Title: **Application of Seismic Isolation Systems In Japanese High-Rise Buildings**

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Application of Seismic Isolation Systems In Japanese High-Rise Buildings


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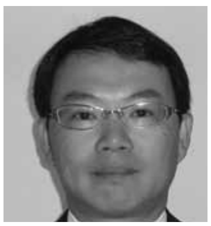
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Kentaro Nakagawa has directed a variety of structural engineering projects for office buildings in Japan, including Fuji Xerox R&D Square and Shimizu Corporation's Tokyo Headquarters. Both buildings adopted seismic isolation systems, and he received JSSI (Japan Society of Seismic Isolation) awards in 2011 and 2014 for his work on these projects.

Dai Shimazaki has engaged in several significant projects in Japan, the UK, and the UAE, and became a group leader of the structural engineering department for office buildings in 2014. He received a JSSI Award in 2014 for his work on the Shimizu Corporation Tokyo Headquarters.

Satoshi Yoshida is the chief structural engineer of the Nakanoshima Festival Tower project. He joined Nikken Sekkei Ltd. in 2007 and continues to work there as a structural engineer. He received a JSCA (Japan Structural Consultants Association) Award in 2014 for his work on the Nakanoshima Festival Tower.

Ken Okada received a Dr. Eng. degree in 2003 in the seismic performance of steel structures. He joined Nikken Sekkei Ltd. in 2005. For the Nakanoshima Festival Tower project, he worked as a structural engineer and as a construction administrator.

In this paper, state-of-the-art technologies and design methods for seismic isolation systems are introduced in detail, through two practical examples of newly-built high-rise buildings. In both cases, seismic isolation systems contribute to minimize the seismic responses of high-rise superstructures and, as a result, enable the exploration of new structural systems that can mitigate structural damage from earthquakes.

Impetus Behind Seismic Isolation Technology Development

Over the decades, structural engineering and technologies on buildings have advanced drastically in Japan, as the nation experienced more earthquakes. The Great Hanshin Earthquake that struck the Kansai Region in 1995 is considered the seminal earthquake that changed Japan's overconfidence about earthquake resilience and increased public interest in structural safety. In order to meet the needs, for both mitigating damage due to earthquakes and sustain living standards in densely settled cities, high-rise structures and seismic isolation systems were to be considered the most appropriate and favorable technologies.


Figure 1. Sendai MT Building, Sendai. © Neuropower. Source: Wikimedia Commons

The number of high-rise buildings with seismic isolation systems has been increasing in Japan since the debut of the Sendai MT Building in 1999 (see Figure 1), which is 85 meters tall (18 floors) and was the first newly-built high-rise building with this system. The main reason for this trend is supported by recent developments in structural engineering and seismic-mitigation technologies, which enable us to widen the capacities of isolation devices and produce high-strength steel and concrete. The merits of connecting high-rise superstructures and isolation devices in series are remarkable, and will lead to more robust and redundant structural systems.

Recent High-rise Buildings With Seismic Isolation Systems

Nakanoshima Festival Tower, Osaka

The original Festival Hall in Osaka was constructed in 1958. The hall boasted 2,700 seats and was characterized by excellent acoustics, referred to as "sound from the heavens." However, in December 2008, it was torn down on its 50^{th} anniversary, to be rebuilt as a new hall.

Nakanoshima Festival Tower (see Figure 2) is a 200-meter-high skyscraper complex comprising offices and the rebuilt Festival Hall. The building is comprised of three major sections (see Figure 3). The lower-level floors include the performance hall. The intermediate-level floors directly above the hall and the upper-level floors are used for offices.

Structural features

The most important proposition from a structural planning aspect was how to achieve the construction of high-rise offices above the large hall while maintaining high structural performance. The following structural strategies were employed:

- Giant trusses to transfer the load of the upper-level floors to the perimeter of the hall and secure the large open space of the hall.
- Mid-story seismic isolation systems on the boundary between the hall and the office floors.

Megatruss/belt truss/prime columns

Between the intermediate-level and upper-level floors, two major types of trusses – megatruss and belt truss – are installed (see Figure 4). Through the giant trusses, the entire weight of the upper-level floors was transferred to the 16 columns, which project practitioners referred to as "prime columns," standing outside of the hall.

The megatruss is a gigantic three-dimensional truss structure with a height of approximately 20 meters, extending from the floor of the Level 13 to the floor of the Level 15. It supports a total load of approximately 38,000 metric tons, borne by the nine concrete-filled tube (CFT) columns of the core of the upper-level floors That load flows down to the prime columns.

On the other hand, the belt truss is a planar truss installed as a strip around the perimeter of the 14th floor, and performs the work of consolidating the axial forces of the 128 columns standing around the perimeter of the upper-level floors into the prime columns.

Figure 2. Nakanoshima Festival Tower, Osaka. © Nikken Sekkei

As a result, the prime columns become the columns that support the entire load of the 13th floor and above, and by causing all of the load for the upper-level floors to concentrate via the megatruss and the belt truss into the prime columns, the large hall space of the lower-level floors was realized.

The megatruss diagonals are box braces with a parallelogram cross section (see Figure 5). The unique shape of the diagonals was designed to place the upper and lower surfaces of adjacent diagonals in the same plane, and, in addition, allow the vertical surfaces on both sides to complete within the skin plates of the box columns. The trapezoid and parallelogram shapes of the prime columns were also decided through consideration of the continuity of the plate materials of the diagonals and lower chords. By employing this cross-section shape, simplification of the joint section and

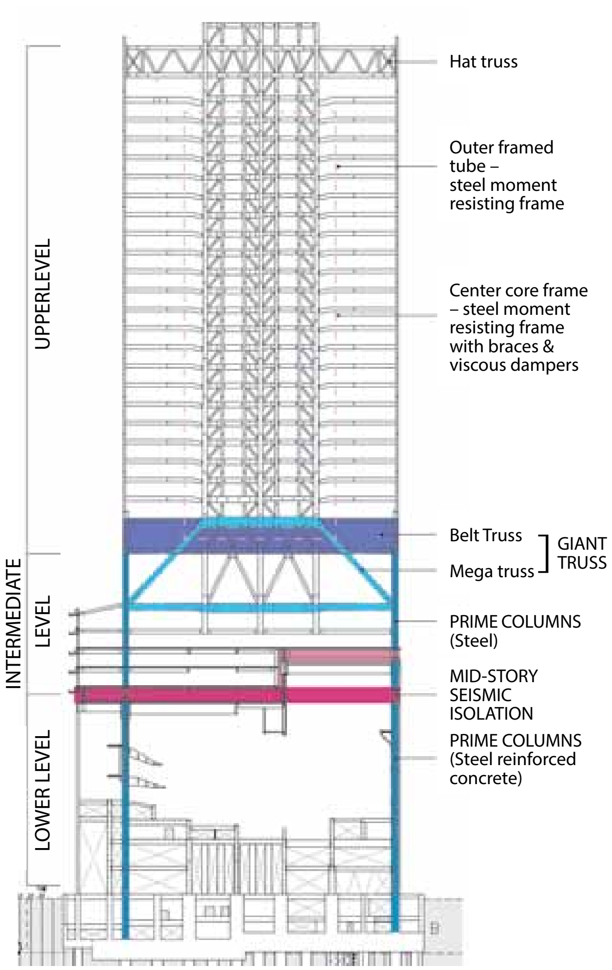

Figure 3. Cross section of building framework.

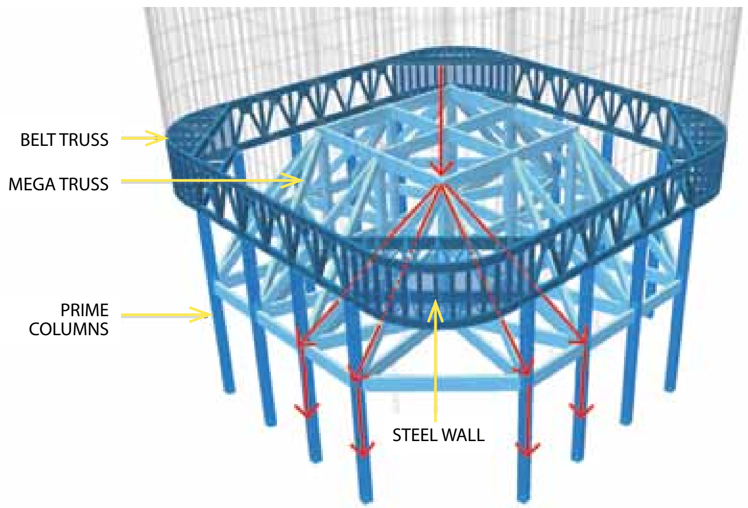

Figure 4. Megatruss/belt truss/prime columns.

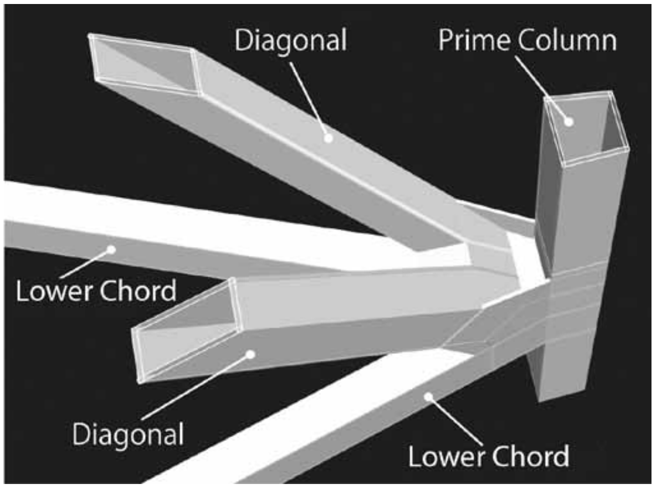

Figure 5. Megatruss diagonals connection.

Figure 6. Lead Rubber Bearings (LRBs) prior to installation.

smooth transmittance of stresses was achieved.

Mid-story seismic isolation

The other characteristic feature of this building, the mid-story seismic isolation layer, is installed between the lower-level floors and the intermediate-level floors. Lead Rubber Bearings (LRBs) – rubber bearings with lead plugs – are employed as the isolation devices. Oil dampers are employed as energy-absorbing elements. A set of two extra-large 1.5 by1.5-meter LRBs (see Figure 6) are used directly under the prime columns in order to support the prime column axial forces of as much as 6,000 metric tons. Sixteen sets of the large square LRBs are installed to support the prime columns, which bear 95% of the building weight above.

> “Reinforced concrete core walls of the superstructure support up to 80% of the entire shear force. Thus, the size of exterior precast concrete frames can be minimized, providing flexible spaces for office layouts.”

Figure 7 shows examples of results from a dynamic response investigation. Since the lower-level floors are reinforced concrete construction with a rather rigid structure, seismic force is largely amplified at the top of the hall. The mid-story seismic isolation layer reduces the acceleration into the intermediate-level floors to around 25%. The maximum story drift of the upper-level floors is more than 30% smaller than that of typical high-rise office buildings. Even during very strong earthquakes, which Japanese code considers "extremely rare," the stress that occurs in the structural members of this building does not exceed the short-term allowable stress of the materials.

Due to the mechanical properties of rubber bearings, tension forces in a rubber bearing (a result of overturning moment) and vertical seismic force must be suppressed in the design of a seismic isolation system. Since the building weight is concentrated into the large square LRBs, which are laid out along the perimeter line of the upper-level floors, the uplift force caused by overturning moment is theoretically minimized. The large square LRBs are always under compression

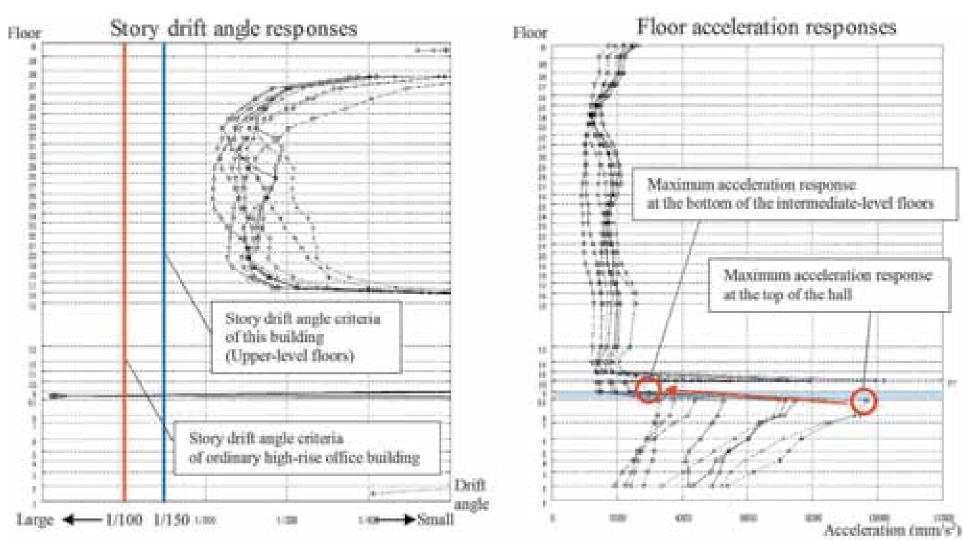

Figure 7. Example of results of dynamic response analyses.

stress, even considering the coupling effect of overturning caused by horizontal earthquake forces and uplift effects caused by vertical earthquake forces.

Shimizu Corporation Tokyo Headquarters

Shimizu Corporation, which is one of the major general contractors in Japan, completed its new headquarters in 2012 (see Figure 8). It incorporates various advanced technologies, which include precast concrete perimeter frames incorporated with solar panels and a radiant air-conditioning system. This building is designed to achieve a 70% reduction of CO_2 emissions by the end of 2015, and ultimately to establish zero-carbon status, by combining the built systems with carbon credits. In order to assure business continuity in the event of large earthquakes, a seismic isolation system is introduced.

Structural features

This building is the first high-rise office tower over 100 meters tall to deploy a reinforced concrete (RC) structure and seismic isolation system combination. The primary reasons for selecting this structural system were: the desire to build a structure that has an outstanding seismic performances, which plays an pivotal role in providing a disaster-relief facility; and the desire to create columnless office space that maximizes flexibility of office layouts.

The standard floor has a regular-plane surface with a size of 34 by 63 meters. RC core walls are located around the center core zone. The exterior precast concrete (PC) panels are acting as both structural components and cladding. RC core walls and exterior PC panels make it possible to achieve an outstanding gravity and lateral load-resisting system (see Figure 9).

Seismic isolation system

Forty-two seismic isolators are located between the second basement floor and the first basement floor (see Figure 10). The system consists of 32 LRBs, 10 NRBs (Natural Rubber Bearings), and 10 oil dampers. The restricted maximum acceleration of office-floor response under large

Figure 8. Shimizu Corporation Tokyo Headquarters.

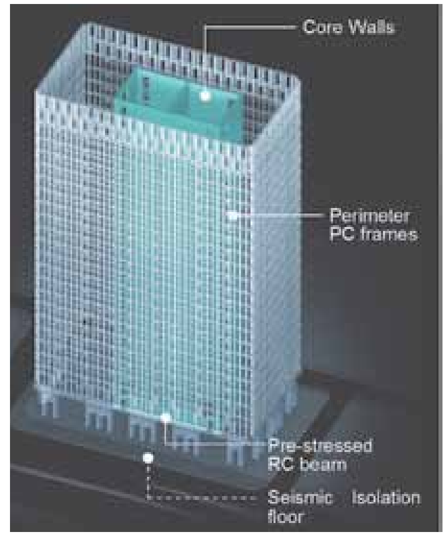

Figure 9. Schematic diagram of the structural system.

Figure 10. LRBs below core wall.

“The megatruss is a gigantic three-dimensional truss structure with a height of approximately 20 meters, extending from the floor of the 13th floor to the floor of the 15th floor. It supports a total load of approximately 38,000 metric tons, borne by the nine concrete-filled tube (CFT) columns of the core of the upper-level floors. That load flows down to the prime columns.”

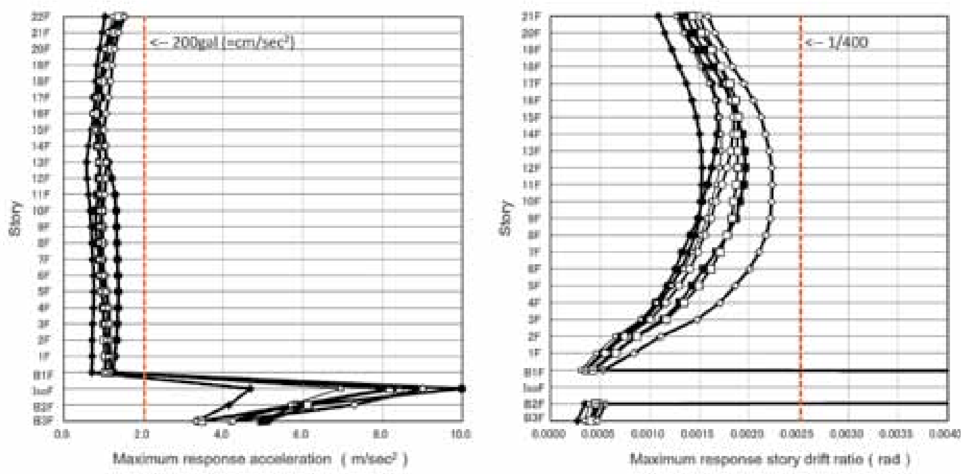

Figure 11. Example of dynamic response analyses.

earthquakes is expected to reduce maximum ground acceleration by 15–20% in every floor, including the roof level of the building at 100 meters above the ground (see Figure11).

In this building, a high-rise superstructure consisting of RC core walls and exterior PC frames is incorporated with seismic-isolation systems. As seismic-isolation devices have their own characteristics for dissipating seismic energy and act as damping components, seismic inputs to the superstructure are drastically reduced. RC core walls of the superstructure support up to 80% of the entire shear force, and, as a result, the size of exterior PC frames can be minimized and provide flexible spaces for office layouts. This building is designed to be able to perform without severe damage to structural components in the event of Level 2 earthquakes, which are categorized as "extremely rare earthquakes" in the seismic guidelines of Japan. In combination with seismic-isolation systems, this building system can serve as a robust and redundant structure during earthquakes.

Precast-concrete perimeter frames
The exterior PC panels are made of high-strength concrete with design standard strength $Fc=80N/mm^2$, to minimize the sizes of structural members (see Figure 12). Panels must be protected from cracking, which includes thermal cracks caused by hydration heat, cracks due to autogenous shrinkage during production processes, and other cracks resulting from drying shrinkage or ambient temperature changes after erection. Therefore, limestone, which has minor shrinkage strains, is used as the concrete aggregate. Additionally, Advanced Fire-Resistant (AFR) high-strength concrete containing polypropylene (PP) fibers is used to prevent panels from exploding in the event of fire. ■

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Figure 12. Installation of perimeter precast frames.

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