles and spread foundations bear loads according to their rigidity.

Response-control structure

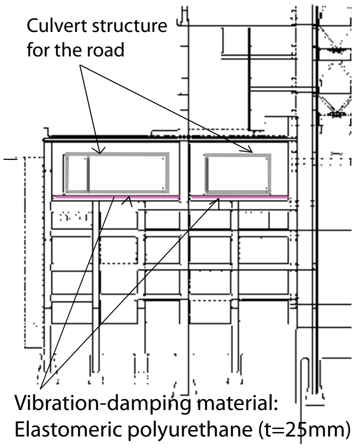
A response-control was selected for the superstructure, 85 meters by 61 meters in plan, and response-control devices were positioned in different sections of the center core.

A mega-structure that carries the 1st to the 51st stories created in order to effectively suppress bending deformation of the entire building. The structural design also called for a combination of inclined roofing and shifted rooftops to form a distinctive roof frame. All of these structures are linked via response-control devices.

A combination of three kinds of response-control devices was used: oil dampers, buckling-restraint braces and friction dampers. A response-control mechanism that takes advantage of this kind of combined use can successfully secure high seismic resistance by reducing the inter-story drift ratio during an earthquake to two-thirds that of common high-rise buildings (see Figure 5).

Connections for the tilted-column section

The tilted-column system was adopted for the northwest, southeast, and southwest corners



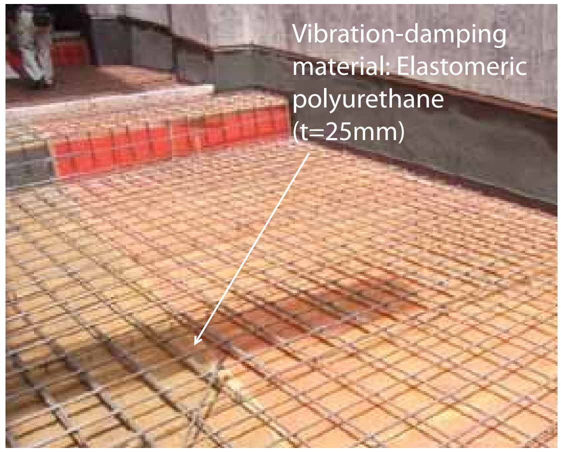


Figure 6. Toranomon Hills vibration-damping material (elastomeric polyurethane) between the culvert bottom slab's lower section and the building structure

of the building, because columns could not be positioned above the area covering Loop Road No. 2, and the corners of the building had to be finished with sharply acute angles for aesthetic purposes. From the 8th to the 13th floors, two tilted columns on each upper floor intersect and combine to form a single column on the floor below. Cast steel connections, each weighing about 20 tons, were adopted where the columns intersect, so that the stress carried by the two upper columns could be securely transferred to the single column below.

Countermeasures against road vibration

Loop Road No. 2 connects on the east side of the building at the second-basement level, through an underground tunnel that begins outside the development site, and then resurfaces on the west side of the site. The road runs through a culvert structure that was built independently of the building structure. To prevent road traffic vibration from affecting the building, the building structure is insulated from the culvert structure by sandwiching vibration-damping material (elastomeric polyurethane) between the culvert bottom slab's lower section and the building structure (see Figure 6).

Otemachi Tower: Using Ultra-High-Strength CFT Columns

Two requirements have increasingly emerged in recent high-rise building construction projects: longer spans to enhance freedom in the space design of standard floors, and wide atriums that promote structural continuity between the lower floors and the surrounding external space. In order to realize these two requisites, it is generally necessary for the structural members used in framing to bear large forces and, as a result, to grow in volume. However, the appropriate combination of high-strength members can prevent excessive increases in member volume.

> “The brake dampers are structured like automotive disc brakes. The vibration energy of the building is converted to friction heat due to the dampers' sliding under certain loads so that the response and damage to the building are mitigated.”

As a structural technology to cope with this task, ultra-high-strength, concrete-filled tubular (CFT) columns, manufactured by combining high-strength (150 N/mm^2) concrete and high-strength (tensile strength: 780 N/mm^2) steel products were developed. These ultra-high-strength CFT columns were used to construct the low-rise floors of the Otemachi Tower.

Building and structural outlines

This high-rise building has 38 stories above ground (including a three-story penthouse), stands 199.7 meters tall and has six basement floors extending to a depth of 35.1 meters (see Figure 7). The total floor space is about 198,000 square meters. The main building contains offices, a hotel, and shops.

The underground floors are built of reinforced concrete, and the above-ground floors form a steel structure that uses CFT columns for the 1st through 32nd floors. The above-ground floors form a moment-resisting frame structure with response-control braces arranged at the core of the building. Oil dampers are used as viscous dampers, while buckling-restraint braces employ low-yield-point steel (LY225) for the axial members, and are used as hysteresis dampers. They are appropriately arranged so that seismic energy can be effectively absorbed (Matsumoto et al. 2012 & 2014).

Megatruss frames are adopted for the 4th and 32nd floors. These are transfer floors, in which the structural positions of the columns change in order to realize a framing system that allows different floor spans on the upper and lower floors. In order to secure adequate habitability during strong winds, a response-control device (active mass damper) is installed on the rooftop (see Figure 8).

Supporting a "forest" with CFT columns

A unique feature of the Otemachi Tower is the creation of the "Otemachi Forest" (see Figure 7), a verdant 3,600 square-meter area of soil and greenery provided on the ground floor of the building site. In this regard, an important task in the building plan was the resolution of how to build safe structural framing with no structural hindrances in the large space provided between the "Otemachi Forest" and the subway concourse below.

The ultra-high-strength CFT columns applied in the low-rise section of the building give the columns world-class strength.

Adoption of these ultra-high-strength CFT columns in the low-rise section satisfies the subway-bridging task in the building plan. In addition, these columns meet the requirements for seismic safety. The elevated strength of these CFT columns eliminates the need to increase the volume of the column members, which in turn leads not only to a reduction in the use of structural materials, but also to the mitigation of associated environmental burdens.

Figure 9 shows the relation between the strain and stress applied to the steel and concrete. The critical strain is nearly identical for both the 780 N/mm^2 steel and the Fc 150 N/mm^2 concrete, which indicates the great advantage obtained by combining the use of high-strength concrete with high-strength steel. In addition to the extremely high vertical supporting capacity that these ultra-high-strength CFT columns possess, they also exhibit a high yield ratio and low elongation under tensile stress, thereby offering sufficient allowance to keep the building frame within its elastic range.

Figure 7. Otemachi Tower, Tokyo. © Taisei Corporation

ARK Hills Sengokuyama Mori Tower : Using Advanced Precast Concrete Technologies

The ARK Hills Sengokuyama Mori Tower represents one element in the large-scale Toranomon-Roppongi District Urban Development Project in Tokyo. This development project covers about 2.0 hectares and was completed in August 2012 (see Figure 10). Surrounding the redevelopment area are many embassies and hotels that anchor the area's role as an important international and cultural center in Tokyo.

The 47-story complex sits on relatively high ground and consists of commercial and residential sections (Floors 1–24) and an office section (Floors 25–47). A separate seven-story residential building (with a

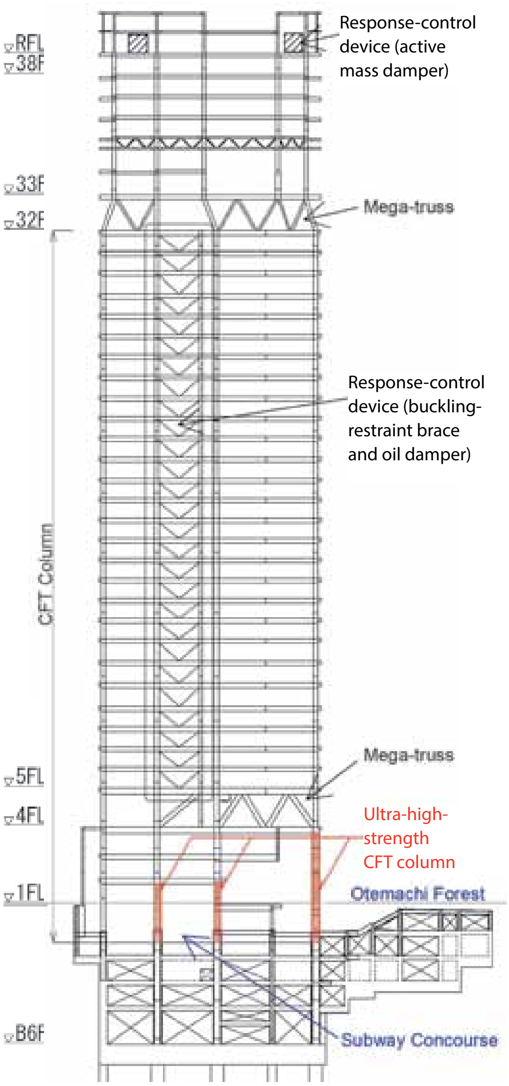


Figure 8. Otemachi Tower structural framing.

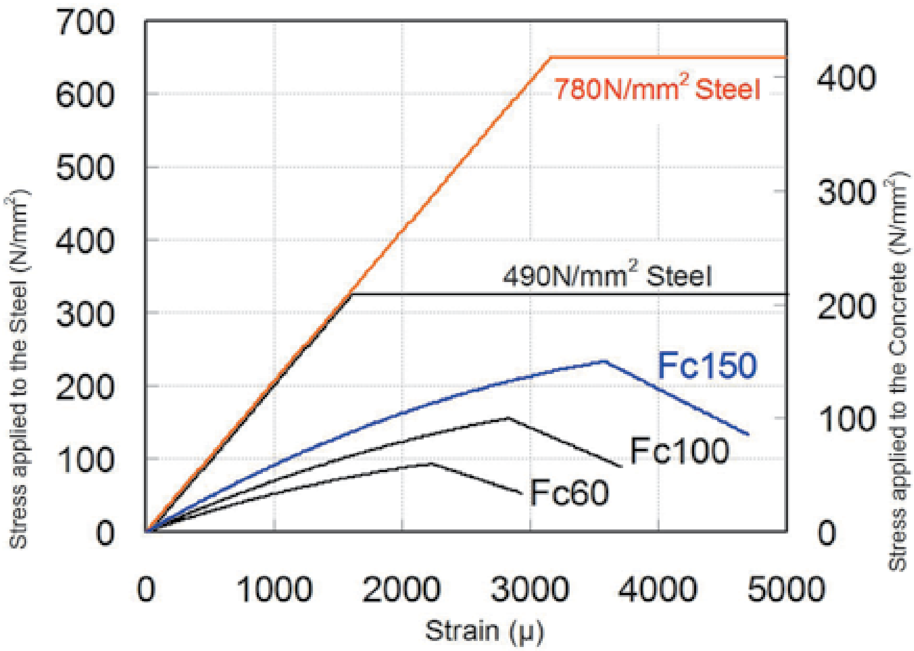


Figure 9. Relation between stress and strain of materials (steel and concrete).

Figure 10. Ark Hills Sengokuyama Mori Tower, Tokyo. © Mori Building

seismically isolated structure) is planned for erection on the south side of the complex.

Outline of structural type and design

Rigid reinforced concrete framing was adopted for the building structure. The standard floor plan was 50.4 meters x 50 .4 meters (7.2 meters x 7 spans). For the high-rise office floors, steel girder framing with a length of 2–3 spans was adopted to realize wide, column-free spaces. In the center core section, viscous-response-control walls (see Figures 11 and 12) and hysteresis-response-control walls (brake dampers) were installed (Otaka et al. 2012).

The main structural materials were high-strength concrete (Fc120 N/mm^2 max.) and high-strength steel reinforcing bars (σy: 685, 785 N/mm^2). Support is provided by spread foundations, consisting of 4.5-meter-thick mat slabs, and was installed on a supporting layer of sandy soil with a long-period soil bearing strength of 1,000 kN /m^2 or more.

The brake dampers are structured like automotive disc brakes. The vibration energy of the building is converted to friction heat, due to the dampers' sliding under certain loads so that the response and damage to the building are mitigated. The brake damper system can be used repeatedly, without maintenance.

Precast methods

- *LRV Method*
  In the LRV (left-right-vertical installation precast) method, partially connected precast beam members are adopted. The precast members are of two types. The first type is a beam connection with integrated precast members (LR beams) in which the primary mode of column reinforcement is pass-through penetration holes made using sheath pipes. The second type uses precast columns (V columns), in which mortar-filled mechanical joints (sleeve joints) are built into the column heads, from which column-reinforcing bars protrude from the bottom and pass through the penetration holes in the beams. Mortar is used to fill in the joints between precast members, the main reinforcement penetration holes, and the LR beam-V column joints so that the respective members are integrated into the framing structure (see Figures 13 and 14).

- *LRV-H Method*
  In the LRV-H (left-right-vertical-horizontal installation precast) method, two types of members are adopted: precast column members (H columns) that integrate columns and joints into a single structure and have a full length that is similar to the floor height, and precast beam members (H beams) that use the inner web depth as a member. In the column members, the penetration holes for primary reinforcement run horizontally. A sleeve joint is installed near the end of the intersecting beams, and the primary reinforcing bars extend to the end of the precast beam on the opposite side of the sandwiched column. The beam reinforcing bars pass through the beam reinforcement penetration holes provided in the column and are then inserted into the sleeve at the beam end on the other side (see Figure 13). ■

Figure 11. Structural framing plan of standard office floor.

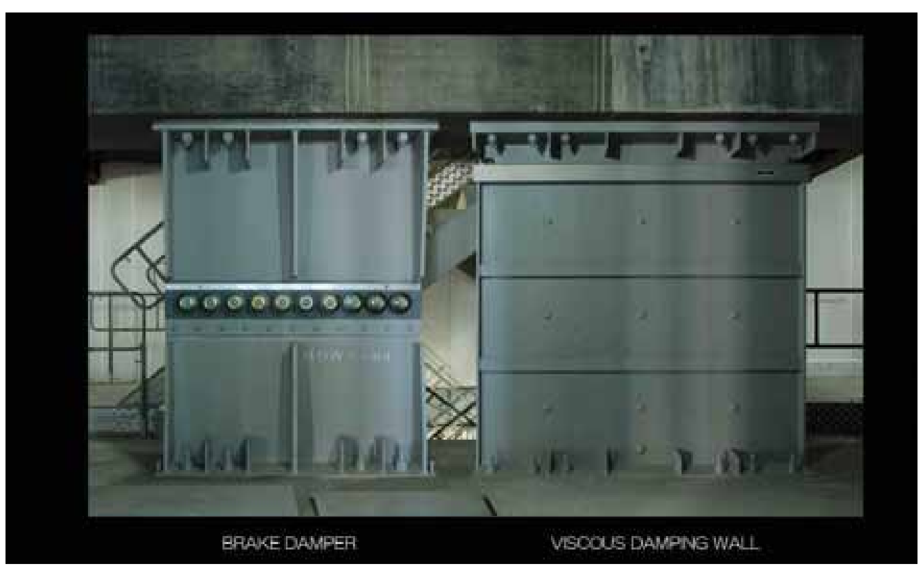


Figure 12. Response-control walls (viscous damper and hysteresis brake damper).

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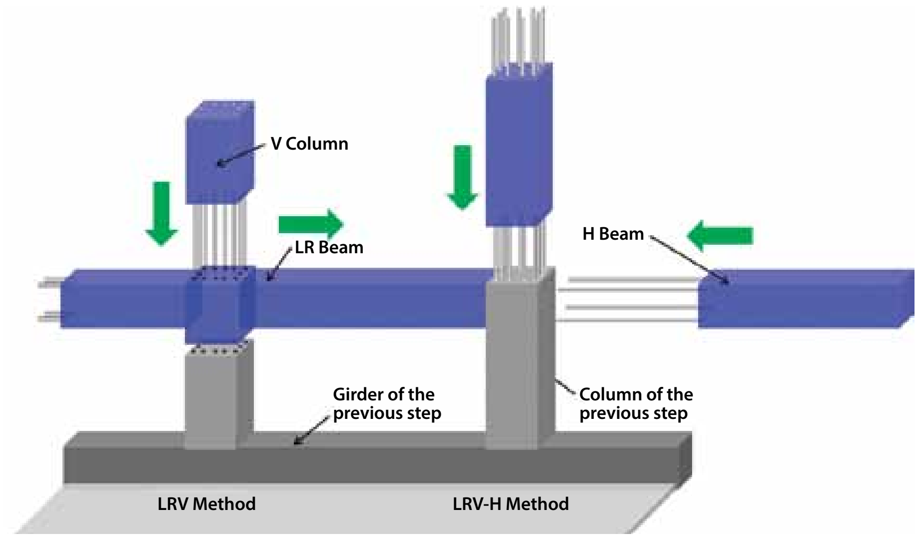

Figure 13. Overview of LRV Method and LRV-H Method.

Figure 14. V column and LR beam used for LRV Method. © Obayashi Corporation