Journal of Advanced Research in Ocean Engineering 4(1) (2018) 007-015
https://dx.doi.org/10.5574/JAROE.2018.4.1.007

Empirical Initial Scantling Equations on Optimal Structural Design of Submarine Pressure Hull

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(Manuscript Received January 12 2018; Revised February 10, 2018; Accepted March 15, 2018)

Abstract

The submarine is an underwater weapon system which covertly attacks the enemy. Pressure hull of a submarine is a main system which has to have a capacity which can improve the survivability (e.g., protection of crews) from the high pressure and air pollution by a leakage of water, a fire caused by outside shock, explosion, and/or operational errors. In addition, pressure hull should keep the functional performance under the harsh environment. In this study, optimal design of submarine pressure hull is dealt with 7 case studies done by analytic method and then each result's adequacy is verified by numerical method such as Finite Element Analysis (FEA). For the structural analysis by FEM, material non-linearity and geometric non-linearity are considered. After FEA, the results by analytic method and numerical method are compared. Weight optimized pressure hull initial scantling methods are suggested such as a ratio with shell thickness, flange width, web height and/or relations with radius, yield strength and design pressure (DP). The suggested initial scantling formulae can reduce the pressure hull weight from 6% and 19%.

Keywords: Underwater weapon system, survivability, Pressure hull, Optimal design, Finite Element Analysis (FEA), Initial scantling methods

1. Introduction

As an underwater weapon system, a submarine is used for a variety of purposes, including anti-surface ship/submarine warfare, covert intelligence, surveillance, and special forces delivering. For these performance, it can secretly attack the enemy silently, and it shall have good mobility and ensure the safety of its crew and its ability to sustain operations at underwater. In addition, weight minimization shall be achieved with a strength that can withstand the depth of collapse.

The scantling of the pressure hull shall be determined to enable weight optimization in association with structural strength, and the suitability shall be evaluated. In this regard, the ideal pressure hull shape is the sphere, but cylindrical structure is applied due to the hydrodynamics characteristic, the effectiveness of the space, and the advantages of its workmanship.

For the design of the pressure hull, the initial scantling of pressure hull shell plates and reinforcements shall be calculated based on different equations applicable depending on each country, and actually there are few published data.

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Therefore, in this study, seven cases are selected in accordance with the design pressure and the radius of the pressure hull shaped a cylindrical structure. The thickness of pressure hull shell plate, the ring frame distance, the height and thickness of ring frame web, and the width and thickness of ring frame flange are selected as design variables, shell yielding, shell buckling, general instability, frame tripping and out of roundness are selected as design constraints, and weight minimization is selected as an objective function. Based on these conditions, parametric studies are performed and the initial scantling equations are proposed. However, the initial scantling equations derived from this study is the result of no consideration of the effects of general arrangement.

The strength calculation for selecting the principal dimensions of pressure hull is performed for shell yielding, shell bucking, general instability, frame tripping and out of roundness in accordance with BV1040-2 (1989), and FEA is carried out for checking the integrity of this structure. The stress of pressure hull shell plate, shell yielding, shell buckling, general instability, and frame tripping are calculated based on DTMB reports (J. G. Pulos and V. L. Salerno, 1961; M. E. Lunchick, 1961; T. E. Reynolds, 1960; J. G. Pulos and M. A. Krenzke, 1965; W. E. Ball, 1962; W. E. Blumenber, 1965; E. H. Kennard, 1966; M. Krenzke, K. Hom, and J. Proffit, 1965; T. J. Kiernan and K. Nishida, 1966).

For the performance of this study, strength calculations by analytic methods are carried out using MS Office EXCEL, and for the strength analysis by numerical method to verify the structural safety, the commercial FEA program ANSYS classic is applied.

2. Submarine Structure and Design

The hull structure of the submarine is divided essentially into a pressure hull to withstand the hydrostatic pressure and a non-pressure hull not directly under hydrostatic pressure during the dive. The main structural members of the pressure hull consist of a bulkhead, fore-end/aft-end bulkhead, shell and cone shell, and ring frame as shown in Figure 1. The thickness of the pressure hull shell plates is determined by the inner diameter of the pressure hull, the frame spacing, the design pressure and the material strength. The shell plate reinforcements take the form of ring frame, inner bulkheads and deep frame. Where internal bulkhead is divided by a compartment bulkhead and a pressure bulkhead, serves to support the pressure hull. The ring frame is a typical stiffener supporting the pressure hull, with the most used T-shaped section and is usually located inside the pressure hull. The spacing of inner bulkheads is defined as the horizontal distance between two bulkheads and has a significant influence on the collapse of the hull, so one to two times of the pressure hull diameter is used. Deep frame is used to replace bulkhead with larger stiffness than the ring frame, taking into account weight or arrangement. In the case of fore-end/aft-end bulkhead, various forms exist and are determined to have a minimum weight, taking into account the conditions of operation and general arrangement.

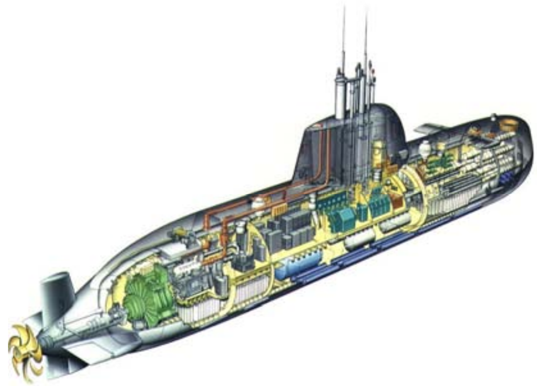
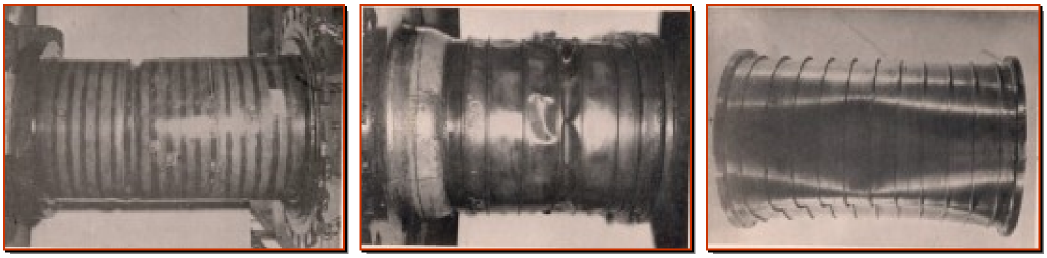


Fig. 1. 214 Class Submarine Structure



(a) Shell Yielding (b) Shell Buckling (c) General Instability

Fig. 2. Submarine Pressure Hull Failure Modes

2.1 Equations for the Submarine Structural Design of Each Country

The design of pressure hull structures for the submarine is normally carried out according to the design concepts, and the independent design loads and strength criteria based on conventions of each country's navy and considering the shell yielding as shown in Figure 2 (a), shell buckling as shown in Figure 2 (b), general instability as shown in Figure 2 (c), and frame tripping.

In consideration of the strength calculation theory of the pressure hull design criteria, the United States uses the equations and experimental results carried out at the DTMB in the 1950s and 1960s. The equations as known as the Pulos & Salerno equation, Windenburg equation, Bryant equation, and Sanden & Günther equation are applied to shell yielding, shell buckling, general instability and frame tripping, respectively. In the U.K., design formulas and design diagrams based primarily on self-performing experimental results, such as the BS 5500 is used, but the Bryant equation and Föpple equation are applied to general instability and frame tripping, respectively. In Germany, the DTMB reports are applied with partial modifications, and the equations as known as the Pulos & Salerno and Lunchick equation, Reynolds equation, modified Bryant equation, and Kennard equation are applied to shell yielding, shell buckling, general instability and frame tripping, respectively (John R. MacKay, 2007).

2.2 Submarine Pressure Hull Strength Calculation Procedure

To the axial and hoop direction's membrane stress, bending stress, and equivalent stress at the cylindrical shell mid-bay and the position where ring frame is located, the stress should not exceed the allowable stress. In addition, the compressive stress at the neutral axis of ring frame and the flange end of the original frame are calculated for the design pressure, and the elastic and non-elastic buckling pressures for shell yielding and shell buckling are calculated. After calculating the overall buckling pressure based on each buckling pressure from the ring frame, pressure hull shell plates, deep frame and bulkhead with the general instability buckling mode, the out of roundness tolerance for buckling pressure is calculated, and this value should be less than production tolerance. The calculation result of frame tripping which is expressed by pre-tilt angle should be larger than allowable value of the manufacture tolerance.

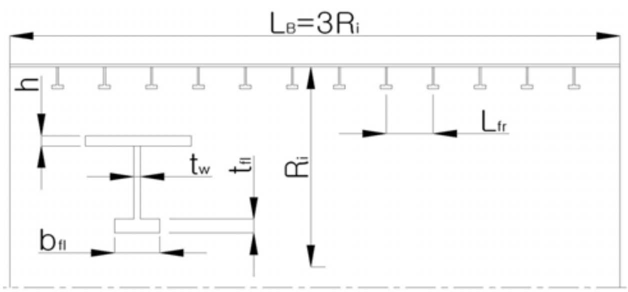


Fig. 3. Typical Cylindrical Shell & Cross Section

Table 1 Parametric Study Data

Case	Design Pressure (DP)	Diameter (m)	Field length (m)	Material	Yield stress (MPa)
1	100% DP	10.0	3xRi	HY100	686
2	94% DP	7.8	3xRi	HY100	686
3	89% DP	9.0	3xRi	HY80	552
4	127% DP	12.5	3xRi	HY130	890
5	75% DP	7.6	3xRi	HY80	552
6	89% DP	6.2	3xRi	HY80	552
7	100% DP	6.8	3xRi	HY100	686

3. Parametric studies

3.1 Design Variables and Objective Function

For seven cases of the different design pressure and radius of pressure hull as indicated in Table 1, the ring frame space (L_{fr}), the thickness of shell plate (h), web height (h_w), web thickness (t_w), the width of flange (b_{fl}) and the thickness of flange (t_{fl}) are selected as design variables shown in Figure 3.
The shell yielding, shell buckling, general instability, frame tripping and out of roundness are selected as design constraints, and weight minimization is selected as an objective function. Based on these conditions, parametric studies perform and the initial scantling equations are proposed. In this case, the bound of design variables is selected by referring to the actual submarine information, and according to the discrete value, the design variables is increased amongst the bound values indicated in Table 2 below.

3.2 Constraints

The constraints for the shell yielding, shell buckling and general instability are defined as below, respectively:

$$P_{Shell\ Yielding} \geq P_{Design}, P_{Shell\ Buckling} \geq P_{Design}, P_{General\ Instability} \geq P_{Design}$$

Where $P_{Shell\ Yielding}$ is pressure of shell yielding, $P_{Shell\ Buckling}$ is pressure of shell buckling, $P_{General\ Instability}$ is pressure of general instability, and P_{Design} is pressure.

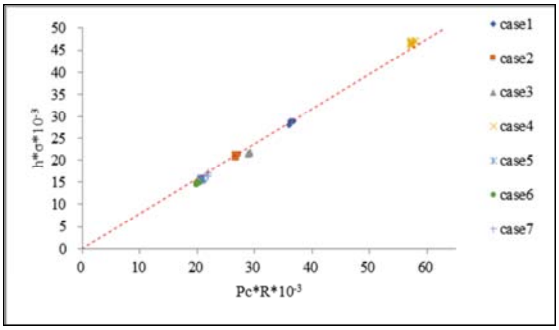
Table 2. The Bound and Discrete value of Design Variables

Case		Shell Thickness (mm)	Frame Space (mm)	Web Height (mm)	Web Thickness (mm)	Flange Width (mm)	Flange Thickness (mm)
1	Bound	41~43	705~740	315~340	26.5~28.0	155~165	51~55
	Discrete value	1	5	5	0.5	1	0.5
2	Bound	30~31	525~560	215~230	18.5~20.0	115~125	45~50
	Discrete value	0.5	5	1	0.5	1	0.5
3	Bound	38.5~40	660~715	275~291	25~26	145~160	54~56.5
	Discrete value	0.5	5	1	0.5	1	0.5
4	Bound	52~53	850~890	375~400	33.5~34.5	185~200	73~75
	Discrete value	0.5	5	5	0.5	1	0.5
5	Bound	28~29	505~545	210~250	17.5~19	100~120	40.5~46.5
	Discrete value	0.5	5	1	0.5	1	0.5
6	Bound	26~27	440~480	195~215	17~18.5	100~110	35~39
	Discrete value	0.5	5	1	0.5	1	0.5
7	Bound	24~25	405~450	190~220	16~18.5	90~115	32~35
	Discrete value	0.5	5	1	0.5	1	0.5

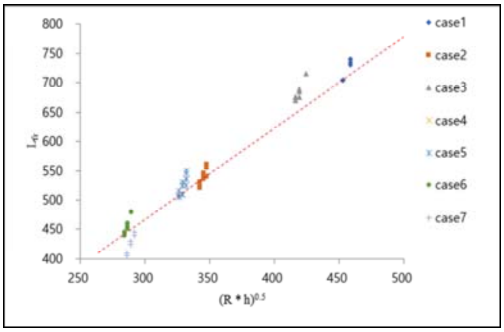
And the calculated allowance of out of roundness should be greater than or equal to the value 0.4% of inner radius of pressure hull in accordance with BV1180-2 (1998) or to the agreed criterion of owner and shipyard. Also, the calculated allowance of tilting angle for frame tripping should be greater than or at least equal to 4˚ in accordance with BV1180-2 (1998) or to the agreed criterion of owner and shipyard.

4. New Initial Scantling Equations from Parametric Studies

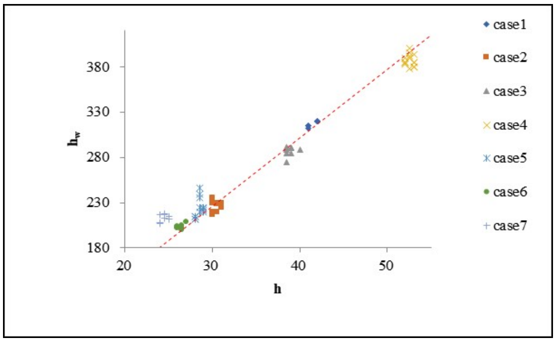
According to the parametric studies, the following equations are derived by curve fitting method as shown in Figure 4 (a) to (f) and the equations are indicated in Table 3.



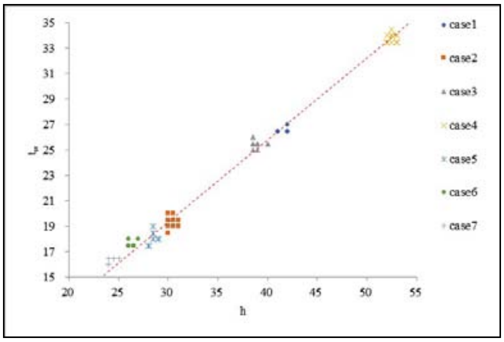
(a) For pressure hull shell thickness



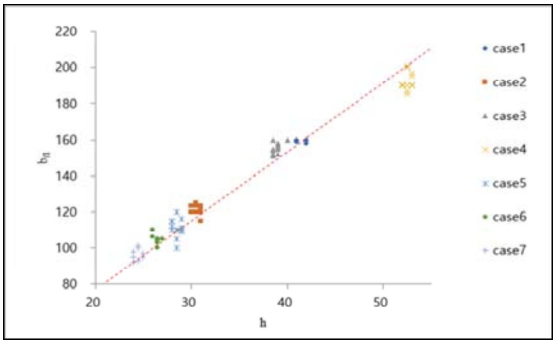
(b) For frame space



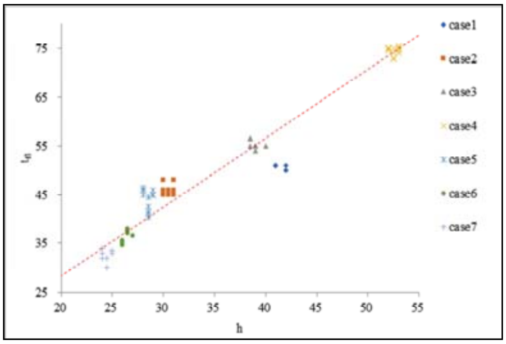
(c) For web height



(d) For web thickness



(e) Flange width



(f) Flange thickness

Fig. 4. Factors for Initial Scantling Equations for Submarine Structure

Table 3. Suggestion of Initial Scantling Formulae

Parameter	Shell Thickness (h)	Frame Space (L_{fr})	Web Height (h_w)	
Initial Scantling Formulae	$h = 0.790 \times \frac{pR}{\sigma_{0.2}}$	$L_{fr} = 1.557 \times \sqrt{R \times h}$	$h_w = 7.552 \text{ x } h$	$h_w = 5.966 \times \frac{pR}{\sigma_{0.2}}$
Parameter	Web Thickness (t_w)			-
Initial Scantling Formulae	$t_w = 0.645 \text{ x } h$	$t_w = 0.0866 \text{ x } h_w$	$t_w = 0.510 \times \frac{pR}{\sigma_{0.2}}$	-
Parameter	Flange Width (b_{fl})			-
Initial Scantling Formulae	$b_{fl} = 3.827 \text{ x } h$	$b_{fl} = 0.507 \text{ x } h_w$	$b_{fl} = 3.025 \times \frac{pR}{\sigma_{0.2}}$	-
Parameter	Flange Thickness (t_{fl})			-
Initial Scantling Formulae	$t_{fl} = 1.414 \text{ x } h$	$t_{fl} = 0.369 \text{ x } b_{fl}$	$t_{fl} = 1.12 \times \frac{pR}{\sigma_{0.2}}$	-

Where P is the applied pressure (design requirement), R is the radius of pressure hull, and $\sigma_{0.2}$ is the yield strength of applied material.

5. Review the Applicability of the New Equations By FEA

In this chapter, the structural design of submarine pressure hull using new initial scantling equations is verified whether it can withstand under the design pressure.

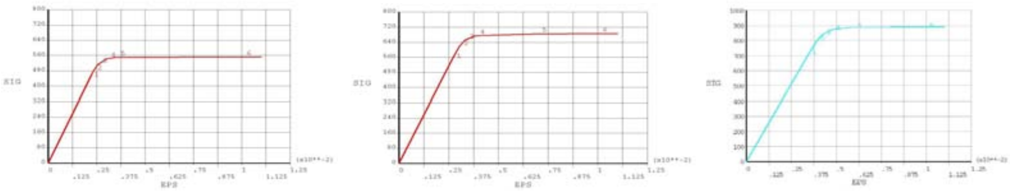
5.1 Material Information for FEA

5.1.1 Material Model

As shown in Figure 5 (a) to (c), multilinear material models are applied to perform nonlinear finite element analysis (NLFEA).

5.1.2 Material Properties and Allowable Stress

The material properties for NLFEA is shown in Table 4, and the allowable stress is same as the yield strength as indicated in Table 4.



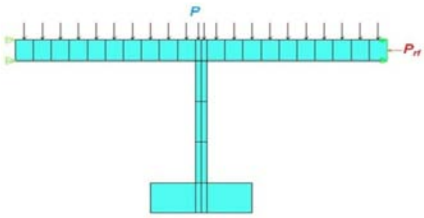
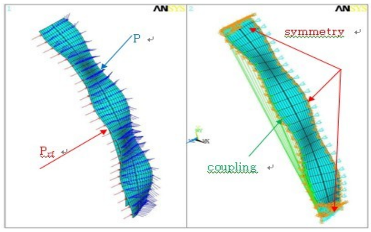
(a)HY80 stress-strain curve (b) HY100 stress-strain curve (c) HY130 stress-strain curve

Fig. 5. Stress-Strain Curve of applied Material Model

Table 4. Material Properties of HY80, HY100 and HY130

Property	HY80	HY100	HY130
Young's Modulus (E, GPa)	206	206	206
Poisson's Ratio (ν)	0.3	0.3	0.3
Density (ρ, g/㎤)	7.85	7.85	7.85
Yield Strength ($\sigma_{0.2}$, MPa)	552	686	890
Tensile Strength (σ_U, MPa)	611	760	986
Elongation (%)	19	17	14

Table 5. FEA Modelling for Shell Yielding and Shell Buckling

		Shell yielding	Shell buckling
Element		Plane 42 (2D structural solid)	SHELL181 (4-Node Finite Strain Shell)
Boundary condition			
	Restraint	Coupling and fixed to longitudinal direction	Coupling and symmetry
	Load	$P = \alpha \times P_{Design}$ and	$P_{rf} = \frac{D_{out}^2}{D_{out}^2 - D_{in}^2} \times P$

5.2 Modelling for FEA

The applied element and boundary conditions are indicated in Table 5. And the ring force (Prf) is defined as the pressure which acts on the fore-end or aft-end bulkhead.

5.3 Review results

The results of comparison of shell yielding pressure calculated by the analytical method and by the numerical method show that the pressure hull dimensioned by the proposed initial scantling equations are safe for shell yielding. The results of the strength calculations by analytical and by numerical method are within the error range of 7.19%, and are shown in Table 6.

The results of comparison of shell buckling pressure calculated by the analytical method and by the numerical method show that the pressure hull dimensioned by the proposed initial scantling equations are safe for shell yielding. The results of the strength calculations by analytical and by numerical method are within the error range of 4.96%, and are shown in Table 7.

Table 6. Comparison of Shell Yielding Pressure by Analytic Method and by Numerical Method

Case		1	2	3	4	5	6	7
A	P_{cr}_analytical (MPa)	8.686	8.331	7.452	11.475	6.420	7.404	7.762
N	P_{cr}_numerical (MPa)	8.272	7.835	7.162	10.830	6.098	7.063	7.204
(A-N)/A*100 (%)		4.77	5.95	3.89	5.62	5.02	4.61	7.19

Table 7. Comparison of Shell Buckling Pressure by Analytic Method and by Numerical Method

Case		1	2	3	4	5	6	7
A	P_{cr}_analytical (MPa)	8.713	8.344	7.481	11.468	6.456	7.444	7.840
N	P_{cr}_numerical (MPa)	8.445	8.058	7.303	10.900	6.260	7.273	7.499
(A-N)/A*100 (%)		3.08	3.43	2.38	4.96	3.04	2.30	4.35

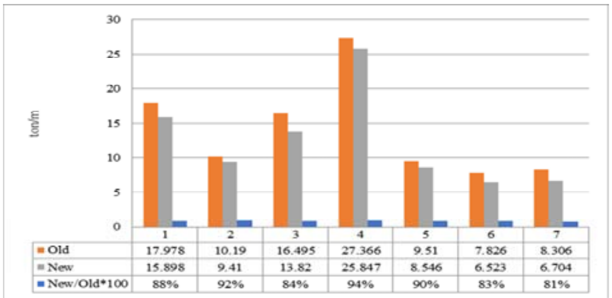


Fig. 6. Pressure Hull Weight per Meter Comparison by Existing Equations and by proposed Equations

6. Weight comparison

The weight per unit length by the principal dimensions of the pressure hull calculated based on the rules for classification (GL, 2008) and by the proposed equations are compared, and the results are indicated in Figure 6.

As shown in Figure 6, the weight of the pressure hull designed according to the proposed equations can be expected to reduce its weight by 6 % to 19 % compared to the weight of the pressure hull designed according to the existing equations.

7. Conclusions

In this study, the submarine pressure hull shapes are selected as cylindrical structures to achieve minimum weight capability. For seven cases of the different design pressure and the radius of pressure hull, the ring frame space, the thickness of shell plate, web height, web thickness, the width of the flange and the thickness of the flange are selected as design variables. The shell yielding, shell buckling, general instability, frame tripping and out of roundness are selected as design constraints, and weight minimization is selected as an objective function. Based on these conditions, parametric studies perform and the initial scantling equations are proposed.

In addition, the structural safety of pressure hull dimensioned by the proposed initial scantling equations is verified by checking the shell yielding and shell buckling capacity.

Finally, the weight of the pressure hull designed according to the proposed equations can be reduced.

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