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Special Issue

Tokyo Sky Tree®

Steel-frame Structures

— Technological Trends and Developments —

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Increasing Application of Seismic-resistant Structures

Fig. 1 shows the percentage of steel-frame high-rise buildings (60 m or higher) designed from FY2000 through the first half of FY2006 that incorporated vibration-control devices and base-isolation devices[1)]. Fig. 2 shows the ratio of various dampers adopted[1)].

Primarily three types of hysteresis dampers have been adopted: steel plate seismic-resistant walls that employ low-yield point steel having lower yield point limits (lower limit for tensile strength) of 80 (200) N/mm^2 and 205 (300) N/mm^2; shear yielding panels of Y-shaped braces and studs; and buckling-restrained braces that employ low-yield point steel and SN490B as the bracing material. The annual ratio of hysteresis dampers adopted in building construction runs between 40% and 65% (refer to Fig. 2).

Among viscous-type dampers are visco-elastic materials, i.e. dampers that absorb energy by means of shear deformation in viscous materials, and oil dampers that adopt cylinder-and-piston energy absorption mechanisms. The ratio of viscous-type dampers adopted each year ranges from less than 30% to more than 40%.

In addition, positive efforts are increasingly being directed toward the development of new dampers and their incorporation in design.

Various methods to improve the seismic resistance of low- and medium-rise steel-frame buildings have also been applied, depending on the application and importance of the buildings. The design input seismic motions for great earthquakes are set at higher levels than those for general buildings. Further, in the case of adopting design criteria to mitigate damage levels, it is considered effective to adopt a design method that suppresses frame damage by incorporating hysteresis dampers in the frame. In order to promote seismic-resistant design methods in the construction of low- and medium-rise buildings, it will be important to develop dampers that are suitable for low- and medium-rise buildings and that are high in recoverability following disastrous events. It will also be important to develop connection details that will enhance the efficiency of damper-to-frame connections.

Diversified Yield Points and Tensile Strengths of Steel Products

In addition to conventional steel with lower yield point limits (lower limits for tensile strength) of 235 (400), 325 (490), 355 (520) and 440 (590) N/mm^2, ministerial approval has been given for steel offering various other levels of lower yield point limits (tensile

Fig. 1 Ratio of Buildings Incorporating Vibration-control and Base-isolation Devices in Steel-frame High-rise Buildings

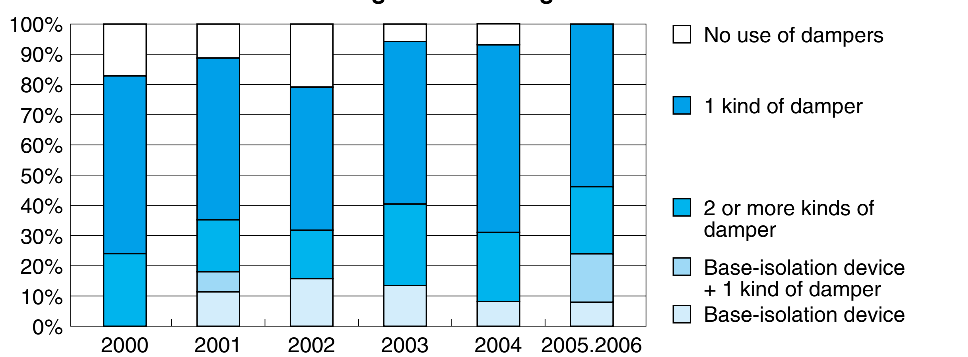
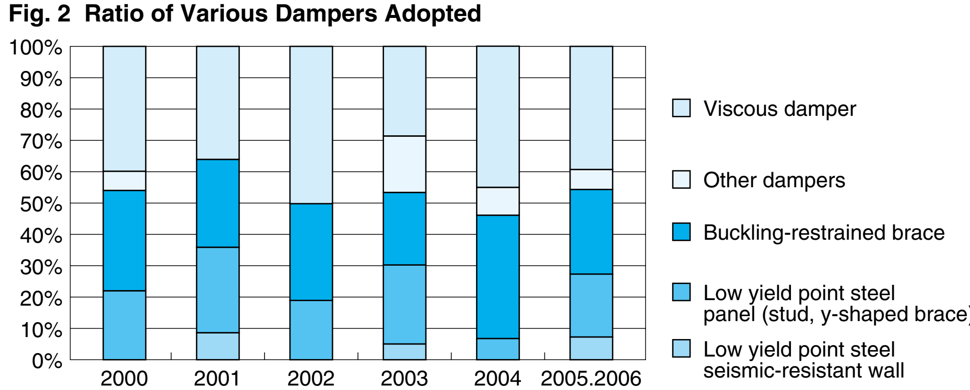


Fig. 2 Ratio of Various Dampers Adopted



strengths). These are:

- Steel grades for plates and circular tubes: 385 (550), 400 (490) ($f_{HAZ} \leq 0.58$ for plate), 440 (590) (conventional SA440 steel for plate), 500 (590), 630 (780) and 700 (780) (only H-SA700 plate)-N/mm^2 and
- Steel grades for square tubes: 385 (550), 400 (490) ($f_{HAZ} \leq 0.58$) and 440 (590)-N/mm^2.

While some of these steel grades require application approval in terms of structural design methods, the available range of yield points now extends from 235 N/mm^2 to 700 N/mm^2. In addition, for steel plates with yield points from 325 N/mm^2 to 440 N/mm^2, steel for large heat-input welding has been developed.

Of these steel products, plates with lower yield point limits of 325 N/mm^2 or more and thicknesses of 40 mm or more are produced by means of the water cooling-type thermo-mechanical control process (TMCP) or by the QQ'T process that involves initial quenching followed by subsequent dual-phase quenching and tempering. However, for steel products having a lower tensile strength limit of 780 N/mm^2, it is expected that steel with high weldability will be developed along with welding materials capable of securing toughness in the weld metal while not lowering that of the base metal. Further, it is considered necessary to organize statistical data on the mechanical properties of steel products produced using these diversified grades and their welds as design data.

Fig. 3 shows the ratio of maximum strengths (lower limits for tensile strength) possessed by steel products adopted for the columns of steel-frame high-rise buildings[1]. When these products are classified by production process, the 325 (490) N/mm^2 grade produced by hot rolling accounts for nearly 30%, and the 325 (490), 355 (520) and 385 (550) N/mm^2-grades by TMCP and the 440 (590) N/mm^2-grade by QQ'T together account for nearly 70%. Recently, 630 (780) N/mm^2-grade QQ'T steel products that take into account cyclic behavior in the plastic range have been adopted for the steel plate seismic-resistant walls of large-span high-rise building structures and for heavy-wall, large-section concrete-filled steel tube columns whose elastic limits are specified in the design conditions.

For the Tokyo Sky Tree®, a steel radio-broadcasting tower now under construction in Tokyo that will be introduced later, diverse kinds of heavy-wall, large-section circular steel pipes in addition to 630 (780) N/mm^2-grade steel products have been adopted as the appropriate materials and in the right sections.

It is considered that structural design freedom has been remarkably enhanced by appropriately selecting the steel products mentioned above according to the performances required of the structural members. Steel-frame structures are the most suitable type of building for creating free space, and their adoption is expected to bring forth demand for new structural space.

Collaboration between Structural Designers and Steel-frame Fabricating Companies

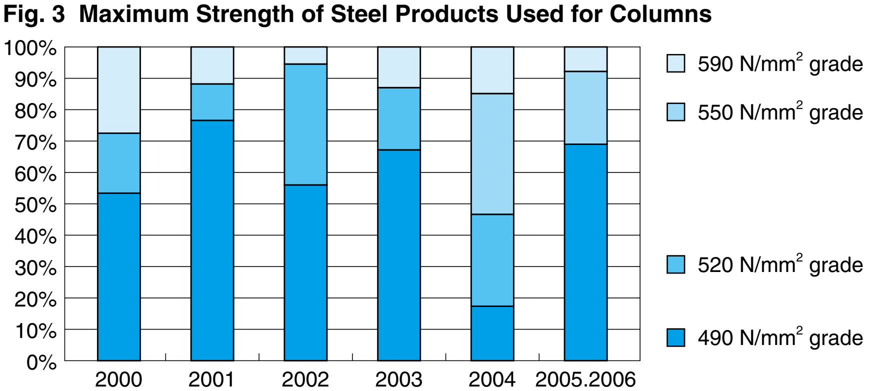
Numerous types of steel-frame fabricating companies are in operation. Certain companies are able to manufacture highly precise structures in which structural members using heavy-wall, large-section high-strength steel products are connected in complex three-dimensional arrays. Other companies engage mainly in the manufacture of rigid steel frames using square tube columns and H beams. All of these companies have accumulated knowhow regarding their respective fabricating technologies and have steadily enhanced their ability to guarantee steel-frame quality. It is regarded that this is largely attributable to the steady technological developments, diffusion activities, and engineer-development activities of the Japan Steel-rib Fabricating Association and the Japan Steel Constructors Association, in addition to the extensive efforts of the respective steel-frame fabricating companies.

Structural designers have enhanced their collaboration with steel-frame fabricating companies through periodic exchanges of technological information and by implementing structural design that features ease of fabrication performance that, in turn, reflects technical proposals from the steel-frame fabricating companies. Further developments in design and fabrication technologies for steel-frame buildings are expected to spring forth from these collaborative efforts.

Further, at steel-frame fabrication companies, diverse operations are being directed toward labor and energy savings, including contributions to the creation of a low-carbon society. Specifically, in welding operations, efforts are being made to reduce welding volume and weld corrections by reviewing current groove standards. Activities are also being promoted that reinforce energy-saving fabrication operations, including process controls to allow optimal fabrication and to lessen member movement. In this regard, close cooperation between designers and fabricating companies will be required, meaning that structural designers and construction companies will need to agree early in the process on design changes, changes in construction methods, finishing degree, the required equipment, and temporary construction metal fitting-related connection details so that the steel-frame fabrication process can be free of disturbance.

A good example of collaboration between structural designers and steel-frame fabricating engineers is the design of the steel-frame details and the fabrication of the steel frames adopted for construction of the Tokyo Sky Tree®. It is regarded that the construction of this, the world's tallest steel tower, has been possible only through collaborative operations based on the advanced design technologies of the structural designers and the advanced steel-frame fabrication technologies and quality guarantee capabilities of the steel-frame fabricating companies.

Fig. 3 Maximum Strength of Steel Products Used for Columns



Reference

1) New Building Technology Report—Performance Assessment and Rating/Examination Certification (June 2000, March 2009): Building Center of Japan, June 2010

Tokyo Sky Tree

— Creation of a Landscape beyond Space-time —

By Shigeru Yoshino
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Facing the Sumida River in the eastern part of Tokyo, the Narihirabashi and Oshiage areas were once flourishing centers of Edo culture (17th to late 19th century). In February 2006 the Tobu Railway Co. proposed to local broadcasting companies and to Sumida Ward that a huge steel tower, called the Tokyo Sky Tree®, be built there. The first thing particularly emphasized by the client at the start of the project was the "creation of a landscape beyond space-time there." During subsequent stages of the design work, consistent efforts were made to realize this theme.

High-rise Tower in the *Shitamachi* District

Rising high above the Narihirabashi-Oshiage area of Sumida Ward, the Tokyo Sky Tree is surrounded by several *shitamachi* areas (traditional shopping and entertainment districts), such as Asakusa and Mukojima. It is also located at a strategic point where the Tobu railway line, subway lines, and waterborne transport services converge. The Tokyo Sky Tree not only serves as a self-supporting radio broadcasting tower that transmits terrestrial digital and other broadcast signals. It also symbolizes the revitalization of *shitamachi* areas and *shitamachi* culture, while at the same time enhancing ties with Asakusa, a famous sightseeing place in Tokyo that is rich in traces of Edo culture. To meet these needs, studies were conducted on the design of the tower to ensure a deep connection with the unique geographical features of these areas.

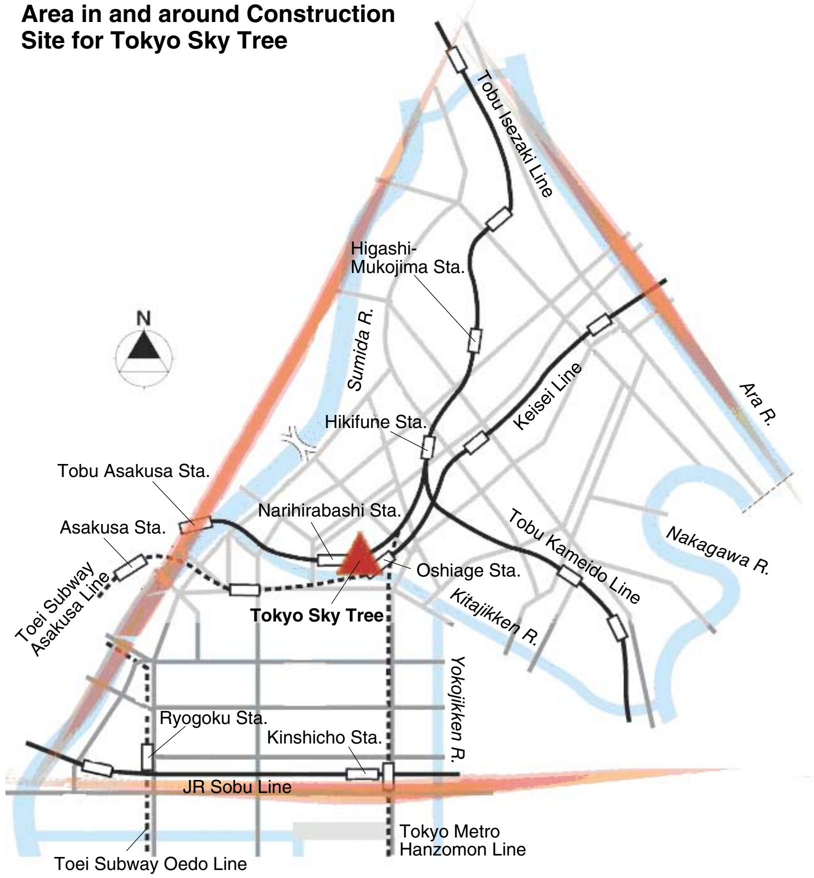
The construction site lies at the center of a topographical triangle bordered on two sides by the Sumida and Ara Rivers that foster the ever-lasting flows beyond the ages and on the south by railways and major highways that run from east to west. The tower is located at a critical point where diverse "avenues" converge that have orthotropic crossing with these three urban axes. Flat triangular framing was examined for the tower base so that it could welcome visitors entering from these avenues.

As a downward sweeping structure, the tower is reminiscent of an ancient Chinese *kanae* or tripod kettle (self-supporting with three legs) that imparts a sense of stability to those who view it. In addition, the triangular shape allowed the maximum possible width for the tower's base within the confines of the construction site and, further, its adoption allowed for the introduction of a stable structure requiring the minimum use of structural members. Also, careful consideration given to the tower design helped to avoid any sense of oppressiveness in surrounding areas.

On the other hand, as regards the tower's two observatories, because it was supposed that visitors might want to look in the direction of their homes, importance was placed on providing a 360-degree view of the entire Kanto area. To that end, it was found that a circular form would be appropriate for the observatories. In addition, the adoption of a circular form would make it more convenient for attaching antennas in any direction. Also, a circular design, when subjected to external forces, is better than a triangular form in meeting external forces exerted from any direction in a well-balanced manner in order to maintain tower stability.

As a result, the tower configuration progressively changes from a triangular shape

Area in and around Construction Site for Tokyo Sky Tree



Aerial View of Tokyo Sky Tree upon Completion

Tobu Railway Co., Ltd. and Tobu Tower Sky Tree Co., Ltd.

Elevation View of Tokyo Sky Tree

at the base to a circular form higher up—giving the tower a unique configuration not found anywhere else in the world.

Changing Configuration of the Tower

The changing configuration of the tower from a triangular to a circular shape produces "warping" and "camper" in the tower design, forms that are found in traditional Japanese culture. The triangular cross-section that dominates the lower section of the tower becomes circular at a height of about 300 m above ground.

When viewed from the side, each of the lines extending upward from the ground along the triangular part of the tower draws a gently depressed arc. Etched clearly against the sky, this arc closely resembles the "warping" seen in *katana*, or Japanese swords. The diagonal lines that girdle the three sides of the triangle form a gentle convex pattern called "camper." An example of this is the subtle swelling seen in the colonnades of Japanese shrines and temples. At first view, the configuration of the tower seems simple, but in actuality it contains extremely complex curves.

Tower Design Transcends Space-time

The world's most prominent towers are commonly located on a clear urban axis, as is the Eiffel in Paris, or next to the sea, a lake, or a river, such as the CN Tower in Toronto and the Oriental Pearl Tower (TV tower) in Shanghai.

There are two perspectives from which a single tower can be viewed: one is from a distance with the tower soaring upward from the ground, and the other is from the base of the tower looking up at the sky. These two perspectives stand out in the memories of tower visitors.

On the other hand, for the Tokyo Sky Tree, it is the distant view from beyond the Sumida River that is most memorable. From the avenues running in diverse patterns in neighboring *shitamachi* to just beneath the tower, the gently changing appearance of the tower from a triangular shape to a circular shape emphasizes the tower's unique interplay of warping and camper. Offering diverse appearances depending on the point from which it is viewed, the tower is linked to the quintessential nature of the *shitamachi* alleyways and to the freedom, change and originality peculiar to the Edo merchant class. Accordingly, the tower is not an independent production; rather, its appearance is brought about by the consolidated embodiment of the tower itself and *shitamachi* characteristics.

A new architectural landscape will be born. In it, the Tokyo Sky Tree will employ advanced technologies and never-before-adopted design approaches. At the same time, it will inherit and embody the deeply rooted culture of the locality in which it stands. We believe that the landscape thus created will manifest the theme: "creation of a landscape beyond space-time."

Tokyo Sky Tree

— Structural Outline of Terrestrial Digital Broadcasting Tower —

By Michio Keii, Atsuo Konishi, Yasuo Kagami, Kazunari Watanabe, Norio Nakanishi and Yoshisato Esaka
Structural Design Department, Nikken Sekkei Ltd.

Construction of the Tokyo Sky Tree®, a digital terrestrial broadcasting tower with a height of 634 m, was started in July 2008 in Sumida City, Tokyo. The tower will not only transmit digital terrestrial broadcasting that is slated to begin in the spring of 2012 in Japan; it will also serve as a symbol of efforts to achieve community affluence.

Photos 1 and 2 Observation of high-level winds by mans of radiosonde

Outline of Tokyo Sky Tree Plan

● Planned Site and Facility Arrangement Plan

The area in and around Oshiage and Narihirabashi Stations, the site planned for the construction of the Tokyo Sky Tree, is located near the center of Sumida City, Tokyo. Specifically, the site is located where two urban axes of Sumida City cross: the central east-west axis that passes through the site via the Azumabashi area from Ueno and Asakusa and the south-north axis that leads to the area in and around Hikifune Station from the area in and around Kinshicho Station.

The facility layout is divided into three sections: the west district mainly for commercial facilities (utilized by local entities), the tower district, and the east district mainly for shops (sightseeing) and offices (refer to Fig. 1). The tower is located in the center of the planned site and will constitute the nucleus of a complex that is rich in enjoyable excursions and bustling activity.

Design Loads and Criteria

● Wind Loads

— Settlement of Height-direction Characteristics of Natural Winds

Because Tokyo Bay is located about 8 km south of the tower and because the tower is 634 m high, it was taken into account that the ground surface boundary layer that reflects the surface roughness of the peripheral districts cannot fully develop, which led to the adoption of the "roughness classification II" prescribed in the *Building Load Guidelines and Commentary* (2004) of Architectural Institute of Japan (AIJ).

The boundary layer height was prescribed to exit above the planned tower, and the average wind velocity was calculated with the provision that the profile of average wind velocity can be extrapolated in the height of Z_G or more in the power law distribution, which is adopted in the AIJ *Guidelines*.

It was also prescribed that the AIJ *Guidelines* be extrapolated in the height of Z_G or more pertaining to the wind scale and the height-direction distribution of wind turbulence, as was done for the profile of average wind velocity. However, the wind turbulence was settled at a minimum of 10% to provide the lower limit. (Refer to Photos 1 and 2)

— Settlement of Assumed Storms in Design and Design Wind Loads

Table 1 shows the storms that are assumed within the design. The wind forces working on the planned tower by each level of storm was found providing that: for level 2 storms, the equivalent static wind load was found according to the procedure shown in Fig. 2; and for level 1 and 3 storms, the wind force is in proportion to the square of the basic wind velocity.

Fig. 1 Entire Arrangement Plan

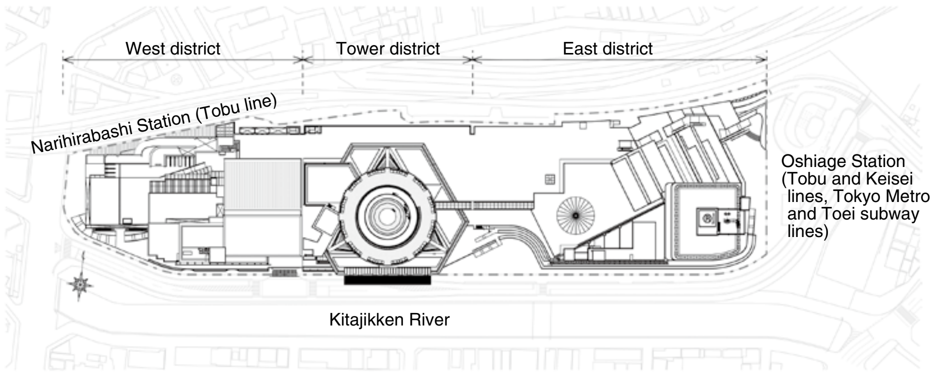


Table 1 Return Period of Storm Level and Average Wind Velocity equivalent to Basic Wind Velocity

Name of storm	Return period	Average wind velocity equivalent to basic wind velocity
Level 1 storm	100 years	36.0 m/s
Level 2 storm	500 years	40.0 m/s
Level 3 storm	2,000 years	44.7 m/s

Fig. 2 Wind Resistance Design Flow (Preparation of Equivalent Static Wind Loads)

(1) Settlement of height-direction characteristics of natural wind
- Taking into account that the ground surface boundary layer that reflects the surface roughness of the peripheral districts cannot fully develop, the roughness classification II is adopted.
- It is provided that the profile of average wind velocity can be extrapolated in the height of Z_G or more in the power law distribution.

↓

(2) Wind tunnel test (physical simulation)
- A wind tunnel test is conducted in which the natural wind height-direction characteristics settled as the target values are simulated in the boundary layer wind tunnel, and the basic data to prepare the simulated wind force wave is measured.

↓

(3) Time-history response analysis by means of simulated wind force wave (logical simulation)
- Targeting the power spectrum density of fluctuating overturning moment found in the wind tunnel test, a simulated wind force wave is prepared by means of the Monte Carlo simulation.

↓

(4) Settlement of equivalent static wind load and analysis of static stress
- Time-history response analysis is conducted by giving to the multi-mass point model the simulated wind force wave prepared based on the wind tunnel test, and the wind response of the tower is found.
- Equivalent static wind load is set at the average load of response story shear force.

↓

(5) Proving structural safety to wind load (confirmation of deformation, examination of sections)
- Structural safety to the wind load is proven by confirming that each structural member satisfies the target criteria pertaining to the equivalent static wind load.

● Seismic Loads
— Directions to Examine Structural Safety during Earthquakes

Because the tower is 634 m high, the higher mode and the axial deformation of the structural members have a large affect, and it is difficult to appropriately define the design seismic load by means of the "envelope load of response layer shearing force" that is conventionally adopted in the design of common high-rise buildings. To meet such a situation, the structural safety of the tower during earthquakes was examined by conducting a member-level time-history response analysis for the adopted seismic motions shown in Table 2 to prove the safety of all structural members.

— Adopted Seismic Motions

The seismic motions adopted for the tower design were selected by preparing a so-called site wave that supposes the case in which a long-period earthquake and an in-land direct hit-type earthquake occur near the tower; also utilized were simulated waves (required in the Building Standard Law of Japan) and observed waves adopted in the design of common high-rise buildings. Fig. 3 shows the response spectrum of part of the adopted seismic motions.

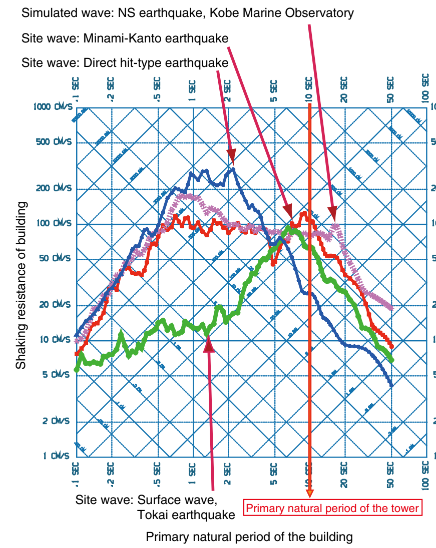
● Design Criteria

The tower was designed so that the stress of the structural members, excluding weld connections, remains within an elastic range against level 2 earthquakes and the wind loads shown in Table 3. Meanwhile, in addition to the above-mentioned design criteria pertaining to structural safety, it is required that the structural performance be

Table 2 Adopted Seismic Waves

Input level	Adopted seismic wave	
Level 1 earthquake (Rarely occurring seismic motion)	Simulated wave Observed wave	
Level 2 earthquake (Extremely rarely occurring seismic motion)	Simulated wave Observed wave Minami-Kanto earthquake Tokai earthquake Tokai earthquake Higashi-Nankai earthquake Nankai earthquake	 (M7.9: Site wave) (M8.0: Substantial site wave) (M8.0: LOVE site wave) (M8.2: LOVE site wave) (M8.6: LOVE site wave)
Level 3 earthquake	In-land direct hit-type earthquake having an epicenter just beneath the surface area (M6.9: Site wave)	

Fig. 3 Comparison of Spectrums



suitable for use as a radio broadcasting tower, the description of which however is omitted in the current article.

Design of Upper Structures
● Framing Plan

A reinforced-concrete (RC) cylindrical-shaped stairwell (*shimbashira*) is located at the center of the tower, and steel-frame cores (intermediate tower and inner tower) into which elevators, EPS and other equipment are incorporated are located around the stairwell. Their outer section is structured as a truss structure employing steel pipes, and the plane configuration of the truss structure at the tower base changes to a circular form. (Refer to Fig. 4)

The trusses, called *kanae* (tripod kettle) trusses, are composed of four main members and are located in each corner of the equilateral triangle of the tower base, and these trusses are connected in the horizontal structural plane as shown in Fig. 5. The *kanae* trusses and the peripheral framing (outer tower) provide the main resistance to seismic forces and wind loads.

● Steel Products Applied

Table 4 shows the steel products applied as the main structural members in the tower construction. In the current design, because not only the tower is high but also its width-to-height ratio is quite large in relation to the site, the sectional force working on each structural member during earthquakes and typhoons becomes large. To meet such needs, structural members having both high strength and a large cross section are required. Due to the same reasons, the premise for the member joining method is

Table 3 Seismic- and Wind-resistant Design Criteria

Input level	Damage level
Level 1 earthquake (rarely occurring seismic motion) Level 1 storm (return period of 100 years)	No damage
Level 2 earthquake (extremely rarely occurring seismic motion) Level 2 storm (return period of 500 years)	Nearly no damage (members in elastic range)
Level 3 earthquake Level 3 storm (return period of 2,000 years)	No collapse

Fig. 5 Floor Plan

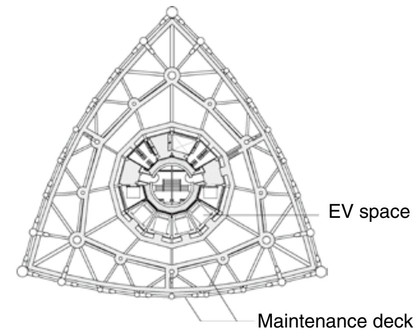
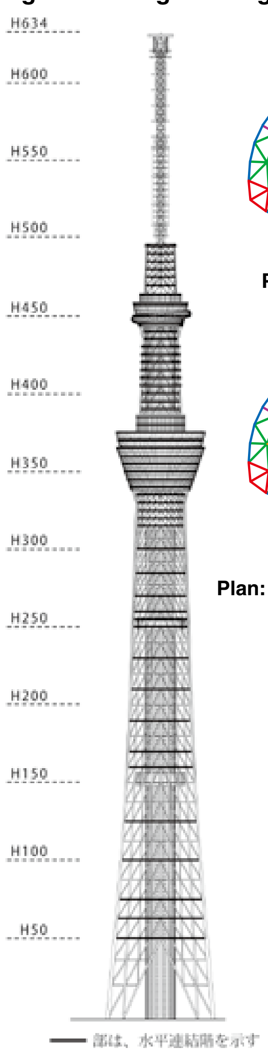
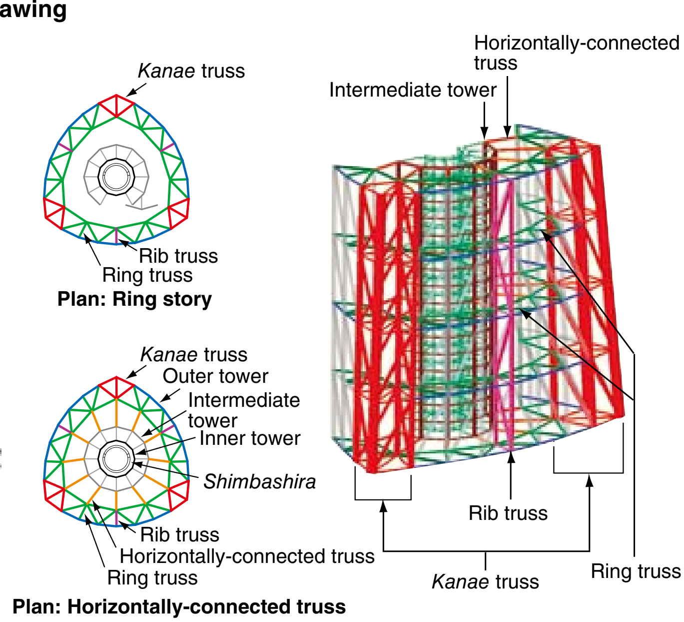


Fig. 4 Framing Drawing





Kanae truss
- Built-up column employing four columns, and horizontal and brace members
- Arranged in the top of the triangular plane form
- Main member to resist horizontal load

Horizontally-connected trusses
- Connecting intermediate tower and ring trusses every two layers (25 m)
- Working as members to transfer the horizontal load (in-plane), and members to stiffen the buckling of *kanae* trusses and peripheral columns

Ring truss
- Horizontal members arranged every layer (12.5 m)
- Working as the member to stiffen buckling of peripheral columns

the adoption of welding. Further, due to the heavy weight of each member, it was determined that the members would be divided into shorter sizes conforming to the transport and lifting conditions, and that these members would then be transported to the construction site and joined together by means of on-site welding.

Given such circumstances, it was necessary to adopt steel products that were not only high in strength and toughness but also excellent in weldability including preheating performance. The steel products having a yield strength of 400 N/mm^2 or more that are used in the construction of the Tokyo Sky Tree satisfy the performances thus required, and, at the same time, have been approved by the Minister of Land, Infrastructure, Transport and Tourism particularly for use in the construction of this tower.

● Design of Tubular Joints

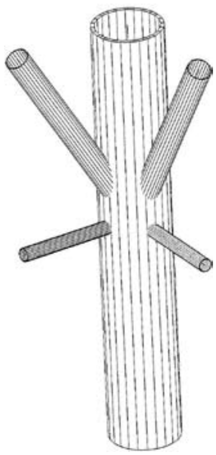
Because *kanae* trusses and structural members such as columns, braces and horizontal members for the outer tower are three-dimensionally linked together to form connections, steel pipe was adopted in terms of the cross section, and the so-called tubular joint method (Fig. 6) was adopted to join the pipe members. The reason why the tubular joint method was adopted in-

Table 4 Steel Product Application Sections and Wall Thicknesses

Structural section	Zone	Outside diameter x Wall thickness (mm)	Yield point	
Column	*Kanae* truss	P-711.2 ø × 28 ~ 2300 ø × 100	400 ~ 500 N/mm^2 grade	Circular pipe
	Outer tower	P-1100 ø × 25 ~ 1016 ø × 60	SN490B, 400 ~ 500 N/mm^2 grade	
	Antenna tower	P-900 ø × 25 ~ 1200 ø × 80	SN490B, 400 ~ 500 N/mm^2 grade, 630 N/mm^2 grade	
Brace	Outer tower	P-508 ø × 16 ~ 1000 ø × 60	SN490B, 400 N/mm^2 grade	
	Antenna tower	P-300 ø × 22 ~ 500 ø × 22	SN490B, 400 ~ 500 N/mm^2 grade	
Horizontal member of tower structure	Outer tower, *kanae* truss	P-267.4 ø × 12 ~ 609.6 ø × 16	SN490B (Partly SCN590B-CF)	
	Horizontally-connected truss, ring truss	BX-300 × 300 × 9 × 9 ~ 500 × 500 × 12 × 12	STKR490, BCP325	Square pipe

cludes, for example, a neat finished appearance and fewer shortcomings with regard to corrosion protection.

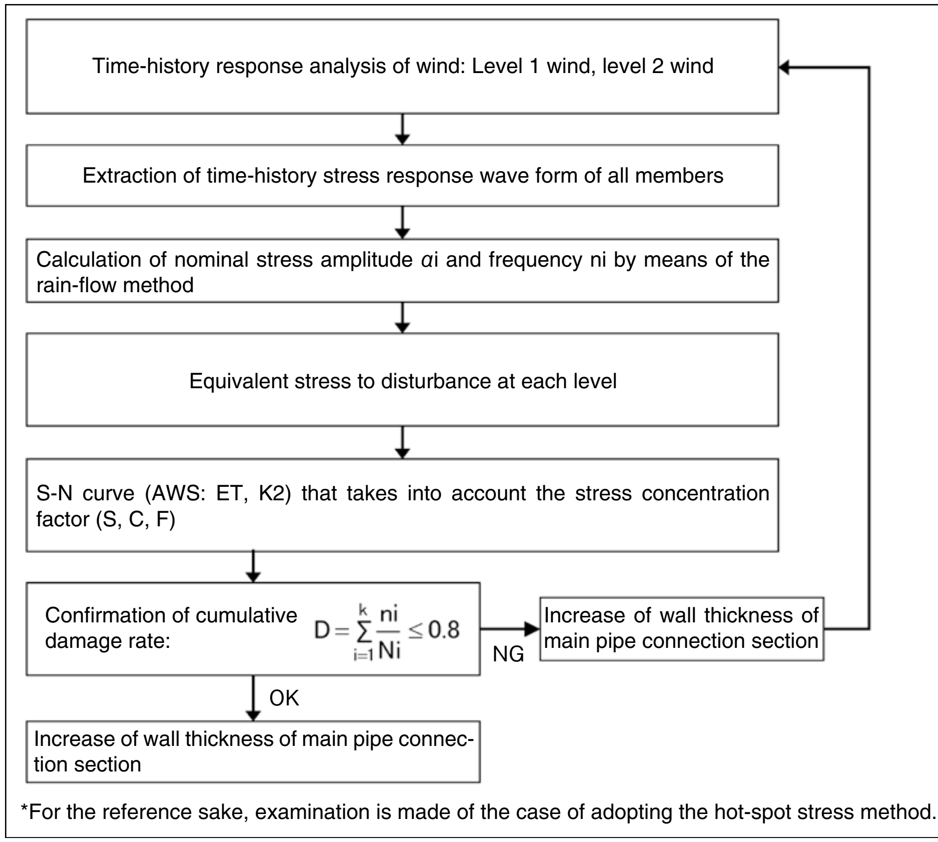
Fig. 6 Tubular Joint Method



However, because there are cases in which confirmation of the safety of tubular joints employing large cross-section high-strength steel pipe used in the current project is beyond the scope of the *Steel Pipe Truss Design Guidelines* of the Architectural Institute of Japan, the strength of the tubular joints including connections was confirmed based on *API (American Petroleum Institute) Specifications* complimented by the use of the AIJ *Guidelines* and FEM analysis.

The strength of these joints was examined as in the following: The strength to support wind loads was examined by means of the design wind load (static load); and, because the static design seismic load is not defined, the strength to support the seismic load was examined by means of a step-by-step approach based on time-history analysis. Further, examinations were made of fatigue in all connections that would be attributable to wind and earthquakes in order to confirm the safety of the connections. Fig. 7 shows the flow chart of the fatigue examination.

Fig. 7 Examination Flow of Fatigue of Tubular Joint



Design of Foundation Structures

● Outline of the Ground at the Site

The planned site is located in a low-lying area of Tokyo surrounded by the Sumida and Ara Rivers. While the surface layer topography at the site is classified as sand bar-back marsh, the surface layer area in and around the planned site is composed extensively of artificial reclamation topography.

The geology in the vicinity of the planned site is composed of such diluvial deposits as the Tokyo gravel layer, Tokyo layer, buried terrace gravel layer and buried loam layer, along with such diluvial layers as the Yurakucho layer in the vicinity of the ground surface, with the Kazusa layer group including the Edogawa layer and Toneri Layer as the foundation bed. The thickness of the Yurakucho layer is about 25~30 m, and its upper section is composed mainly of a loose sandy layer that is 5 m in thickness and its lower section is mainly clay soil.

The ground surveys currently conducted are shown in the following:

- Boring survey
- On-site permeability test
- Borehole horizontal loading test
- Laboratory soil test
- PS logging
- Constant slow motion measurement
- Slow motion array search

Fig. 8 shows the soil boring log obtained from the boring surveys.

— Predominant Period of Ground

The predominant period of the ground was measured for the long period of 1 second or more: 7.0~9.0 and 3.0~4.0 seconds; and of less than 1 second: 0.4~0.5 and 0.6~0.7 seconds.

— Slow Motion Array Search Results

The depth (vs ≥ 3,000 m/sec) of seismic bedrock was assumed to be about 2.5 km.

● Design of Foundation Structures

The foundation structure of the tower was constructed on a bearing stratum composed of a rigid diluvial gravel layer located in GL–35 m or deeper. It is composed of continuous subterranean reinforced-concrete (RC) pile walls with high strength and rigidity and cast-in-place RC piles. In particular, for the base section of the tower structure, common continuous subterranean RC pile walls were arranged, and just beneath the *kanae* trusses, SRC (steel-reinforced concrete) pile walls were arranged (see Fig. 9). In order to provide large withdrawing resistance to SRC piles, a knot was attached to these piles, and these knot-attached SRC piles were driven to depths as great as GL–50 m. Further, H-shapes were arranged within the pile walls to provide higher tensile strength to the wall structure. The withdrawing resistance of the knot-attached piles was confirmed by conducting a full-scale test at the site.

● SRC Foundation Structure to Securely Transfer the Withdrawing Resistance to the Pile

Large bending and shearing forces from the above steel-frame tower work on the foundation structure (Fig. 10), and accordingly the SRC wall into which the steel plate wall is built in conformity with the plane shape of the foundation was arranged

Fig. 8 Soil Boring Log at Construction Site

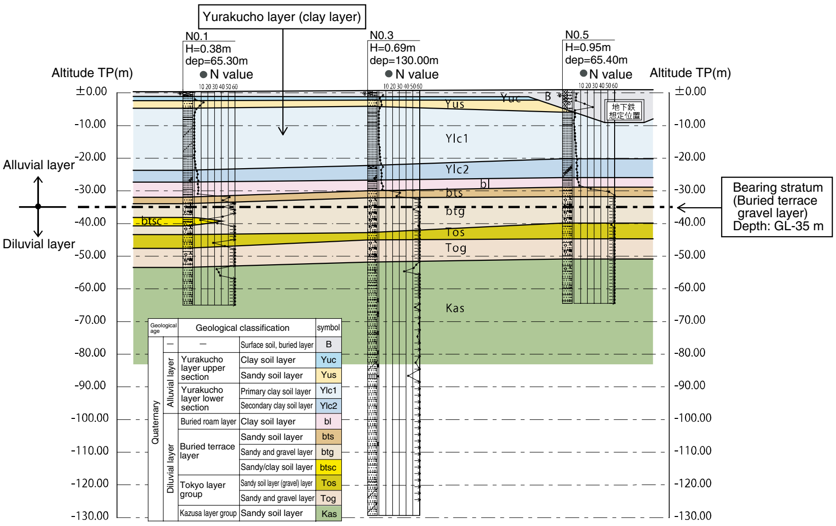


Fig. 10 Foundation Structure

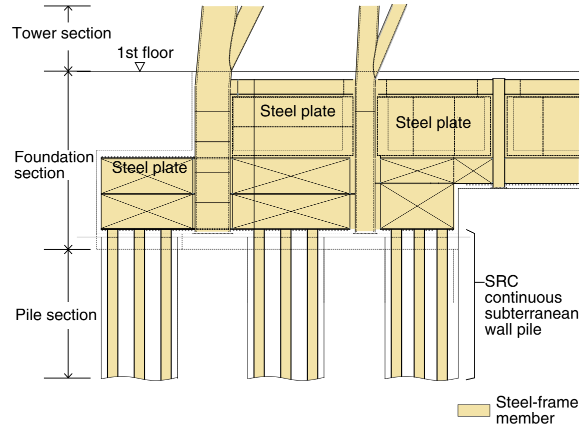
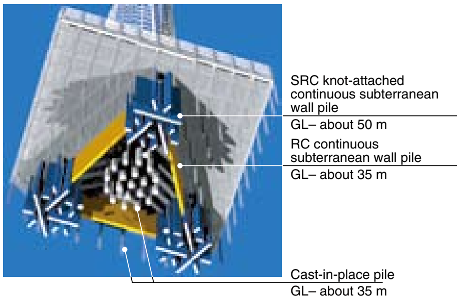


Fig. 9 Piles Adopted

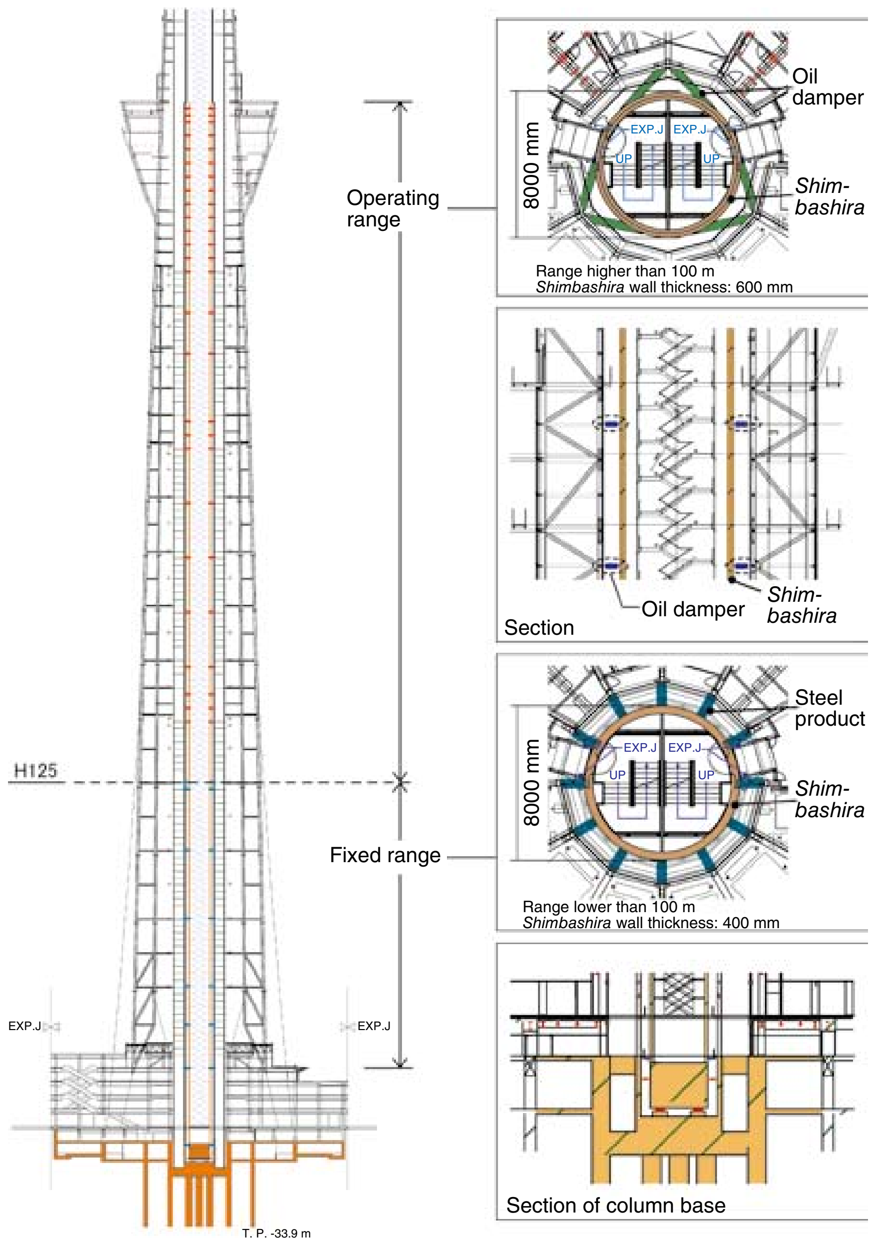


in the foundation structure. The thickness of the steel plate wall was set at 55 mm and 22 mm, and that of the RC wall at 2,700 mm and 1,900 mm.

Outline of Vibration Control by *Shimbashira*

For the tower, the vibration-control system shown in Fig. 11 was adopted to reduce response particularly during earthquakes. Specifically, the RC *shimbashira* and its outside steel-frame section are separated from each other at a height of 125 m or more, and the vibration-control system by means of mass additive mechanism that utilizes the *shimbashira* weight (mass) in the separated section has been devised and adopted. Integration of *shimbashira* and its outside steel-frame section by use of steel products at heights of 125 m or less and installation of oil dampers at heights of 125 m or more not only allow the control of displacement of *shimbashira* but add damping performance to the entire tower structure. The response shearing force can be reduced by about 40% at maximum during great earthquakes through adoption of the *shimbashira* vibration-control system.

Fig. 11 Conceptual Drawing of *Shimbashira* Vibration Control



Tokyo Sky Tree

— Construction of World-class Steel Tower —

By Obayashi Corporation

The tallest self-supporting tower in the world is being constructed in Tokyo. Named the Tokyo Sky Tree®, this 634 m-high tower serves as a freestanding radio broadcasting tower that transmits terrestrial digital and other broadcast signals. Among the major facilities of the tower are an antenna tower, a first observatory (350 m high) and a second observatory (450 m high).

The lowest section of the tower is triangular in plan and supported by three legs. The shape becomes gradually more rounded, until at the height of about 300 m it becomes a perfect circle. The major advanced construction technologies and materials adopted in the construction of the Tokyo Sky Tree are introduced below.

Project Outline
- Name: Tokyo Sky Tree®
- Location: 1-chome Oshiage, Sumida-ku, Tokyo
- Site area: Approximately 36,900 m^2 (tower plus the East and West districts)
- Height: 634 m
- Building type: Observatory (first at 350 m, second at 450 m)
- Structure: Steel, steel-reinforced concrete, and reinforced concrete
- Foundation work: Cast-in-place concrete piles and underground continuous wall piles
- Commencement of work: July 2008
- Planned completion: December 2011
- Client: Tobu Tower Sky Tree Co., Ltd.
- Architect: Nikken Sekkei Ltd.
- Constructor: Obayashi Corporation

Obayashi Corporation

Elevation


Obayashi Corporation

Spring 2009

Assembly of Antenna Tower by the Lift-up Method

The tower's uppermost section, the TV antenna tower, will be assembled on the ground and then hauled up with cables through the inside of the tower to the final height of 634 m, using a dynamic "lift-up method." The on-the-ground assembly of the antenna tower begins with its top section inside the still-hollow space in the center of the tower prior to the construction of *shimbashira* (center column). The antenna tower is gradually hauled up, and successive segments are added below. The completed antenna tower, measuring more than

Fig. 1 Structural Outline of Tokyo Sky Tree

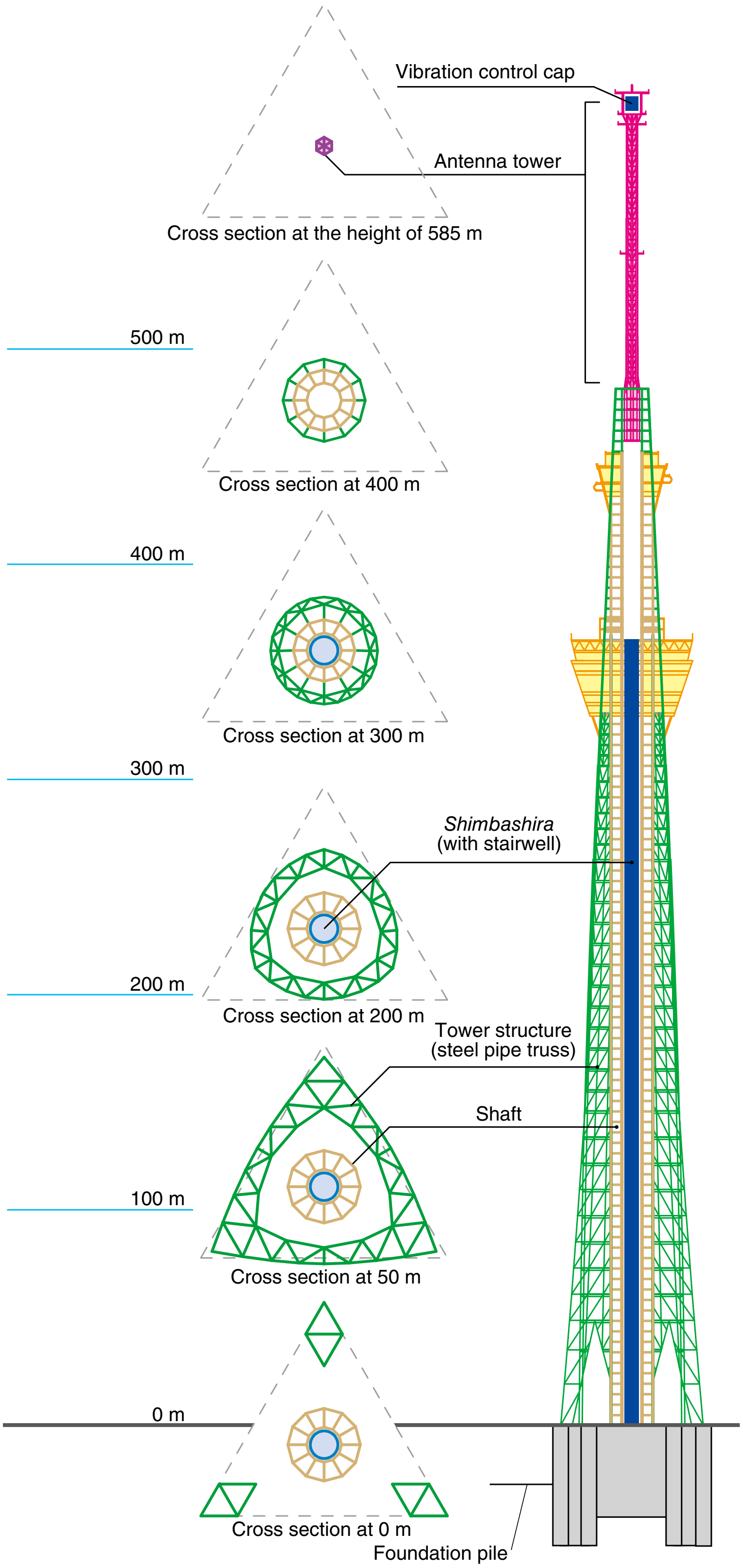


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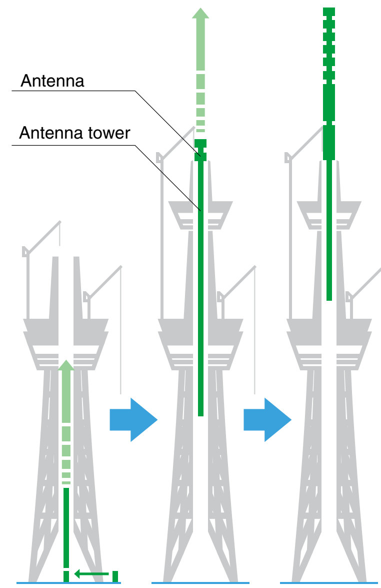
Fig. 2 Lift-up Method



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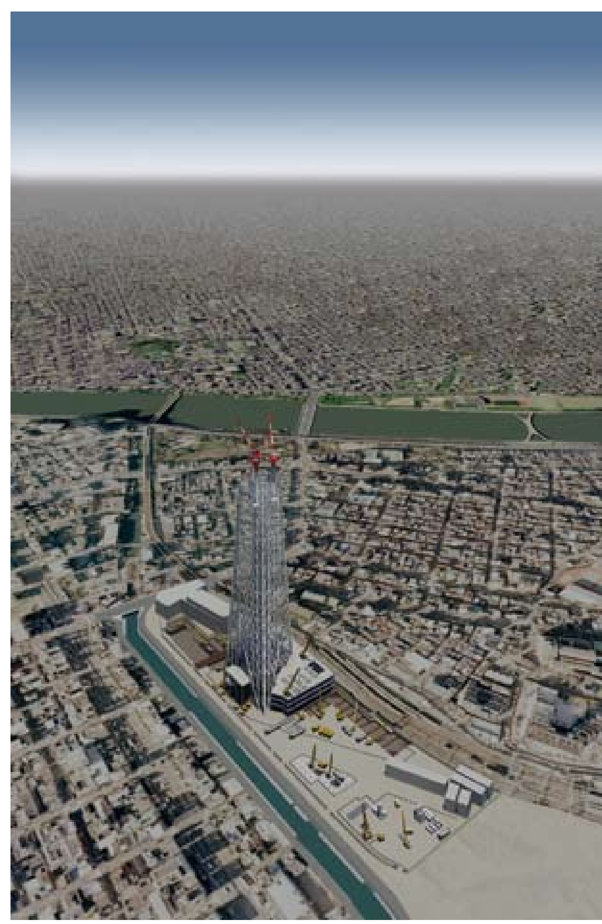

Autumn 2009

Obayashi Corporation

200 m and with a stairwell in its lower section, is then moved up through and out of the tower to its final position on top. (Refer to Figs. 1 and 2)

With the lift-up method, assembling work at an unprecedented height of over 500 m can be omitted, assuring safety and quality. The construction period is greatly shortened as the antenna tower is assembled on the ground in parallel with the construction of the tower above the first observatory.

Construction of *Shimbashira* by Slipform Method

In the space left empty after the lift-up of the antenna tower, the *shimbashira* (center column) will be built using the "slipform method" by which concrete is continuously poured into a form that slips upward as the previously poured concrete hardens behind it (Fig. 3).

With this technology patented by Obayashi Corporation, the cylindrical concrete core can be constructed in a short period of time within the limited space at the center of the tower. The hollow space within the structure can therefore be used for assembling and lifting up the antenna tower before the *shimbashira* is put in place by the slipform method.

Assembly of Giant Steel Pipes

The tower is composed of wide-bore high-strength steel pipes rarely found in building construction. Due to their sheer weight and size and because of transport regulations, the pipes are made in sections weighing under 30 tons at fabrication plants all around Japan. The sections are then transported to the site and assembled using a tower crane with lifting capacity of 32 tons.

The largest sections used at the foot of the tower are 2.3 m in diameter, made from 10 cm-thick steel plates (Fig. 4). Because of weight restraints, these largest sections are only about 4 m long.

Steel Truss Structures

The tower itself is a truss of vertical, horizontal, and diagonal girders. Nearly all of the girders are high-strength steel pipes, which are directly welded together using the "multi-coupling" technique, allowing for clean and smooth joints. (Refer to Fig. 5)

Fig. 4 Giant Steel Pipe

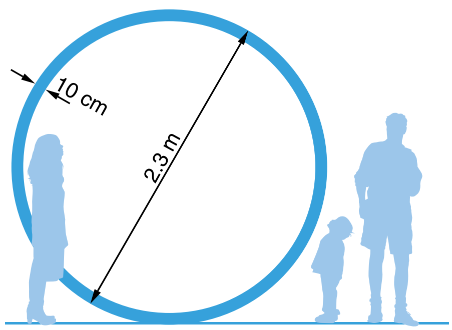

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Fig. 5 Multi-coupling Joint

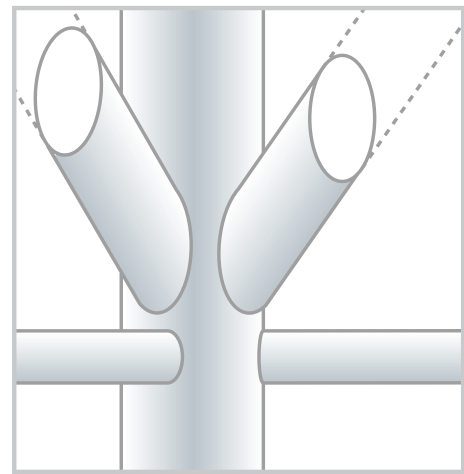

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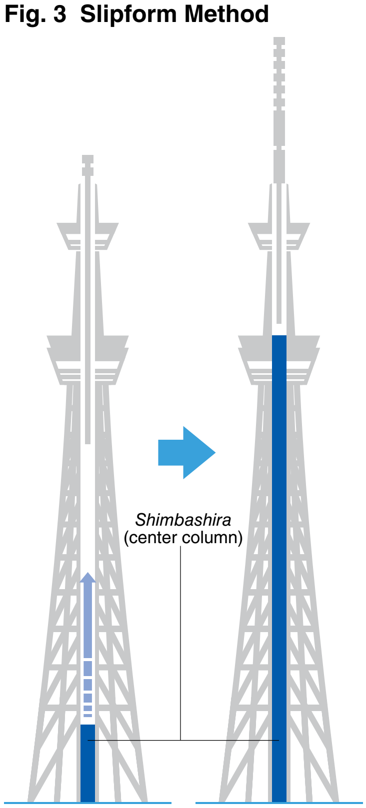
Fig. 3 Slipform Method



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Knuckle Walls

"Knuckle walls" developed by Obayashi Corporation are used as the foundation piles supporting the world's tallest tower. For the tower to be able to withstand the uplift and compressive forces of earthquakes and strong winds, these piles have nodule-like protrusions that work to hold the piles firmly in the ground, greatly increasing their strength in supporting the tower (Fig. 6). The wall shape of the piles also enhances their rigidity and resistance to the horizontal forces generated by earthquakes.

Winter 2010

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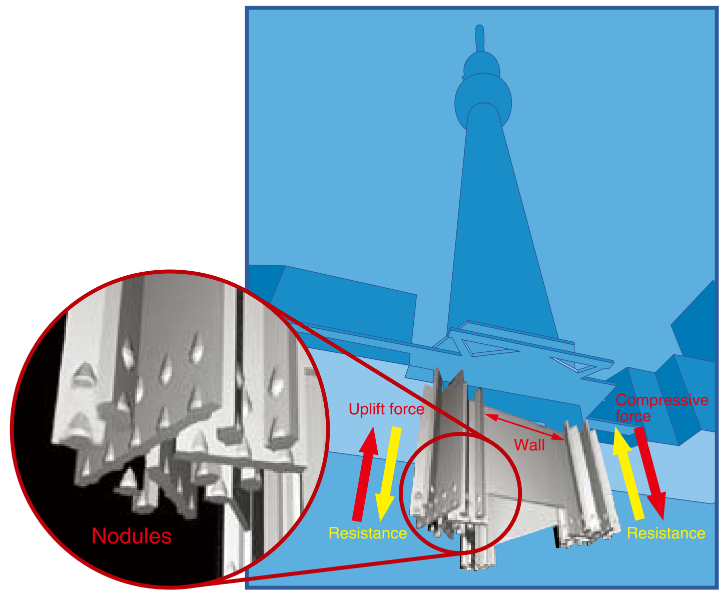
Fig. 6 Knuckle Wall



Obayashi Corporation

Spring 2011

Obayashi Corporation

Tokyo Sky Tree

— High-strength Steel Pipe for Antenna Tower —

In building the steel tower known as the Tokyo Sky Tree®, two grades of high-strength steel pipe are seeing extensive use—400 N/mm^2 grade and 500 N/mm^2 grade. In addition, for the topmost antenna tower, steel pipes for building structures having a strength rating of 780 N/mm^2, the highest in Japan, have been adopted. This is the first instance in Japan of 780 N/mm^2 grade pipe having a maximum wall thickness of 80 mm being applied in the construction of an architectural structure. Table 1 shows an outline of these steel pipes.

The dimensions of the steel pipe thus adopted are 500~2,300 mm in outside diameter and 19~100 mm in wall thickness. The steel pipe used for the lowest section of the tower is 2,300 mm in outside diameter and 100 mm in wall thickness.

Table 1 Outline of High-strength Steel Pipes

New pipe spec.	0.2% offset proof stress (N/mm^2)
630 N/mm^2 grade	630 or more
500 N/mm^2 grade	500 or more
400 N/mm^2 grade	400 or more
JIS G 3475 STKN490B	325~475

Production Processes for High-strength Pipes

The high-strength steel pipes are manufactured by means of the UOE, press-bending or roll-bending process. Examples of these processes are shown in Figs. 1 and 2.

In the UOE process, steel plates are cut to the prescribed sizes and subjected to bevel fabrication. Following this, the plates are formed into a U-shape using a U-press and then into an O-shape using an O-press. Next, the bevel section is cleaned and tack welding is conducted. The seams of O-formed materials are weld-joined from both the outside and inside by means of submerged arc welding, and the pipe thus manufactured is finished to the prescribed size using a mechanical expander. (Refer to Fig. 1)

The roll-bending and press-bending processes are primarily used when the steel pipes have wall thicknesses or outside diameters that are too large for other processes. As shown in Fig. 2, a bevel is fabricated on the edges of the steel plates, and after edge bending using a press, the plates are formed into a perfect cylinder using a roller or press, and the seam is weld-joined by means of submerged arc welding to produce the pipe. A cold, warm or hot forming process is adopted depending on the wall thickness and outer configuration.

Fig. 1 UOE Pipe-making Process

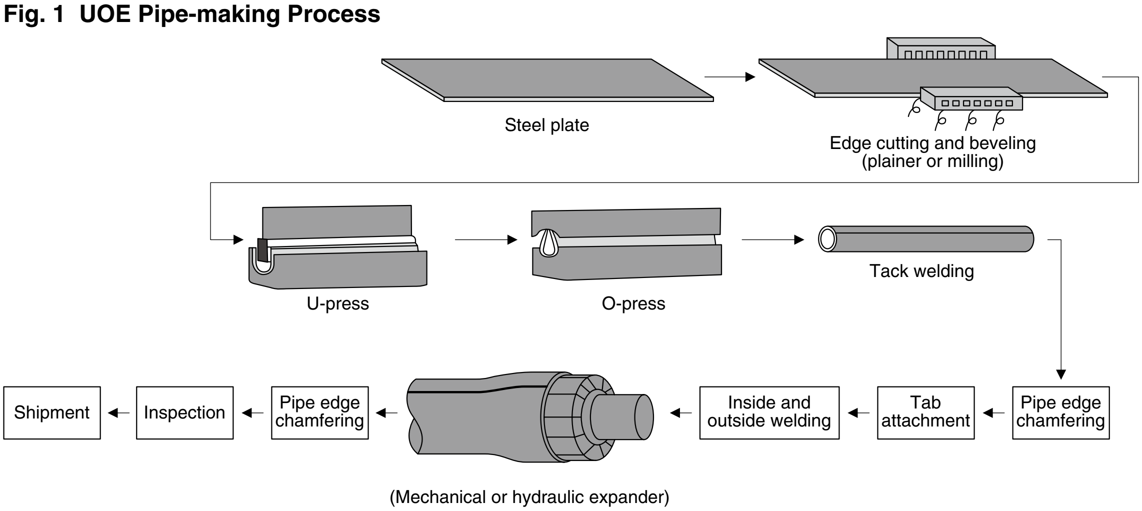
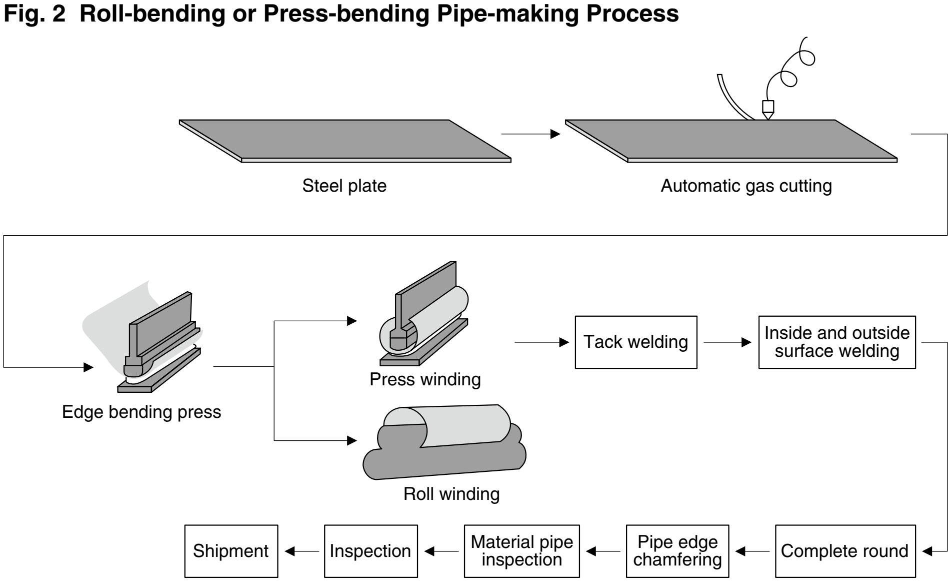


Fig. 2 Roll-bending or Press-bending Pipe-making Process



Steel Plates for High-strength Pipes

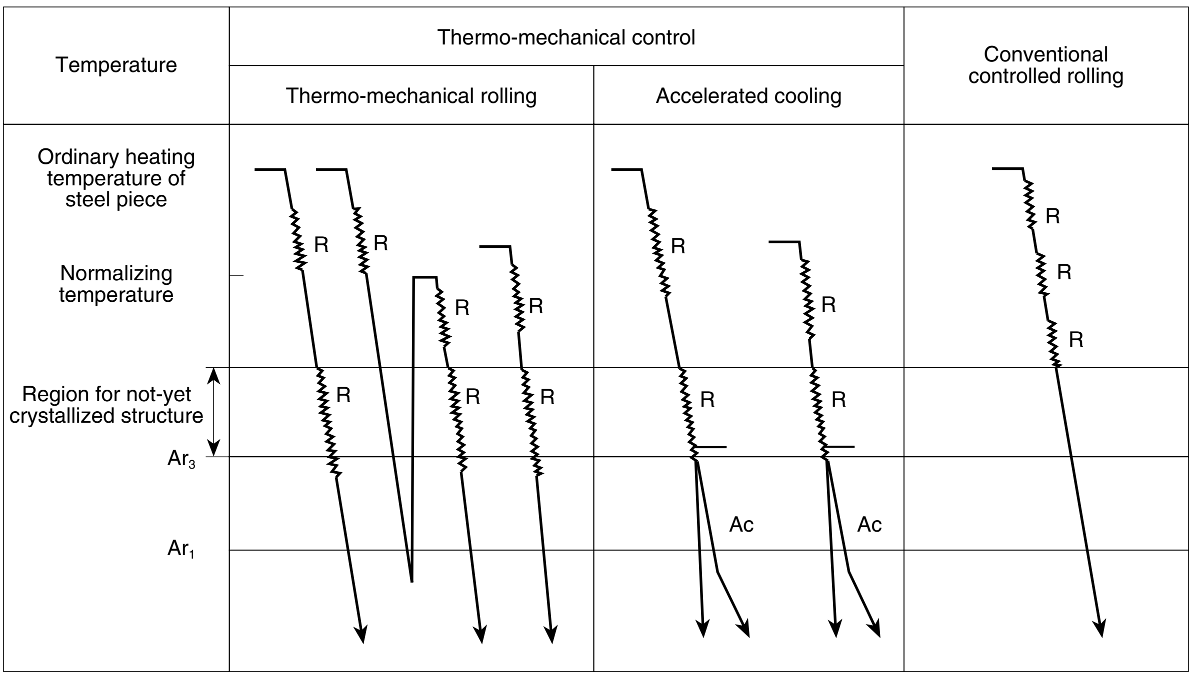
The steel plates used for high-strength pipe making are produced by forecasting the changes that are likely to occur in the material properties of the plate during the pipe-making process. These plates are produced by means of TMCP and heat treatment that uses high-performance furnaces.

TMCP (thermo-mechanical control process) is also called the thermo-mechanical treatment process. It is a process that produces plate with the optimal material properties by controlling the rolling temperatures and reduction patterns during plate rolling and by adjusting the cooling method immediately after rolling as necessary. Fig. 3 shows TMCP in JIS. The four major integrated steelmakers in Japan have developed their own proprietary TMCP, as shown in Table 3.

In addition to high strength, TMCP can secure high toughness (base metal and welds), which is normally incompatible with high strength. Further, TMCP allows the production of steel plates that are suitable for welding operations conducted high above the ground by improving weldability, e.g. welding at low preheating temperatures.

These excellent performances not only meet the needs of high-rise and large-span structures but also allow for smaller cross sections and thinner wall thicknesses in the structural members. This, in turn, contributes to greater aesthetic freedom in building construction and structural design, and to greater economy by reducing transport and fabrication costs and by shortening the on-site construction term.

Fig. 3 Thermo-mechanical Control Process for Plate Rolling (JIS G0201)



R: Under pressure Ac: Accelerated cooling

Table 3 Steelmakers' Own TMCPs

Maker	Abbreviation	Own process
Nippon Steel	CLC-μ	Continuous on Line Control Process-μ
JFE Steel	*Super*-OLAC	*Super* On-line Accelerated Cooling
Sumitomo Metals	DAC	Dynamic Accelerated Cooling
Kobe Steel	KCL	Kobe Steel's Controlled Rolling and Accelerated Cooling

Large-diameter, heavy-thick high-strength steel pipes destined for the construction of Tokyo Sky Tree

CFT Columns

— High-strength Steel-Concrete Composite Column Members —

By Atsushi Fujii, Research Institute of Technology, Konoike Construction Co., Ltd.
Tooru Hirade, Takenaka Research & Development Institute, Takenaka Corporation

In the R&D project introduced in "New Structural System Employing Innovative Structural Materials," a special feature in issue No. 29 (October 2009) of *Steel Construction Today & Tomorrow*, studies were made of CFT (concrete-filled steel tube) columns that use both high-strength steel and high-strength concrete. Specifically, experimental surveys were conducted to confirm the structural characteristics of CFT columns with regard to existing structural design equations.

A major target in the R&D project discussed in "New Structural System Employing Innovative Structural Materials" was to establish a steel-structure building system using innovative structural materials capable of ensuring that the main frame of a building could remain within its elastic range even during earthquakes with a seismic intensity of 7 (the highest seismic level of the Meteorological Agency of Japan). The performances required of the new steel materials to be used in this new structural system include enhanced resources savings, a reduced environmental burden, and higher seismic resistance. In other words, the goal of the project was to develop steel buildings featuring a safe structural system and a long service life.

Table 1 Outline of Specifications for H-SA700 Steel Products

Grade	Application	Plate thickness	Mechanical properties				Impact properties
		t (mm)	YS (N/mm^2)	TS (N/mm^2)	YR (%)	EL (%)	vE (J)
H-SA700A	Non-welding use	6~50	700~900	780~1000	≤98	≥16 JIS No.4	≥47 (0˚C)
H-SA700B	Welding use						≥47 (–20˚C)

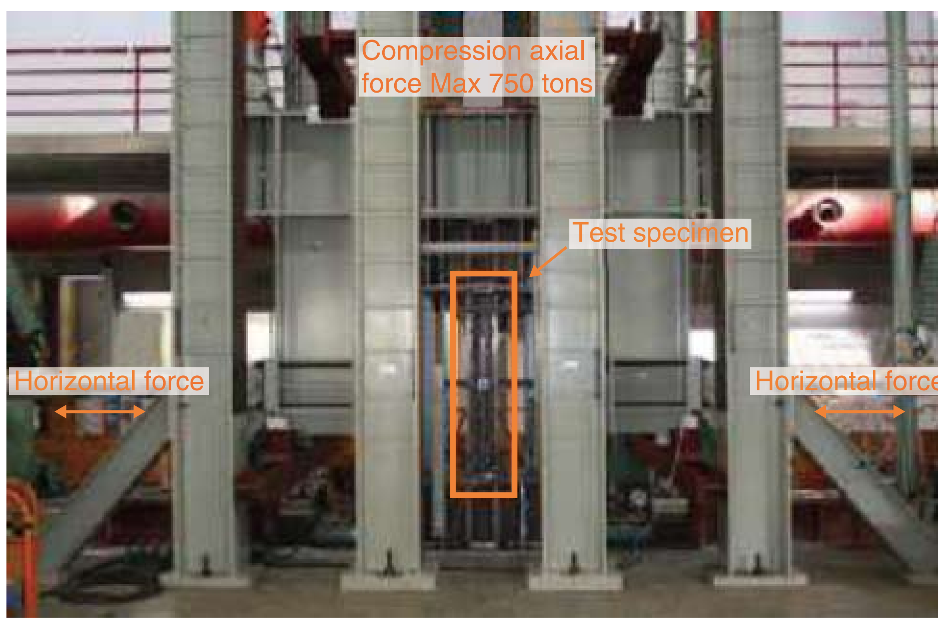


Photo 1 Tests on high-strength CFT columns

New 800 N/mm^2-grade Steel

In order to realize the framing required by the new structural system, the appropriate application of high-strength steel products is needed. Because the structural skeleton remains in its elastic range, it is not necessary to maintain strict application conditions for plastic range, such as the yield ratio. Accordingly, by capitalizing on high strength, it is possible to reduce steel usage and structural weight, thereby leading to lower costs.

Specifically, a steel framing system in which the main frame remains within its elastic range, even in earthquakes having a seismic intensity of 7, can be more rationally realized by fully utilizing high-strength CFT columns, thereby providing more comfortable space.

The 800 N/mm^2-grade high-strength steel that was developed in the current R&D project for use in elastic design for seismic intensity 7 earthquakes offers twice the tensile strength of conventional steel products. The higher tensile strength and environmental friendliness offered by this product were economically and rationally attained by reducing the amount of alloying elements added and by eliminating production processes through the effective use of innovative production technologies. In addition, the higher strength of this material lowers the environmental load by allowing a reduction in the use of steel products. Table 1 shows an outline of the specifications for 800 N/mm^2-grade steel products (H-SA700A and 700B).

Photo 2 Final test conditions of high-strength CFT columns

Structural Characteristics of High-strength CFT Columns

Experimental surveys were made of the structural characteristics of CFT columns manufactured through the combined use of 800 N/mm^2-grade high-strength steel and 100~150 N/mm^2-grade high-strength concrete in order to confirm their relation with existing structural design equations (refer to Photos 1 and 2). The following results were obtained:

- The experimental strength of CFT columns can be assessed by a corresponding application to existing calculation methods.
- As the elastic limit (at the time of yielding) increases, the deformation of CFT columns, manifested by their allowable strength, surpasses that of ordinary steel products.
- The constraint effect of square CFT columns can be applied only to weld built-up CFT columns.
- Under strict application conditions (large width-to-thickness ratio, high axial force), it is necessary to take into account the reduction of concrete strength (Fig. 1).
- In the case of a large width-to-thickness ratio and loading to the 45-degree direction in the adoption of cold-formed CFT columns, it is necessary to consider the shape and material properties of the corner R section (Fig. 2).

High Cyclic Fatigue Performance of High-strength CFT Columns

Because CFT columns are expected to see long-term use, experimental surveys were made, one, regarding changes in structural performance in the elastic range by obtaining multiple repetitive responses during small/medium earthquakes and strong winds and, two, regarding changes in horizontal rigidity in respective cycles (Fig. 3). The survey results show that the effect of the change of horizontal and axial rigidity of CFT columns on the entire building structure is limited.

Applications of New Structural Technologies and Materials

Applicability of the new structural system was proven by testing five applications that most fully utilize the system's characteristic features. Of these five applications, high-strength CFT columns were used in an applicability study conducted in a seismic-resistant medium-rise office building built at the periphery of an urban center (Fig. 4).

In the building, cores were located on both sides of the building, into which vibration-control braces were strategically arranged to treat most seismic forces. High-strength CFT columns were arranged at the building's center, and slender high-strength steel columns were positioned at the building's outer periphery. As a result, a 22 m-wide open space with high flexibility was secured. (Refer to Fig. 5)

Fig. 1 Treatment of Value $_c\gamma_U$ depending on Axial Force Ratio and Width-to-Thickness Ratio

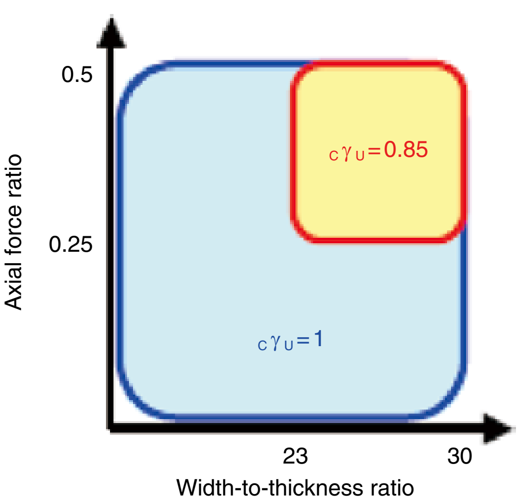
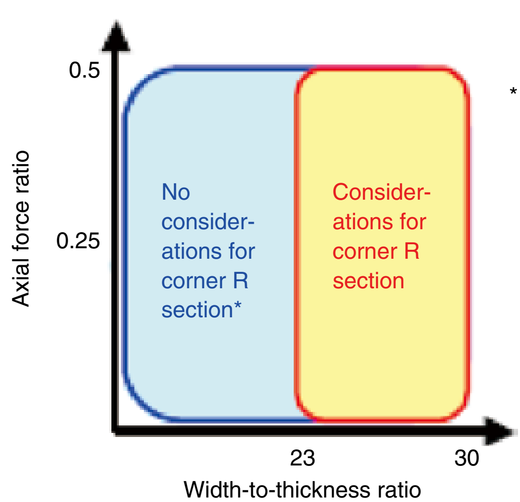


Fig. 2 Treatment of Corner R Section depending on Width-to-Thickness Ratio



* In the case of 45˚-direction loading, it is necessary to pay due considerations to the shape and material properties of corner R section.

Fig. 3 Relations between Horizontal Rigidity Reduction Rate and Number of Excitation Cycles of High-strength CFT Columns

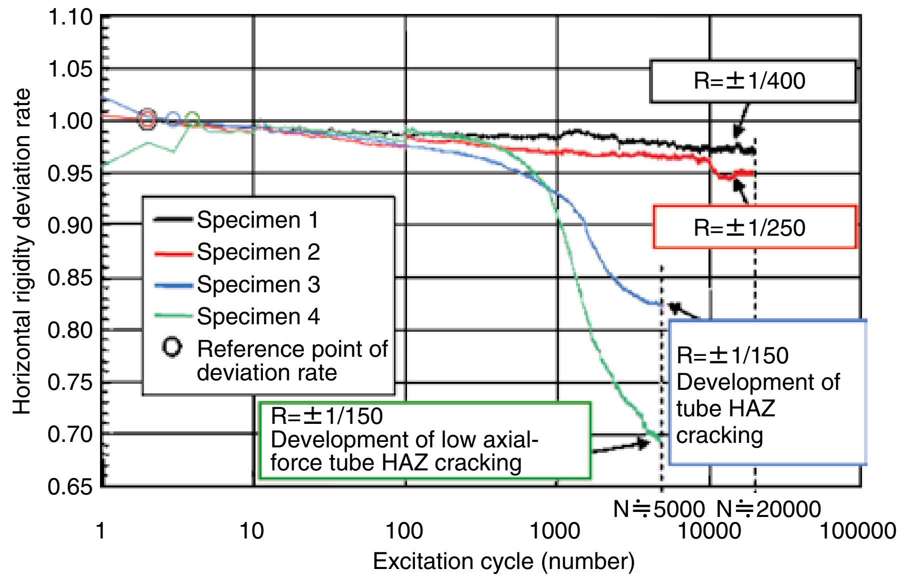
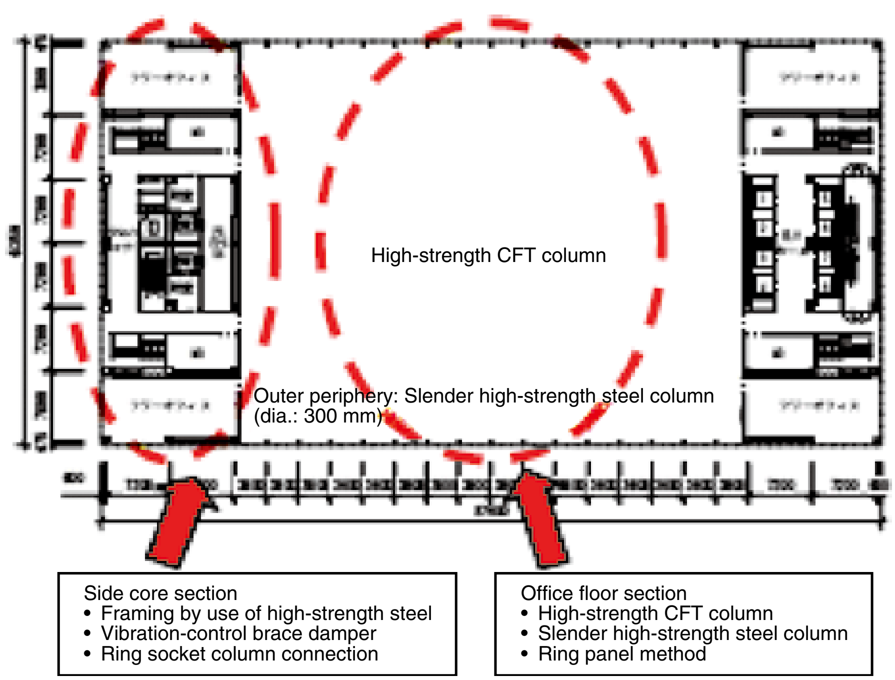


Fig. 4 Appearance of Highly Seismic-resistant Medium-rise Office Building to Be Built in the Periphery of Urban Center Employing the New Structural System

Fig. 5 Composition of Structural Systems Adopted for Highly Seismic-resistant Medium-rise Office Building



Southeast Asia Steel Construction Seminar for 2010

The Committee on Overseas Market Promotion of the Japan Iron and Steel Federation (JISF) has held the Southeast Asia Steel Construction Seminar since 2002. The major aim of the seminar is to promote a wider range of applications for steel structures and to develop markets for Japanese steel products in Southeast Asian nations, where improvements in social infrastructure are actively being promoted and the demand for steel civil engineering products is increasing.

In 2010, the seminar was held in Indonesia and Vietnam with extensive cooperation and support from government officials and academics involved in steel construction and from the Japanese Embassies located in the two nations as well. Specifically, the seminar was held in November 2010 in Jakarta and Hanoi and was centered on lectures citing examples of bridge and port/harbor construction and on the attainments of research on corrosion and corrosion protection. Outlines of the seminar are introduced below:

Outline of Jakarta Seminar

● Date (venue): November 9, 2010 (Hotel Grand Hyatt Jakarta)
● Participants: 130 from government and academic fields, fabricators, design companies, construction companies
● Lectures: Seven themes (four from Japan, three from Indonesia)
— "Steel Bridge Maintenance in Japan" (Prof. Masatsugu Nagai)
— "The Infilled Steel Concrete Structure for Health Sciences Faculty in University of Indonesia" (Dr. Henki W. Ashadi)
— "Recent Development in Indonesian Railway Steel Bridges" (Dr. Heru Purnomo, Mulia Orientilize, M.Eng)
— "The Need of Steel Bridges Maintenance in Indonesia" (Mr. Herry Vaza)
— "Current Topics of Steel Structures In Tokyo Bay" (Prof. Osamu Kiyomiya)
— "Life Extension of Steel Structures by Corrosion Prevention Technology — Especially Port and Harbor Steel Structures" (Prof. Hidenori Hamada)
— "New Seismic Design for Port & Harbor Structures" (Prof. Osamu Kiyomiya)

Outline of Hanoi Seminar

● Date (venue): November 12, 2010 (Hotel Hilton Ha Noi Opera)
● Participants: 110 from government and academic fields, fabricators, design companies, construction companies
● Lectures: Six themes (three from Japan, three from Indonesia)
— "Design Codes and Construction Trend on Steel-concrete Composite Bridges in Japan" (Prof. Masatsugu Nagai)
— "Evaluation of Loading Testing Results on Can Tho Cable Stayed Bridge (Prof. Dr. Nguyen Viet Trung)
— "Applications of Steel Construction in Transportation Engineering in Vietnam (Mr. Nguyen Trung Hong, Mr. Tran Quoc Bao)
— "Design & Construction of Port Structures by Steel Piles" (Prof. Osamu Kiyomiya)
— "Some Applications of Steel Construction in Bridge Engineering in Vietnam" (Dr. DO Huu Thang and Mr. BUI Xuan Hoc)
— "Life Extension of Steel Structures by Corrosion Prevention Technology — Especially Port and Harbor Steel Structures" (Prof. Hidenori Hamada)


Seminar scenes (Jakarta) (Hanoi)

No. 31
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COVER
Artist's sketch of Tokyo Sky Tree upon completion

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