

Design of the Grand Roof at Tokyo Station

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Abstract

This paper describes the design method of long and unique shape membrane structure in capital Tokyo. The membrane structure, designed to create an impression of Japan's traditional Washi paper, forms gentle curves of varying size and inclination, to become the new face of the Yaesu side of the Tokyo Station. To achieve such a light membrane structure in Japan where many natural disasters such as earthquakes and typhoons occur frequently, we adopted some ideas in order to solve technical problems.

Keywords : Membrane structure, wind resistant design, seismic design

1. Building overview

This paper describes redevelopment work on the Yaesu side of the Tokyo Station. The project involves the construction of high-rise twin towers measuring approx. 200 meters tall on the southern and northern ends of a narrow strip of land, with a plaza outside the train station lying in the middle.

The Grand Roof is a roof stretching approx. 240 meters in the north-south direction to bridge the two high-rise buildings. The membrane structure forms gentle curves of varying size and inclination.

Underneath the Grand Roof lies a corridor linking the Tokyo Station and the Yaesu Exit Plaza area, featuring a meeting place for station users, fluid space and various facilities including those associated with the train station. South Tower and North Tower will be linked with a pedestrian deck, built approx. 7.5 meters above ground, to create a smooth network of traffic within the development area. The first basement floor mainly features commercial facilities to offer an underground network of pedestrian walkways linked to the underground shopping mall at the Tokyo Station. The second basement floor and levels below provide parking areas. (Fig. 1,2)

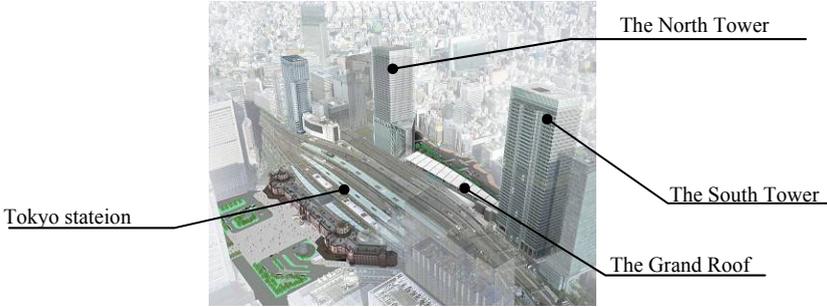


Figure 1: Perspective view of the Tokyo station



The South Tower The Grand Roof The North Tower

Figure 2: Perspective views of the Grand Roof

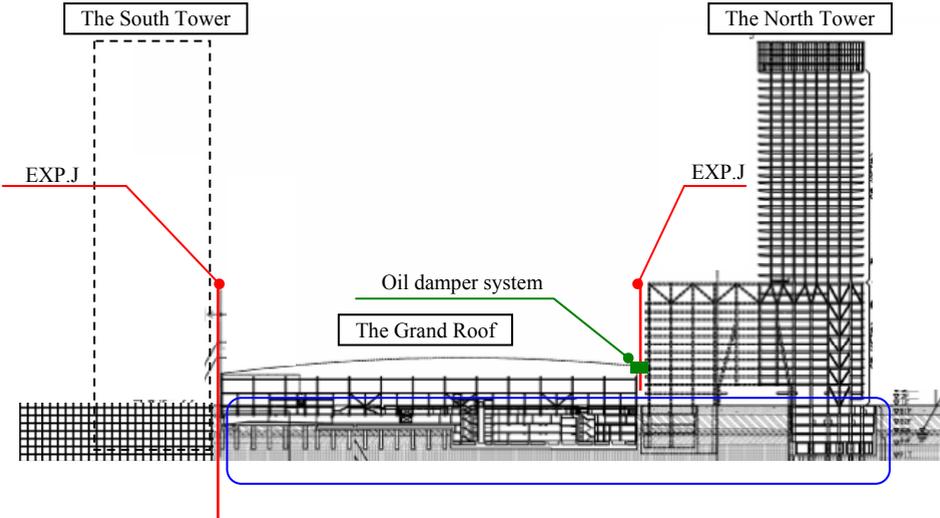


Figure 3: Conceptual diagram for the structural plan

2. Structural plan

2.1. Overall structural plan of this project

This section describes the overall structural plan of this project.

The above-ground section of the high-rise twin towers and the Grand Roof will use expansion joints to make them structurally independent. The Grand Roof will be partially linked to North Tower with an oil damper system to reduce movements in the lengthwise (north-south) direction at the time of an earthquake or strong gusts.

As for the underground section, North Tower and the Grand Roof are integrated, while South Tower is a standalone structure, with all of them designed for structural stiffness and strength. (Fig. 3)

2.2. Frame design of the Grand Roof's above-ground

This section describes the frame design of the Grand Roof's above-ground section.

The above-ground section consists of the pedestrian deck stretching approx. 240 meters in the north-south direction at approx 7.5 meters above ground, and a membrane roof structure that extends above the deck.

The pedestrian deck is supported with steel-braced rigid frames with the buckling-restrained braces. (Fig. 4,5)

The Grand Roof consists of cantilever columns erected on the pedestrian deck level, thin tilted pillars on the station plaza side, and main girders joining them together.

There are a total of 14 frames at the pitch of 18 meters.

The following are sectional shapes of main above-ground components:

Columns: Steel (Sectional shape: Welded oval cross-section, circular sectional shape)

Girders and beams: Steel (Sectional shape: Welded H-shaped sectional shape, welded semicircular oval sectional shape)

Slabs: Reinforced concrete, PC concrete (with top concrete) (Fig. 5)

2.3. Roof structure of the Grand Roof

This section describes the roof structure of the Grand Roof.

The membrane roof is made of a PTFE-coated fiberglass fabric, supported by main girders at 18-meter intervals and edge cables. The short-side component of the membrane's tension (initial tension of 200 kN/m) balances with the tensile force of the edge cables extending in the north-south direction (initial tensile force of 250kN), whereas the long-side component balances with the compressive force of the trusses on the southern and northern ends and the three continuous beams that run through the middle of the main girders. This means the roof structure forms a self-balanced system by itself.

The out of plane deformation of the membrane is contained through binding battens, placed along the lines that divides each membrane's 18-meter span into three equal sections, to

cantilever beams from the main girder and three continuous beams at the center. Figure 6 shows the self-balanced system, while Figure 7 shows details of the roof structure.

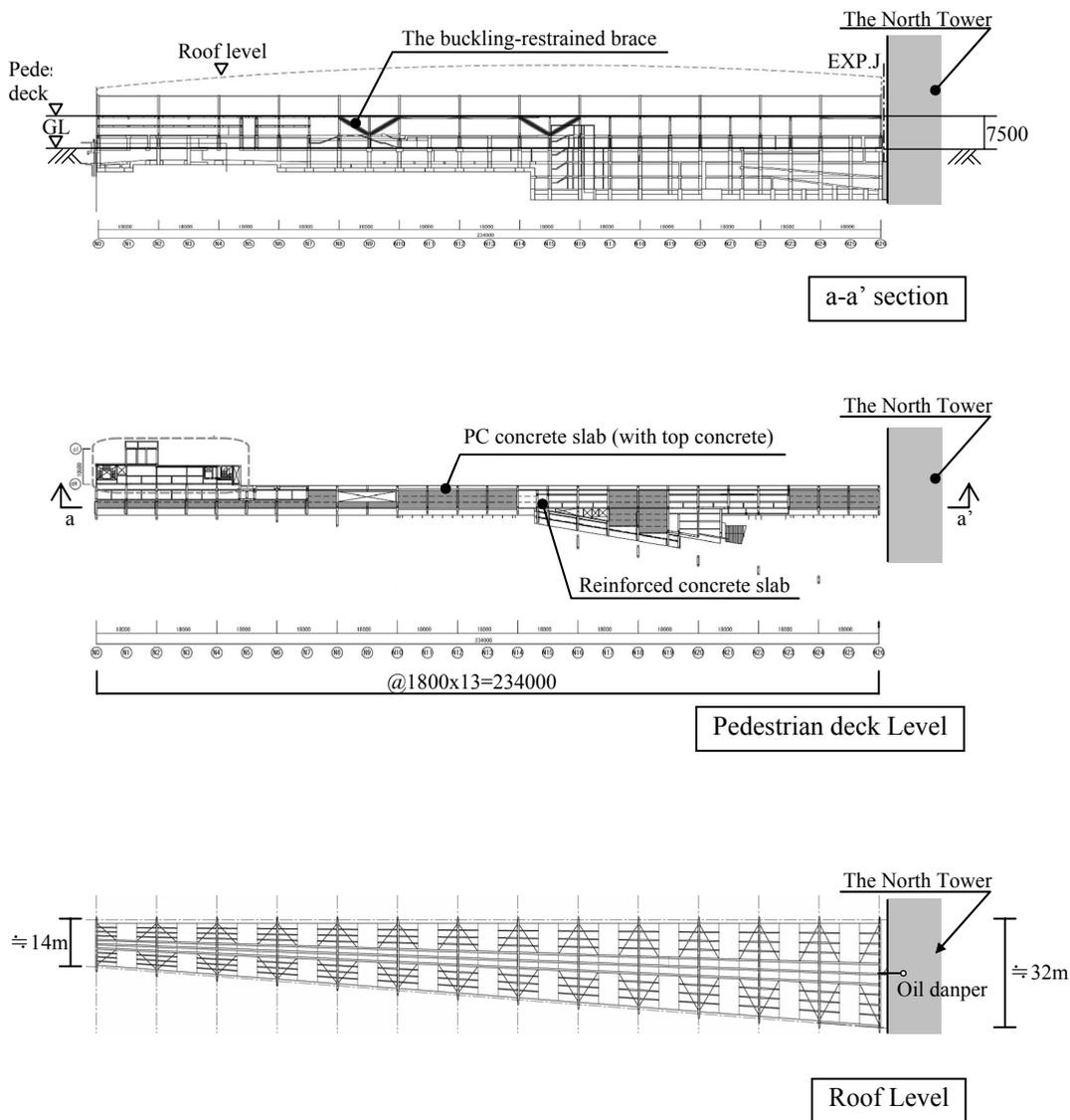


Figure 4: Frame design of the Grand Roof's above-ground(1)

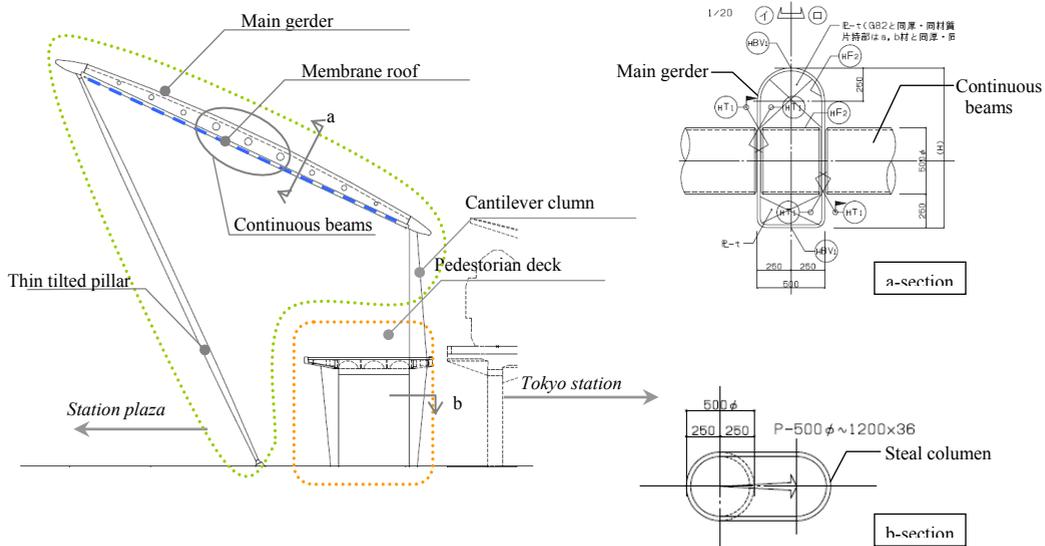


Figure 5: Frame design of the Grand Roof's above-ground(2)

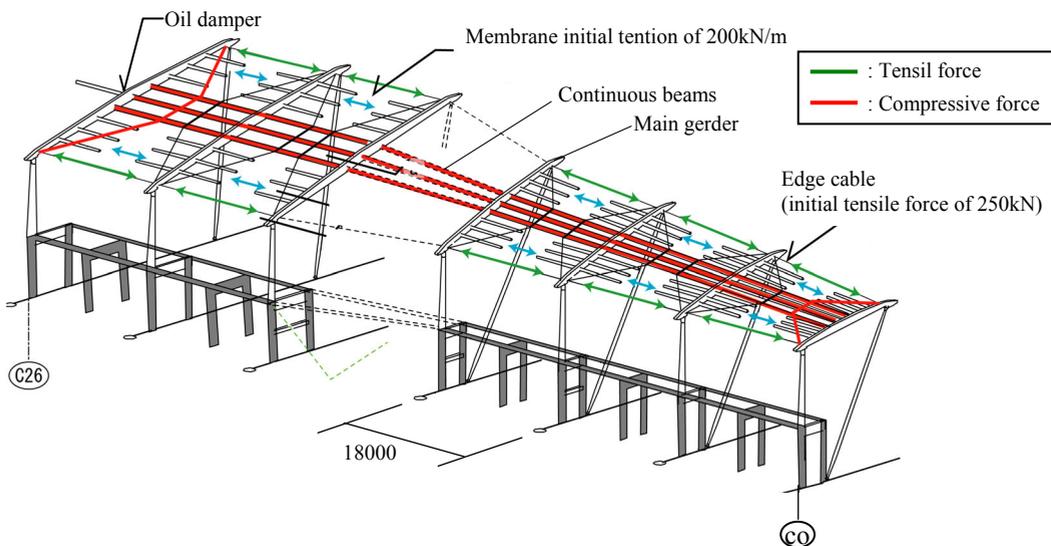


Figure 6: The self-balanced system of the roof structure

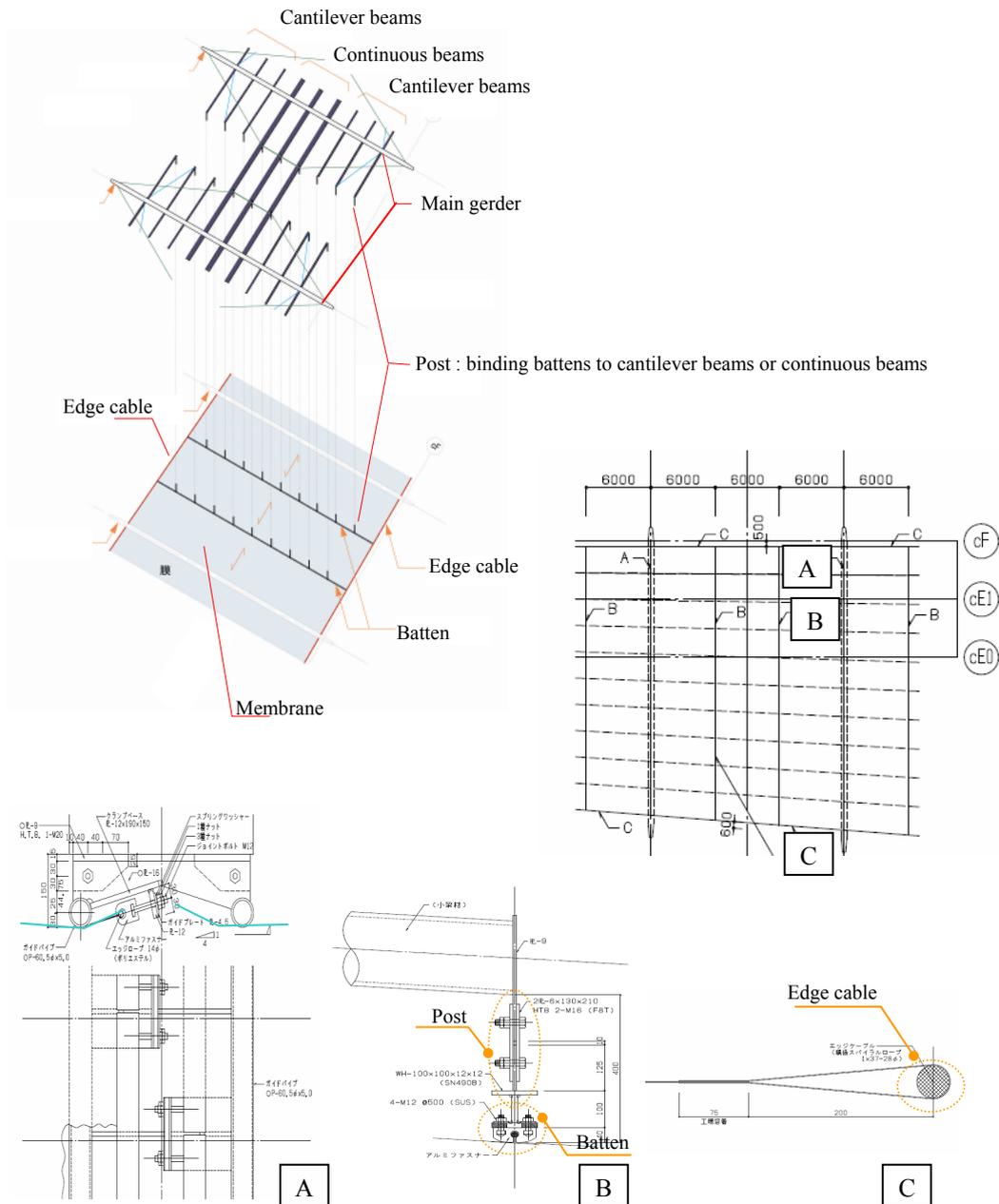


Figure 7 : Details of the roof structure

3. Wind resistant design

3.1. Wind tunnel test

Wind tunnel tests have been conducted to evaluate the wind load. The model used in the wind tunnel tests was built to the scale 1:400 to reproduce the Grand Roof and surrounding buildings and covering an 800-meter radius area. Main measurement points on the membrane surface include two in the bottom row, two in the middle row and two in the top row of each span, all on the front and back surfaces. Measurement was taken for a total of 72 wind directions (5 degree intervals). (Fig 8)

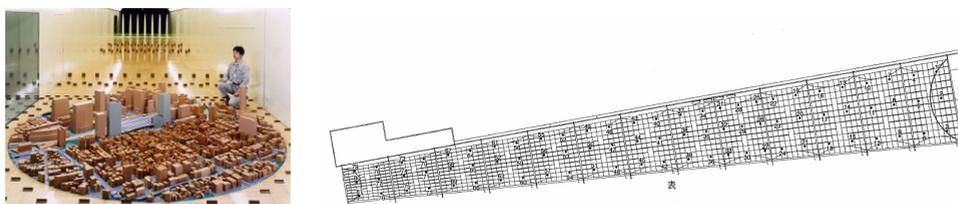


Figure 8: Wind tunnel test model and Measurement point

3.2. Design wind load and criteria

The design wind load is evaluated in the unit of frames to examine each membrane span's safety. This wind load is based on the wind-force coefficient, obtained by adding together time-series wind pressure data at measurement points included in each frame's control region. Level 1 wind load is equivalent to the value associated with return period of 100 years, while Level 2 wind load is equivalent to the value associated with return period of 500 years.

These wind load figures and corresponding criteria are as shown in Table 1.

Table 1: Wind load figures and corresponding criteria

Load	Criteria
At Level 1 wind load downward : 997 N/m ² upward : 1676 N/m ²	Within the short-term allowable intensity of stress for all materials. Membrane deformation is within 1/15 of the span ($\varrho=18000$). Membrane's contact not allowed.
At Level 2 wind load downward : 1363 N/m ² upward : 2291 N/m ²	Stress generated in the membrane is within the ultimate allowable intensity of stress. Within the short-term allowable intensity of stress for all the other materials

In addition, to examine membrane safety to the effect of localized wind load or ultimate margin on the membrane, wind load obtained from the highest and lowest peak wind force coefficients at each of the measurement points is evaluated.

3.3. Analysis model

Each single-unit span of the roof is modeled for analysis, featuring a membrane surface, cables, continuous beams, and the cantilever beam. The boundary condition at the main girder's position is rigid joint.

The analysis on the membrane roof structure was conducted in the finite element approach, and handled as geometric non-linear analysis.

The membrane and cable materials were non-rigid materials with no resistance to compression or bending stress, and regarded as orthotropic materials, to which the Hooke's Law applies.

Figure 9 shows the membrane of analysis model.

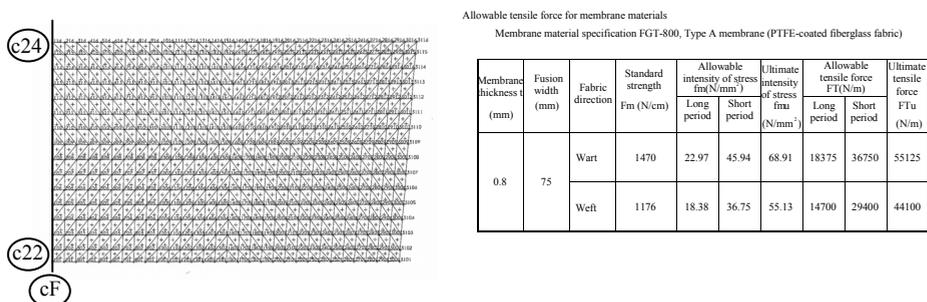


Figure 9: The membrane of the analysis model (c22 – c24)

3.4. Examination results

The analysis for c22 - c24 produced findings described below.

It was confirmed that the membrane's tensile strengths all conformed to the criteria.

Figure 10 shows the membrane surface's deformation, while Table 2 shows the surface's maximum displacement. The maximum displacement was approx. 45 centimeters at Level 1 wind load, and approx. 50 centimeters at Level 2 wind load.

Figure 10 shows the deformation of the membrane and frames by upward Level 1 wind load, and confirms that there was no contact at any of the examined cross sections.

Table 2 : Membrane surface's deformation

	At Level 1 wind load		At Level 2 wind load	
	Downward	Upward	Downward	Upward
Displacement(mm)	X : 2	X : 39	X : 2	X : 46
	Y : 117	Y : -164	Y : 137	Y : -191
	Z : -306	Z : 424	Z : -349	Z : 476
	Vec. : 325	Vec. : 456	Vec. : 375	Vec. : 514
Criteria and Judgment	1/15 600mm OK	1/15 600mm OK	—	—

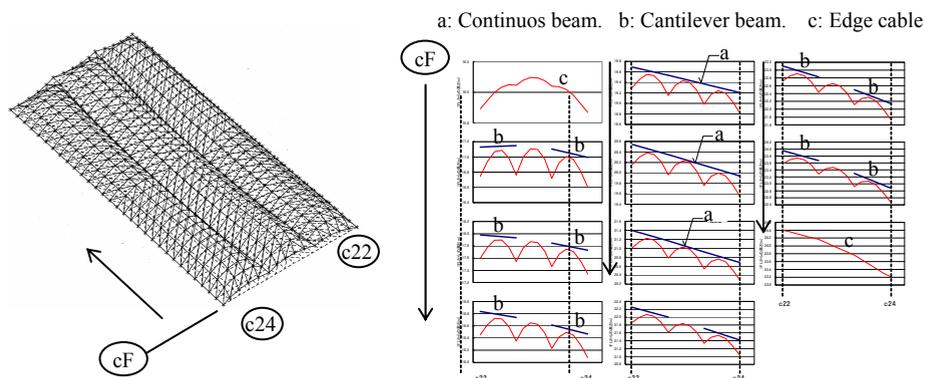


Figure 10: Deformation diagrams of membrane and frames for wind load level 1

4. Seismic design

4.1. Seismic design

This section describes the seismic design for the Grand Roof.

Design policy for the seismic design is that each member was designed to have enough strength against assumed seismic force on its supporting area, considering the independent movement of each part at the earthquake due to its long stretching shape.

- Longitudinal direction (north-south)
 Providing structural resistance to seismic force with braced rigid frames stretching in the north-south, and consisting of welded oval cross-section columns, steel tube columns and welded H-shaped cross-section beams on the pedestrian deck level
- Transverse direction (east-west)
 Providing structural resistance to seismic force with 18000-pitch rigid frames consisting of welded oval cross-section columns and welded H-shaped cross-section

beams on the pedestrian deck level, and rigid frames in-between, consisting of steel tube columns and welded H-shaped cross-section beams on the pedestrian deck level. Some are braced rigid frames.

- Roof structure

In-plane rigidity of the roof structure is secured with the Vierendeel frame, consisting of 18000-pitch main girders and three continuous beams that run in the long-side direction at the center of the main girder and the cable truss. The cantilever columns on the west side (on the station side) fully bear the seismic force on the roof.

For the long-side direction, the oil damper system, installed at the joint with North Tower, absorbs energy and distributes some of the seismic force to North Tower.

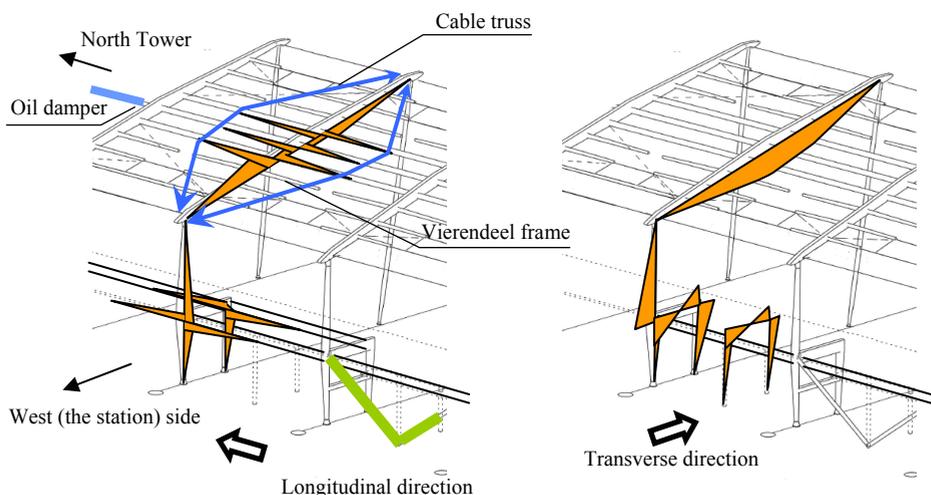


Figure 11: System of structural resistance to seismic force

4.2. Design basis earthquake ground motion and criteria

The design basis earthquake ground motions evaluating large earthquake are as follows:

- Notification wave : The simulated earthquake ground motion defined in the Construction Ministry's notification.
- Art wave : The simulated earthquake ground motion that prepared to achieve $S_v=100\text{cm/sec}$ (when $h=5\%$) in the long period range.
- Observed wave : Observed seismic motions with the maximum velocity amplitude 50cm/sec .

Table 3: Max acceleration of The design basis earthquake ground motions
 (Large earthquake level)

	Notification wave			Art wave	EL CENTRO CALIF. 1940. 5.18 NS	TAFT CALIF. 1952. 7.21 EW	HACHIN OHE 1968. 5.16 NS
	Pase characteristics						
	HACHINOH E EW	TOHOKU U. NS	JMA KOBE NS				
m/s	3.49	2.93	3.81	2.76	4.90	5.00	3.34

4.3. Analysis model: 74 lumped masses 3D model

The time history response analysis was conducted in the matrix displacement approach. Since the basement floors have a highly rigid structure with sufficient bearing walls, only the above-ground section was modeled, with the first floor defined as the input point of design earthquake ground motion. (Fig. 12)

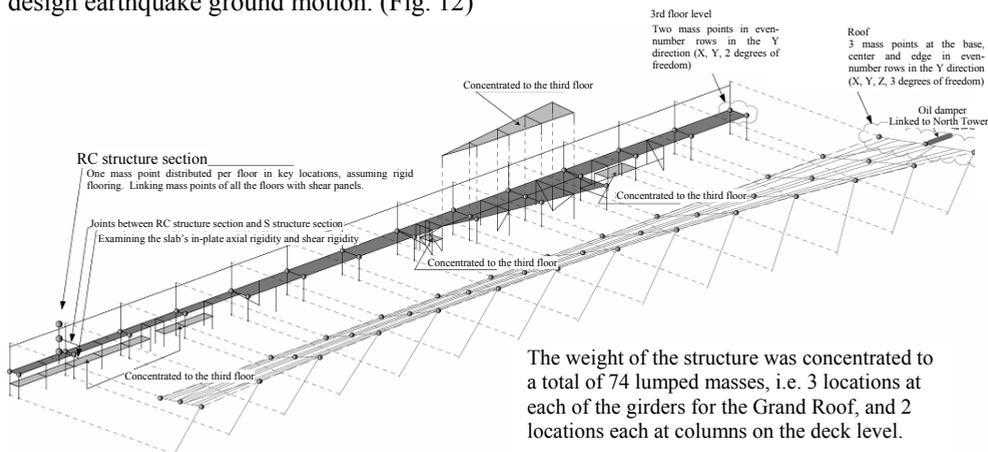


Figure 12: 74 lumped masses 3D model for the time history response analysis

- Each floor was assumed to be non-rigid, with the in-plate rigidity reflecting the transverse rigidity of floor slab and top concrete.
- Rayleigh-wave attenuation was assumed as $h_i = 0.02$ through to approximately 20s.
- Figure 13 shows the history characteristics of the oil damper system, used at the joint with North Tower.

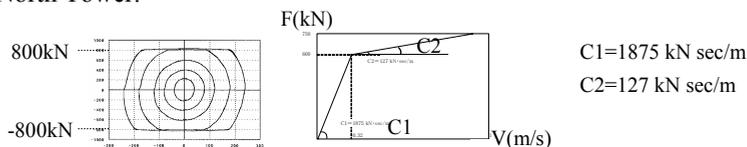


Figure 13: the history characteristics of the oil damper system

4.4. Examination results

(1) Natural period

Table 3 shows natural period of the Grand Roof.

Table 3: Natural period

	1 st mode	2 nd mode	3 rd mode	4 th mode
sec	0.956	0.774	0.734	0.68

(2) Response results at an extremely rare seismic ground motion

Longitudinal direction

- The relative deformation angle of the pedestrian deck level against the ground floor is 81.5mm, 1/92 (TAFT EW) at maximum, and satisfies the criterion of approx 1/100.
- The maximum deformation of the roof is 232mm (EL CENTRO NS), which is within the criterion of 600mm.

Transverse direction

- The relative deformation angle of the pedestrian deck level against the ground floor is 81.2mm, 1/92 (EL CENTRO NS) at maximum, and satisfies the criterion of approx 1/100.
- The maximum deformation of the roof is 292mm (EL CENTRO NS), which is within the criterion of 600mm.

5. Conclusion

The design method of long and unique shape membrane structure was described.

To achieve a light membrane structure, we adopted several ideas.

- 1) A beautiful steel frames were adopted in the design
- 2) The membrane structure with a low curvature that almost look like flat was designed.
- 3) In order to reduce the response displacement of the roof, the oil damper system connected to the North Tower was installed.

The Grand Roof is now under construction and the schedule of the completion is in 2013.