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Research Article

Development of Laminated Egg-Shaped Tsunami Shelter Structure Made of Steel-Cushioning-Steel

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Abstract

When a tsunami is caused by an earthquake or other event, spherical shelters are developed to protect people from the tsunami. This study proposes a new egg-shaped laminated tsunami shelter with a buffer layer to improve the functionality of traditional spherical shelters. The inner and outer shells of this shelter are made from thin-walled stainless steel, using the integral hydro bulge forming (IHBF) process. The space between these two layers was filled with urethane foam, providing an elastic buffer. This resulted in a laminated egg-shaped structure designed for tsunami protection. To verify the proposed laminated egg-shaped tsunami shelter and its processing method, an egg-shaped shell with an external shape (length 660 mm, width 493 mm) was fabricated using a 1.0 mm thick stainless plate, and a laminated egg-shaped tsunami shelter with a 25 mm thick intermediate layer made of urethane foam was fabricated. The shape accuracy of the processed egg-shaped laminated tsunami shelter structure was measured, and the maximum error between the surface shape of the molded egg-shaped shell and the true egg shape was -4.13 mm, and the relative error to the maximum radius of the egg shape of 246.5 mm was -1.68%. In addition, to assess the buffering effect under external impact loads, acceleration sensors were attached to both the inner and outer layers of the fabricated egg-shaped laminated tsunami shelters. A hammer was used to apply an impact load to the outer layer, and the response acceleration values recorded by the sensors on both layers were compared. It was found that the response acceleration of the inner layer was 15.81% lower than that of the outer layer.

Keywords

Egg-Shaped Laminated Shell, Egg-Shaped Floating Tsunami Shelter, Integrated Bulge Processing Method, Elastic Cushioning Laminated Shell, Impact Cushioning Experiment

1. Introduction

Natural disasters, such as earthquakes and tsunamis, can cause great harm to people. Therefore, floating tsunami shelters have been designed to safeguard individuals from ocean tsunamis. When a natural tsunami occurs, people enter floating tsunami shelters to evacuate, and the shelters float with the tsunami waves, saving lives [1-5].

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To design and create a functional floating tsunami shelter, it is crucial to study the distribution of current velocity and wave forces as a tsunami nears the shore. In addition, the wave pressure acting on the structure and movement characteristics of shelter structures have been studied [6-10].

Currently, floating tsunami shelters are broadly classified into two types. The first type is connected to the coast by a soft chain or guide link that can move up and down the coast. When an ocean tsunami occurs, tsunami shelters float and sink within a certain range of the coast but do not move far away [11-13]. Second, the tsunami shelter is independent of the coast and floats on the sea surface. When an ocean tsunami occurs, the floating tsunami shelter separates from the coast and floats along the waves [14-16].

Among these two types of tsunami shelter structures, the floating tsunami shelter, which is independent of the land coast, has the advantage of being relatively simple in structure and inexpensive. Furthermore, when subjected to random wave forces from an ocean tsunami, it can mitigate the stress concentration and impact forces that occur in the linked soft chains. In addition, a spherical tsunami shelter with symmetry is considered to be relatively easy to use. Therefore, spherical tsunami shelters have been studied from various perspectives, including their mechanical properties [17-20], and commercially available products have been developed [21].

However, it is difficult to process a typical metallic spherical shell structure with high precision, and the processing costs are high [22, 23]. To solve this problem, an integrated hydro bulging method (IHBF) was proposed, in which water pressure is applied to the inside of a preformed box assembled by welding flat plate parts to expand and form a structure [24-26]. This is expected to solve the processing problem of spherical tsunami shelter structures.

The current spherical tsunami shelters are made of a single layer of thin material, which has the drawbacks of being weak when hit by rocks and generating loud noise when hit by waves. To address these issues, a laminated spherical tsunami shelter structure with an elastic buffer layer has been proposed instead of a single-layer spherical tsunami shelter structure and is currently under study [27].

Typically, when tsunamis do not occur, the aesthetic appeal of tsunami shelters is important when they are placed in parks or homes. In addition, when a tsunami occurs, the mobility of the shelter and the placement of the entrance and observation windows must be considered. Therefore, changing the shape from a sphere to an egg and examining the structure of an improved tsunami shelter are promising research topics. However, to achieve this, it is necessary to consider the design and processing methods of the single-layer egg-shaped shell structure [28, 29].

In this study, a new egg-shaped laminated tsunami shelter structure and its processing methods are proposed. The inner and outer layers of the egg-shaped tsunami shelter, which consisted of a three-layered shell, were made of stainless steel and processed using the IHBF method. An egg-shaped laminated tsunami shelter was created by filling the space between the inner and outer layers with urethane foam. The processing method for this egg-shaped laminated shelter was analyzed, and a formula for determining the key dimensions of the inner and outer egg-shaped shells was developed. The outer shape of the fabricated shelter was then measured and compared to the ideal egg shape to assess the accuracy of the IHBF processing method. Finally, the shelter was subjected to an impact load in a hammer impact test to evaluate its cushioning effect and overall practicality.

2. Materials and Methods

2.1. Single Layer Egg-shaped Shell Structure

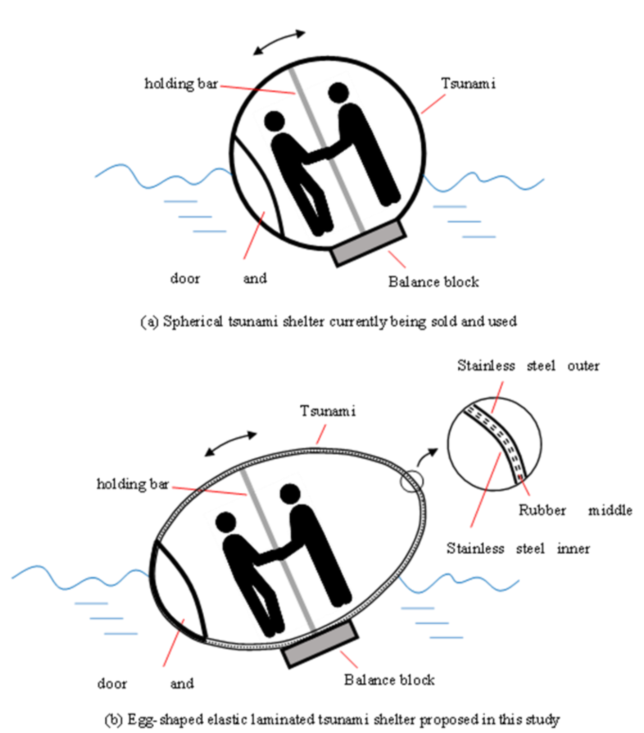


Figure 1. *Tsunami shelter structure to avoid damage from marine tsunami disasters.*

To mitigate tsunami damage, spherical floating tsunami shelters like those depicted in Figure 1(a) have been developed and are available on the market. These shelters move with the waves during a tsunami, providing a means of survival for occupants [21]. Typically, these spherical shelters are used in landscaping or near residential areas. To address the limitations of existing single-layer spherical designs, a new laminated spherical floating tsunami shelter with an elastic buffer layer has been proposed and is currently being investigated. [27].

This study presents a design for an egg-shaped laminated floating tsunami shelter, as shown in Figure 1(b). The egg-shaped floating tsunami shelter had better volumetric performance than the conventional spherical shell, and the entrance and windows were installed on the head of the egg-shaped shelter. The egg-shaped floating tsunami shelter looked better even when placed next to a park or house as a regular landscape.

As shown in Figure 1(b), the walls of the proposed egg-shaped floating tsunami shelter had a three-layer structure, with the outer and inner layers made of stainless steel plates and the middle layer between the outer and inner layers made of urethane foam. Therefore, when used as floating tsunami shelters, they can contribute to improved safety and comfort when colliding with waves or rocks.

The first stage in developing the egg-shaped laminated floating tsunami shelter structure shown in Figure 1(b), it is necessary to consider a method for manufacturing single-layered metal egg-shaped shells.

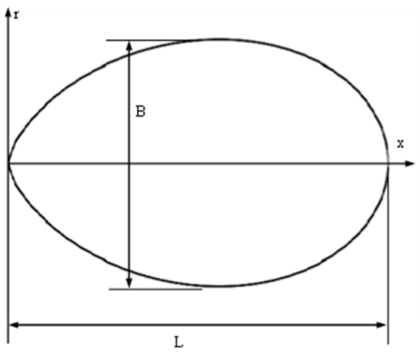


Figure 2. *Egg-shaped shape function.*

The shape of the egg-shaped shell is shown in Figure 2, where L is the axial length of the egg-shaped shell and B is the width of the egg-shaped shell. The contour curve of the axially symmetric egg shape shown in Figure 2 can be expressed as follows [30]:

$$r = \pm\sqrt{L^{\frac{2}{n+1}}x^{\frac{2n}{n+1}} - x^2} \tag{1}$$

$$n = 1.057\left(\frac{L}{B}\right)^{2.372} \tag{2}$$

where n is the egg-shape index determined by the axial length and width of the egg-shaped shell.

The process shown in Figure 3 was used to fabricate a single-layer egg-shaped shell structure, as shown in Figure 2, using thin steel plates.

First, as shown in Figure 3(a), the egg shape was divided into stages along the axial direction, and the nodal coordinate values (x_i, r_i) of each stage were calculated using equations (1) and (2), respectively.

Subsequently, as shown in Figure 3(b), each stage was unfolded, bent into a circle, as shown in Figure 3(c), and welded into a ring shape.

The stages shown in Figure 3(c), which were divided and processed in the axial direction, were welded to create a sealed axisymmetric box.

Finally, water pressure was applied inside the sealed axisymmetric box, causing it to expand outward and resulting in a single-layer egg-shaped shell structure, as shown in Figure 1(d).

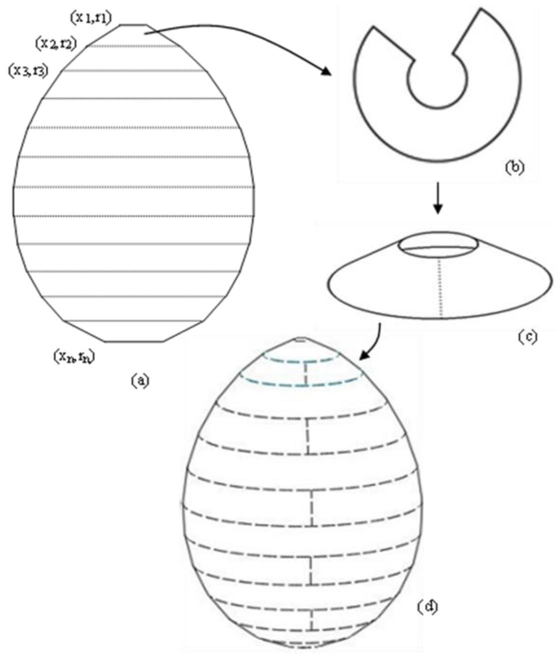


Figure 3. *Fabrication process of single layer egg-shaped shell structure made of thin steel plate.*

2.2. Laminated Egg-shaped Floating Tsunami Shelter Structure with Elastic Buffer Layer

Based on the single-layer egg-shaped shell structure examined in the previous section, we propose a laminated floating tsunami shelter, as shown in Figure 4, and consider its design and processing methods. As shown in Figure 4, the inner and outer shells of the egg-shaped floating tsunami shelters were fabricated with thin stainless-steel plates using the method shown in Figure 3. An elastic cushioning layer of urethane foam is placed between the inner and outer shells. Thin connecting rods were installed between the inner and outer shells to fix their relative positions.

The detailed dimensions of the egg-shaped floating tsunami shelter examined in this study were 660 mm in length and 493 mm in width, with a urethane foam middle layer thickness of 25 mm.

2.2.1. Components and Their Parameters Design

The processed parts of the egg-shaped layered floating tsunami shelter shown in Figure 4 can be designed according to the following procedure, starting from the stainless-steel outer layer that determines the target external shape, the urethane foam intermediate layer with uniform thickness, and finally, the stainless-steel inner layer.

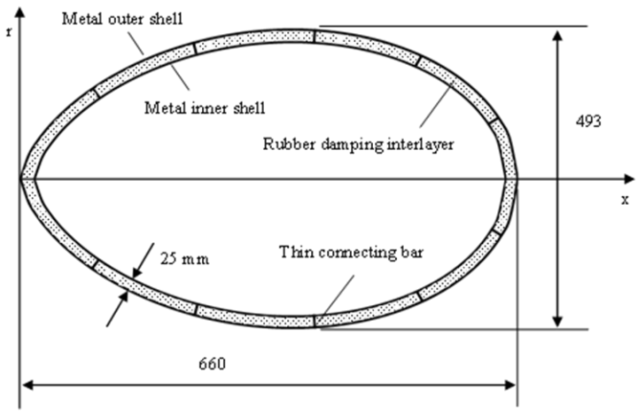
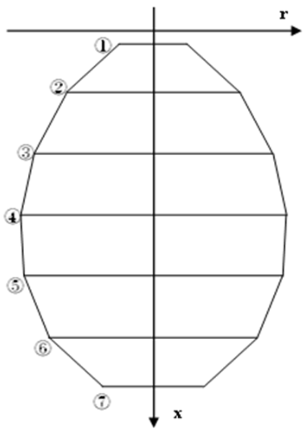


Figure 4. *Proposed laminated egg-shaped tsunami shelter structure with elastic buffer layer.*



Node No.	x [mm]	r [mm]
①	22.00	60.85
②	110.00	160.02
③	220.00	220.83
④	330.00	245.24
⑤	440.00	238.30
⑥	550.00	192.59
⑦	638.00	94.07

Figure 5. *Component parameters of the outer shell of egg-shaped laminated tsunami shelter.*

Step 1: Outer shell parts design

The egg-shaped layered floating tsunami shelter shown in Figure 4 was divided into seven stages along the axial direction of its external shape (length, 660 mm; width, 493 mm). The trapezoidal shape of each stage is then expanded, as shown in Figure 3(b). The intermediate model and shape parameters (x, r coordinate values of the key nodes of each stage) are shown in Figure 5.

Step 2: Intermediate buffer layer design

The internal water pressure was expected to proceed along the normal direction of the outer surface of the eggshell. Based on the outer shell shown in Figure 5, the connecting rods between the inner and outer shells were established, as shown in Figure 6. The connecting rods were set up symmetrically at the key nodes of the outer shell. The length of the connecting rods was 25 mm, and the diameter was 2 mm.

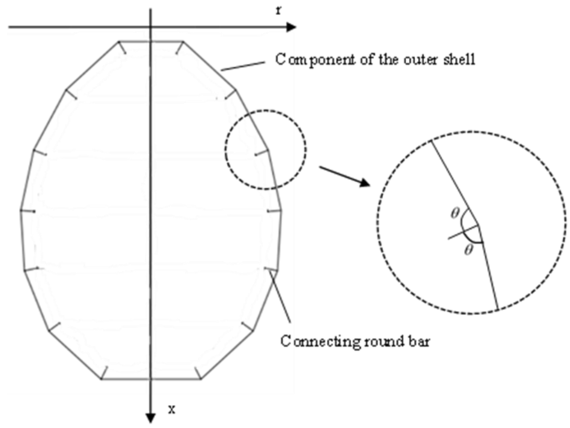
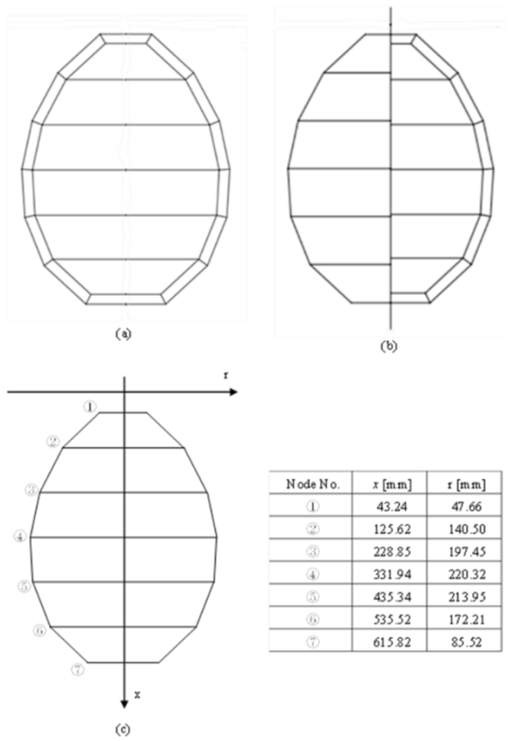


Figure 6. *Design of the round bar connecting the outer and inner shells of the egg-shaped tsunami shelter.*

Step 3: Inner shell part design

By connecting the tips of the connecting rods shown in Figure 6, the design drawing of the double-shell structure shown in Figure 7(a) was obtained. The left side of Figure 7(b) shows the outer shell shape and the right side shows the symmetrically cut inner structure. Furthermore, by removing the outer shell structure and connecting rods, an intermediate model of the inner shell was obtained, as shown in Figure 7(c). The x and r coordinate values of the key nodes of each stage are summarized as shown in the table in Figure 7. Finally, by expanding the trapezoidal shape of each stage, as shown in Figure 3(b), the flat parts of the inner shell are obtained.



Node No.	x [mm]	r [mm]
①	43.24	47.66
②	125.62	140.50
③	228.85	197.45
④	331.94	220.32
⑤	435.34	213.95
⑥	535.52	172.21
⑦	615.82	85.52

Figure 7. *Component parameters of the inner shell of egg-shaped laminated tsunami shelter.*

2.2.2. Manufacturing Experiment

The processed parts obtained using the method shown in Figures 5 to 7 were used to fabricate a laminated egg-shaped floating tsunami shelter structure with an elastic buffer layer. The fabrication process consisted of the following four steps:

Step 1: Processing of egg-shaped inner shell

First, a flat strip-shaped part, as shown in Figure 8(a), was cut from a 1.0 mm thick stainless steel plate using a laser cutter based on the part shape and dimensions of the inner layer of the egg-shaped shell shown in Figure 7(c). However, the parts at both ends were circular. The strip-shaped parts were then bent into circles individually, as shown in Figure 8(b), and welded along the joining lines, resulting in a ring-shaped part, as shown in Figure 8(c). Each ring-shaped part was welded along the axial direction to obtain a sealed preformed box, as shown in Figure 8(d). Finally, a manual water-pressure pump was used to apply water pressure inside the sealed preformed box, as shown in Figure 8(e), causing it to expand uniformly, resulting in an egg-shaped inner layer shell.

Figure 8. Fabrication of the inner shell of a laminated egg-shaped shell.

Step 2: Processing of outer layer sealed preformed box

Figure 9. Fabrication of the middle layer connecting rods and the egg-shaped outer shell.

For the egg-shaped inner shell processed by the method shown in Figure 8, a circular hole was cut around the water inlet, as shown in Figure 9(a) and (b), and the connecting rods were welded along the weld circumference of the egg-shaped inner shell, according to the method shown in Figure 6. Subsequently, as shown in Figure 9(b)–(d), a new egg-shaped outer shell was welded to the tip of the connecting rod according to the method shown in Figure 5. Consequently, an outer-sealed preformed box, as shown in Figure 9(e), is obtained.

Figure 10 presents a cross-sectional view of the welded, outer-sealed preformed box. The inner shell, which features a circular hole, ensures that when water pressure is applied externally, the pressures on both sides of the inner shell remain balanced. Consequently, the inner shell remains unaffected by plastic deformation, while the outer sealed preformed box experiences bulging deformation.

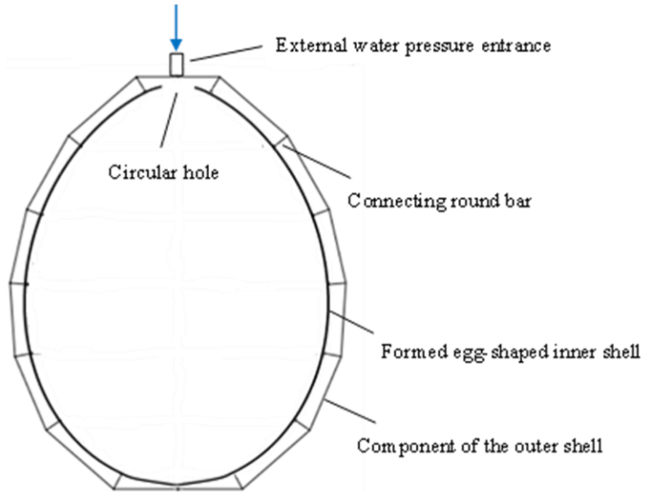


Figure 10. *Cross-section of egg-shaped thin-walled laminated shell structure.*

Step 3: Bulge forming of outer shell

The double-sealed preformed box shown in Figure 9 was bulged by applying water pressure to its interior using a manual water-pressure pump, as shown in Figure 11. Consequently, a bulge-shaped, egg-shaped, laminated floating tsunami shelter structure was obtained.

Figure 11. *Forming egg-shaped laminated shell structure by internal.*

Step 4: Elastic cushioning intermediate layer processing

An egg-shaped laminated floating tsunami shelter structure, featuring an elastic buffer intermediate layer, was created using the double egg-shaped thin shell depicted in Figure 11. The fabrication process followed the steps outlined in Figure 12.

As shown in Figure 12(a), a circular hole was made at the center of the water pressure inlet on the egg-shaped shell. Figure 12(b) shows the temporary sealing of this hole on the inner shell using adhesive tape. In Figure 12(c), a mixed urethane foam liquid is injected between the inner and outer layers of the double-shell structure, as depicted in Figure 12(d). A funnel and soft pipe were used to gradually inject the urethane foam from the bottom of the shell structure so that air was not trapped inside. The filled, foamed, and expanded interior states are shown in Figure 12(e). Finally, as shown in Figure 12(f), the urethane foam at the circular hole was cut out, and the elastic buffer intermediate layer between the double egg-shaped shell structure was confirmed from the circular hole.

Figure 12. *Manufacturing process of egg-shaped laminated tsunami shelter structure.*

3. Results and discussions

3.1. Shape Accuracy of Bulge-formed Egg-shaped Shell

To verify the shape accuracy of the fabricated egg-shaped laminated tsunami shelter, a measurement system was assembled as shown in Figure 13. A camera stander and a laser displacement meter (OPTEX CD22-35VM12, measurement accuracy ±0.01 mm) were used to measure the surface shape data of the processed egg-shaped laminated tsunami shelter. The distance from the base to the laser displacement meter was determined by adjusting the vertical position of the stand's horizontal beam. A laser displacement meter was affixed to the end of this beam. The measurement of the distance between the laser displacement meter and the sample point was then recorded in a data logger.

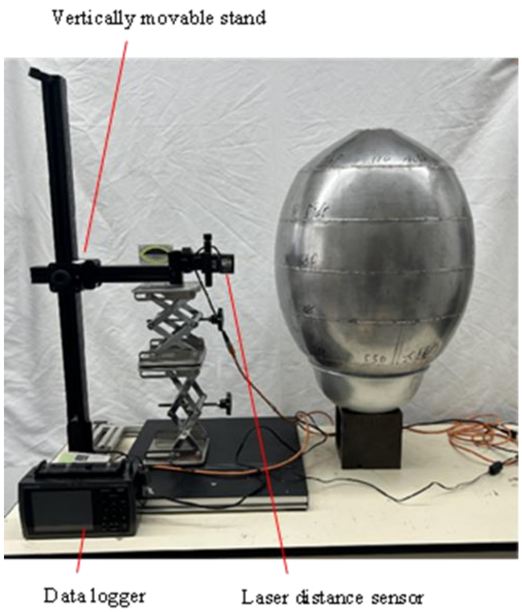


Figure 13. *Measuring device for the shape accuracy of formed egg-shaped tsunami shelter.*

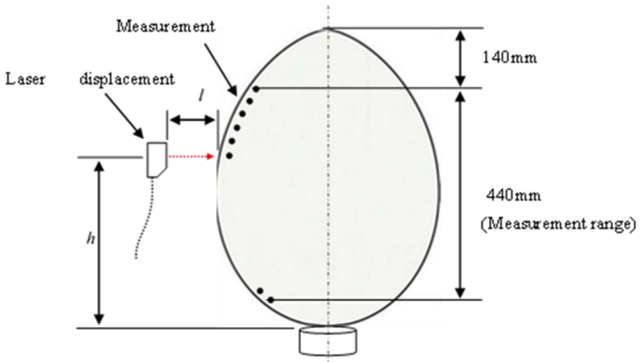


Figure 14. *Measurement sample points and range of formed egg-shaped tsunami shelter.*

During the actual measurements depicted in Figure 14, the height *h* of the laser displacement meter and the distance *l* from the laser displacement meter to the surface of the egg-shaped layered floating tsunami shelter were recorded. Coordinate transformation was then applied to determine the coordinate values of the sample points on the surface of the egg-shaped layered floating tsunami shelter.

However, because the laser displacement meter measured in the horizontal direction, the measurement accuracy dropped significantly near both ends of the egg-shaped shell. Therefore, as shown in Figure 14, the measurement range was a 440 mm wide area around the center of the egg-shaped tsunami shelter, and sampling points were set at 5 mm intervals along the outline.

The results of the measured sampling points are shown in Figure 15. The red dotted lines show the coordinate positions of the sampling points, and the blue solid line shows the true egg-shaped curve.

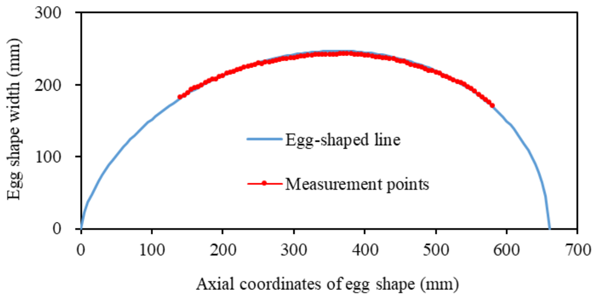


Figure 15. *Results of measuring the shape of the formed egg-shaped tsunami shelter.*

The shape of the processed egg-shaped laminated floating tsunami shelter (red sample points) matches well with the target egg shape (blue solid line), as shown in Figure 15. The maximum error of the processed egg surface shape was -4.13 mm, and the relative error to the maximum radius of the target egg shape was -1.68%.

Therefore, it was confirmed that the design method of the basic processed parts proposed in this study is valid and that the shape accuracy of the processed egg-shaped laminated floating tsunami shelter is good.

3.2. Confirmation of Manufacturing Performance Using FEM Analysis

In reality, it is difficult to measure the stress distribution and thickness changes during the plastic formation process of an egg-shaped shell structure. The plastic-forming process of the egg-shaped shell was simulated using FEM analysis, and the processing performance was evaluated.

Figure 16 shows an analytical model for processing an egg-shaped shell using the IHBF method. The analytical model included 37,300 nodes, 37,080 quadrilateral elements, and 436 triangular elements. The plate thickness is 1.0 mm. Stainless steel SUS304 is used as the material property. The forming load was uniformly distributed and applied to the inner surface of the sealed preformed box. Based on the results of the actual forming experiments, the maximum load value for the analysis was set to 2.5 MPa.

Figure 17 shows the analysis results of the Mises stress when processing an egg-shaped shell using the IHBF method. Figure 17 shows that the Mises stress was relatively high along the weld line and relatively low near the weld line. This is because the box, made of welded flat plates, is deformed into an egg-shaped curved surface. The maximum Mises stress generated around the center was 348 MPa.

Figure 18 shows the analysis result of the thickness distribution of the processed egg-shaped shells. As shown in Figure 18, the thickness around the center of the egg-shaped shell was relatively thin and gradually thickened toward both ends. The thickness is distributed along the striped part. The thickness before forming was 1.0 mm, and the lowest thickness was 0.98 mm. Therefore, the change in thickness was small during the forming process, indicating that an egg-shaped shell can be stably formed using the IHBF method.

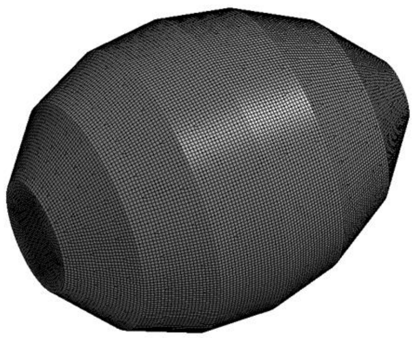


Figure 16. FEM analysis model for making egg-shaped shells using the IHBF method.

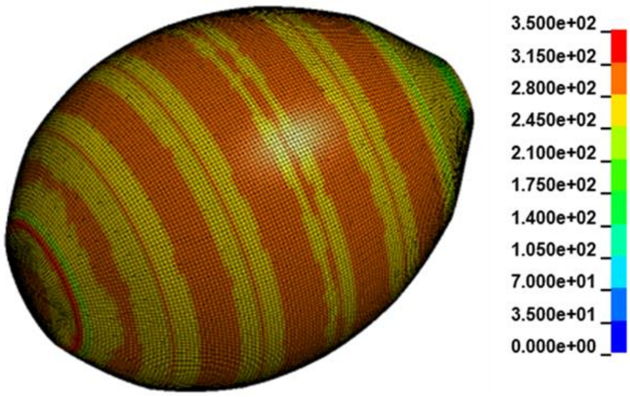


Figure 17. FEM analysis results of Misses stress when processing egg-shaped shells using.

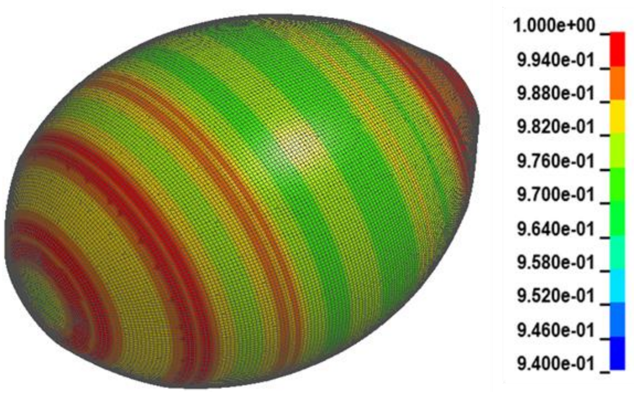


Figure 18. FEM Analysis results of thickness when processing egg shells using IHBF method.

3.3. Cushioning Effect of the Egg-shaped Layered Floating Tsunami Shelter

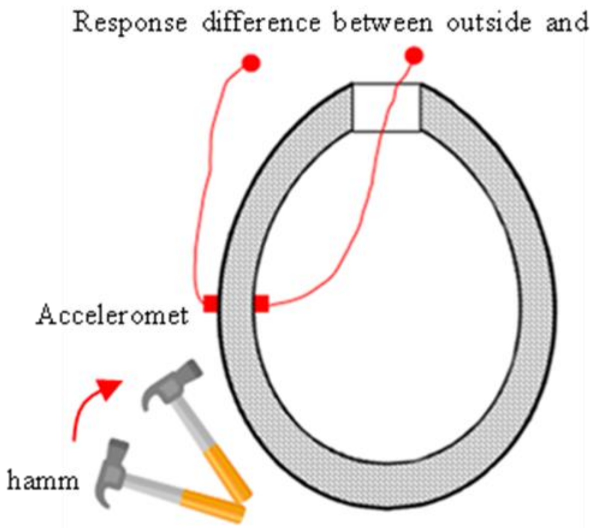


Figure 19. Schematic diagram of impact test to verify cushioning effect of egg-shaped tsunami shelter shell.

A hammer impact test was performed, as illustrated in Figure 19, to verify the cushioning effect of the proposed egg-shaped layered floating tsunami shelter. Acceleration sensors were installed on both the outside and inside of the egg-shaped layered floating tsunami shelters. Acceleration data were recorded when the egg-shaped layered floating tsunami shelter was hit with a hammer, and the cushioning effect was evaluated based on the difference in acceleration. In addition, because the measured acceleration signal was randomly distributed, the standard deviation S_a of the acceleration, expressed by the following formula, was used to evaluate the degree of up and down fluctuation.

$$S_a = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(a_i - a_{aver})^2} \quad (3)$$

where a_i is the measured acceleration, a_{aver} the average value of the measured acceleration, and N the total number of samples measured in the impact test. The constructed impact test equipment and measurement system are shown in Figure 20(a). It consisted of an egg-shaped layered floating tsunami shelter, an impact hammer, two acceleration sensors, an FFT analyzer, and a PC. To measure the cushioning effect, acceleration sensors were attached to corresponding locations on the outer and inner surfaces. As shown in Figure 20(b), a hammer was used to strike as close to the acceleration sensor as possible. Figures 20(c) and 20(d) show the acceleration sensors attached to the outer and inner surfaces, respectively.

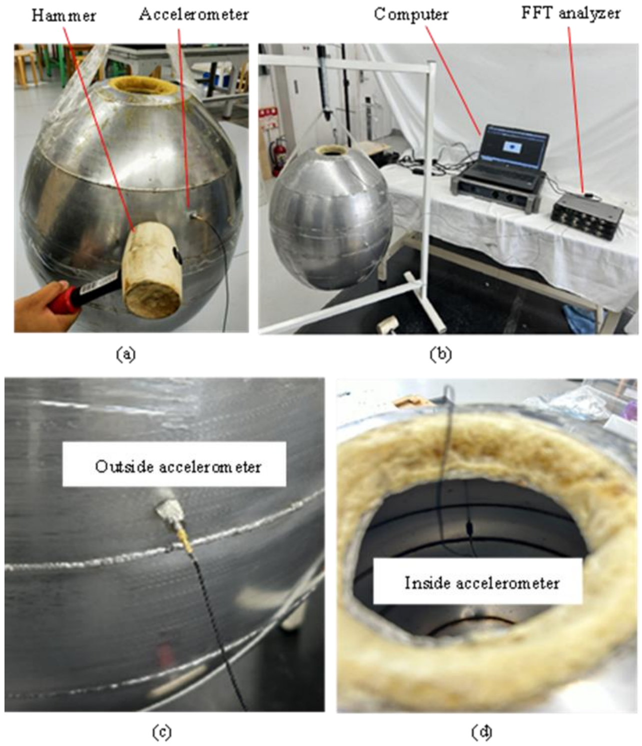


Figure 20. *Impact test to verify cushioning effect of the laminated egg-shaped tsunami shelter.*

The measurement results obtained using the acceleration sensor are shown in Figure 21. The acceleration data for the outer surface is represented by the solid red line, while the inner surface acceleration data is depicted by the dotted blue line.

The maximum acceleration value of the outer surface is 6.19 m/s^2, and the maximum acceleration value of the inner surface is 5.21 m/s^2. The maximum acceleration of the inner surface decreased by 15.81%.

When evaluating the fluctuations in acceleration, the outer surface exhibited a standard deviation of 0.77 m/s^2, while the inner surface showed a standard deviation of 0.54 m/s^2. This indicates a 29.87% decrease in the acceleration standard deviation on the inner surface. Consequently, it is evident that the egg-shaped, layered floating tsunami shelter provides a cushioning effect.

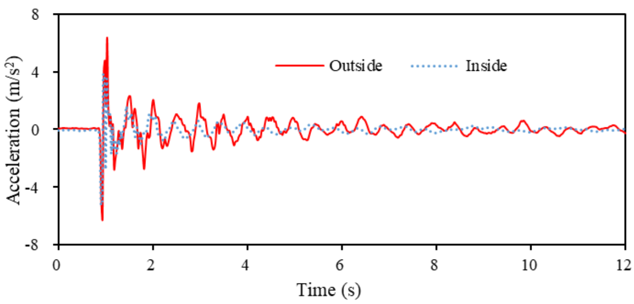


Figure 21. *Measurement result of acceleration of the laminated egg-shaped tsunami shelter.*

4. Conclusions

In this study, an egg-shaped-layered floating tsunami shelter with an elastic buffer layer is proposed. Verification was performed through processing experiments using the actual IHBF method, and impact tests were conducted on the resulting egg-shaped layered floating tsunami shelter, leading to the following conclusions:

(1) The proposed IHBF method for fabricating an egg-shaped laminated floating tsunami shelter involves cutting strip-shaped plate parts from a flat steel plate and welding them along the edges of the plate parts. This naturally creates an egg shape geometrically, eliminating the need for a jig to determine the welding position. The experimental results demonstrate that an egg-shaped shell structure can be fabricated with good performance using a simple process.

(2) To put the laminated floating tsunami shelter and its processing method into practical use, a theoretical egg-shaped function was used to propose a design method for the basic processed parts. The results of the actual forming experiments verified the proposed design method for the basic processed parts.

(3) The experimental results validated that the egg-shaped shell's shape accuracy was high. In the prototype tests, the maximum deviation from the intended shape was -4.13 mm, with a relative error of -1.68% when compared to the maximum radius of 246.5 mm for the egg-shaped shell.

(4) The actual forming experiments and FEM analysis results confirmed that the processing performance and shape accuracy of the laminated egg-shaped floating tsunami shelter processed using the IHBF method were satisfactory.

(5) To validate the impact absorption capabilities of the egg-shaped laminated floating tsunami shelter, which was manufactured using the suggested IHBF processing technique, a hammer impact test was performed. The results demonstrated effective cushioning. However, the level of cushioning can differ greatly depending on the type of material used between the inner and outer layers. This study employed urethane foam for cushioning; however, future research is expected to investigate alternative cushioning materials that may further improve impact absorption capabilities.

Abbreviations

IHBF Integral Hydro-bulge Forming

Author Contributions

Junfu Hou: Validation, Writing – original draft

Li Chen: Data curation, Methodology
Chenghai Kong: Data curation, Investigation, Methodology
Jingchao Guan: Writing—review and editing, Methodology
Wei Zhao: Conceptualization, Software
Xilu Zhao: Conceptualization, Writing – review & editing

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

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