Structural Design and Construction Method for "Apple-Shaped Liquefied Natural Gas Cargo Tank" for LNG Carriers

MICHIHISA WATANABE*1 RYUSUKE TAKADA*2

TAKASHI OKAFUJI*3 HIROSHI TSUJI*4

MASAHIRO KASHIWAGI*3 YOICHI KAMITANI*3

Recently, the demand for Liquefied Natural Gas (LNG) as power-generating fuel has rapidly increased. On the other hand, the production of a new type of natural gas, due to the development of technologies for gas extraction from shale formations (referred to as "Shale Gas Revolution"), has been expanding mainly in the United States. Due to the increasing demand for this natural gas, the marine transport of LNG is expected to increase significantly. Currently, regarding the transport of American shale gas, which has attracted enormous attention, there are concerns such as restrictions on the dimensions of vessels after the expansion of the Panama Canal and long-distance transport across the Pacific Ocean. Therefore, it is important for LNG carriers to achieve a high level of safety and improve cargo loading space efficiency. Mitsubishi Heavy Industries, Ltd. (MHI) developed the 155 km^3 Sayaendo LNG carrier in 2011, and has delivered five vessels of the same model so far. In order to satisfy the needs of our customers, MHI has completed the development of an "Apple-Shaped Tank" that inherits the features of the existing MOSS spherical tank, which has enjoyed a great reputation for reliability. As of April 2016, MHI has received orders for eight new LNG carriers with apple-shaped tanks, and began the manufacturing of aluminum tanks in October 2015.

1. Introduction

While accumulating experience in constructing MOSS type LNG carriers, in order to satisfy the needs of our customers such as increased cargo loading capacity, MHI has sought to increase the capacity of the existing MOSS spherical tank. In the "155 km^3 Sayaendo," MHI has adopted a stretch tank in which a cylinder is inserted into the equatorial portion of the tank in order to enhance the transport efficiency of LNG. In response to the grand transformation of the LNG transport market, MHI has successfully developed the world's first "Apple-Shaped Tank," which is an upgrade of our existing model with the equivalent level of safety, in order to increase the cargo loading capacity while taking the restrictions at the Panama Canal into consideration. We will introduce the technical details below.

2. Apple-Shaped Tank

The MOSS-type tank has been a popular choice because its sphere shape provides the most stable strength that reduces the plate thickness of the tank's surface material. Subsequently, the adoption of a stretch tank has become widespread for the purpose of increasing cargo loading capacity. On the other hand, the newly-developed apple-shaped tank adopts an axisymmetric tank shape, and inherits the same conventional concept of supporting internal pressure via hoop stress. It is categorized as a MOSS-type tank, with its considerable amount of construction experience and great reliability, and is classified as an IMO Type B independent tank. The tank structure consists

*1 Nagasaki Ship & Ocean Engineering Department, Shipbuilding & Ocean Development Division, Commercial Aviation & Transportation Systems

*2 Ship Engineering Department, Mitsubishi Heavy Industries Shipbuilding Co., Ltd.

*3 Strength Research Department, Research & Innovation Center

*4 Chief Staff Manager, Shipbuilding Department, Mitsubishi Heavy Industries Shipbuilding Co., Ltd.

of a combination of three elements, i.e., a spherical shell, torus portion and cylinder portion, which achieves high flexibility in terms of the shape and capacity.

The new apple-shaped tank was developed for the purposes of meeting two contradicting demands, i.e., to deal with the restriction on the ship breadth in order to pass the Panama Canal and to increase the transport efficiency through greater capacity. For example, **Figure 1** shows comparisons between a 180 km^3 apple-shaped tank with a 155 km^3 stretch tank, as well as with a 180 km^3 spherical tank. The adoption of the apple-shaped tank has led to a successful increase in cargo capacity by more than 15% without making the hull dimensions greater than the LNG carriers equipped with stretch tanks.

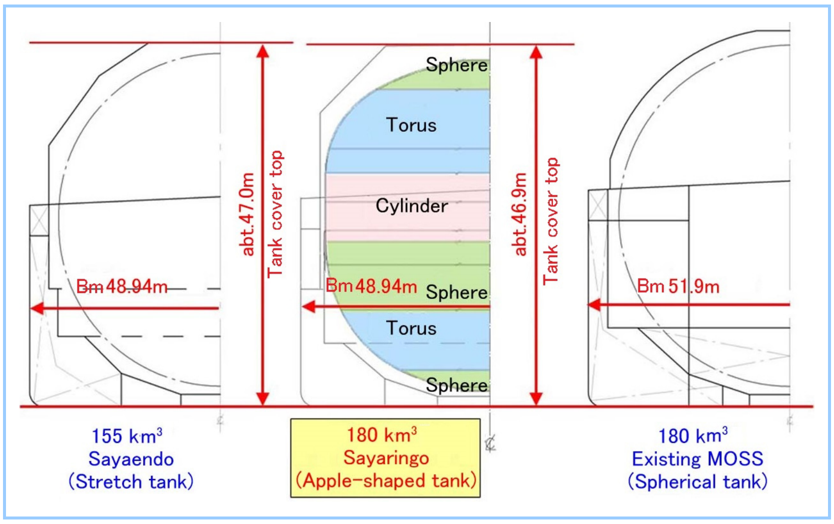

Figure 1 Comparison of tank types and hull dimensions

3. Development of apple-shaped tank

3.1 Structural design of MOSS spherical tank

Figure 2 illustrates the structure of the existing MOSS spherical tank. The tank surface material, with no inner structural members, is connected together to form a sphere. The center portion of the tank height is supported by a cylindrical structure called a tank skirt. The bottom of the tank skirt is secured to the hull structure. In the center of the spherical tank, a pipe tower is arranged vertically, which contains pipes, cargo handling instruments and access equipment to allow people to enter and exit the tank.

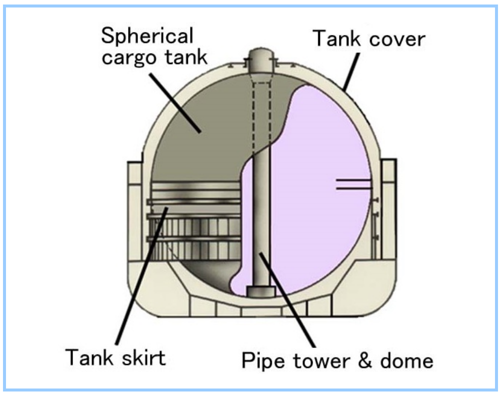

Figure 2 MOSS spherical tank structure

The structural design of the existing MOSS spherical tank needs to conform to the requirements specified in the IGC Code (the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk) where a strength evaluation is conducted in terms of various different loads, such as the inertial force and sloshing load of the cargo due to the ship motion and the heat load due to temperature swings inside the tank from the extreme low of -163°C to room temperature, assuming every possible operational condition in practice. The spherical tank needs no inner structural members as the tank surface material mainly supports the load via membrane stress, which means that the surface material alone is sufficient to stably support the load. In the actual structural design, in addition to ductile failure due to membrane stress, fatigue failure, buckling failure and brittle failure are also evaluated. In order to enhance safety, LNG leakage is also taken into consideration. A crack propagation analysis is conducted assuming that there are initial cracks on the tank surface material, and it is confirmed that there is sufficient duration before the surface material would be penetrated. Furthermore, a simulated calculation for LNG leakage is carried out assuming that the cracks penetrate the tank surface material. As a result, it was confirmed that the LNG leakage can be handled within the partial secondary barrier, and that the gas detector was able to detect the cracks in the early stage when they were still micro-cracks. This design concept is called "Small Leak Protection" and is incorporated into the MOSS tank, as well as some prismatic tanks.

3.2 Extracting verification items in the structural design of apple-shaped tank

In the structural design of the apple-shaped tank, in order to achieve the equivalent level of reliability as the existing MOSS spherical tank, the same strength evaluation procedure is applied. Furthermore, it has become necessary to review a new fracture mode due to changes in form and to establish an evaluation procedure thereof. **Figure 3** shows the design flow of the MOSS spherical tank. We found that it was necessary to examine the buckling strength and sloshing load evaluation, which were affected by the changes in form.

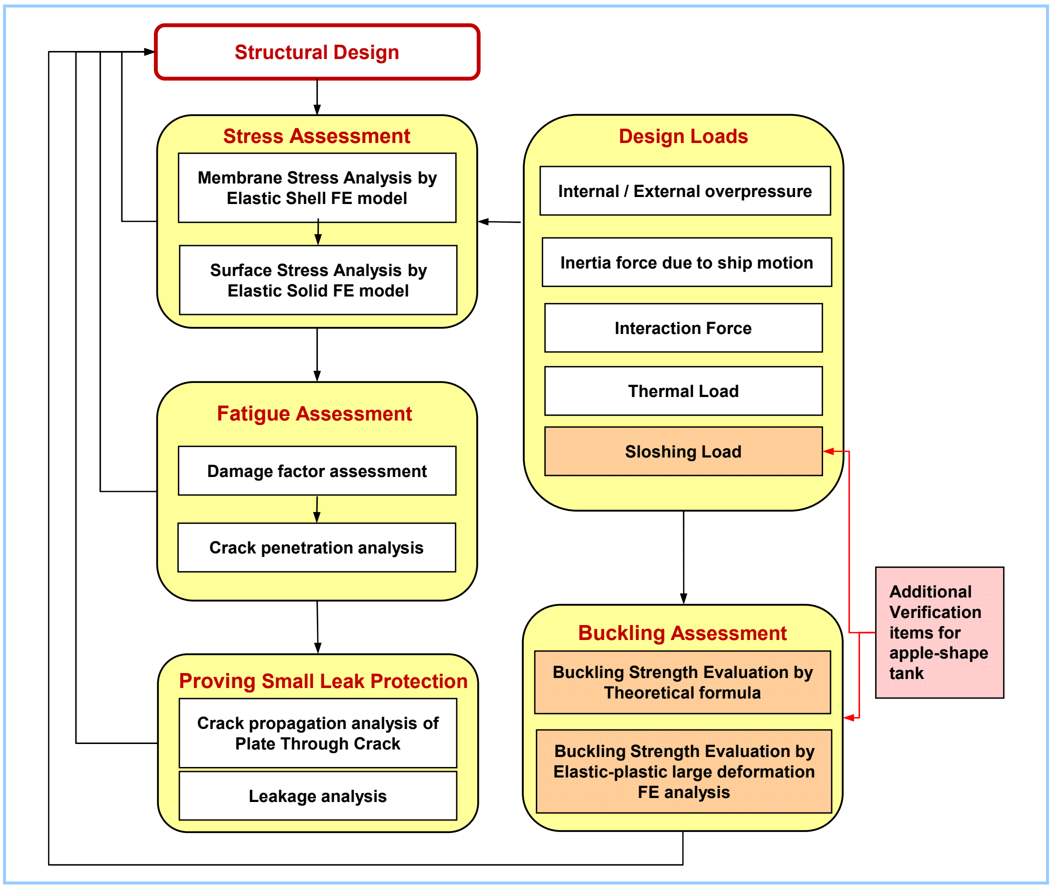

Figure 3 Design flow of MOSS spherical tank and verification items of apple-shaped tank

3.3 Buckling strength evaluation

In the buckling assessment of the existing MOSS spherical tank, there are two types of buckling phenomena to be evaluated: the buckling due to external pressure and the circumferential compressive buckling at the medium liquid level (a phenomenon in which the tank structure near the liquid surface is pulled toward the meridian and deforms toward the inside of the tank due to the motion of the fluid, leading to the occurrence of circumferential compressive stress). On the other hand, as shown in **Figure 4**, for the apple-shaped tank, it is necessary to conduct evaluation not only regarding the buckling caused by the external pressure and the circumferential compressive buckling at the medium liquid level, in terms of the spherical shell, torus portion and cylinder portion, respectively, but also regarding "the buckling due to internal pressure" where circumferential compressive stress occurs in the torus portion under the internal pressure load due to the difference in curvature between individual portions. A long cylinder portion may cause shear buckling in the cylinder portion due to the ship motion under full load (lateral acceleration).[1]

Regarding each of the expected buckling phenomena, by conducting evaluation in accordance with a theoretical design formula taking the initial imperfections based on the construction tolerance into consideration and the elastic-plastic large deformation FEA (finite element analysis), it has been confirmed that sufficient buckling strength to support the design loads was provided. Moreover, regarding the buckling due to internal pressure, which is a buckling phenomenon specific to the apple-shaped tank, an internal pressure loading test was conducted in terms of two types of models; a 1/20-scale model of an actual tank, and a model in which a buckling due to internal pressure is more likely to occur by a lower curvature in the torus portion than that of an actual tank. The results of the testing of the individual models and an analysis thereof are shown in **Figure 5**. In the test for the model with a low curvature in the torus portion and with a high possibility of buckling, the buckling mode and loads in the test were consistent with the simulation analysis, which verified the accuracy of the elastic-plastic large deformation FEA. In the 1/20-scale model of an actual tank, the test and analysis verified that no buckling occurs under a pressure sufficiently greater than the designed internal pressure.

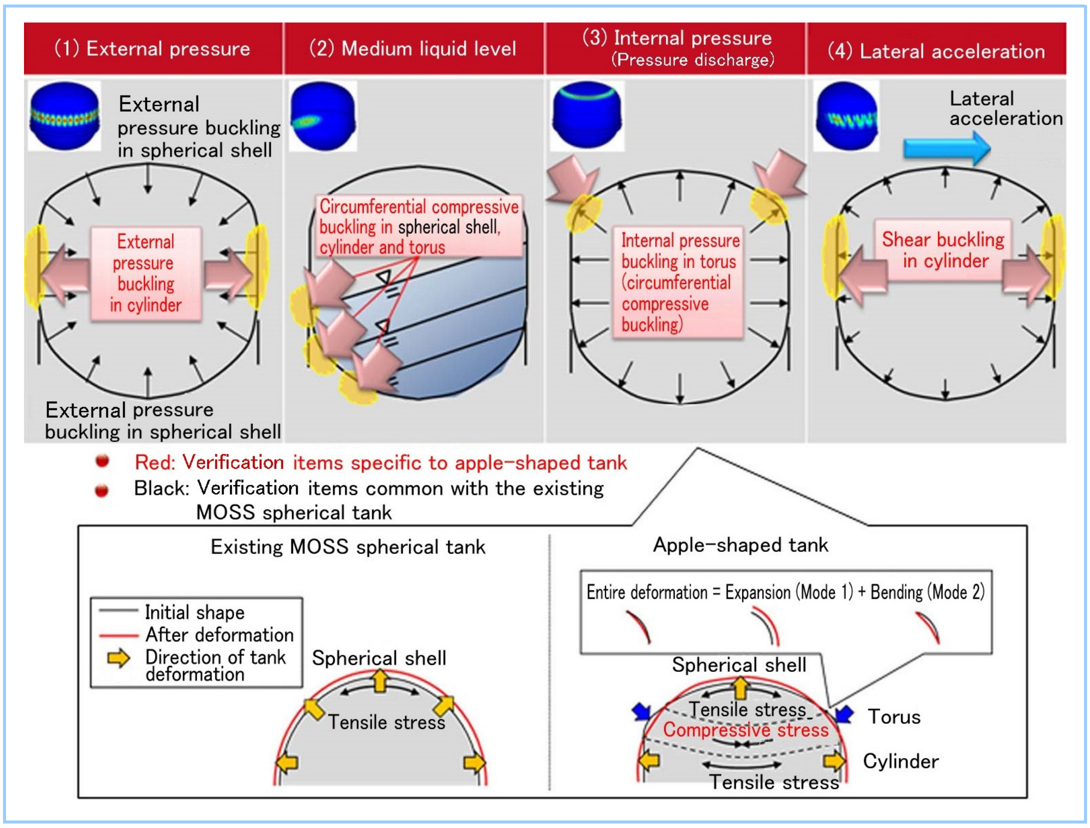

Figure 4 List of buckling modes expected in apple-shaped tank

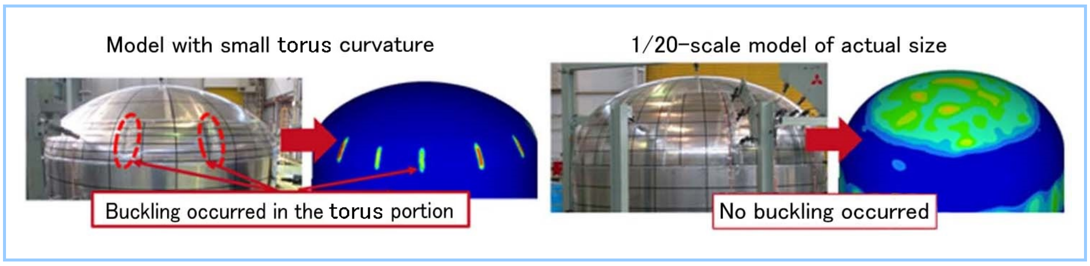

Figure 5 Results of internal pressure loading test (at 1/20 scale) and simulation analysis

In terms of the initial imperfections and plate thickness, which are the major factors for the buckling strength, it was confirmed that the incidence of the combination of the values used for the buckling strength evaluation was sufficiently low, by calculating individual variations (probability distribution) according to the past construction records of spherical tanks. As shown in **Figure 6**, the probability distribution of the buckling strength was calculated using the Monte Carlo Simulation, where the buckling strength calculation is conducted numerous times by giving values of individual factors as random numbers that follow the probability distribution, and assigning those values to the buckling strength evaluation formula, in order to obtain the failure probability. As a result, it was confirmed that the failure probability due to the buckling of the apple-shaped tank was expected to be the equivalent of or less than that of the MOSS spherical tank if the initial imperfections and plate thickness were controlled at the same level as in the existing spherical tank. Accordingly, we have set new construction tolerances in the torus and cylinder portions of the apple-shaped tank so that the tolerances will be at a similar level as the existing MOSS spherical tank.

The torus portion has a different curvature for the circumferential and meridian directions. As the curvature in the circumferential direction varies, the manufacturing difficulty in the bending process is likely to be higher than the spherical shell. However, through the bending test described in 4.2 below, we have confirmed that bending accuracy equivalent to the spherical tank can be secured without issue, and that the newly developed apple-shaped tank realizes a tank structure which has a buckling strength equivalent to or greater than the existing MOSS spherical tank.

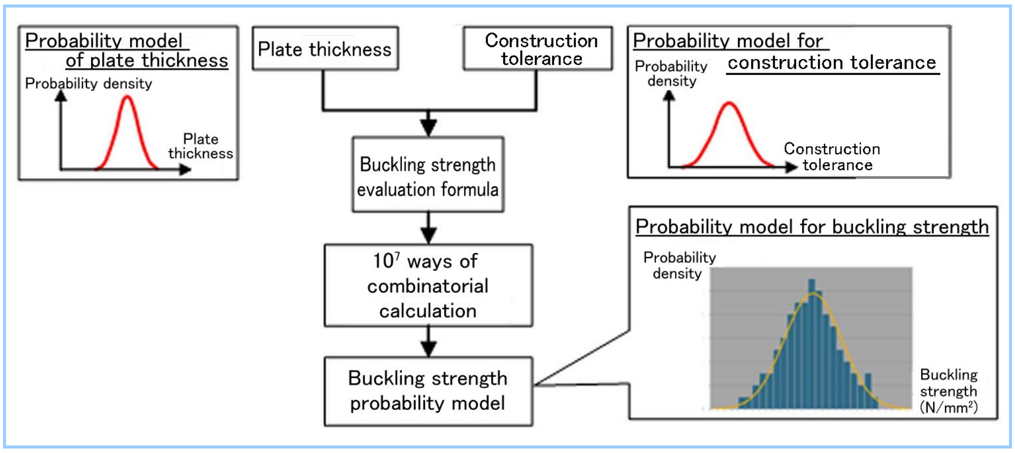

Figure 6 Calculation of probability distribution of buckling strength utilizing Monte Carlo Simulation

3.4 Strength evaluation for sloshing

Sloshing refers to the movement of liquid having a free surface, causing a large impact pressure when the liquid inside the tank is undergoing a strong motion and is hitting the tank walls due to a particular situation of the loading condition, LNG liquid level and sea state. In the existing MOSS spherical tank, the curved surface makes the liquid shift along the tank walls. Therefore, compared with prismatic tanks such as membrane tanks, the impact pressure due to sloshing is negligible. The apple-shaped tank also has a smooth shape that does not concentrate pressure in a particular area. However, since there has been a gradual change of shape from the spherical tank, we have verified that it has the same level of excellent sloshing properties as the existing model, just to be safe.

Upon discussing the sloshing properties here, we have conducted examination in terms of regular wave excitation and irregular wave excitation. Regular wave excitation is an evaluation method using a constant excitation amplitude/cycle. In recent years, numerical simulation technology has developed rapidly, enabling sloshing evaluation based on irregular wave excitation taking the ship motion into consideration, which is closer to what happens in reality.

Firstly, MHI internally conducted evaluation based on a model experiment using regular wave excitation with a constant excitation amplitude and cycle, as well as computational fluid dynamics (CFD Analysis), in order to compare the sloshing load between two models: the apple-shaped tank under development and the existing spherical tank. The analysis accuracy was verified in the model experiment and it was confirmed that the extent of the sloshing load in the apple-shaped tank for the actual project was the same as the spherical tank, and that the increase in the load was within 10%.

Secondly, the sloshing load was evaluated by DNV-GL* which has a sloshing evaluation technique under irregular excitation conditions. The evaluation method based on irregular wave excitation is shown in **Figure 7**. In this evaluation, it is important to identify the condition where the sloshing load increases. Therefore, a numerical analysis was conducted through irregular wave excitation for a duration of about 30 minutes. Then, a screening of conditions where the maximum load occurs (situations of loading condition, LNG liquid level and sea state) was carried out.

Especially when identifying the sea state, evaluation needs to be conducted for both the sea state close to the tank resonance period and those in which the inertial force due to the ship motion is large. The sloshing load was compared between two analysis models of the apple-shaped tank and spherical tank, by conducting a detailed analysis in terms of irregular wave excitation for two hours, utilizing the condition in which the maximum sloshing load identified in the screening analysis occurred. The results were sufficiently consistent with the results of our study. Evaluation of the experiment/analysis under regular wave excitation and irregular wave excitation concluded that the sloshing loads that occurred in both cases were the same level (an increase of within 10%). Based on these evaluation results, in the design of the apple-shaped tank, strength evaluation was conducted allowing for a 10% increase in the sloshing load, and is even safer than the spherical tank.

* DNV-GL: International service provider for certification, technical consulting, classification, etc.

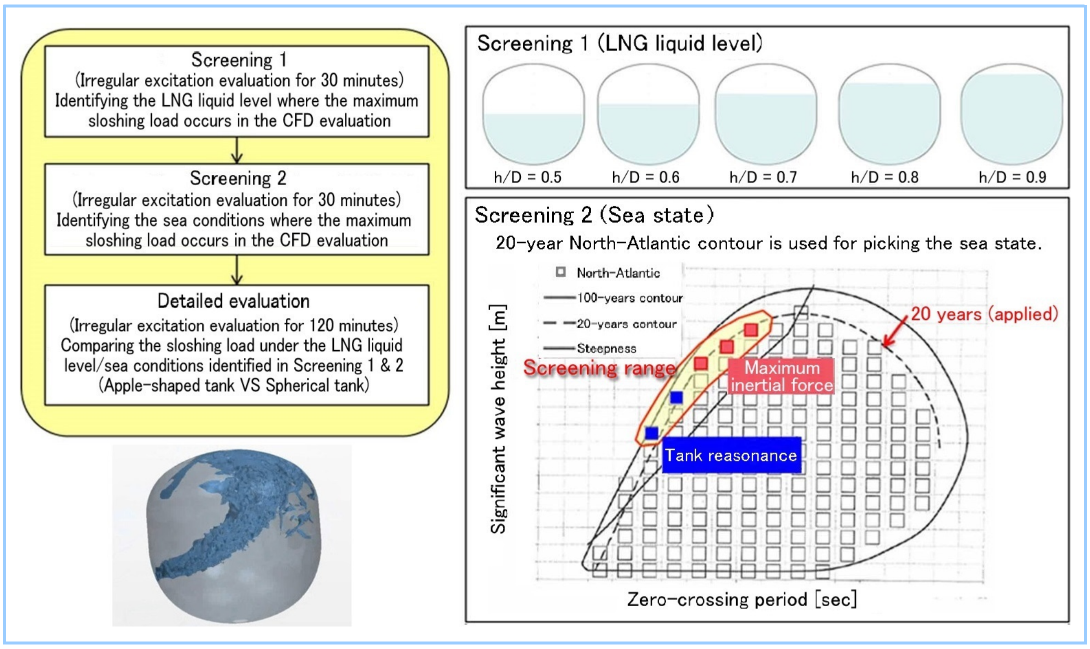

Figure 7 Sloshing evaluation method under irregular excitation

4. Construction method of the apple-shaped tank

4.1 Difference from the construction method of the existing MOSS spherical tank

In the construction of the existing spherical tank, cold press bending is applied to the material, aluminum plates to form a shape like a flower petal. The petals are welded together by MIG welding to form a spherical tank. The petals for the spherical tank were bent with the same amount of R (radius) in every direction, including the meridian and circumferential directions, to form a sphere-shape. Although some of the petals for the apple-shaped tank have a constant amount of R in the meridian direction, a toroidal shape was adopted where the Bending R in the meridian direction changes according to that in the circumferential direction. Therefore, in the cold press bending of the petals, because the apple-shaped toroidal petals have a different Bending R in the meridian and circumferential directions, and the circumferential bending changes in accordance with the meridian bending, it is necessary to bend the petals while always checking the status of the bending. Accordingly, we examined this complex bending mechanism in a simulated bending test utilizing a miniature model. Based on the results of the test, we established a bending method by selecting the optimum mold shape and pressure conditions.

In the assembly process of the petals, after the bending process, up to four petals which have undergone edge preparation are connected together by a large current automatic MIG welding device to form an assembly block. Subsequently, multiple assembly blocks form a grand assembly block of a spherical tank which consists of three portions: the Northern Hemisphere, Equatorial Zone and Southern Hemisphere. The grand assembly block consisting of the three portions is built on the spherical tank in the building dock. In the torus portion of the apple-shaped tank for actual ship construction, in order to cope with a different Bending R in the meridian and circumferential directions, we will manufacture and utilize a new numerically controlled three-dimensional edge preparation device, a universal supporting jig for the plate joint positioner of the large current automatic MIG welding device for block assembly, a binding mount for grand assembly, and rails for the automatic MIG welding device specific for the Bending R in the torus portion.

4.2 Bending of the toroidal portion

Because the aluminum petals are large in size, for the convenience of the press forming machine, it is necessary to form them by performing press bending multiple times regardless of whether spherical or toroidal. There is, however, little research focused on incremental press bending and its shape estimation. In this project, we determined the shape of the die for actual ships after providing some shape options, creating 1/20 scaled-down model dies which correspond to the options, and evaluating them by conducting press bending multiple times using aluminum alloy sheet. In connection with this, the dies were designed according to the springback estimation formula[2] for a surface with an anisotropic shape or the simulation results where a single press forming is assumed. A 1/20 scaled-down model die is shown in **Figure 8**.

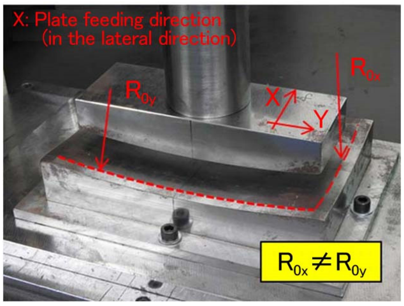

Figure 8 1/20 scaled-down model die

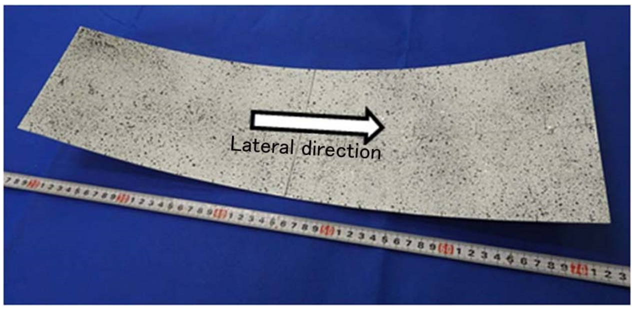

Figure 9 Aluminum flower petals formed with a 1/20 scaled-down model die

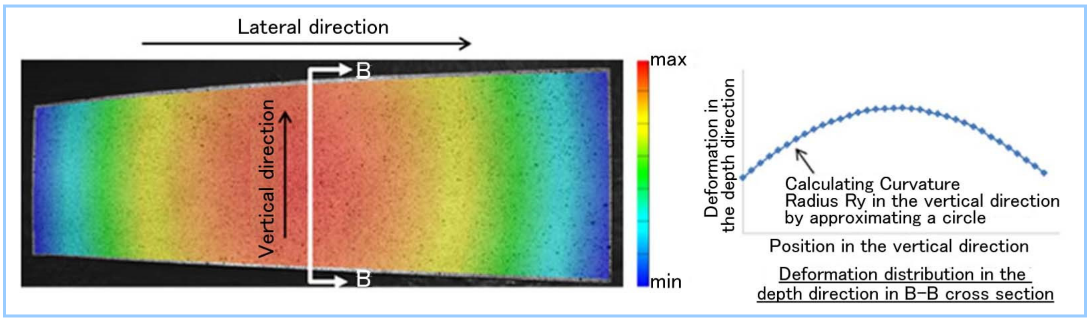

Figure 10 Measurement result by ARAMIS (Deformation contour in the depth direction)

In the press experiment using the 1/20 scaled-down model die, all the plate dimensions were scaled down to 1/20 of the real thing. The press load is related to the bending stress, and since the bending stress is inversely proportional to the square of the plate thickness, the press load was 1/400 times that of the real thing. The post-press shape was measured using ARAMIS, a three-dimensional deformation measuring device that utilizes a digital image correlation technique. The post-press 1/20 scaled-down aluminum petals are shown in **Figure 9**. The petals' surfaces are painted white to facilitate measurement by ARAMIS. The measurement results by ARAMIS are shown in **Figure 10**. The curvature radius in the vertical direction at respective positions in the lateral direction, that was calculated utilizing the measurement results from Figure 10, is shown in **Figure 11**. As a result of the press experiment, we adopted die A, which was the closest to the drawing shape, prepared a die for the actual ship on the basis of this and carried out a full-scale prototype test for verification. The resulting prototype is shown in Figure 11. As a result, although the curvature radius became smaller, the curved shape obtained was almost as expected. Currently, the press load is being adjusted so that the target shape can be obtained. After having grasped the shape variation of each plate, we are in the process of acquiring data to establish standard press conditions to obtain consistent quality.

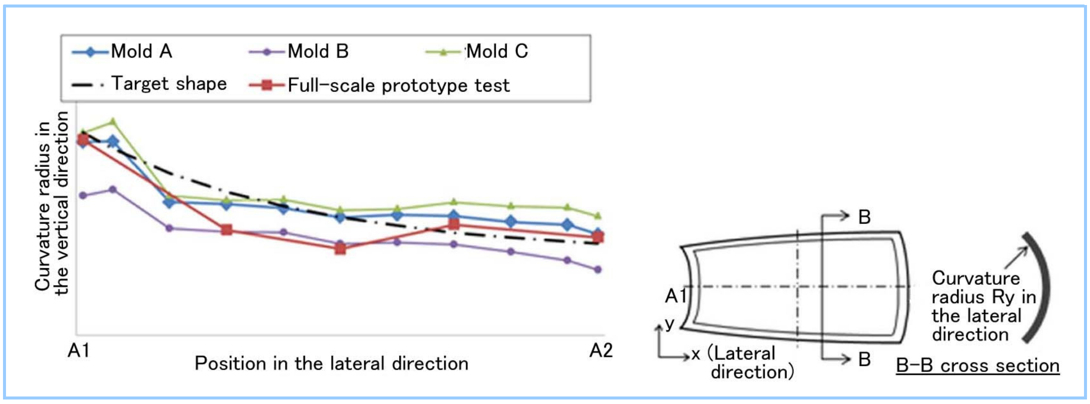

Figure 11 Results of press experiment and full-scale prototype test

5. Conclusion

In order to respond to the needs of our customers for increased cargo capacity and greater transport efficiency, MHI has developed the apple-shaped tank as an upgrade of the existing MOSS spherical tank. We have successfully established the design process for the new tank as a result of a variety of technical assessments in terms of the change in shape. The apple-shaped tank has buckling strength and excellent sloshing resistance properties equivalent to those of the existing MOSS spherical tank. Furthermore, it is possible to design the tank shape flexibly. MHI will continue to actively contribute to the development of the LNG supply chain both at home and abroad, by applying our new innovation to LNG ship design as a key technology for the ongoing diversification of LNG transport.

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