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Self Mass Damper (SMD): Seismic Control System Inspired by the Pendulum Movement of an Antique Clock

Ryota Kidokoro[1]

[1] *Ove Arup and Partners Japan Ltd*
Email: ryota.kidokoro@arup.com

ABSTRACT :

Completed in May 2007, the Swatch Group's new flagship building in Tokyo, the Nicolas G. Hayek Center, is filled with an array of innovative elements ranging from elevating showrooms to multi-storey retractable glass exterior walls to moving floors for reducing the seismic forces induced into the building. Utilizing a combination of base isolation technology and a mass damper scheme, the Self Mass Damper (SMD) system is the result of a seismic control concept inspired by the pendulum movement of an antique clock.

Typically, a mass damper type seismic control systems are integrated into the building by augmenting a significant amount of mass on top of a structure – characteristically detrimental to the overall seismic performance of the building. However by utilizing the existing mass, the actual floor plates in this case, as a mass damper to counteract the seismic response of the building, the unfavorable addition of mass was avoided. The SMD system was implemented by disconnecting four of the upper floors (9F, 10F, 12F, 13F) from the main structure through a combination of slider and high-damping rubber bearings placed at the interface. Each combination of bearings was tuned to provide the maximum damping to the overall structure while maintaining an acceptable lateral relative deformation limit in all directions. To bring about this system from concept to reality, rigorous structural analyses and full scale device testing was conducted to validate that the SMD system would reduce seismic forces in the structure by up to 37% under a large scale earthquake loading.

KEYWORDS:	mass damper, passive control systems, Japan, high-damping rubber bearings

1. INTRODUCTION

Autumn of 2004, an international competition was held by Swatch Group Japan for their mixed retail and office tower in downtown Ginza, Tokyo. Subsequently, architect Shigeru Ban's unorthodox design of creating a public atrium space at the ground level with individual glass lifts that provides direct access to the boutiques placed throughout the vertical retail space proved to be victorious. Supporting the architect from a structural engineering front, as part of the competition submission Arup proposed a seismic response damping system inspired by the pendulum movement of an antique clock. This paper will focus on the development of this idea – eventually evolving to the realization of the Self-Mass Damper (SMD).

2. OVERVIEW OF STRUCTURE

The key structural features of this building include: 1) creation of multiple atriums throughout the building 2) implementation of an innovative seismic passive control system, the Self Mass Damper (SMD) system 3) the sculptural undulating roof at the top level. The structural system is the outcome of an endeavor to resolve the unique spatial layout while satisfying Swatch Group's demand for a highly seismic resistant structure (See Figure 1). To summarize the overview of the structure from bottom to top:

- Due to the stiff soil layer located 14m below grade in the Ginza district, the building utilizes a raft foundation system.
- The existing basement structure was hollowed out and the basement walls utilized for temporary shoring.
- Numerous openings were required at the ground level to accommodate 9 elevators, 2 stairwells, and a car lift to access the parking spaces – leaving very little floor plate area left to transfer the lateral forces into the surrounding basement walls. To resolve this force transmission, the ground level slabs were reinforced with steel plates of 6mm to 12mm thick.

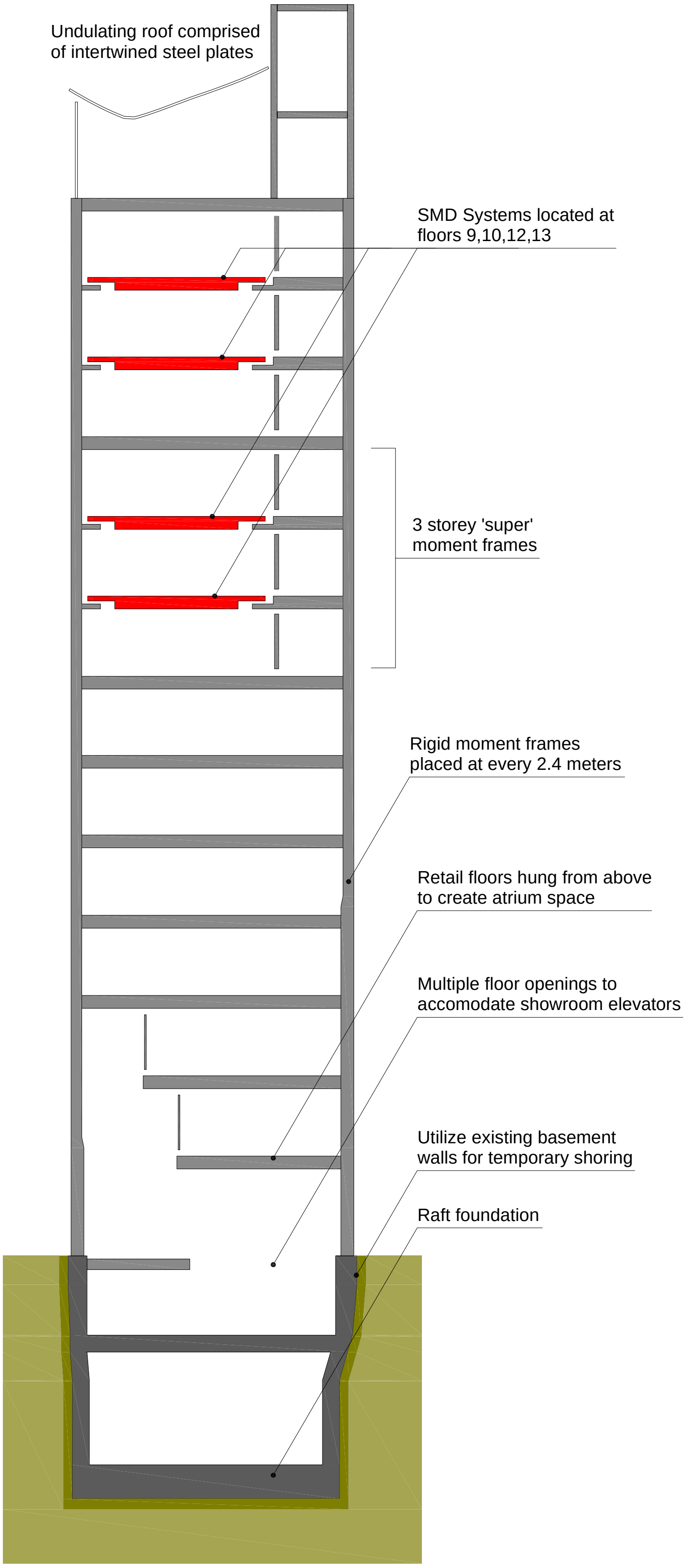

Figure 1: Structure Diagram

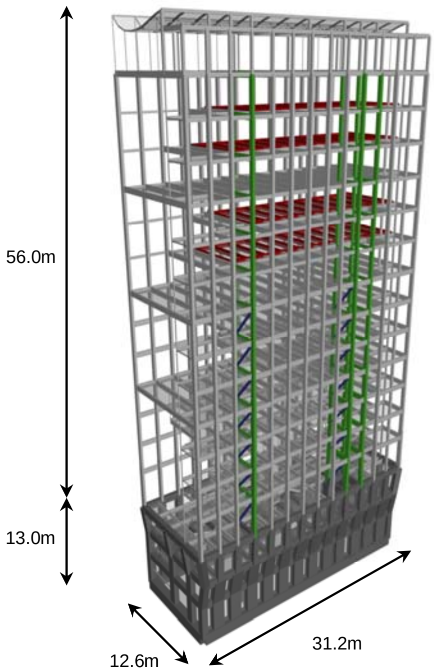

Figure 2: 3D Structure Frame

- From the ground level, a 3 storey retail atrium extends through the longitudinal direction of the building – effectively carving away the much needed moment frames at the base of the structure. To reinforce the lateral stability of these bottom few levels, three sets of core framing (colored green) were introduced into the system. (See Figure 2)
- The general superstructure system is comprised of a rigid steel moment frame placed at every 2.4 meters along the longitudinal direction.
- To counter the seismic response of the building, SMD systems were located at floors 9, 10, 12 and 13 (colored red). Details of this system will be expanded upon in the following sections.
- In contrast to the box shape of the building, architect Shigeru Ban envisaged a light, free form roof floating above the structure. The geometry of this roof was determined by a series of form-finding techniques available in GSA – software developed by the R&D division of Arup. In accordance with the architect's image of a woven object, the structural scheme comprised of a pair of stacked steel plates extending in three directions. (Figure 4)


Figure 3: Retail Atrium at Ground Floor


Figure 4: Undulating Roof Structure

3. SELF-MASS DAMPER (SMD) SYSTEM

3.1. Background

According to Japan Structural Consultants Association's (JSCA) performance based design practices in Japan, the structural design grades for seismic resistance are grouped into three categories as shown in Table 1. Whilst code minimum requirements stipulate 'Standard Grade', through numerous discussions during the schematic design stage, it became apparent that Swatch Group wished to target an onerous 'Special Grade' structure with additional requirements of, 1) main structural elements to remain elastic under Level 2 (500 yr return period) seismic event, 2) and 'life safety' under Level 3 (1000 yr return period) seismic event. In order to achieve such targets with economical feasibility, it was determined that implementation of a damping system to reduce the seismic response would be essential. Subsequently, the design team commenced a thorough exploration of damping systems that would best fit the structure without imposing upon the architectural intent.

Table 1: JSCA Seismic Performance Grades

	Rare Seismic Event (Level 1 Seismic Force)	Extremely Rare Seismic Event (Level 2 Seismic Force)
Special Grade	Building to be fully operational No damage Repair not required	Main functions to be operational Very minor damage Very minor repairs required
High Grade	Building to be fully operational No damage Repair not required	Specific functions to be operational Minor damage Minor repairs required
Standard Grade	Building to be fully operational No damage Repair not required	No loss of life Limited functions to be operational Intermediate to major damage Intermediate to major repairs required

At the onset of design, a pendulum type mass damper system was proposed – whilst an interesting concept, it necessitated much convincing that such a system would be appropriate and effective for this building. Armed with a plethora of damping devices available in Japan, the design team began investigating the effectiveness and pros/cons of various systems. To achieve a ‘Special Grade’ structure with additional stringent design targets, it is common practice that a base isolated scheme would be the system of choice. However, as the plot of land in the Ginza district being one of the costly in the world, allocating a +1.0m wide strip of clearance around the perimeter of the building to absorb the base isolation movement was deemed inappropriate. Installing hysteretic or viscous damping devices within the allowable three core frames were studied but resulted in mediocre effectiveness due to the bending deformation shape of the slender core frames. Although dependent upon the mobilized mass amount and tuning of the system, preliminary studies indicated that a mass damper type system had potential to be extremely effective for this slender building.

3.2. Evolution of the Mass Damper Scheme

The key point in utilizing a mass damper system to deal large seismic forces, unlike the types used to control low energy wind responses, is that a tremendous amount of mass must be mobilized in order to be effective. Characteristically, the mass damper begins exhibiting practical effectiveness at around 5% mobilization of the building mass. As the mobilized mass is further increased, the system can be more appropriately categorized as a mid-level isolation system, and finally when mobilized mass is 100% of the building mass it becomes a base isolated structure. Typically, mass dampers are integrated into the building by augmenting unutilized mass into the structure, but as one can imagine, if say 10% of the total building mass is added atop the structure for seismic control purposes it would prove to be detrimental in terms of global impact onto the building. Sheds light on why mass dampers are not utilized to control seismic responses. However, to overcome this obstacle the design team was contemplating on ways of mobilizing existing, necessary mass to use as a mass damper.

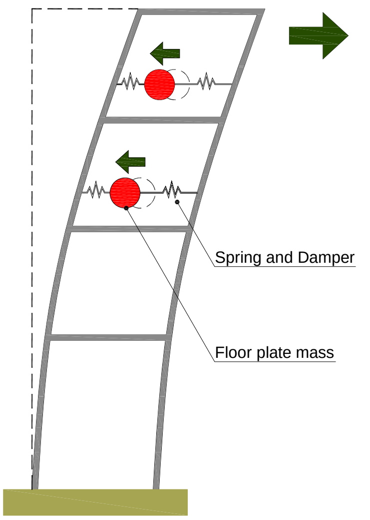

Figure 5: SMD Concept Diagram

Eyeing the upper sky garden blocks and the resulting 3 level ‘super-frame’ impression, the first attempt was to hang two of the floors and release them from the building to recreate a swinging pendulum utilizing the floor plate’s self mass. However, due various issues such as the hanger elements intruding into the office space and vertical displacements of the floors due to the rocking movement of the pendulum, alternatives were explored.

As a result, instead of being hung, it was decided that the floor plates were to be supported vertically by corbels extending from the main structure within the beam depth. These floor plates are effectively isolated laterally with special spring and damper devices connecting the floors to the main structure (See Figure 5). Although no longer a pendulum, this system utilizes its own self weight of the structure to form a mass damper with significant mass. The next step was to find a suitable device that exhibits the required characteristics to realize this system.

3.3. Development of Devices

The devices that link the mass damper floor plates to the main structure were envisaged as follows:

1. To consistently support vertical loads of the floor plates
2. Bi-linear property that prevents lateral movement during small earthquakes and typhoons but deactivates restraints under a large seismic event
3. Damping effects due to the hysteretic behavior of the bi-linear material
4. Sufficient stiffness that would restrain total lateral movement to under 300 mm
5. Restoring force to restore original position after movement
6. A small device to fit within the available 150mm height between the corbels

At first base isolator bearing products were researched but the available configurations were too large and too stiff for the intended system. Bearing devices used in isolating houses were intriguing but difficult to implement and too soft. Realizing that a suitable product did not exist in the market, we contacted one of the leading isolator bearing manufacturers (Toyo Rubber) for their expertise.

High-damping rubbers used in typical base isolator bearings exhibit bi-linear behavior – initially very stiff but subsequently softer beyond a certain applied shear force. In addition, this bi-linear stiffness can be adjusted accordingly by varying the height and area of the high-damping rubber material. Typically, in order to prevent crushing of the rubber material under the weight of a building, multiple steel plates are sandwiched between the layers of rubber, which also makes the bearing extremely stiff laterally. Following several discussions, a solution of creating a device that only includes the layers of high-damping rubber and sized according to the required bi-linear property was reached. A newly developed device using familiar material (see Figure 6). Since these rubber dampers are unable to resist vertical loads due to the exclusion of steel plates, a decision was made to support the vertical loads of the floors by a separate device all together – by slider bearings (see Figure 7). The combination of high-damping rubbers and slider bearings were placed accordingly in plan to balance the required vertical supports and lateral stiffness (see Figure 8). Thus the final scheme for this mass damper system was envisioned and the design moved forward.

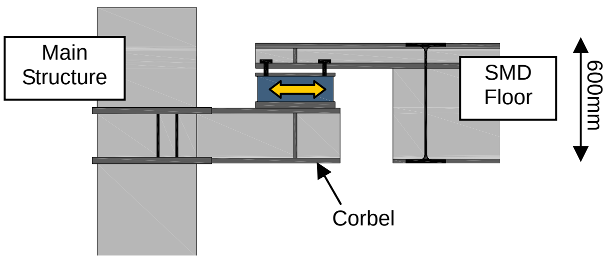

Figure 6: Section View of Rubber Bearings

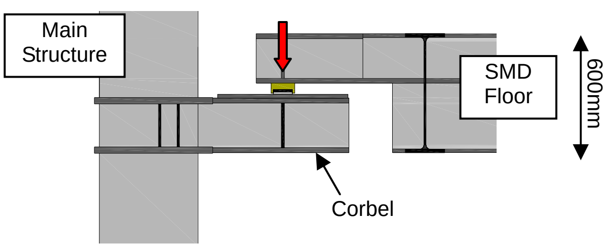

Figure 7: Section View of Slider Bearings

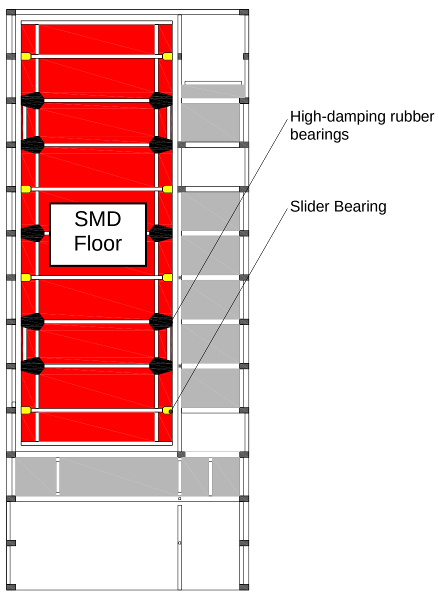

Figure 8: Plan View of SMD Floor

3.4. The Self-Mass Damper System

The floor plates on levels 9, 10, 12, and 13 are isolated from the main structure and utilized as a mass damper to reduce the seismic response of the building during a large earthquake. This new seismic control system was aptly named *Self Mass Damper* to highlight the use of existing mass instead of the typical mass augmentation seen in TMD systems. Key characteristics of this SMD system include the following.

1. Each SMD floor plate is approximately 100 tons, with a combined mass of the 4 floors equivalent to 10% of the superstructure mass.
2. A combination of slider bearings and high damping rubber bearings are place at the interface of the SMD floor and main structure. These devices rest upon a set of corbels extending from the main structure, and fit within the beam depth of 600 mm. (Figure 9)
3. Each combination of bearings for each level is tuned to provide maximum damping to the overall structure while maintaining an acceptable level of lateral deformation. The SMD floor is allowed to move in all directions, thus also effective in all directions. Note the SMD system is not tuned to the building frequency.
4. Slider bearings support the vertical loads without restraining the horizontal movement of the floors. Friction coefficient of the sliding surface is 0.013. Allowable tilt angle is 1 degree to absorb the construction tolerances and actual leaning of the corbel supports (and main structure) during an earthquake.
5. Materials used in the rubber damper bearings is the same high-damping rubbers used in typical base isolator devices – key difference being steel plates are not sandwiched between each layer of rubber. The rubber dampers were specially developed for this project by Toyo Tire & Rubber Co., Ltd.
6. Each rubber damper unit was tested to confirm characteristics, followed by a full scale push-release test on site. Measurement devices were installed into the building to verify movement following a seismic event. (Figure 10)


Figure 9: Corbel from Column (on its side)


Figure 10: Rubber Damper Testing

4. ANALYSES AND RESULTS

Non-linear three dimensional time history analyses were conducted to simulate the SMD system and building's behavior during large seismic events. Although, a stick model analysis approach is commonly used in Japan to simulate building and damping behavior, unprecedented nature of this system necessitated the analyses to be conducted using a full three dimensional model.

A suite of 7 seismic time history inputs, each with varying characteristics were utilized to assess and validate the performance of the structure and damping system. This suite constitutes of, a) three measured signals scaled up to meet the required PGV (peak ground velocity), El Centro NS, Taft EW, Hachinohe NS, b) three artificial 'Kokuji' signals that incorporates the soil behavior of the site, Hachinohe, Kobe, random, and c) one site specific wave, Kanto.

The rubber dampers were modeled as bi-linear elements with zero vertical stiffness. Slider bearings were modeled to reflect the friction coefficient of the material. Numerous parametric studies were performed to properly assess the sensitivity of the SMD system. The parameters include: a) variations of material properties to take into account differences due to temperature, workmanship, etc., b) mass of floors, c) uneven live loading of SMD floors, d) varying the building dynamic properties.

Although the effectiveness of the SMD system fluctuates depending upon the seismic time history input, it was established that seismic response of the structure decreased in all cases. The SMD system is most effective against earthquakes that resonate with the building's dynamic properties, resulting in a maximum base shear reduction of 37% (Kokuji Hachinohe signal). On the other hand, the system is least effective under a seismic event with a strong sudden pulse, in this case El Centro NS. As such, the seismic design load was governed by the Level 2 (500yr) El Centro signal (PGV of 50 cm/sec). Figure 11 illustrates the SMD System's on-off (activated, deactivated) behavior upon the building.

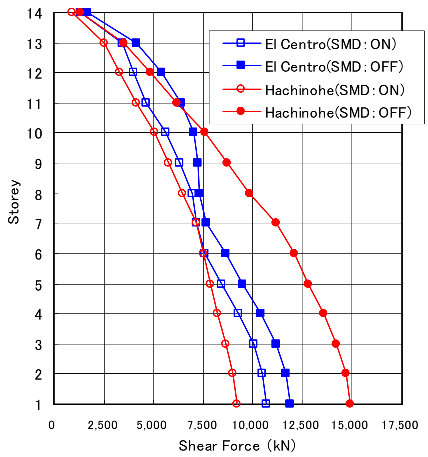

Figure 11: SMD 'On-Off' Behavior

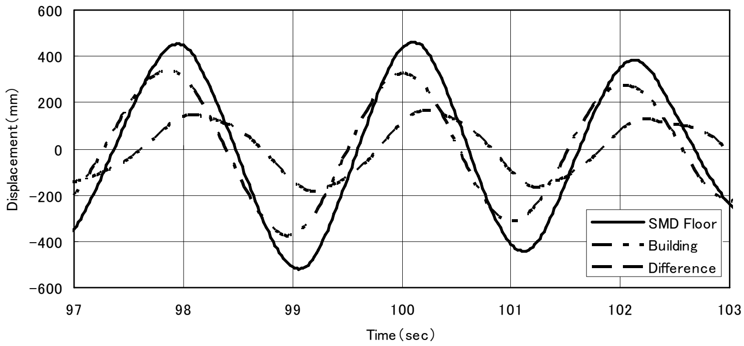

Figure 12: Horizontal Displacement Time History Plot

The maximum displacement of the SMD floor relative to the main structure is 147mm in the short direction of the building, and 215mm in the long direction. Thus the allowable clearances were set respectively as 200mm in the short and 265mm in the long direction. Figure 12 illustrates the time history plots of the horizontal displacements of the SMD, building, and their relative movements – note the phase difference. Although the maximum instantaneous difference in acceleration between the SMD floors and building is approximately +200 cm/sec^2, the peak acceleration of the SMD floor is a mere +14% – demonstrating the stable behavior of the SMD system. In addition, due the difference in dynamic properties of the SMD system compared with the building, the system will not resonate nor respond uncontrollably during any earthquake.

5. CONCLUSION

The daring architectural concept combined with the Swatch Group Japan's wish for a structure with high seismic resistance resulted in the implementation of a newly developed mass damper type passive control system, the Self-Mass Damper. Evolved from a pendulum damping scheme inspired by the movement of an antique clock, the SMD system was found to successfully reduce the seismic design load by over 30%. Leading to a robust yet efficient structure and increasing the potential life span of the building.

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