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Development of Sandwich-Structure Submerged Tunnel Tube Production Method

Hideo KIMURA*1 Ichio KOJIMA*1
Hiroo MORITAKA*1

Abstract

Since 1988, Nippon Steel Corporation has developed a new submerged tunnel tube production method consisting of prefabrication method which does not required graving docks, composite structure, and reliable flexible joint. The Kobe Minatojima Submerged Tunnel, the first steel-concrete sandwich tunnel tube, was produced in the graving dock. This development has been completed with the first tube completion of The Naha Submerged Tunnel, which the double-skin steel tube shell body including a bellows joint was towed to Okinawa from Kitakyusyu and was placed high fluidity concrete while afloat early spring in 2001.

1. Introduction

The production methods of submerged tunnel tubes are classified into "steel shell tunnels" and "concrete tunnels." By steel shell tunnels, steel shells of a tunnel tube bodies are fabricated at a green field site and then launched to the sea, reinforcing bars are arranged in the shells kept floating on the sea, forms and timbering are fitted to them, and a submerged tunnel tube bodies are completed by concrete placing. By concrete tunnels, on the other hand, tunnel tube bodies of reinforced concrete are produced in graving docks. While the former is the popular practice in North America, the latter is widely practiced in European countries.

Steel shell tunnels were popular in Japan, but because of the unpleasant and troublesome work of concrete placing in a closed space in steel shell bodies, concrete tunnels have come to be widely practiced like in Europe since the large graving dock was constructed at Oh-i, Tokyo. However, with increasing number of seaside area development projects recently, a shortage in the capacity of graving docks for the production of submerged tunnel tubes has come to be felt strongly, but good locations for new construction of graving docks are not always easily available near the sites of tunnel installation.

Whereas, in the structure of steel shell tunnels, the steel shell working as an outer form for the concrete placing works also as water-tightness, in concrete tunnels, steel plates 6 to 8 mm or so in thickness are used in the outer walls of the tunnel tubes for watertight purposes, too. In either of the tunnels, tubes are designed basically in reinforced concrete structure wherein, after completion of the tunnel, the loading is borne by the reinforced concrete and the steel shell on the outer wall of the tunnel tube work for watertight purposes only. In pursuit of design rationality, however, submerged tunnel tubes of a composite structure (steel-concrete open-sandwich structure), in which the steel shell from structural members, were produced in the graving dock for the installation of Sakishima Tunnel in the Osaka Port for the first time in Japan. The composite structure, in which a significant proportion of destructive energy is absorbed by the toughness of the steel plates, is suitable for earthquake-proof structures and thus, it has since been regarded as the most promising structure for submerged tunnel tubes.

Since the installation of the No. 2 Shipping Lane Tunnel in the Tokyo Port, a new technique has been introduced for the seismic joints of submerged tunnel, wherein flexible joints are formed in the immersion joints between tunnel tubes using the rubber gaskets for hydraulic pressure jointing as compression springs and PC wires as tension springs. This technique has been used in 8 tunnels already. Meanwhile, ever larger deformation capacities have been required of the rubber gaskets because of the revision of the design standards on earthquake movement and to be used as countermeasures against soil settlement, and large rubber gaskets near the limit of manufac-

*1 Civil Engineering & Marine Construction Division

turing have been developed as a response. However, the long-term reliability of the flexible joints, in which organic rubber gaskets are used under high compression strain, was seriously shaken as a result, especially, of a collapsing accident of rubber gaskets during the hydraulic pressure jointing work of Kawasaki Shipping Lane Tunnel installation. In this background, development of a new joint structure has been awaited.

Facing the technical challenges in the fields of the production method, structure and joints of submerged tunnel tubes, Nippon Steel Corporation has proceeded with research and development towards a new production method of submerged tunnel tubes on the concepts of "prefab units not requiring a graving dock," "composite structure" and "reliable flexible joints." This paper reports "the sandwich-structured submerged tunnel tube production method" developed as a result of the above research and development.

2. Sandwich-Structure Submerged Tunnel Tube Production Method

Fig. 1 shows the structure of the developed submerged tunnel tube. The steel-concrete sandwich-structure of the tunnel tube makes it possible for the steel shell to work not only as water-tightness but also as reinforcing members, concrete forms and timbering, and thus,

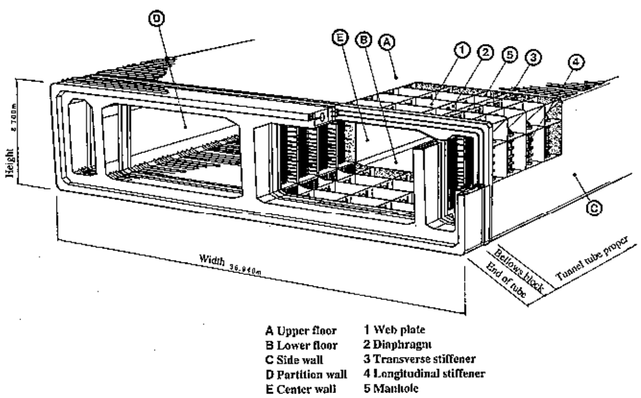


Fig. 1 Steel shell body of sandwich-structured submerged tunnel tube

cost and manpower saving and short installation period are realized. Additionally, the developed method does not require a graving dock, which has been indispensable for producing the conventional concrete tunnels.

Fig. 2 shows the basic production sequence of the submerged tunnel tube according to the developed method. The steel shell of the tunnel tube is fabricated in a green field site in blocks of an adequate dimension. After assembly on a launching skid way, a completed shell body is loaded onto a semi-submersible barge, tied down thereto and is towed to the site of concrete placing. Arriving at the site, the tethers are removed and the shell body is made to float by itself by letting water into the barge and towed to a concrete placing quay, where it is moored. Then, high fluidity concrete is cast in the shell to complete a tunnel tube unit.

By the method, instead of conventional seismic joints formed at the immersion joints, flexible joints are made of high ductility steel so as to guarantee perfect water-tightness and are prefabricated in the steel shell body at the green field site during its assembly. A highly reliable flexible joint under certain quality control is provided in this way.

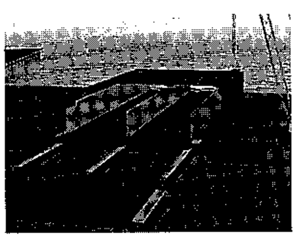
A series of research and development were carried out for establishing the component technologies of the new method, namely, the steel-concrete sandwich structure, the casting work method of high fluidity concrete, the bellows joint and the production works of submerged tunnel tubes while afloat.

2.1 Steel-Concrete Sandwich Structure

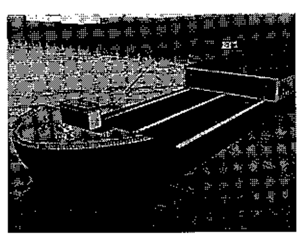
2.1.1 Basic Structure of Sandwich-structured Submerged Tunnel Tubes

In consideration of the production work of the submerged tunnel tubes, the steel-concrete sandwich structure shown in **Fig. 3** was adopted as the basic structure of the submerged tunnel tubes for the developed method, wherein the steel structure at the fabrication stage matches structurally with the composite structure in place.

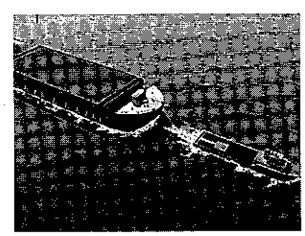
The members of the submerged tunnel tubes are totally free of reinforcing bars; the steel plates of both the side walls working as compression and tension reinforcing members are connected to each other by the upper and lower floor composed of web-plates (running



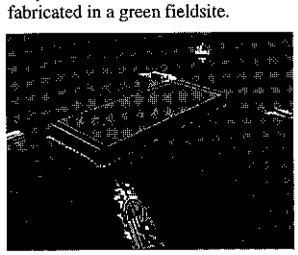
(1) Fabrication of tunnel tube steel shell body: A tunnel tube steel shell body is fabricated in a green fieldsite.



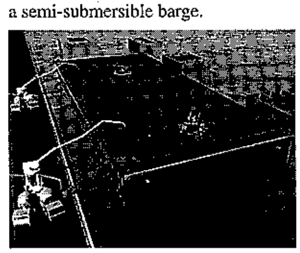
(2) Loading to barge: A completed tunnel tube steel shell body is loaded onto a semi-submersible barge.



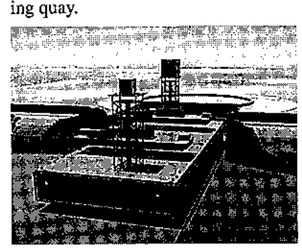
(3) Transportation: The steel shell body on the barge is towed to a concrete casting quay.



(4) Launching: The steel shell body is launched to the sea by introducing water into the barge.



(5) Casting of self-compacting high fluidity concrete: Self-compacting high fluidity concrete is cast to the steel shell body moored to the quay.



(6) Rigging and installation: A complete tunnel tube is rigged and installed by submersion (same as in conventional method).

Fig. 2 Production sequence by sandwich-structured submerged tunnel tube

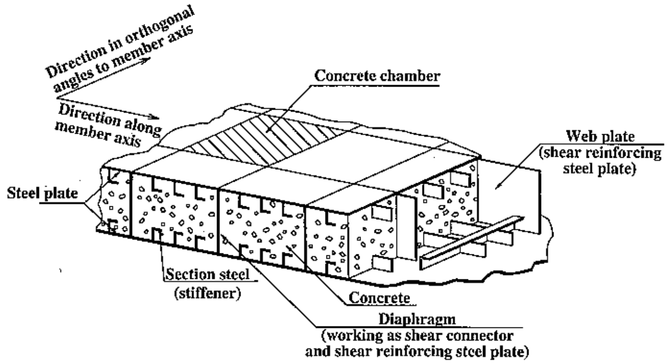


Fig. 3 Sandwich-structured member

in the axial direction of the member) working as shear reinforcing plates (also working as compression and tension reinforcing members) and diaphragms (running in orthogonal angles to the axial direction of the member) working as shear connectors (also working as shear reinforcing members).

Concrete is placed compactly in the closed section chambers formed by these steel plates so as to prevent it from falling out. Section steels (angles and flat bars) or the like are welded onto the steel plates of the compression and tension reinforcing members for the purpose of securing stiffness during the fabrication and transportation and reinforcing the steel shell body during the concrete placing. They also work as shear connectors in place, contributing to the integration of the steel-concrete structure.

2.1.2 Design Code of Steel-Concrete Sandwich Structures

The characteristics of the steel-concrete sandwich structures were being made clear at the time of the development of the new method through examinations and studies, but the findings had not been sorted out systematically to form a design code. In this situation, the Society for the Study of Double Steel Shell Structure (organizing company: Nippon Steel) commissioned the Japan Society of Civil Engineers to study the nature of the structure and as a result, "The Design Code for Steel-Concrete Sandwich Structures (draft)" [1] was prepared by the Study Sub-committee for Steel-Concrete Sandwich Structure (headed by Okamura, A.). Thus, the design of submerged tunnel tubes of the steel-concrete sandwich structure has been made possible.

The following points regarind the design code are particularly noteworthy.

(1) Handling of the stress occurring to steel plates during concrete placing:
When the stress of a member during the service life of the tunnel is a tensile stress, the influence of the stress during production can be evaluated as an issue of the tensile strength of a steel plate having an initial strain. The code judges that the influence of the initial strain of a steel plate, which has sufficiently large plastic deformability, on ultimate strength is negligibly small. For the case of a compressive stress, on the other hand, the code proposes a formula for calculating the post-buckling strength of the steel plate.

(2) Method of determining the number of shear connectors:
Since shear connectors are arranged in a scattered manner, it is difficult to obtain a really composite state at every part of the structure. In this situation, it is desirable to arrange the shear connectors so that the distribution of axial forces of the steel plates is as close to the distribution of a completely composite structure as is possible. For this end, the code recommends to make the sum of the shear strengths of the shear connectors arranged between a section where the bending moment is zero and a section where the bend moment is the largest greater than the variation of the axial force of the steel plate, as a simple and practical solution. The code also proposes, based on past test results, a formula for calculating the shear strength of the section steels used as the shear connectors.

2.2 Casting Works of High Fluidity Concrete

For realizing the steel-concrete sandwich structure, it was imperative to develop a concrete material that could eliminate compacting works, which had been indispensable in conventional concrete placing, and the casting method of such a concrete material. It was also necessary to work out, on the basis of the material and casting method to be developed, the details of the steel shell structure to enable sound casting of the concrete material.

2.2.1 Development of Self-compacting High Fluidity Concrete

Steel Structure Development Center of Nippon Steel's Steel Research Laboratories developed new self-compacting high fluidity concrete having high resistance against separation of component materials by adequately combining fine-grained blast furnace slag, which is an economical multi-purpose material, with super plasticizer and brought the material to practical application[2]. For verifying actual applicability of the new powder-based self-compacting high fluidity concrete material to the production of the sandwich structure, it was used for the construction of underground electric cable culvert at Nippon Steel's Kimitsu Works[3]. After that, the self-compacting high fluidity concrete was used in the casting works of the closure joint steel shells of the Tamagawa and Kawasaki Shipping Lane Tunnels[4], and then it came to be widely used for the production of submerged tunnel tubes.

2.2.2 Casting Method and Structural Details

A series of concrete casting tests were carried out using a real sized model of the concrete chambers of the sandwich-structured submerged tunnel tube. As a result, the required characteristics of the concrete material were made clear and on that basis, the casting method and structural details shown in **Fig. 4** were worked out.

(1) Required performance of concrete material:
The following items were specified as the required performance of the high fluidity concrete at acceptance inspection.
Slump flow value $SF = 65 \pm 5$ (cm)
V-funnel test value $V = 10 \pm 5$ (s)

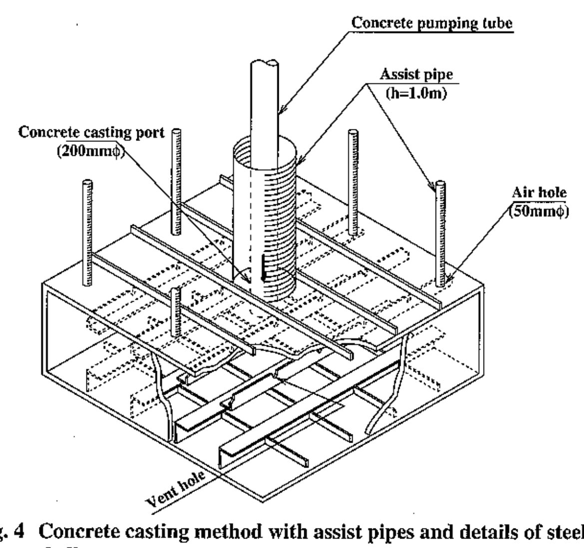


Fig. 4 Concrete casting method with assist pipes and details of steel shell structure

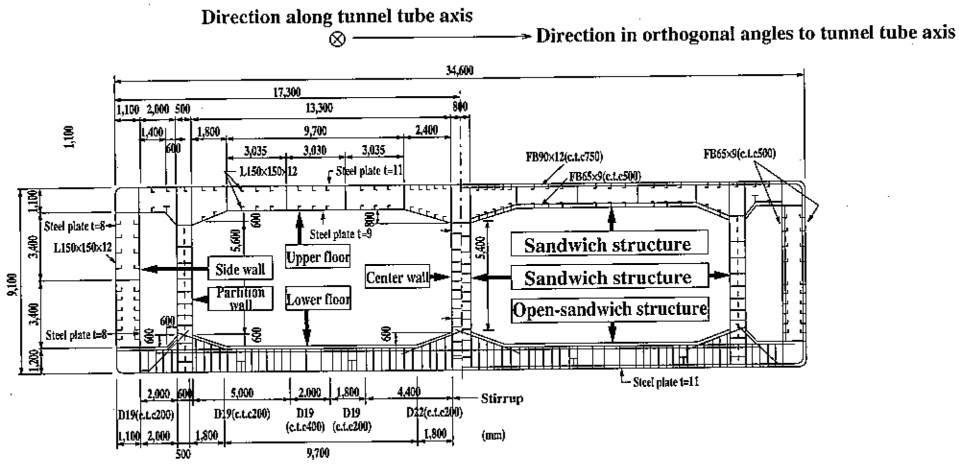


Fig. 5 Section view of submerged tube for Kobe Port Minatojima Tunnel

(2) Casting method with assist pipes:
As simple tools to assist the casting work not requiring a special apparatus for forcing concrete into the steel shell spaces, pipes 1 m tall were set at the concrete casting port and air holes. It is possible to cast the concrete to every corner of concrete chambers in a high density thanks to the pressure head of the high fluidity concrete rising in the assist pipes.

(3) Optimum arrangement of casting port and air holes:
In the outer wall steel plates of the shell, of which water-tightness is required, it is necessary to arrange as small a number of air holes as possible because they have to be closed later by welding. The optimum number and arrangement of the casting port and air holes were determined based on the casting test.

(4) Details of steel shell structure:
The cuts and scallops required for the fabrication of the steel shell are fully utilized for enhancing casting efficiency. Structural details were specified in consideration of the casting efficiency of concrete; vent holes were formed in the angle steels welded to the upper steel plate, around which the concrete casting is most difficult; and a gap was provided at the upper end of every vertical stiffener.

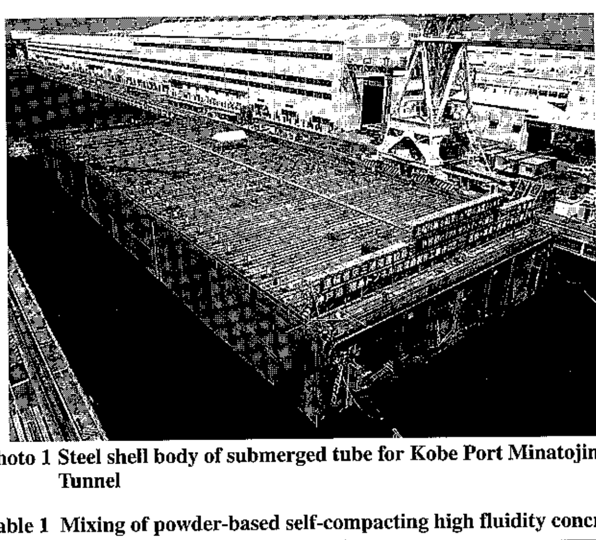


Photo 1 Steel shell body of submerged tube for Kobe Port Minatojima Tunnel

Table 1 Mixing of powder-based self-compacting high fluidity concrete

Slump flow value (cm)	Coarse aggregate volume (l/m^3)	W/(C+Sg) (%)	s/a (%)	Unit amount(kg/m^3) W	C	Sg	S	G	SP/(C+Sg) (%)
65±5	300	30	50	176	176	411	778	777	1.3

2.3 Production Works of Submerged Tunnel Tubes for Kobe Port Minatojima Tunnel

The Minatojima Tunnel is a 1.6-km underwater tunnel constructed as the second link, after the Kobe Ohashi Bridge, between Port Island and the main urban area of Kobe City. The 520-m portion by the submerged tunnel method installed six submerged tunnel tubes. As seen in **Fig. 5**, the lower floor is of the open-sandwich structure and the side walls and the upper floor are of the sandwich structure first applied to submerged tunnel tubes. The high fluidity concrete was cast in the sandwich structure portions. **Photo 1** shows the steel shell of a submerged tunnel tube body of the tunnel being transported for dock shift for concrete placing works. The powder-based self-compacting high fluidity concrete the mixture of which is shown in **Table 1** was cast in the shell in a graving dock[5].

Among various investigations, studies and verification tests in preparation for the design and production works of the first submerged tunnel tubes of the sandwich structure, results significant for the design and works control of the project were obtained especially in the following tests.

2.3.1 Load Capacity Test of Shear Connectors of Section Steels[6]

With regard to the load capacity of the real-size section steel stiffeners, it was found out through the test illustrated in **Fig. 6** that the load capacity value calculated according to "Design Code for Steel-Concrete Sandwich Structure (draft)" was not necessarily on the safe side as far as the section steels were used as shear connectors. At this finding, it was decided that structural safety should be confirmed in design works by setting a design load capacity figure for each section size based on the test results.

2.3.2 Mechanical Properties of Incompletely Filled Composite Sandwich Members[7]

For the control of the casting works of the self-compacting high fluidity concrete, a non-destructive test was applied using a void detector having a small capacity neutron beam source. For the purpose of specifying a permissible depth of voids, a series of test was carried out for confirming the load capacity of incompletely filled composite sandwich members using the void depth as parameter. Based on the results of the test, a work control standard was set forth, wherein the permissible void depth was set at 5 mm.

2.4 Bellows Joints

The bellows joint is a flexible joint having a high deformability

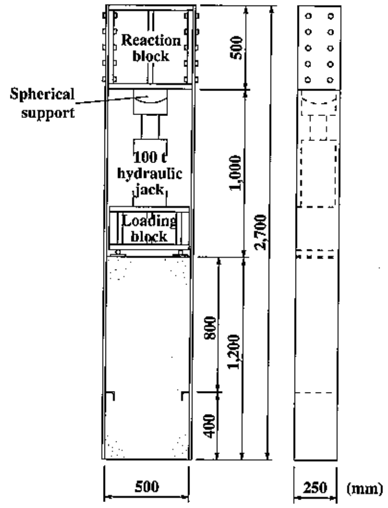


Fig. 6 Load capacity test of section steel stiffeners

that has been widely used, mainly in the field of piping, for absorbing the dislocations subjected to thermal expansion/contraction and earthquakes. This being the case, its design techniques, quality control in the manufacture and long-term corrosion protection methods are well established. For this reason and because of its excellent durability and reliability, the bellows joint was adopted as the flexible joint for the submerged tunnel tubes in place of conventional seismic joints.

Note that, in the developed method, the rubber gaskets indispensable for sealing water in the hydraulic pressure jointing works of submerged tunnel tubes are used only during their immersion works, and the bellows joints installed in the steel shell body, as shown in **Fig. 7**, are provided separately. The bellows joints are fixed to the tubes with temporary fasteners capable of withstanding the hydraulic pressure jointing force, which will be removed after the hydraulic pressure jointing of all the tunnel tubes are completed.

For the application of the bellows joints to the submerged tunnel tubes, FEM elasto-plasticity analysis and model tests and studies on mechanical characteristics, fatigue properties, etc. were carried out on reduced scale models and then, the manufacturing and inspection methods and the low cycle fatigue property were confirmed through a test using a real-size model.

2.4.1 Manufacturing Method

Under a condition of the outer water pressure at a depth of roughly 20 m acting on a tunnel tube of a rectangular section, a thickness of 14 mm is required for a bellows joint to achieve a target deformability of ± 100 mm or so in the axial direction of the tunnel. Since few bellows of such a large size and thickness had been used for piping, its manufacture constituted a big challenge.

After studies, the bellows joint for submerged tunnel tubes as shown in **Fig. 8** was designed as follows: 14 mm of plate thickness, 250 mm of corrugation amplitude, the inner radius of bend being 3 times the plate thickness, the number of corrugations (peaks) of 2. The same material as that of the tunnel tube steel shell body proper was selected also for the bellows, namely the rolled steel for welded structure (SM490Y) under Japanese Industrial Standard (JIS). Further, in accordance with the conventional philosophy of the safety in water-tightness, two bellows joints were arranged at a section in double layers and for avoiding stress concentration, the corner portions were formed in round.

After trial manufacturing, the manufacturing sequence was decided as illustrated in **Fig. 9**: a straight bellows segment is formed by cold bending of a steel plate the rolling direction of which runs in parallel to meridian of the bellows, or in the longitudinal direction of the tunnel; and a corner segment is formed by cold bending of a straight segment into round shape. Note that residual stress from the forming works is removed by several times of heat treatment during the forming works. The bellows segments thus manufactured are welded to the size of a tunnel tube section and assembled as a part of the tunnel tube steel shell body in the form of a complete flexible joint.

Since the bellows joint is placed in as an arbitrary part of the tunnel, it is possible, unlike conventional joints, to arrange it at a position to minimize the sectional force of the tunnel at an earthquake.

2.4.2 Low Cycle Fatigue Property

The fatigue damage of the bellows joint subjected to temperature fluctuation, water level change and the response to seismic movements is checked in terms of the cumulative fatigue damage ratio by

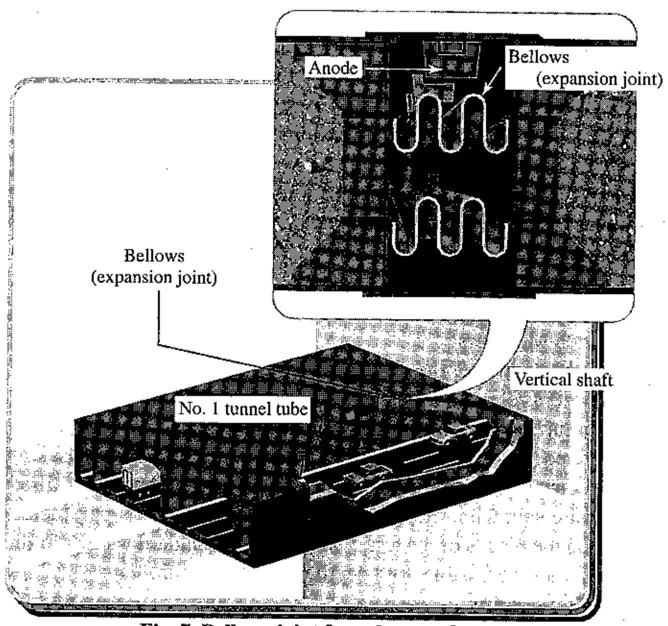


Fig. 7 Bellows joint for submerged tunnel

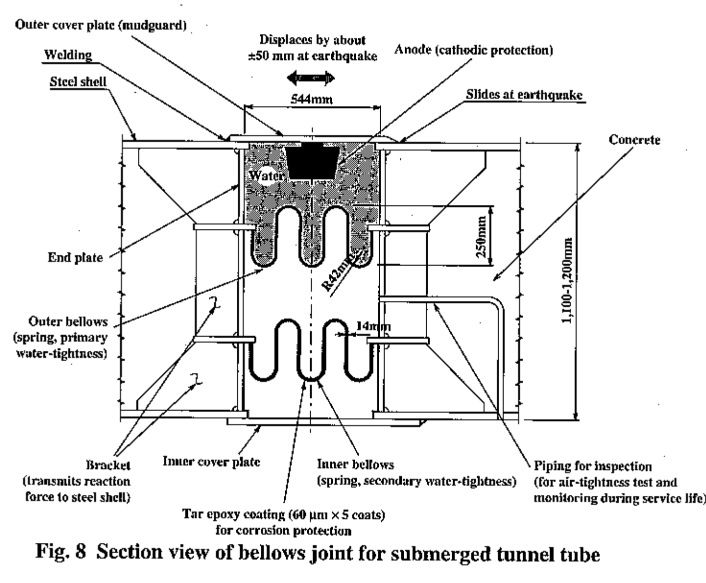


Fig. 8 Section view of bellows joint for submerged tunnel tube

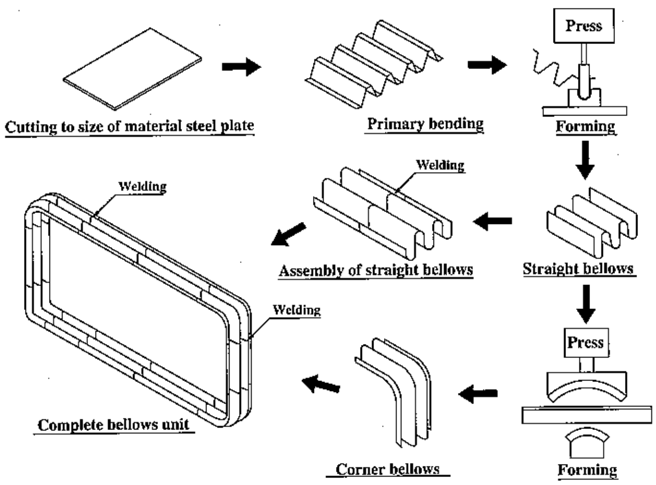


Fig. 9 Manufacturing sequence of bellows joint for submerged tunnel tube

the Miner's rule. In the response to seismic movements, which accounts for the most part of the fatigue damage, the peaks and depressions of the corrugation undergo the so-called low cycle fatigue in which the material is plasticized in meridian direction of the bellows. The occurrence of fatigue fracture of the bellows, of which water-tightness is required, was confirmed through a fatigue test using a real-size model. The test was conducted on corner segments as seen in **Photo 2** using a 2,000 kN pulsator assuming two different amplitudes of seismic movement, level 2 (±43 mm) and twice that (±86 mm). The test results are summarized in **Table 2** and plotted in **Fig. 10** together with an applicable fatigue curve. The test result values are in good agreement with the fatigue curve by ASME.

For the purpose of preventing toughness deteriorating from strain

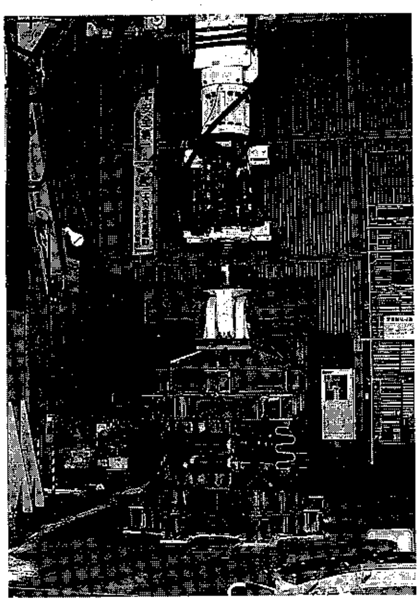


Photo 2 Fatigue test of bellows for submerged tunnel tube

Table 2 Fatigue test result of bellows for submerged tunnel tube

	Displacement (mm)	Number of cycles to crack occurrence	Design number of cycles
Level 2	±43	700	10
Level 2 × 2	±86	140	-

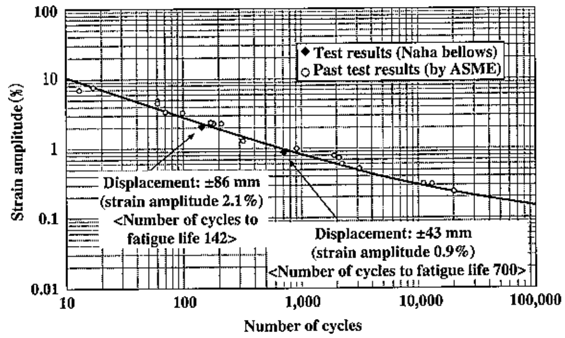


Fig. 10 Fatigue curve by ASME and test results

ageing by the heat treatment during the cold forming of the bellows, the Charpy absorbed energy specification of the steel material was newly included in the design guideline, although there is little worry about such a trouble with a steel plate 14 mm or so in thickness. The specification is expected to be effective also for preventing the fall in toughness caused by strain ageing after the low cycle fatigue.

2.5 Production Works of Submerged Tunnel Tubes while afloat

Because of the fact that all the reinforcing bars, concrete casting forms and timbering are substituted by the steel shell in the sandwich-structured submerged tunnel tube, the new method is, unlike conventional steel shell tunnels, free from the complicated processes of the production works and, in addition, deformation of the tube is smaller than that in the conventional steel shell tunnels and it is more easily controllable because of the following reasons:

- The stiffness of the steel shell body is large even before the concrete is cast because of the double steel skin plate structure;
- Concrete placing works can be programmed chamber by chamber (about 10 m^3 each) and thus the order of concrete casting of the chambers can be scheduled as convenient; and
- It is possible to place concrete in wall chambers before lowerfloor chambers and thus, the flexural rigidity in the axial direction of the tunnel tube can be effectively increased from the early stage of production.

In the production works of the submerged tunnel tube while afloat, while no special attention is required regarding the sectional deformation of a tunnel tube unit caused by the dead weight of concrete since it is small enough within the tolerance range of its internal space, it is desirable to minimize the deformation in the vertical direction along the tube axis, which is the direction most prone to deformation, since the deformation in this direction has a significant influence on the hydraulic pressure jointing. An effective countermeasure for this is to place concrete in a sequential order to minimize the deformation, but how to predict the deformation was a problem.

In the production works of the submerged tunnel tubes for the Kawasaki Port Tunnel, which was the steel shell tunnels, the axial deflection of the tunnel tubes was as small as 50 to 70 mm or so, but the deformation of the submerged tunnel tubes calculated using the dead weight of concrete as the only external force upon a beam on an elastic foundation did not conform to the actual deformation not only in its amount but even in the trend of its change[8].

Seeking a solution in the situation, the factors of the deformation of a tunnel tube were expressed in the form of a dynamic model wherein the change of sectional rigidity during temperature change was assumed to accumulate as deformation. In the dynamic model, the bending moment caused by temperature difference ($M_{\textcircled{t}}$), which is expressed by the formulae below, caused by ups and downs of

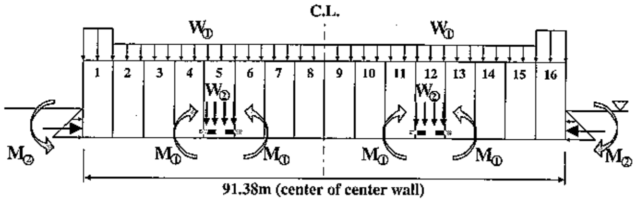


Fig. 11 Loads acting on tunnel tubes during production works while afloat

temperature because of the heat during the hardening of concrete, was counted as a load factor in addition to the dead weights of the steel shell and concrete (W①, W②), as shown in **Fig. 11**.

$$P_i = A_i \times E_i \times \alpha \times \Delta t_i \quad (1)$$

$$M_i = \Sigma(P_i \times h_i) \quad (2)$$

where, A_i : sectional area (m^2),

E_i : Young's modulus (tf/m^2),

α : coefficient of linear thermal expansion (1/°C),

Δt_i : temperature variation range (°C), and

h_i : deviation from the neutral axis of the tunnel tube (m).

In the analysis using the dynamic model: assumptions were made about the adiabatic heating curve of concrete, atmospheric temperature, air temperature in the tunnel tube, concrete temperature at the end of mixing, sea water temperature and heat transfer coefficient between tunnel members and atmosphere; a temperature change model was set forth for each member in a tunnel tube section based on one-dimensional FEM heat transfer analysis; deformation during the production works was estimated based on this models and work schedule; and the estimated figures were compared with actual measurements. As a result, the model proved capable of reproducing, if roughly, actual deformation within a tolerance range acceptable for execution management. The dynamic model has been turned into a program for selecting a suitable concrete placing order from among theoretically huge amount of possible cases and is now used for the scheduling of actual production works.

2.6 Production Works of Submerged Tunnel Tubes for Naha Port Tunnel

The Naha Port Tunnel is an underwater tunnel connecting the Naha Airport with the Naminoue area of Naha City, Okinawa, across the entrance of the bay of the pier area. Its 724-m section from the vertical shaft on the airport side to that on the Miegusuku side was installed submerged tunnel using 8 tubes. As seen in the section shown in **Photo 3**, the submerged tunnel tubes have the sandwich structure.

In the production works of the submerged tunnel tubes, the steel shell bodies were fabricated outside Okinawa Prefecture and transported to Naha on barges, and the submerged tunnel tubes of the sandwich structure were produced on the sea. The bellows type flexible joint was used for the first time for submerged tunnel tubes in this project. **Photo 4** shows a section of the bellows block for this tunnel during manufacturing and a complete bellows block being assembled to a tunnel tube steel shell body. This body, 4,400 t in total weight (including the rigging), fabricated at Wakamatsu Fabrication Center of Nippon Steel in the north of Kyushu Island were loaded onto the semi-submersible barge "Ocean Orca" (see **Photo 5**) using 114 units of air caster, having a transportation capacity of 53 t each, and shipped for Okinawa.

Then, the steel shell body was moored in the Naha Port and completed there after 2 months of casting works of the self-compacting high fluidity concrete (**Photo 6**). The casting works were done as follows: the concrete placing sections were divided into 8 blocks one-sided along the axis of the tunnel and each block was divided symmetrically with respect to its axis as shown in **Fig. 12**; for the purpose of effectively increasing the flexural rigidity of a tube section in the axial direction from the initial stage of the casting works, the concrete was cast first in the wall portions in the order of the blocks to minimize the bending moment of the tube resulting from its dead weight; and then the concrete was cast in the lower floor and then upper in the same order of the blocks in the axial direction as in the walls.

More than 200 measuring points were provided on the inside and outside surfaces of a tube, the deformation of the tube during the

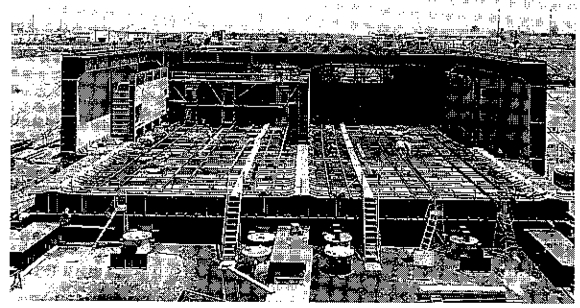
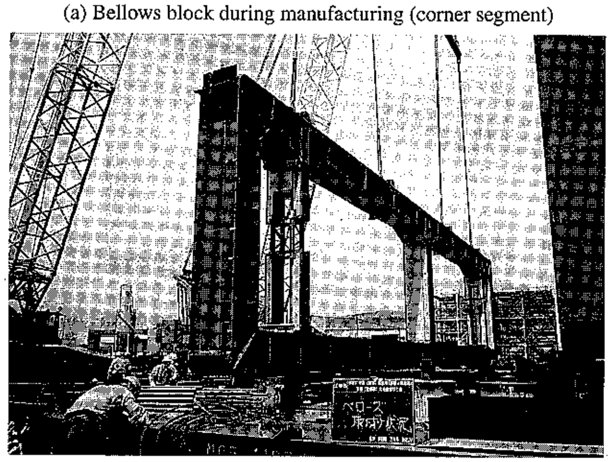


Photo 3 Steel shell for Naha Port Tunnel's tube under fabrication

(a) Bellows block during manufacturing (corner segment)



(b) Installation of bellows block

Photo 4 Bellows joint

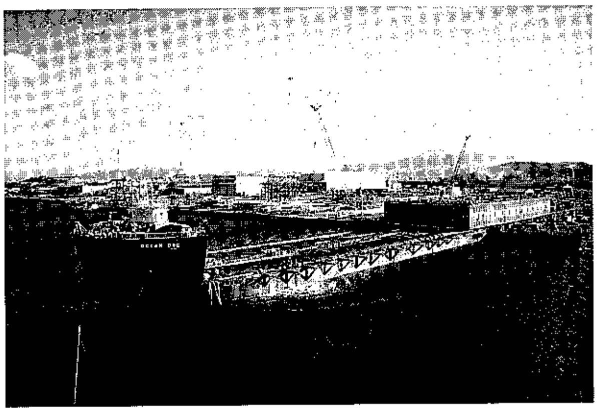


Photo 5 Loading of steel shell body to barge

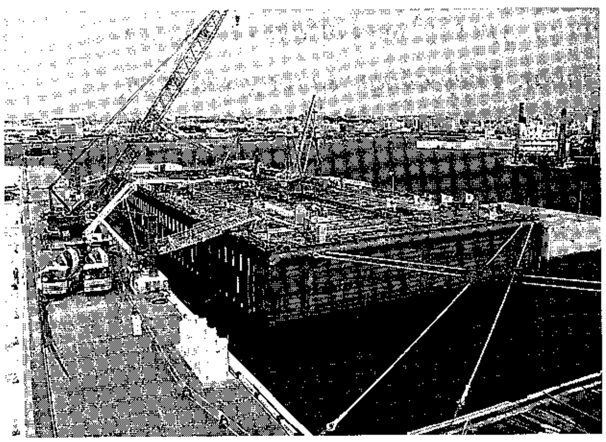


Photo 6 Concrete casting in submerged tunnel tube while afloat

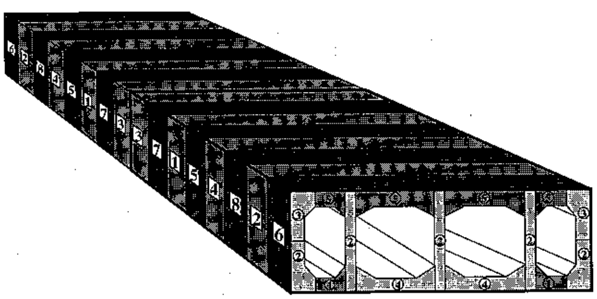
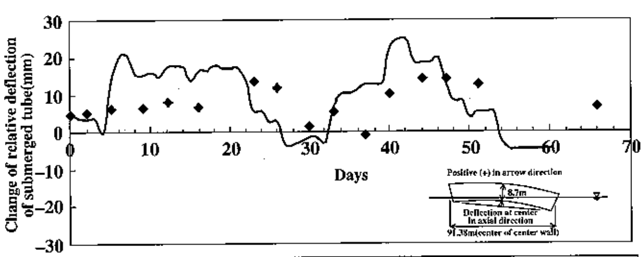


Fig. 12 Order of concrete placing



— Simulation result (atmospheric temperature 25°C, water temperature 26°C, concrete temperature at the end of mixing 27°C, air temperature in tunnel tube 30°C)
◆ Relative change of measured deflection

Fig. 13 Comparison of the history of relative deflection with the simulation result during concrete placing to tunnel tube while afloat

concrete placing works was monitored 19 times by 3-dimensional coordinates measurement using electronic total stations, which was done in midnight to eliminate the influence of the deformation because of sunshine, and thus the works were controlled confirming, through comparison with simulation results, that unexpected deformation did not take place. **Fig. 13** shows the comparison of the history of relative deflection with the simulation result. The simulation reproduced the actual deformation in pretty good agreement although the relative deflection change was as small as 20 mm or so. When the deflection is as small as this, the out-of-verticalness of the end faces of a tunnel tube is only about 1 mm. With this deviation from verticality, there is no problem in the hydraulic pressure jointing works. Therefore, it is not necessary to worry about the final dimensional accuracy of the tunnel tube because of the construction work while afloat.

3. Summary

The establishment of the design method of sandwich structure and the casting method of self-compacting high fluidity concrete has enabled a new type of structure and a new production works as a manpower-saving prefab production method of underwater tunnels to replace conventional RC structure. For the Yumeshima Tunnel at Osaka Port, which is now being produced, the method is used not only for submerged tunnel tubes but also for the caisson steel hulls of vertical shafts.

The sandwich-structured submerged tunnel tube production method, which comprises component techniques of the sandwich structure, casting work of self-compacting high fluidity concrete, bellows joint and production works of submerged tunnel tubes whileafloat, has made it possible to install an underwater tunnel at any place in a port or a bay in whichever country by transporting steel shell bodies to the production site and completing the submerged tunnel tubes while afloat, without being restricted by the availability of graving docks.

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