STRUCTURAL DESIGN OF TOKYO SKYTREE

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SUMMARY

This paper describes the structural design of TOKYO SKYTREE® which was completed in May last year. This tower is the world's highest freestanding steel tower, and it was planned to be the central facility for digital broadcasts in the Tokyo area. Structures in Japan are required to be sufficiently safe against the severe natural environment of Japan, which include not only earthquakes but also typhoons. This tower is also to serve the important role of distributing information during disasters, so even more severe criteria were provided for its design.

The following is an introduction to the structural design of TOKYO SKYTREE, which satisfies the strict design conditions using a unique The Core Column System, vibration control system.

Keywords: TMDs, Core Column, Subduction Zone Earthquake, Balloon-launching system

INTRODUCTION

TOKYO SKYTREE (Fig. 1) which was completed in May 2012 was planned as the central facility for digital broadcasts for Tokyo and the surrounding areas. Its maximum height is 634 m. Observation facilities are provided at heights of 350 m and 450 m; and above 500 m is a gain tower, which is installation space for TV antennae. This was a major project because in addition to the tower itself, offices and commercial facilities, a planetarium, an art gallery, etc., are included, with a total area of 230,000 m². It is a major tourist facility, and in the first year after opening, the tower alone had 6.38 million visitors, and the scheme as a whole had more than 50 million visitors.

Figure 1: TOKYO SKYTREE

It is well known that Japan is one of the few countries in the world with severe natural environment. Large earthquakes frequently occur and typhoons occur every year between summer and autumn. Not only is TOKYO SKYTREE about twice as high as the previous highest structure in Japan, but it also has the major public role of transmitting information during a disaster, so it has been designed to more severe criteria than ordinary structures.

In undertaking the challenge to design a building with an unprecedented height, various methods were used to set the unknown external forces. In addition, to satisfy the high target performance, it was necessary to develop mechanisms to artificially reduce the oscillations during earthquakes and strong winds; and a new concept of vibration control system was adopted that uses the mass of a central shaft.

1. POSTULATED EXTERNAL DISTURBANCE CRITERIA

In order to achieve the high target performance, so-called "unexpected natural disasters" were set that exceeded those set by Japanese law, so that the structure was designed having allowance on the safe side. (Table 1)

Table 1: Design criteria

Level	Standards of domestic law	Specification of design for disturbance	Structural safety limit
L1	Rare	Strong wind: Return period = 100 years Earthquake: middle	No damage
L2	Very rare	Strong wind: Return period = 1350 years Earthquake: Big	Virtually no damage
L3	Unexpected	Strong wind: Return period = 2000 years Earthquake: Hidden faults	Elastic behaviour

In the seismic design, the fundamental natural period of the tower was about 10 seconds, and the fundamental natural period of the ground at the site was about 8 seconds, so designing against long-period seismic motions caused by Subduction Zone Earthquake, occur at ocean trough, was essential. Directly below the project site there is about 2.5 km of sedimentary layers. To determine their condition, a micro-tremor array survey was carried out, which assisted in producing the input seismic motions used for design. Also, although there is no record of an active fault near the tower, a magnitude 7.3 earthquake whose epicenter was a nearby active fault was postulated as an unexpected earthquake, and the tower was designed for this earthquake.

Furthermore, as regards wind loading, to determine the properties of wind blowing at heights greater than 600 m, the wind speeds at high altitudes were measured using balloons, and for two years, fixed winds were measured using an ultrasonic wind gauge and wind velocity meter and a anemo-cinemograph installed on an existing 65 m high communication tower on the site. The flow of the wind design included: setting the mean wind velocity distribution in the height direction based on the high level wind measurements; directly verifying the wind force properties and the wind response properties using wind tunnel testing; producing mock wind force waveforms based on this basic material obtained; and performing time history response analysis using a computer in the same way as for seismic response. (Figs. 2 to 5)

Figure 2: Balloon-launching system

Figure 3: Observation of wind with GPS sonde

Figure 4: The entire wind tunnel test

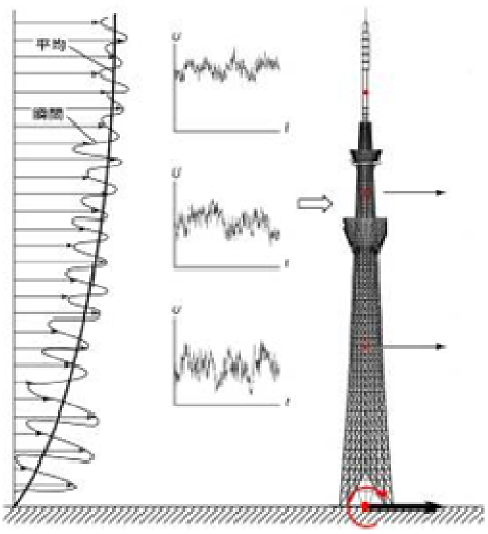

Figure 5: Time history response analysis with an artificial wind fluctuation data

The design targets for each part of the building structure were "virtually no damage" for the highest level of horizontal force L2 defined in the legal standards to which high-rise buildings normally comply in Japan, so that broadcasts, communications, and the tower's function for disaster recovery can be maintained, and in addition, there should be "elastic behavior" against unexpected loads L3 exceeding the L2 level.

2. STRUCTURAL SCHEME

The site of the tower is a former railway shunting yard, with the feature that it is long in the east-west direction, but only about 80 m in the north-south direction. In order to construct a building taller than 600 m under Japan's severe natural environment, it is difficult to provide a plan shape at the base to securely withstand the horizontal forces, when the width is not necessarily sufficient. To solve this problem, and as a result of considering various conditions, the plan shape at the base was chosen to be a triangular shape. On the other hand, as a result of considering the function of the observation deck at the upper levels, a circular plan shape is desirable. As a result, TOKYO SKYTREE has a unique shape in which the plan shape gradually changes from a triangular shape at the lower levels to a circular shape at the observation deck. This change in shape has an impressive effect on the tower's silhouette. On the other hand, one side of the triangular shaped plan is about 70 m or only 1/9 of the height, which is a very severe proportion for resisting horizontal forces. (Fig. 6)

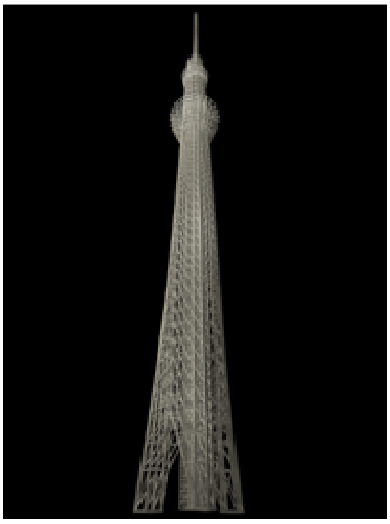

Figure 6: Superstructure

The intention was to make the structural form as lightweight as possible, with a design that is not intimidating to the surrounding area, so a truss form was selected for the structural steel, and mainly steel tubes were adopted as the structural members.

The steel members with the highest standard strength were the 630 MPa steel members for the base of the gain tower, which had a standard strength about double that of the steel used in a ordinary building. The members with the largest cross-section were 2.3 m diameter steel tubes used in the ridges of the tower at the lowest level, and the maximum thickness of the steel tubes was 10 cm.

3. VIBRATION CONTROL SYSTEM

Two types of vibration control system are used on TOKYO SKYTREE .

3.1. TMDs on the top (added mass control mechanism)

As a tower that is used for terrestrial digital broadcasting, it is necessary to suppress the wind response of the gain tower at the top of the tower on which the broadcasting antennae are installed. Specifically, the velocity of the oscillations of the gain tower due to normal wind, which has a high frequency of occurrence, was required to be maintained less than a specified value. For this purpose two TMDs were installed on the top of the tower. The required performance could be assured with at least one device, but by providing the second device higher performance could be ensured and it can be used as a backup in case of emergency.

3.2. The Core Column System (core column type added mass control mechanism)

A vibration control system using The Core Column provided in the center of the core as added mass was newly developed. (Fig. 7)

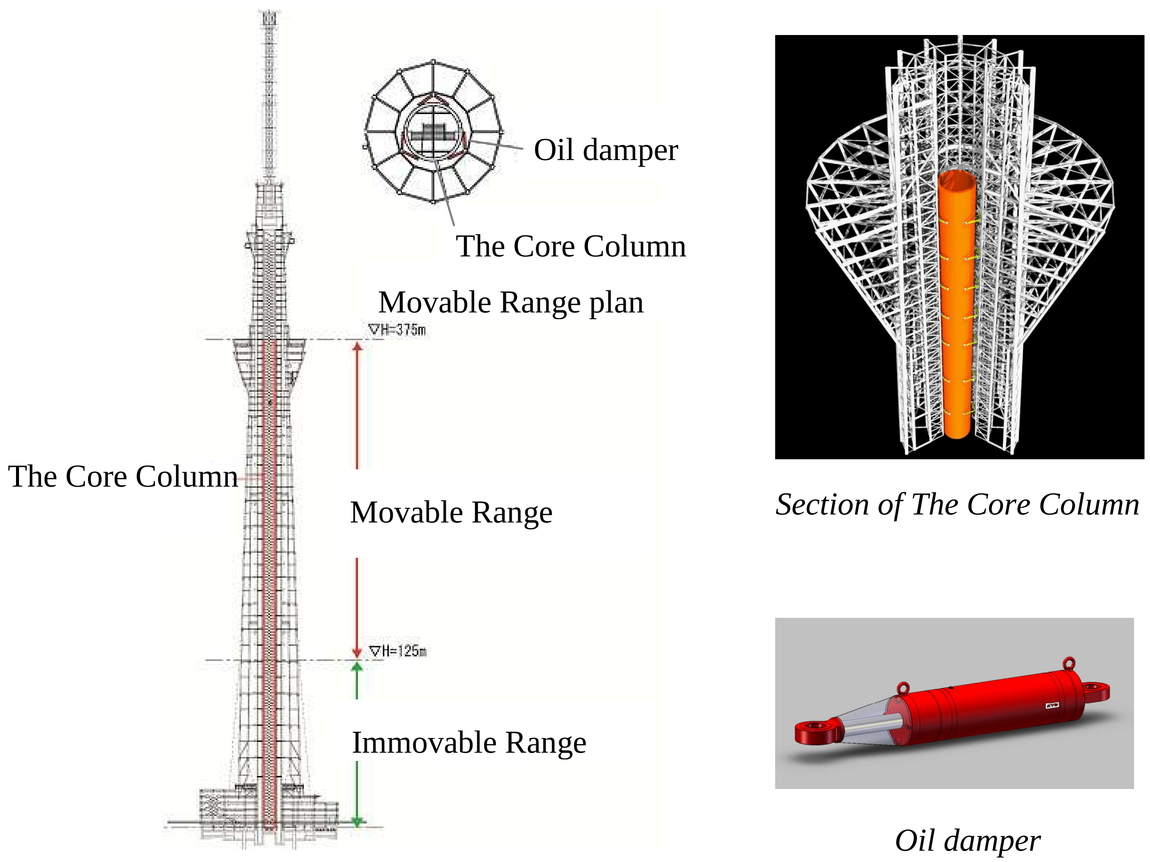

Figure 7: Notion of the response control system with The Core Column

The Core Column is used as the evacuation stairs, and was a reinforced concrete cylindrical shaped column of diameter 8.0 m, maximum thickness 60 cm, and height 375 m. This column was connected to the main structural steel frame of the tower up to 125 m above ground, and the portion above this height was connected to oil dampers to suppress the motions of The Core Column itself, so it acted as a vibration control column that was structurally independent of the tower. This system is effective in various types of earthquake such as long period earthquake motions and epicentral earthquake motions, and compared with the case where there is no center column effect, the response accelerations are reduced by a maximum of 50% in earthquakes and a maximum of 30% in strong winds.

4. CONCLUSIONS

The external forces postulated during the design of TOKYO SKYTREE were strong winds with a return period of 2000 years, and an epicentral earthquake that exceed the framework of the Building Standards Law. The tower can withstand these forces with virtually elastic behavior, and is capable of continuing broadcasting without being affected by major damage. This performance against high external forces was set taking into consideration the public and social role of the tower.

In order to achieve this high performance, The Core Column System was developed, which is a new concept of system for controlling vibrations using the mass of the central shaft. By verifying the effect with and without the system, it was confirmed that the acceleration response during an earthquake is reduced by a maximum of 50%, and the acceleration response during strong winds is reduced by a maximum of 30%.