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A Study on the Buckling Strength of Stern Skeg Shell Plate

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선미 스케그 외판의 좌굴강도에 관한 연구

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ABSTRACT

Most container ships are currently being constructed as Ultra-Large Container Ships. Hence, the equipment of the ships is also becoming relatively large. In particular, propellers, rudders, and rudder stocks are large in the stern structure, and in relation, efficient design of the hull structures to safely secure these parts is important. The bottom shell plate surface of a stern skeg is a perforated plate from which the rudder stock penetrates, so it is an important component for the stern structure. In this paper, to determine the critical buckling of the shell plate, an interaction curve equation for the two-axis compression of the shell plate was derived using the maximum value of the static structural stress multiplier in a load multiplier mode. This equation predicts the timing of the buckling occurrence. By analyzing this interaction curve equation, the buckling behavior of the plates subjected to a combination load was determined and the usefulness of applying it to ship building was investigated.

Keywords : Aspect Ratio(종횡비), Critical Stress(임계응력), Commercial Finite Element(상용 유한 요소), Critical Buckling Stress(임계좌굴응력), Rudder Force(타력), Buckling Behavior Phenomenon(좌굴 거동 현상)

1. Introduction

Due to the recent increase in global trade volume, the length of container ships capable of loading a large amount of cargo has been extended to nearly 400m. For this reason, studies on the development of propulsion devices, the adjustment performance, and the design of the shape around the stern skeg adjacent thereto have been steadily conducted[1-2]. In addition, in terms of structure, research using optimization techniques for ships that are increasing in size[3-4] and studies regarding the development of systems related to the load of in-plane and out-of-plane plate members[5-6] have been performed. The stern of a vessel must have a solid structure to support stern aggregates, rudders, and propeller shafts, in addition to resistance to external forces. Due to the characteristics of the stern structure, the rudder is constructed in the form

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of a cantilever in which the rudder stock penetrates the rudder body and fixes the connection to the stern trunk. In this case, because the rudder stock is located in an important position connecting the protruding rudder and the hull body, the skeg is composed of plate members in a typical perforated form. Although the perforated plate on the vessel is installed in parts where there is no high strength requirement, because the skeg is inevitably installed in the areas undergoing high stress resulting from the rudder force and other rotational forces, it is important to accurately analyze the behavior phenomena, such as buckling and strength reduction. Previous studies have explored various topics, including the strength analysis regarding the perforated plate of the non-watertight bulkhead in the vessel, the presence or absence of reinforcement, and the collapse analysis of the aluminum reinforced plate[7-9], while no studies have been conducted on the perforated plate of the skeg passing through the watertight bulkhead. Thus, because it is difficult to determine the quantitative safety factor due to the design without considering the post-buckling behavior, or applying excessive thickness, designs have been created based on experience. Regarding the buckling behavior phenomenon, which is important among vessel design factors, this study aimed to identify the elastoplastic deformation behavior of the perforated plate in the nonlinear skeg bottom plate by setting the slenderness ratio, aspect ratio, and aspect ratio of the hole passing through the plate as design variables. It also aimed to reveal the usefulness of the elastoplastic deformation behavior applicable to actual vessels.

2. Skeg Bottom plate Model for Actual Vessels

2.1 Target Model

Buckling, which lacks structural rigidity, typically represents a failure mode that loses stability. Because Euler's formula, which generates a narrow curve with respect to critical stress, does not provide an accurate expression for a specific shape, the critical buckling strength value in most of the classification rules is calculated by substituting and plastically modifying the elastic buckling strength using the approach by Johnson-Ostenfeld. However, because the critical buckling strength value obtained by this plastic modification tends to be higher than the actual value in the perforated plate, the calculated values are different from the property values of the perforated plates used in actual vessels. In particular, the form factor of the bottom section in the case of the stern skeg bottom plate is nonlinear, which is not found in the non-perforated and perforated plates of conventional vessels. Because the stern skeg bottom plate is a part that receives large force in the stern of the vessel, and the perforation ratio varies depending on the size of the rudder stock, the stern skeg bottom plate is crucial in the stern of the vessel. The shape of the stern skeg bottom plate is determined by the form factor of the section to calculate the area of the

Table 1 Investigated data of rudder profiles

Ship type	Rudder Force (kN)	Rudder Torque (kN.m)	Rudder Profiles
300K VLCC	6320.39	4717.45	NACA 0021/0018
ULCS Container	9672.95	9542.50	Hollow
LNG 173,700m3	3225.15	1622.65	Hollow
207k BC	3336.68	2688.99	NACA 0024

Fig. 1 Nonlinear perforated SKEG bottom plate

rudder and the rudder force. In this study, the form factor of the rudder section in the actual vessels used in shipyards was surveyed, as shown in Table 1. The vessels were sorted by vessel type, and the one with the highest rudder force from the data was selected as the target model. In the survey of the rudder force by vessel type, and the cross-sectional form factor of the rudder, which are most commonly used in actual vessels, the rudder force of the large container vessel was the largest, and the cross-sectional form factor in this case was confirmed to be of the hollow type. Fig. 1 shows the shape of the nonlinear perforated skeg bottom plate in container vessels.

2.2 Finite Element Analysis (FEA)

To perform the FEA, the size of the perforation (d), aspect ratio (a/b), and thickness (t) were set as the main variables for the stern skeg, as shown in Fig. 2. The main dimensions and properties used in the analysis are as follows: length of plate (a): 10400mm; maximum width (b): 2718mm; thickness: 100mm in the center of the perforation and 49mm in the bow/stern direction; Poisson's ratio (ν): 0.3; elastic modulus (E): 205.8 GPa; and yield stress (σ_y): 235 MPa. The skeg has a nonlinearity different from the shape of the conventional square-shaped perforated plate, which was obtained by calculating the ratio of the length and width of the plate as area. The thickness of the plate is 100mm from the center of the perforated circle by 2m in the forward and rear directions, and the thickness otherwise is 49mm. Furthermore, as the length of the plate exceeds 10m, the buckling factor was introduced, and the critical stress value was calculated as the boundary condition of the combined load subjected to simultaneous biaxial compression due to the characteristics of the structure applied in actual vessels. The analysis was performed on the assumption of elastic-perfectly plastic behavior of property materials.

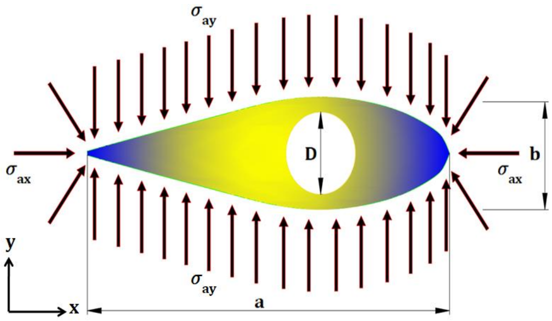

Fig. 2 Loading and boundary condition for SKEG bottom plate

2.3 Elastic Buckling by Biaxial Compression

The boundary condition that best represents the behavior related to the buckling strength in the actual plate member is the four-sided simple support condition presented by each class. Thus, the plate member constituting the structure is a continuous structure that is connected to other plate members in the structure. The coupling condition constraining the displacement in the in-plane direction is applied, and the analysis is performed to maintain all four sides straight with respect to the in-plane load. However, because the buckling calculation formula in each class is composed of only a function of the size of the perforated plate and the plate's aspect ratio tends to be evaluated higher than the actual final strength, the structures in actual vessels are often subjected to complex compression of two or more axes and buckling of simple support plates. As in Fig. 2, the curve (a) is the side of the length parallel to σ_{ax} and (b) is parallel to σ_{ay}. Thus, the work (W) applied to biaxial compression can be expressed as Equation (1)[10] as follows.

$$W = \frac{t\pi^2}{8}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} C_{mn}{}^2\left(\frac{b\sigma_{ax}}{a}m^2 + \frac{a\sigma_{ay}}{b}n^2\right) \qquad (1)$$

Here, the length of the plate a is in the x direction, and its width b is in the y direction.

m, n refers to the number of sine half-waves in a x, y axis direction, and the aspect ratio (a/b) is defined as δ and shown in Equation (2). The strain energy of the plate subjected to biaxial compression is also expressed as the aspect ratio δ, as shown in Equation (3).

$$W = \frac{at\pi^2}{8b} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} C_{mn}^2 [(\frac{m}{\delta})^2 \sigma_{ax} + n^2 \sigma_{ay}] \quad (2)$$

$$U = \frac{ab\pi^2}{8} D \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} C_{mn}^2 [(\frac{m}{a})^2 + (\frac{n}{b})^2]^2 = \frac{a\pi^4}{8b^3} D \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} C_{mn}^2 [(\frac{m}{\delta})^2 + n^2]^2 \quad (3)$$

If work (W) and strain energy (U) are equal, it can be expressed as in Equation (4) according to the principle of virtual work.

$$[(\frac{m}{\delta})^2 \sigma_{ax} + n^2 \sigma_{ay}]_{cr} = \frac{D\pi^2}{b^2 t}[(\frac{m}{\delta})^2 + n^2]^2 \quad (4)$$

In addition, to derive the interaction curve for biaxial compression, the critical stress equation of the long plate and the wide plate was substituted, as shown in Equation (5), where $(\sigma_{ax})_{cr}$ refers to the critical stress in the σ_{ax} direction and $(\sigma_{ay})_{cr}$ refers to the critical stress applied only in the (σ_{ay}) direction. D refers to the bending stiffness of the plate, which is a function of t as a variable where the plate thickness is determined at the design stage.

$$(\sigma_{ax})_{cr,1} = 4\frac{D\pi^2}{b^2 t}, \ (\sigma_{ay})_{cr,1} = [1 + (\frac{1}{\delta})^2]^2 \frac{D\pi^2}{b^2 t} \quad (5)$$

Based on Equation (5), Equation (4) was made dimensionless, and the interaction curve for biaxial compression, which is a complex stress state, was expressed as in Equation (6).

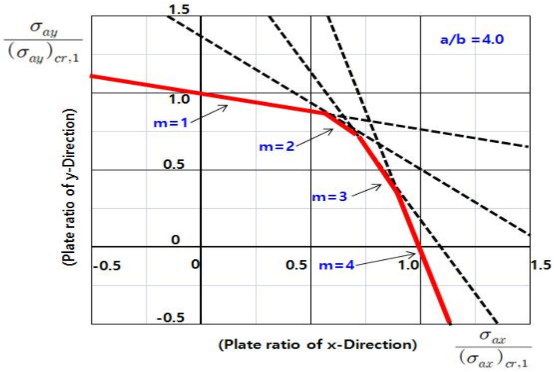

Fig. 3 Critical stress of plates with different aspect ratio under 2 axis compression

$$[(\frac{m}{\delta})^2 \frac{\sigma_{ax}}{(\sigma_{ax})_{cr,1}} + n^2 \frac{\sigma_{ay}}{(\sigma_{ay})_{cr,1}} \frac{1}{4}(\frac{\delta^2+1}{\delta^2})^2]_{cr} = \frac{1}{4}[(\frac{m}{\delta})^2 + n^2]^2 \quad (6)$$

To obtain the curve for the critical buckling stress of the biaxial load, the graph shown in Fig. 3 was obtained by substituting the interaction curve in Equation (6) when the aspect ratio (a/b) of the skeg deck is 2, 3, and 4, respectively. The x and y axes correspond to $\sigma_{ax}/(\sigma_{ax})_{cr,1}$ and $\sigma_{ay}/(\sigma_{ay})_{cr,1}$, and various straight lines are illustrated according to the value of m, which is the number of sine half-waves in each axis direction. Moreover, the critical buckling stress curve for the biaxial load can be obtained by connecting the tangent lines to the innermost lines. Based on this calculation, because the stress ratio of the critical stress value of the wide surface vulnerable to buckling around the perforated circle in the nonlinear skeg bottom is $\sigma_{ax} = 0.39\sigma_{ay}, \delta = 3.9$, a substitution by Equation (4) results in simplification, as in Equation (7). Fig. 4 represents the critical buckling stress for each axis direction as a result of the number of sine half-waves for the short and long axes, where n is always 1 as the number of sine half-waves for the short axis. In addition, when m is 1, 2, 3, and 4,

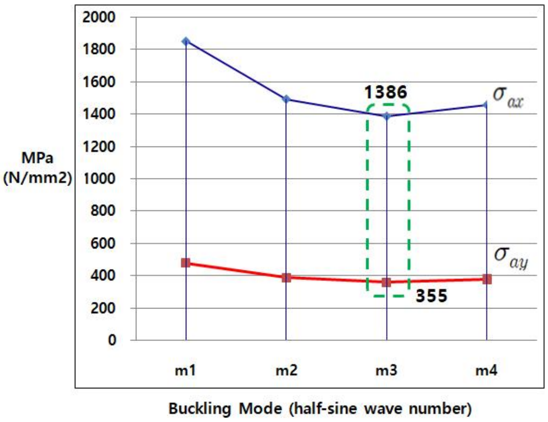

Fig. 4 Buckling critical stress value for sine half waves length

$$[(\frac{m}{3.9})^2+0.2n^2](\sigma_{ax})_{cr}=\frac{\pi^2}{(718)^2(100)}*$$

$$\frac{(205{,}800)(100)^3}{100(1-0.3^2)}*\frac{[(\frac{m}{3.9})^2+n^2]^2}{[(\frac{m}{3.9})^2+0.2n^2]^2} \quad (7)$$

which is the number of sine half-waves for the long axis, it shows the results of the critical stress values. As shown in the results, for the maximum strain m, which represents the strain the skeg bottom can withstand without being destroyed, σ_{ax} is 1,386 MPa and σ_{ay} becomes 355 MPa at the stress ratio of 3.9.

3. Evaluation of Strength of Skeg

3.1 Strength Analysis of Skeg under Biaxial Compressive Load

To examine the buckling safety of perforated plates subjected to combined load, this study set design parameters for the perforation diameter of the skeg bottom based on actual vessels and further considered the size of the perforation, slenderness ratio, and properties of plate thickness. ANSYS linear buckling V13, a commercial finite element structural analysis program, was used to perform the buckling strength analysis for the target model. A 100-mm (wide/long) grid was formed to closely discriminate the behavior of the perforated column, which has 68,870 nodes and 12,950 elements, and a shell element with six degrees of freedom was applied at each node of the finite element. Because the skeg bottom is a typical cantilevered structure, the fixed support point was selected as the end of the hull 3m above the skeg bottom. The size of the perforation occupies 20% of the skeg deck, which is 2,000mm long in the bow and stern directions of the hull from the center of the aforementioned perforation and 100mm thick. The thickness otherwise is set as 49mm. The analysis was conducted with the strongest rudder force of 9,672kN among the possible resistances at the upper structure of the vessel’s stern. Fig. 5 shows the result of static structural stress, indicating that the load is concentrated due to the influence of the width direction where the section modulus is small around the perforation and that the allowable stress is satisfied because the maximum stress is 78 MPa.

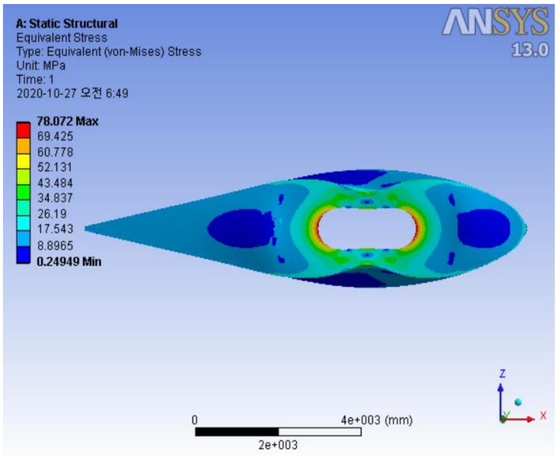

Fig. 5 Von-Mises stress for SKEG bottom plate

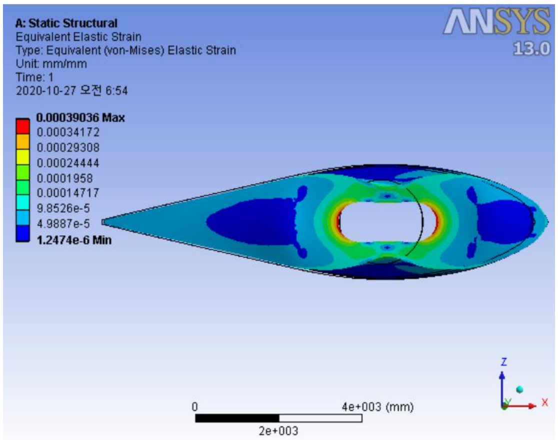

Fig. 6 Elastic strain for SKEG bottom plate

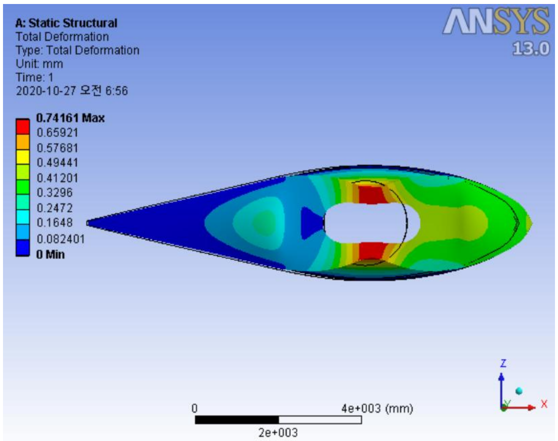

Fig. 7 Deformation for SKEG bottom plate

Fig. 6 shows the results for the stress equivalent to elastic strain, and as shown in the results, the strain due to compression from the vertical strain is determined as 0.0003mm/mm compared to the initial length in the longitudinal direction, which indicates that there is a sufficient margin to reach the ultimate strength. Fig. 7 shows that the load in the width direction with a smaller section modulus than the longitudinal direction with a large section modulus around the perforation occurred as the maximum strain.

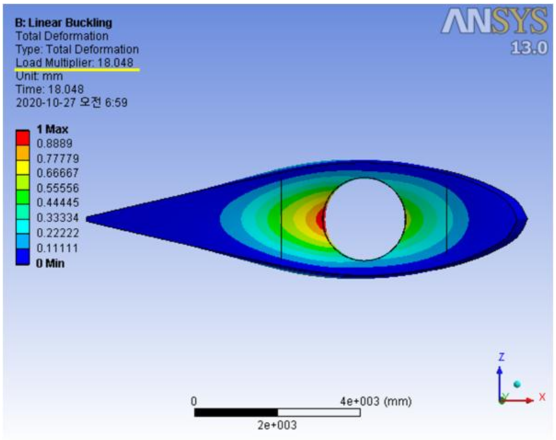

Fig. 8 Linear buckling for SKEG bottom plate

3.2 Elastic Buckling Strength of Skeg

Typically, structural calculation is performed using the buckling discrimination equation by uniaxial load in the buckling analysis of vessels. However, this study considered the extreme situation subject to the biaxial combination load in that the stern structure of the hull is the protrusion in the form of a cantilever. Before performing the elastic buckling analysis to determine through which behavior the shape of the perforation affects the skeg bottom, the strength analysis was first performed. When a force of 9762 kN, which was the maximum variable rudder force considered in the upper structure of the stern, was applied as the load condition, the yield strength was 78 MPa. If the maximum load in this case is multiplied by the load multiplier of the buckling analysis, and the load factor according to the buckling mode is substituted, the result of buckling occurrence can be obtained. In this respect, the buckling analysis was performed as follows. Fig. 8 shows the results to compare the critical stress value when the maximum strain of the skeg bottom is 3, obtained by substituting the previously derived interaction curve equation regarding elastic buckling due to biaxial compression. In this case, the results show that the load multiplier in mode 1 is 18. The

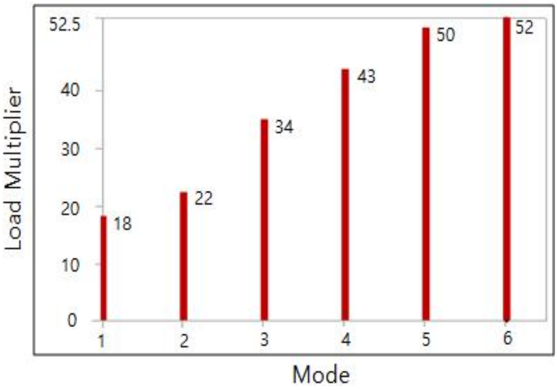

Fig. 9 Load multiplier for linear buckling

safety factor for buckling and extreme strength evaluation of steel plates in vessels is typically 1.0[10],while the safety factor differs by classification association. Fig. 9 shows a graph of the load multiplier results for modes 1 to 6 of the buckling analysis. In the critical buckling analysis, based on the value of 18.048, which is greater than the safety factor of 1 in the load multiplier mode 1, the value is greater than the safety factor used in the applied blade edge thickness where the maximum safety factor in the class rule is applied. If the maximum value in static structural stress is substituted, the maximum strain is 1,404 MPa. In addition, considering that the stress ratio is 3.9, the strain is 360 MPa, which indicates that the results obtained from the theoretical curve equation for the critical buckling stress of the actual secondary load and those obtained through the linear buckling analysis are similar.

4. Conclusion

The hull's skeg bottom is located at the stern of the vessel, and despite its 100% exposure to the rudder force in the form of a cantilever, there is no calculation formula for calculating the thickness, because each classification rule is missing. For this reason, the thickness has been generally applied based on experience. In particular, the skeg bottm has a typical shape of a hull with a perforated plate through which the rudder stock passes while functioning as a watertight bulkhead. The perforated plate of the hull is the most important design factor for a vessel, and the phenomenon of buckling behavior must be understood. In addition, when a notch occurs at the thick plate of the hull of 65mm or more, the stress typically propagates straight through the cracks regardless of the stress proportionality. Thus, although a thick plate that guarantees brittle crack arrestability should also be considered, a general thick steel plate is used. To solve this problem, first, the critical stress was theoretically calculated using the interaction curve equation according to the combined load for the buckling behavior of the stern skeg bottom in which the biaxial compression acts, and the following conclusions were drawn through the linear buckling analysis.

1. The excessive thickness of the hull plate around the perforation was applied in the design although the stress was 78 MPa, which is far below the allowable yield stress, even when applying the rudder force of a large container ship, which can occur at the stern of the vessel, as the maximum force.
2. According to the result obtained by the theoretical curve equation for the critical buckling stress regarding elastic buckling by biaxial compression, σ_{ax} is 1386 MPa and σ_{ay} is 355 MPa. Considering 1404 MPa at the stress ratio 3.9 in the analysis, σ_{ay} is 360 MPa, which is similar to the theoretical value. As a result, the maximum strain was confirmed at the aspect ratio of 3, and this result shows that the section modulus in the width direction from the perforated skeg bottm is more important than the thickness. An optimized design is necessary with its focus on section geometry to secure the

section modulus.

3. In the case of the skeg bottom, the thickness has been determined based on experience without the calculation formula of the classification due to the long-lasting patents of foreign companies. However, due to the expiration of the patent period, revision of the calculation formula is required for each class. This study first identified the elastic buckling phenomenon due to the biaxial compressive load of the skeg bottom for the buckling behavior and further investigated the suitability of the skeg bottom applied to actual vessels. The results of this study will provide basic data to develop a calculation formula that determines the thickness of the stern skeg bottom in the future by evaluating the final strength with buckling.

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