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An optimal arrangement method of blast hardened bulkhead for surface warships using a simplified vulnerability evaluation

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ABSTRACT

One of the critical performances of a surface warship is its survivability, which consists of susceptibility, vulnerability and recoverability. As an effective design option to improve the vulnerability, blast hardened bulkhead (BHB) is installed within the warships. BHB aims to prevent internal explosion in a compartment from propagate to its adjacent ones; at the same time it unavoidably increases the total weight of the hull structure. In this research, we propose an optimal BHB arrangement methodology for the early stage of the warship design. A simplified vulnerability evaluation method is developed to consider the structural failures against the blast pressure and used as one of the objective functions for the optimal arrangement. Based on this evaluation method and number of BHBs, optimal BHB locations are determined using genetic algorithm to suggest optimal BHB design decision. For the verification, the analysis results are compared with those of the previous research on a virtual warship.

1. INTRODUCTION

A surface warship is a vessel to carry out military missions. However, in a modern combat environment, there exist plenty of unspecific threats which are difficult to predict(ISTK report 2012). Thus, it should have not only a sufficient capability of offense but also that of defense even if our surface warships are exposed to the threat of the hostile forces(Kim 2006). One of the critical defense capabilities of a surface warship is its survivability, which consists of susceptibility, vulnerability and recoverability(Ball and Calvano 1994). Susceptibility is the inability of a surface warship to avoid being damaged, vulnerability is that to withstand damage mechanisms by threat weapons and recoverability is the ability of the ship and its crew to prevent loss and restore mission(Said 1995). It is difficult to predict the combat environment, so the warship

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should be designed as aspects of vulnerability to minimize the damage by unpredictable hits(Kim 2011). In order to effectively improve the vulnerability, blast hardened bulkhead (BHB) is transversely installed within the warships against internal explosion threat such as Fig.1(Cowardin et al. 2013). A conventional watertight bulkhead was designed to withstand hydrostatic pressure, whereas it was is not designed to sustain the internal blast pressure(SNAK 2012). The BHB aims to prevent internal explosion in a space from propagate to its adjacent spaces(ROKN 2009); at the same time it unavoidably increases the total weight of the hull structure, and it results in the reduction of other performance such as mobility. Therefore, it is very important to compare the benefits and drawbacks between the improved survivability and the increased weight in the early stage of the warship design.

In the previous research, a structural vulnerability assessment was conducted to allocate the BHB within the warship(MOTIE&DARPA report 2014). After figuring out structural failures against the internal blast using empirical equation about characteristics of explosive and bulkhead structures, the BHB installation was considered. However, the method was difficult to judge a vulnerability reduction effect for entire warship. As the other method to evaluate the vulnerability, damage volume was used in a damage ellipsoid method(Shin et al. 2013). Its primary goal was to analyze an appropriacy of compartments or critical components arrangement. It could assess the vulnerability of entire warship using a stochastic/statistical hit distribution, whereas the method didn't consider about a thickness of structures because the damage volume was estimated based on the features(equivalent TNT weight, shape of warhead etc..) of threatening weapon.

This research suggests a new methodology for evaluating the vulnerability of warship considering a structural damage and stochastic/statistical hit distribution. And the simplified vulnerability evaluation method used as one of the objective functions for the optimal BHB arrangement. Comparing the allowable pressure of hull structures and the shock pressure by each hit, the vulnerability is calculated. Based on this evaluation method and number of BHBs, optimal BHB locations are determined using genetic algorithm to suggest optimal BHB design decision. For the verification, the analysis results are compared with those of the previous research on virtual warship. Also assuming various hit distributions, some case studies are conducted.

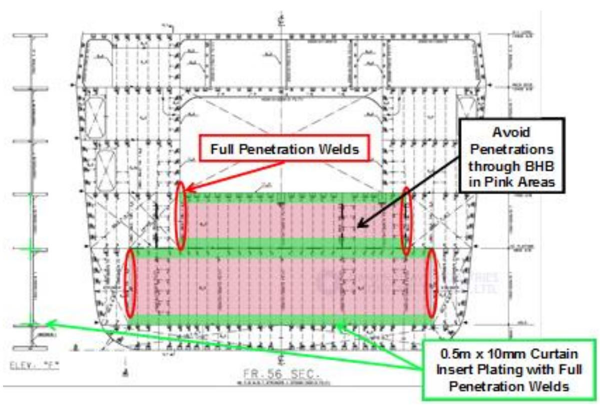


Fig. 1 Typical BHB curtain design shipboard installation (Cowardin et al. 2013)

2. A SIMPLIFIED VULNERABILITY EVALUATION METHOD

Surface warships should be designed to reduce its vulnerability to improve its survivability. In the previous research, as a first step for evaluating the warship vulnerability, critical compartments or components were selected according to professionals' opinion. For facilitating the assessment without a detailed components arrangement information, compartment vulnerability is quantified(Shin 2013). We follow the procedures outlined in previous studies which can form the basis of evaluation. Fig.2 shows 4 steps for the simplified vulnerability evaluation.

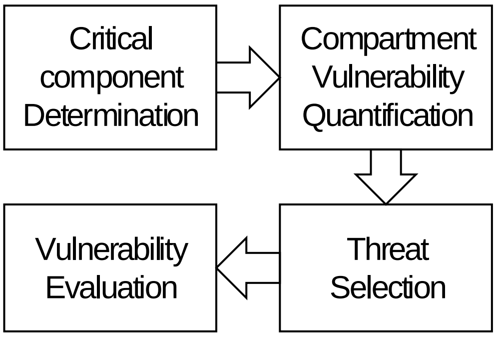


Fig. 2 A simplified vulnerability evaluation flowchart

2.1 Critical component determination and Compartment vulnerability quantification

A vital or critical component has been referred to as any components, which, if damaged or destroyed, would yield a defined or definable kill level(Ball 1985). The criticality of a given component is closely related to functionality and the kill levels are classified into four divisions upon damage of a warship. Table 1 shows the definition of kill levels. By Kim(2011)'s method, critical components are determined using a failure modes and effects analysis(FMEA) and fault tree analysis(FTA) after identifying a ship work breakdown structure(SWBS) which forms relationships of mission, function, system and subsystem.

Table 1 Definition of Kill Levels(Ball and Calvano 1994)

Division	Definition
Total kill	Ship is lost entirely because sinking occurs or fire(or other phenomenon) forces abandonment
Mobility kill	Immobilization or loss of controllability occurs
Mission kill	Particular ship mission area(e.g.anti-airwarfare) is lost
System kill	Damage to one or more components results in loss of a system

As the compartment quantification procedure for the vulnerability assessment, a vulnerability score is allocated to the identified critical components according to the kill levels. The score is determined based on the collection of professionals' opinions. The compartment vulnerability is quantified by adding the score of arranged components in each compartment(Shin 2013). This research refers to that of the previous research for the comparison.

2.2 Threat selection

The warship vulnerability evaluation result is changed in accordance with a damage zone by a hit, because the damaged compartment would be changed upon characteristics of explosive(e.g. weight). Therefore, a threat scenario should be carefully selected considering a combat environment. In this research, we assume a virtual combat condition, because it's difficult to access to a detailed information in the defense area. The threats which results in structural damage are categorized as external blast, internal blast and penetration(MOTIE & DARPA Technical report 2014). The internal blast of them is considered to assess the vulnerability for the optimal BHB arrangement. Also equivalent TNT weight and stochastic/statistical hit distribution are selected for comparison of the previous research results and some case studies. Fig.3 shows the hit distribution example.

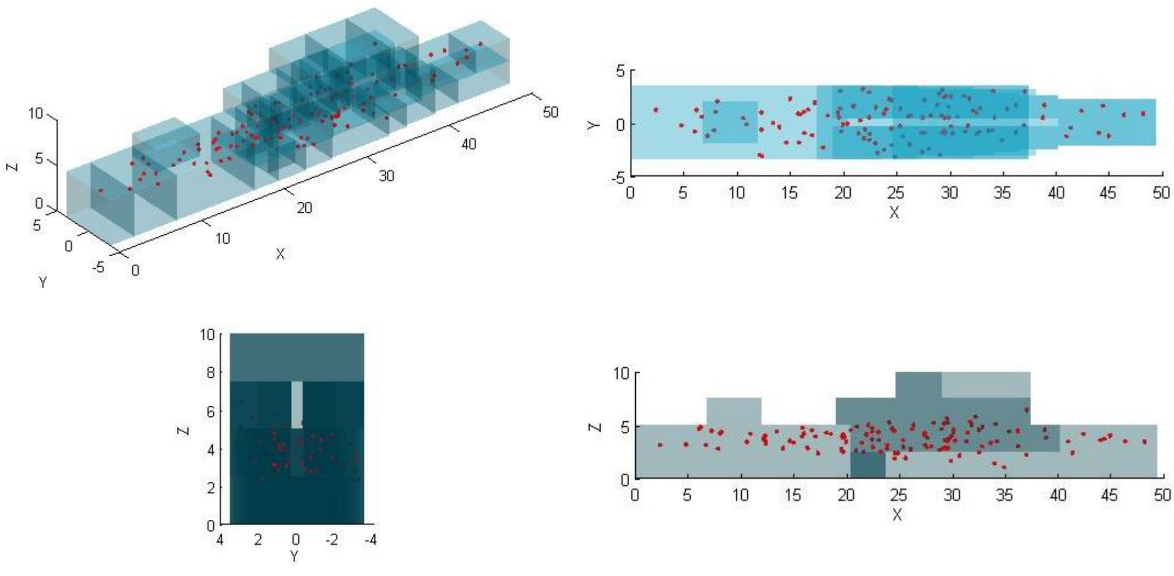


Fig. 3 Hit distribution example

2.3 Vulnerability evaluation

Each side of compartments of the surface warship is influenced by hit(Fig. 4). Internal blast mechanism is very complex, and a blast pressure consists of shock pressure and gas pressure called by quasi-static pressure(Theoder 2008). The shock pressure is made up of equivalent TNT weight and distance from center of the blast to

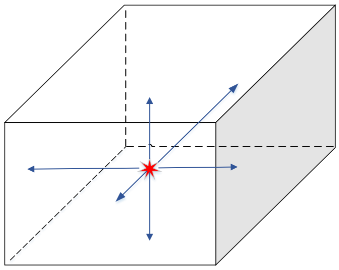


Fig. 4 Internal blast pressure in the compartment

the structure. The gas pressure is made up of equivalent TNT weight and compartment volume(Department of the army 1990). If the gas pressure is used for the vulnerability evaluation, it can't consider the structural damage by the hit location in the compartment. Therefore, in this research, shock pressure is used for the assessment as shown in Eq. (1) (Stark, 2012). It was developed based on empirical equation by the Alion which is technology solutions company and operational support to the U.S. department of defense.

$$P_R = 2 \times P_0 \times [P_{Snd} + \frac{2.4P_{Snd}^2}{0.4P_{Snd} + 2.8}] \quad (1)$$

where P_0 = Ambient air pressure[Pa], P_{Snd} = Non-dimensional side-on overpressure, is defined as Eq. (2)

$$P_{Snd} = 0.55\left\{R \times \left[\frac{P_0}{E_W \times W}\right]^{1/3}\right\}^{-1.95} \quad (2)$$

where R = Distance from center of the blast to the bulkhead[m], E_W = Explosive energy per unit mass[m^2/s^2] and W = Charge mass[kg].

For effectiveness of curtain plate BHB design, the formulation for allowable pressure of structure was also developed by the Alion(Stark, 2012). Eq. (3) is applied to BHB structure and Eq. (4) is applied to non-BHB structure.

$$P_{BHBallowable} = \frac{1}{2B_e\lambda_I^2\left[\sqrt{3+\left(\frac{L}{B_e}\right)^2} - \frac{L}{B_e}\right]^2} \times \min\left\{\frac{24M_{PC}}{L^2}, \frac{\frac{12M_{PA}}{L^2-6A^2}\frac{4M_{PC}}{L^2}\frac{12M_{PB}}{L^2-6B^2}\frac{4M_{PC}}{L^2}}{2}\right\} \quad (3)$$

$$P_{nonBHBallowable} = \frac{1}{2B_s\left[\sqrt{3+\left(\frac{H}{B_s}\right)^2} - \frac{H}{B_s}\right]^2} \frac{16M_P}{H^2} \quad (4)$$

$$B_e = -\left[2 + \left[1 + \frac{2.75}{\left\{\frac{B_s}{t_C}\sqrt{\frac{\sigma_y}{E}}\right\}^2}\right] - \sqrt{\left[1 + \frac{2.75}{\left\{\frac{B_s}{t_C}\sqrt{\frac{\sigma_y}{E}}\right\}^2}\right]^2 - \frac{10.4}{\left\{\frac{B_s}{t_C}\sqrt{\frac{\sigma_y}{E}}\right\}^2}}\right] \times B_s \quad (5)$$

$$M_{PA} = \sigma \cdot Z_{PA} \quad (6)$$

$$M_{PB} = \sigma \cdot Z_{PB} \quad (7)$$

$$M_{PC} = \sigma \cdot Z_{PC} \quad (8)$$

$$\sigma = \frac{F_{DI} \cdot \sigma_y}{\sqrt{1 - \nu + \nu^2}} \quad (9)$$

$$Z_{PA} = A_W \cdot \left[0.5 \cdot h_W + t_A\left(\frac{A_A - A_W}{2 \cdot A_A}\right)\right] + A_A t_A \cdot \left[\left(\frac{A_A - A_W}{2 \cdot A_A}\right)^2 - \left(\frac{A_A - A_W}{2 \cdot A_A}\right) + 0.5\right] \quad (10)$$

$$Z_{PB} = A_W \cdot \left[0.5 \cdot h_W + t_B\left(\frac{A_B - A_W}{2 \cdot A_A}\right)\right] + A_B t_B \cdot \left[\left(\frac{A_B - A_W}{2 \cdot A_B}\right)^2 - \left(\frac{A_B - A_W}{2 \cdot A_B}\right) + 0.5\right] \quad (11)$$

$$Z_{PC} = A_W \cdot \left[0.5 \cdot h_W + t_C\left(\frac{A_C - A_W}{2 \cdot A_A}\right)\right] + A_C t_C \cdot \left[\left(\frac{A_C - A_W}{2 \cdot A_C}\right)^2 - \left(\frac{A_C - A_W}{2 \cdot A_C}\right) + 0.5\right] \quad (12)$$

A = BHB Lower Curtain Plate Vertical Height [m]
B = BHB Upper Curtain Plate Vertical Height [m]
L = Effective BHB Vertical Height (= λ×H) [m]
H = BHB Vertical Height (typically vertical distance between deck plating) [m]
λ, λ_I = Boundary Condition Coefficient and Inverted Coefficient, given as:

$$\lambda := \begin{bmatrix} 1 & if\ (A > 0m) \cap (B > 0m) \\ 0.788 & if\ (A \le 0m) \cup (B \le 0m) \\ 0.577 & if\ (A \le 0m) \cap (B \le 0m) \end{bmatrix}$$

$$\lambda_I := \begin{bmatrix} 0.577 & if\ (A > 0m) \cap (B > 0m) \\ 0.788 & if\ (A \le 0m) \cup (B \le 0m) \\ 1 & if\ (A \le 0m) \cap (B \le 0m) \end{bmatrix}$$

B_e = BHB effective beam column span [m]
t_C = thickness of the main plate [m]
E = BHB material modulus of elasticity [Pa]
σ_y = BHB material yield strength [Pa]
B_s = Typical Stiffener Spacing on BHB [m]
M_{PA} = Lower Curtain Plate Plastic Bending Moment [N·m]
M_{PB} = Upper Curtain Plate Plastic Bending Moment [N·m]
M_{PC} = BHB Plate (Between Curtains) Plastic Bending Moment [N·m]
σ = Dynamic material strength [Pa]
Z_{PA} = Lower Curtain Plate Plastic Section Modulus [m^3]
Z_{PB} = Upper Curtain Plate Plastic Section Modulus [m^3]
Z_{PC} = BHB Plate (Between Curtains) Plastic Section Modulus [m^3]
Z_{PN} = non-BHB Plate Plastic Section Modulus [m^3]
F_{DI} = BHB material Dynamic Increase Factor (related to strain rate)
v = BHB material Poisson's Ratio
A_w = BHB stiffener cross sectional area [m^2]
h_w = BHB stiffener cross sectional area geometric center [m]
t_A = thickness of the BHB lower curtain plate [m]
t_B = thickness of the BHB upper curtain plate [m]
A_A = BHB lower curtain plate cross sectional area [m^2]
A_B = BHB upper curtain plate cross sectional area [m^2]
A_C = BHB plate cross sectional area between curtains [m^2]

Fig. 5 and Table 2 show the vulnerability calculation procedure example by a hit. Fig. 5 shows a plan view of the partial warship and a rectangular box means a compartment. A first number means a compartment number and the one within parenthesis means the vulnerability score. If no.5 compartment is hit, then a, b, c bulkheads are influenced by shock pressure. Table 2 shows the damaged bulkheads and compartments by comparing the shock pressure with the allowable pressure. According to the damage, vulnerability scores are added, then this one is 0.7+1.3 = 2. A total vulnerability is quantified by calculating mean value score of damaged compartment by each hit. A designer had better set multiple hit scenarios than a hit or less hit number for evaluating the vulnerability. Fig.6 shows a vulnerability evaluation algorithm.

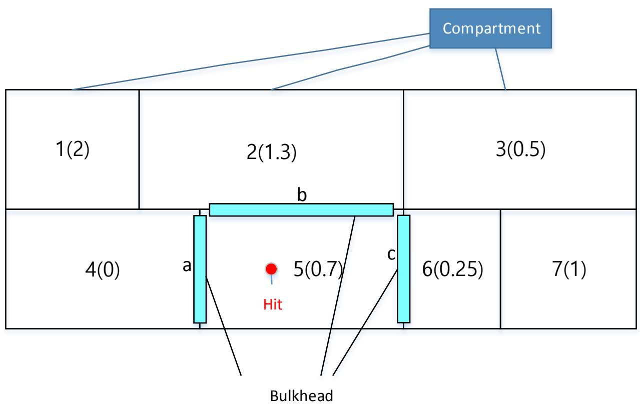


Fig. 5 Vulnerability calculation example

Table 2 Damage judgement for vulnerability calculation

Bulkhead	Adjacent compartment	Adjacent compartment vulnerability	Shock pressure (Mpa)	Allowable pressure (Mpa)	Damage
a	4	0	6.5	1.5	O
b	2	1.3	8.7	1	O
c	6	0.25	1.2	1.5	x

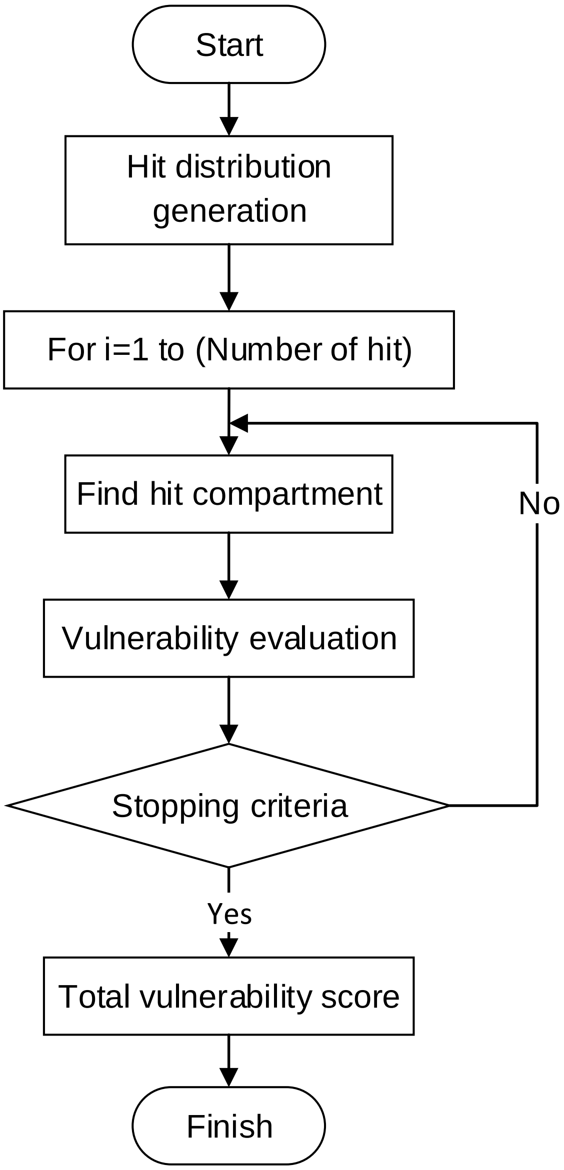


Fig. 1 Vulnerability evaluation algorithm

3. AN OPTIMAL BHB ARRANGEMENT USING GENETIC ALGORITHM

3.1 Methodology

Based on the proposed evaluation method, optimal BHB locations are determined using genetic algorithm to suggest optimal BHB design decision. The genetic algorithm is one of the stochastic optimization algorithms based on the rules of natural selection and survival of the fittest(Goldberg 1984). In every iteration, a population which consists of chromosomes is reproduced in accordance with fitness evaluations by genetic operators. Genetic operators are modeled on the procedure of evolution and contain selection, crossover and mutation. In this research, an initial population and reproduced one are generated satisfying the feasible region of possible solutions. The reproduced population has improved candidate solutions and searching is terminated when it reaches a stopping criteria. The optimization problem is modeled as some single optimization problems according to the number of BHBs, so this method can suggest that a warship designer judges the proper BHB installation based on the optimal BHB locations.

3.2 Design variable, Objective function, Constraint

The objective of this optimization is to search a global optimal solution for evaluating the vulnerability of warship based on the BHB installation. Thus, the design variable is considered as a binary number according to the installation of BHB and the chromosome is represented as a binary string as shown in Fig. 7.

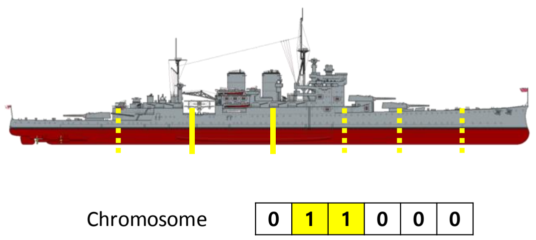


Fig. 2 Chromosome example

The Objective function is a basis of fitness evaluation, in this research, using weight factor it is formed the vulnerability score and the increased weight due to installed BHBs. The formulation of objective function is as shown in Eq. (13).

$$Objective\ function = a * Vu\ln erability + b * Increased\ weight \quad (13)$$

Here, a and b are weight factors. Those are just defined to search the solution which has a less vulnerability preferentially. And, if the vulnerabilities are equal among chromosomes with different BHB locations, but same number of BHB, the solution with fewer increased weight is selected. In this research, the values of a and b are assigned 10 and 10^{-6} because the whole weight of installed BHB within the virtual warship of case studies is below 10 tons. For example, if the vulnerability and the increased weight are 2.903 and 2254kg, the fitness value is calculated as 29.032254.

This optimization problem is a constrained minimization one. So the constraint can be represented as the Eq. (14).

$$g(x) : \sum_{i=1}^{n} x_i \le k \qquad x_i = \begin{cases} 0, & \text{if } BHB \text{ is not installed} \\ 1, & \text{otherwise} \end{cases} \qquad k = 1, \ldots, n \tag{14}$$

where k and n represent the number of BHBs and the maximum potential installation number of BHBs. According to the constrained number of BHBs, each single optimization is performed.

4. CASE STUDIES

4.1 A surface warship modeling

The dimensions of virtual warship were assumed as length over all 50m, beam 7m and deck height 2.5m. The origin of coordinate system is intersecting point of after perpendicular(A.P.), baseline and centerline of warship. And the x-axis, y-axis and z-axis are constituted as a longitudinal, transverse and vertical direction of the ship.

Table 3, 4 show the information of bulkhead, deck, BHB and stiffener. Also the compartments were assumed 3D box for simplified analysis(Chung 2008). The dimensions of BHB referred to the curtain type BHB design which was applied to existing warship. With stiffener, it assumed as T type.

Table 1 Bulkhead structures information

	Main Plate thickness	Curtain Plate thickness	Stiffener spacing	Material
Bulkhead & Deck	7mm	-	0.625mm	AH36
BHB	7mm	11mm	0.625mm	AH36

Table 2 Stiffener information

	Web Height	Web thickness	Flange width	Flange thickness
T type Stiffener	75mm	5mm	75mm	7mm

Fig. 8 shows the installable locations of BHB. This research examines two type of case. The upper one considers the case of entire transverse BHB installation, and the lower one considers the case of partial transverse BHB installation including the upper case. So the chromosome of upper figure has 6 genes, and the lower one has 11 genes meaning design variables according to installation of BHB.

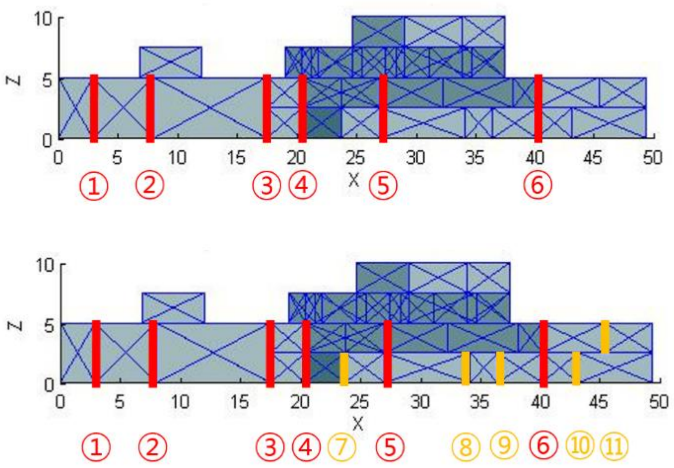


Fig. 3 Installable locations of BHB

4.2 Threat selection

The vulnerability evaluation is usually done considering either a specific threat or a specific damage mechanism. For the verification, this step referred to the example of the previous research(Shin 2013). The equivalent TNT weight and damage mechanism were considered as 10kg and internal explosion. Some hit distributions are dealt with upon each case including previous research ones.

4.3 Optimization options

To use genetic algorithm, the optimization options should be determined(Table 5). During successive generation, a proportion of the old population is selected to breed a new population according to their fitness values. In this research, roulette-wheel selection method was used to choose the proper chromosomes to contribute to the next population. Also, as terminating condition, we considered fixed number of generation. Allowing the newly generated chromosomes to be in feasible region, the optimization algorithm might be more efficient in terms of a speed of convergence.

Table 3 Optimization options

Option	Value
Population size	30
Number of generation	60
Selection method	Roulette Wheel
Selection probability	30%
Mutation probability	0.03%

4.4 Case I

Because the vulnerability analysis performed by each country is confidential, it is difficult to compare with the vulnerability results about real surface warship. Therefore, for verifying the vulnerability evaluation method of this research, in this case study, the vulnerability scores were compared with those of previous research which didn't consider the structural vulnerability on virtual warship. The prior one was performed assuming the consistent damage zone only based on the explosive. In accordance with three alternatives consisted to same compartment vulnerability, the evaluation was conducted, but each one had the different compartment arrangement. The table 6 and Fig. 9 show the hit distribution. Each intersection of grid in the surface warship means the internal explosion and the total number of hit is 94.

Table 6 Hit distribution for Case I, II

	Starting point	Ending point	Partition
x	2m	48.75m	17
y	-1.5m	1.5m	-
z	1.25m	8.75m	3

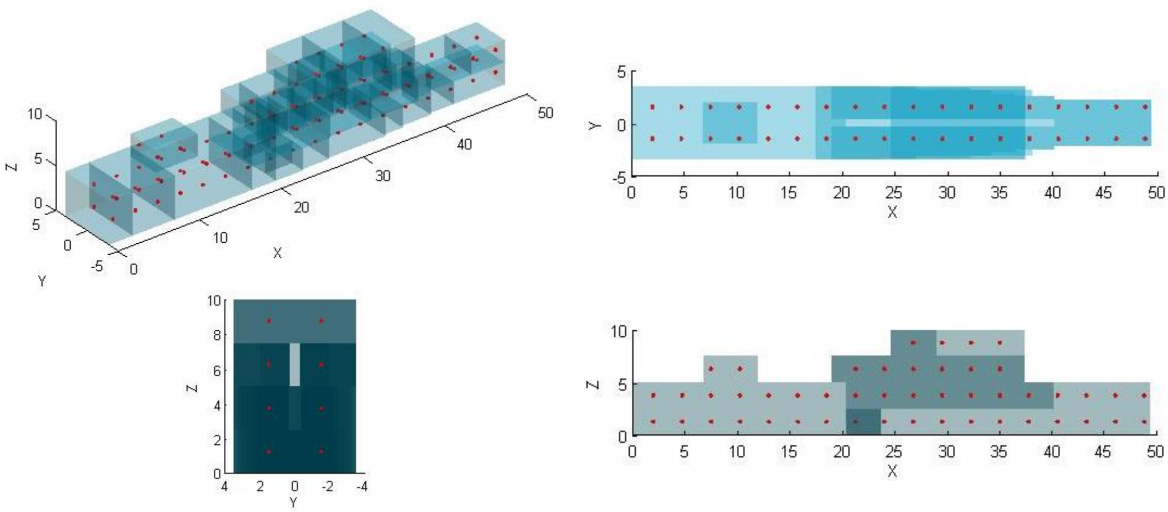


Fig. 9 Hit distribution visualization for Case I, II

The vulnerability evaluation was performed without BHB consideration, so that the optimization process was not included. The table 7 shows the results of evaluation.

Table 7 Vulnerability comparison with previous research

	Alternative 1	Alternative 2	Alternative 3
Shin(2013)	2.825	2.689	2.782
This research	3.09	2.43	2.871
Survivability ranking	3	1	2

4.5 Case II

The alternative 1 of virtual warships was chosen as a model of following cases. The reason is that the model is similar to a real warship based on designer's experience. In this case study, using the hit distribution like Case I for same threat condition, the optimization procedure was performed. The Type 1 is that the entirely transverse BHBs were installed below main deck. The Type 2 is that the partially transverse BHBs were installed below main deck including the Type 1. Table 8 shows the each single optimization result according to the installable number of BHB. Fig. 10 shows the vulnerability value on the number of BHB and Fig 11, 12 show convergence history for the Type1, 2.

Table 8 Optimization results for Case II

Number of BHB	Type 1		Type 2	
	Optimal value	BHB location	Optimal value	BHB location
0	30.900000	000000	30.900000	00000000000
1	28.400524	010000	28.400524	01000000000
2	27.781048	010010	27.781048	01001000000
3	27.281572	011010	27.281572	01101000000
4	26.982096	111010	26.861737	01101000010
5	26.782418	111011	26.572261	11101000010
6	26.582942	111111	26.362426	11101000011
7	-	-	26.152688	11101010011
8	-	-	25.943010	11101110011
9	-	-	25.743534	11111110011
10	-	-	25.743534	11111110011
11	-	-	25.743534	11111110011

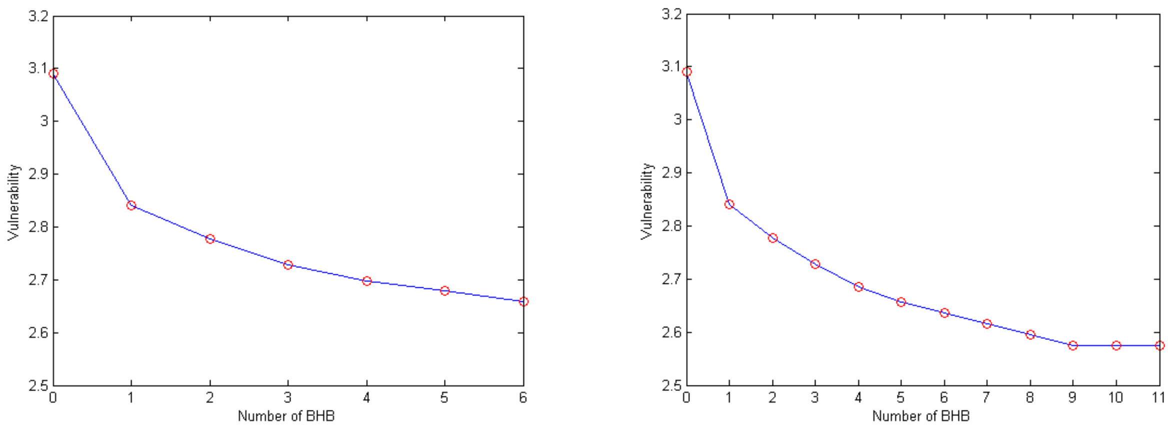


Fig. 10 Vulnerability value for Case II

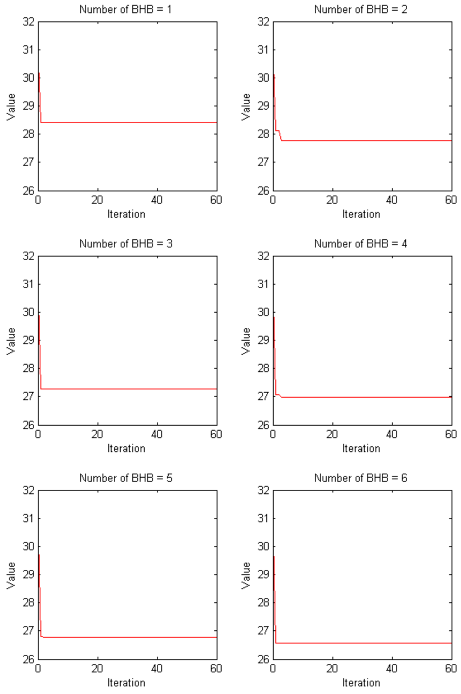


Fig. 11 Convergence history for Type 1 of Case II

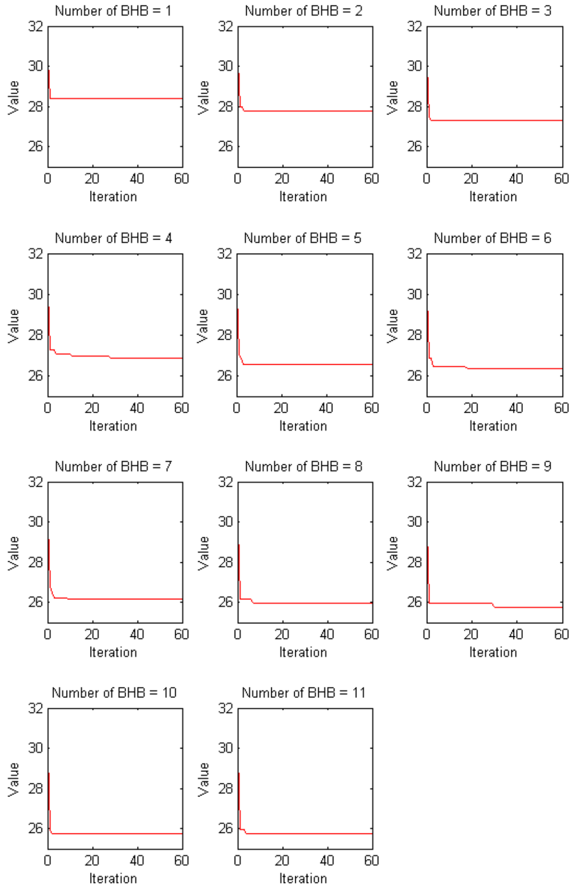


Fig. 12 Convergence history for Type 2 of Case II

4.6 Case III

The hit distribution of Case III consisted of normal distributions on the each axis. A missile for the target is known having normal distribution function(Driels 2004). In this case, the center of the overall warship was assumed as the target. The Table 9 shows the hit distribution and the total number of hit is 120. Table 10 shows the each single optimization result according to the installable number of BHB. Fig. 13 shows the vulnerability value on the number of BHB

Table 9 Hit distribution for Case III

	Average(μ)	S.T.D.(σ)
x-axis	25 m	10 m
y-axis	0 m	2 m
z-axis	3.75 m	1 m

Table 10 Optimization results for Case III

Number of BHB	Type 1		Type 2	
	Optimal value	BHB location	Optimal value	BHB location
0	29.48	000000	29.48	00000000000
1	27.350524	001000	27.350524	00100000000
2	26.031048	011000	26.031048	01100000000
3	25.531572	011010	25.531572	01101000000
4	25.032097	011110	25.032097	01111000000
5	24.742620	111110	24.742620	11111000000
6	24.662943	111111	24.662786	11111000001
7	-	-	24.573048	11111010001
8	-	-	24.493370	11111110001
9	-	-	24.493370	11111110001
10	-	-	24.493370	11111110001
11	-	-	24.493370	11111110001

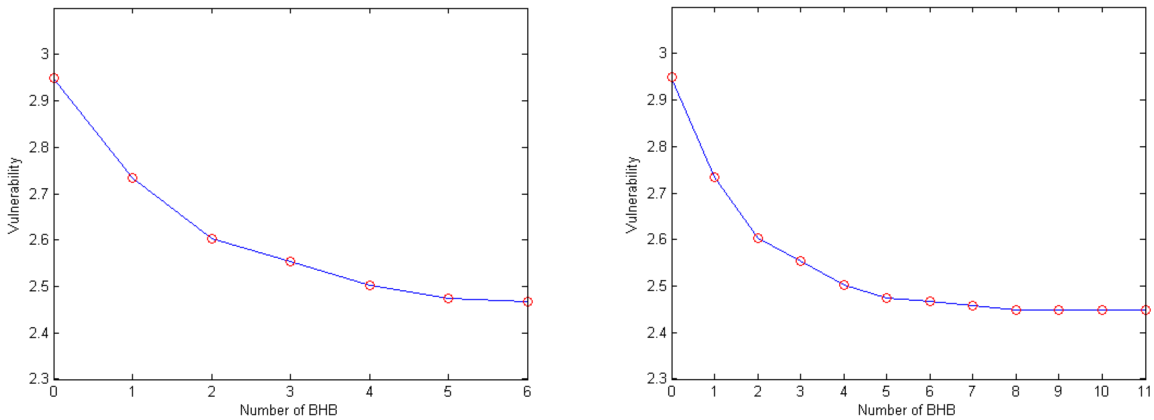


Fig. 13 Vulnerability value for Case III

4.7 Case IV

The hit distribution of Case IV consisted of uniform distribution from 0m to 50m on the x-axis and normal distribution on the y, z-axis. Likewise the Case III, the center of the overall warship based on y, z-axis was assumed as the target. The Table 11 shows the hit distribution and the total number of hit is 120. . Table 12 shows the each single optimization result according to the installable number of BHB. Fig. 14 shows the vulnerability value on the number of BHB

Table 11 Hit distribution for Case IV

	Average(μ)	S.T.D.(σ)
y-axis	0 m	2 m
z-axis	3.75 m	1 m

Table 12 Optimization results for Case IV

Number of BHB	Type 1		Type 2	
	Optimal value	BHB location	Optimal value	BHB location
0	35.57	000000	35.57	00000000000
1	31.680524	010000	31.680524	01000000000
2	30.681048	011000	30.681048	01100000000
3	30.101572	111000	30.101572	11100000000
4	29.762097	111100	29.762097	11110000000
5	29.602621	111110	29.602261	11110000001
6	29.602621	111110	29.432786	11111000001
7	-	-	29.432786	11111000001
8	-	-	29.432786	11111000001
9	-	-	29.432786	11111000001
10	-	-	29.432786	11111000001
11	-	-	29.432786	11111000001

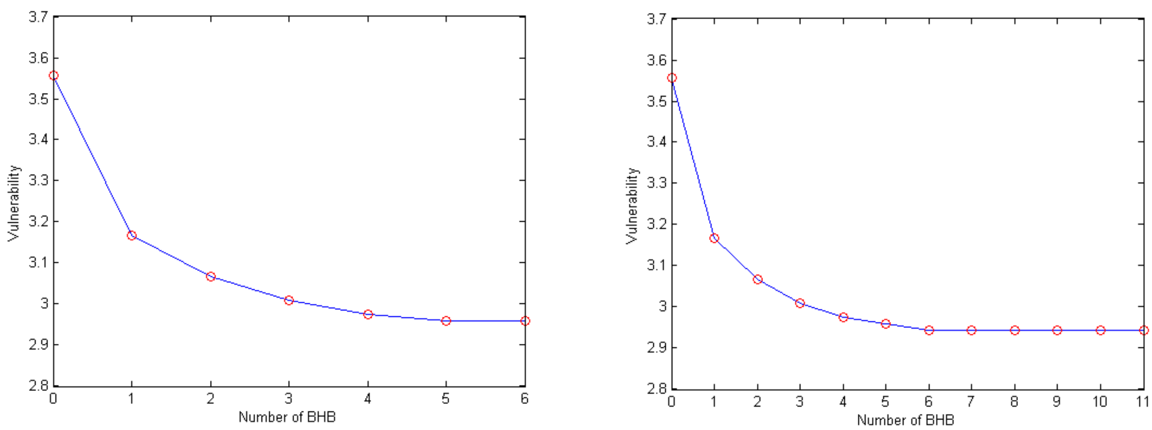


Fig. 14 Vulnerability value for Case IV

4.8 Case V

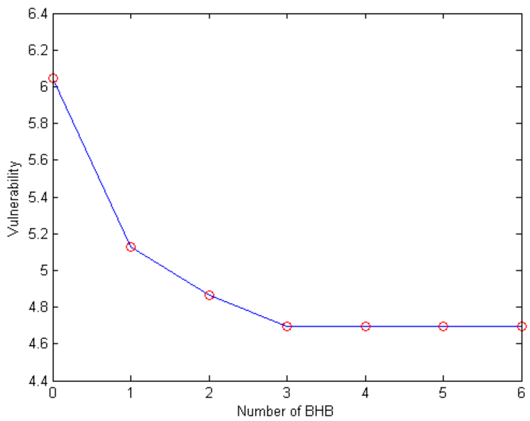
The hit distribution of Case V consisted of normal distributions on the each axis. In this case, the center of the engine rooms of the warship was assumed as the target. The Table 13 shows the hit distribution and the total number of hit is 50. The Table 14 shows the each single optimization result according to the installable number of BHB. Fig. 15 shows the vulnerability value on the number of BHB

Table 13 Hit distribution for Case V

	Average(μ)	S.T.D.(σ)
x-axis	8.75 m	3 m
y-axis	0 m	2 m
z-axis	3.75 m	1 m

Table 14 Optimization results for Case V

Number of BHB	Type 1		Type 2	
	Optimal value	BHB location	Optimal value	BHB location
0	60.46	000000	60.46	00000000000
1	51.300524	010000	51.300524	01000000000
2	48.661048	011000	48.661048	01100000000
3	46.981572	111000	46.981572	11100000000
4	46.981572	111000	46.981572	11100000000
5	46.981572	111000	46.981572	11100000000
6	46.981572	111000	46.981572	11100000000
7	-	-	46.981572	11100000000
8	-	-	46.981572	11100000000
9	-	-	46.981572	11100000000
10	-	-	46.981572	11100000000
11	-	-	46.981572	11100000000



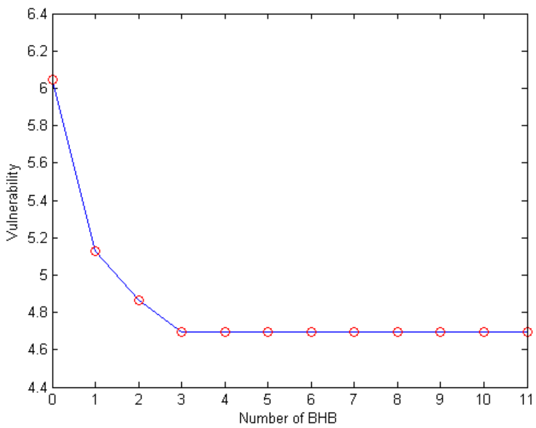


Fig. 15 Vulnerability value for Case V

5. CONCLUSIONS

Case I study was conducted to compare with previous vulnerability assessment results not considering structural vulnerability. For case II~V, according to the number of restricted BHB each single objective optimization problem was solved. The case studies show that engine room, support equipment room and fuel tank which include critical components such as the generators, transformer, diesel engines, sea water pump, fire fighting pump, distilling plant, fuel delivery pump and fuel should be especially protected to enhance the survivability. Also, for some levels, even if the installable BHB number is increased, we can recognize that the vulnerability value is constant. It means that even though BHB is installed additionally, the survivability is not enhanced.

In this research, we proposed the optimal BHB arrangement method using the vulnerability evaluation considering structural damages and stochastic/statistical hit distributions. Based on this methodology, the trade-off effects between the improved survivability and the increased weight due to the installation of BHB could be suggested for a warship designer. Furthermore, this methodology has a capability which can be applied to not only the conventional operated warship but also newly designed one. The warship modeling for the case studies was simple and had less number of cases for the installation of BHB, so the optimal solution was converged quickly. However, in the future, for complex and large ship consisting of lots of bulkhead and separation and distribution of critical components, we expect that this research is more meaningful.

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