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REVIEW ARTICLE

ON THE ASSESSMENT OF SURVIVABILITY OF SURFACE COMBATANTS

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ABSTRACT

Survivability of a naval surface ship is defined as the durability of the ship to a defined weapon threat, and, the degree of its ability to maintain at least the basic safety and operability of the ship, and is composed of a combination of the ship's susceptibility, vulnerability and recoverability. The empirical stability criteria laid down by Sarchin and Goldberg in 1962 are used to assess the survivability of warships. In recent years, along with deterministic rules, the probabilistic approach that has been made mandatory for the passenger / Ro-Ro ships by the International Convention on the Safety of Life at Sea (SOLAS) have been used for warships. In this study, the fundamentals of using the concepts of the deterministic and stochastic approaches and the concept of probability used in assessing the survivability of warships are emphasized.

Keywords: *Warship, Survivability, Susceptibility, Vulnerability, Recoverability*

SUÜSTÜ SAVAŞ GEMİLERİNİN BEKA KABİLİYETİNİN DEĞERLENDİRİLMESİ

ÖZ

Bir suüstü savaş gemisinin beka kabiliyeti, tanımlanmış bir silah tehdidine karşı dayanımı ve asgari olarak geminin temel emniyetini ve işlerliğini sürdürme yeteneğinin derecesi olarak tanımlanmakta olup geminin vurulabilirlik, yaralanabilirlik ve geri kazanabilirlik özelliklerinin bileşiminden oluşmaktadır. Savaş gemilerinin beka kabiliyetinin değerlendirilmesinde temeli 1962 yılında Sarchin ve Goldberg tarafından atılmış olan ampirik stabilite kriterleri kullanılmaktadır. Son yıllarda ise deterministik kuralların yanında Denizde Can Güvenliği Uluslararası Sözleşmesi (SOLAS) ile yolcu/Ro-Ro gemileri için zorunlu hale getirilen olasılık yaklaşımı, savaş gemileri için de kullanılmaya başlanmıştır. Bu incelemede deterministik ve stokastik yaklaşım ile olasılık kavramının, suüstü savaş gemilerinin beka kabiliyetinin değerlendirilmesinde kullanılma temelleri üzerinde durulmuştur.

Anahtar Kelimeler: *Savaş gemisi, Beka kabiliyeti, Vurulabilirlik, Yaralanabilirlik, Geri kazanabilirlik*

1. INTRODUCTION

The similarity inherent in the design of a warship and a passenger / Ro-Ro ship is the need to survive for both in the event of any damage; of course, by the nature of warships, they are more threatened in the human-made war environment. Besides, while for the survivability of a passenger / Ro-Ro ship to remain in an upright position in any case of damage is sufficient; the ability to remain in an upright position for a warship is a prerequisite and it is of great importance that it fulfills its designated task.

The majority of the stability criteria currently applied to warships are based on the empirical stability criteria produced by Sarchin and Goldberg in 1962. These criteria, which carry out their duties for many years, although they have been renewed over the years by navies such as US Navy (USN) and Royal Navy (RN), have not undergone major changes. However, in recent years - due to the fact that the survivability of the modern warships against the damages caused by the current threats is not known, the modern hull forms and the technique of the structural elements are very different from the ships when the criteria are determined, and the wind and the sea state at the time of the damage must be taken into account - there have been great dissidences about the applicability of these criteria to modern warships [1].

In the late 1950s probabilistic damage stability approach was introduced by K. Wendel. The International Maritime Organization (IMO) adopted the concept of probability for assessing the survivability of passenger ships with SOLAS 1974. Although IMO Resolution A.265 (VIII) was firstly introduced as an alternative to the deterministic stability criteria by SOLAS 1974, with the MSC.19 (58) resolution in SOLAS 1990, the probability concept has been made mandatory for the assessment of the survivability of Ro-Ro ships and dry cargo vessels longer than 100 meters in length. With the MSC.216 (82) (SOLAS 2006) the existing deterministic rules were blended with stochastic process and it became obligatory to be applied for cargo and passenger ships longer than 80 meters in length. The concept of probability was finally finalized by the inclusion of some special vessels such as ocean and fishing boats smaller than 500 tons by the code MSC.281 (85) (SOLAS 2008). At present, studies on probability are underway in the

IMO Working Group on Subdivision and Damage Stability (SDS). For example, as it is mentioned at the report of SDS on 31 October 2018, at the 6th session of the Sub-Committee of Ship Design and Construction new regulations will be discussed to assess the survivability in terms of watertight integrity [2].

In this study, the differences between the methods of assessing the survivability of warships and passenger ships, the methods used to apply the concept of probability of passenger ships to the warships to assess the survivability, and the countermeasures to be taken to increase the survivability of the warship were discussed.

2. WARSHIP SURVIVABILITY

In January 2014, NATO assessed the survivability of warships in terms of susceptibility (how easily the ship can be detected), vulnerability (the ability of the ship and its systems to resist damage.), and recoverability (the ability of the ship personnel to repair and operate the vessel); also pointed out that nuclear, chemical and biological defense should be addressed, as well as the damage caused by collision, grounding or enemy action [3]. These three functions of the survivability is shown in the time-dependent operational capacity diagram in Figure 1.

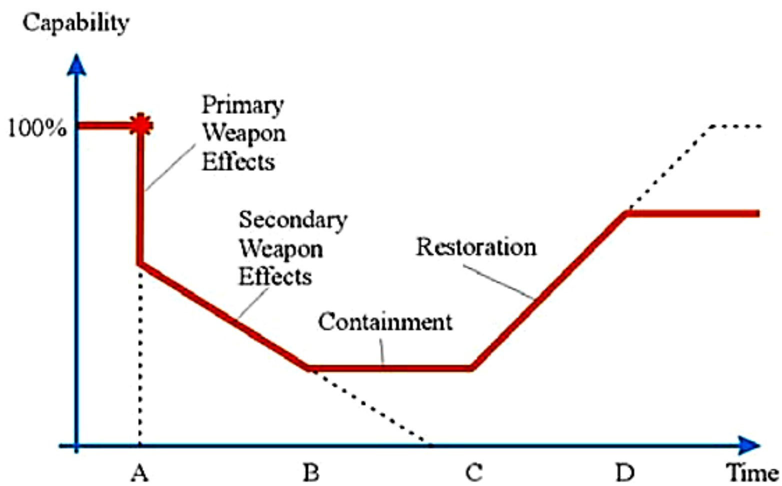

Figure 1. Time-dependent Operational Capacity (Source: [4])

The part up to point A in Figure 1 is a measure of the susceptibility of the ship and up to this point all the functions of the ship are at full capacity. Susceptibility depends on the radar cross section (RCS) of the ship, the threat warning and suppression systems of the ship and the behavior of the attack.

At point A, the ship is hit successfully by the enemy weapon, resulting in a sudden drop in the capacity of the ship's functions after the primary weapon effects such as blast and fragmentation. Secondary weapon effects such as flooding and fire can cause an additional reduction in the capacity of ship functions (from A to B). This will fall to zero in case of ship sinking. The part from point A to point B, represents the ship's ability to resist to the enemy weapons and gives the characteristic of vulnerability.

The part from the point B to the point D, which consists of the prevention and renewal stages, shows the ability of the ship to recover from the damage. In fact, the recoverability process usually starts at the point between point A and point B where the ship personnel would begin their first damage control activities. The capacity of ship functions after recoverability is the indicator of ship design and this capacity is required to be above the operational limit.

In ship design, it is desirable that a warship not to be hit. But this is impossible. No matter how better you design the features that affect the susceptibility of the ship, not being detected by the today's sophisticated radar and weapon systems is out of the question. Therefore, the aim is to reduce the susceptibility as much as possible.

The reverse of survivability is killability. Naturally, in ship design it is desirable to have the killability close to zero. However, it should be taken into consideration that the killability expressed in this article is not expressed only by the total loss of the whole ship. There is a functional hierarchy regarding the initial situation and the whole loss of the ship. Some kill definitions are given below in ascending order [5]:

- **System Kill:** Loss of a system due to damage to one or more components (loss of cooling water system, loss of an auxiliary machine, loss of CIWS, etc.).

- **Operational Kill:** Loss of one or more of the main mission functions of the ship. (Surface warfare, air warfare, submarine warfare and information warfare).
- **Mobility Kill**: Loss of movement or maneuverability of the ship. (Main machine damage, rudder damage, etc.)
- **Total Kill:** Loss of the ship as a result of ship sinking or fire or other phenomenon.

As can be seen, there is a hierarchical structure among these losses. The loss of a system may cause loss of one of the operation functions over time, but a flooding which could lead to the whole loss of a ship may be limited by mobility kill if it can be controlled by ship personnel. Here, the importance of vulnerability and recoverability appears. Because the less is the damage after the ship's being hit, the less will be the losses. Similarly, the greater is the recoverability, the better can the losses be restored and repaired.

3. DETERMINISTIC APPROACH

Until the 1990s, the trend in the design of naval surface ships was about assessing and minimizing susceptibility with detailed platform signature management. Therefore, the probability of the ship's detectability could be generally predictable and accepted as a variable in scenario simulations. Besides, the likelihood of standing vertical has been considered not enough. Most of the simulations have assumed that the probability of being killed by a single hit for small warships was equal to 1.0, while 2 were sufficient for the larger warships to sink. Therefore, survivability analysis was never considered the possibilities of vulnerability and recoverability [6]. For the naval architectures, it was often sufficient to assess the inadequacy of the vulnerability of the design in terms of damaged stability by using deterministic methods imposed by different navies like U.S. Navy (USN) and Royal Navy (RN). Table 1 shows the semi-empirical damaged stability criteria currently used by USN and RN for naval surface ships.

Table 1. US and Royal Navy Damaged Stability Criteria for Warships

Criteria	**RN "DEFSTAN 02-900"**		**USN "DDS-079-1"**	
Damage	LWL<30 m	1 comp	LWL<100 ft	1 comp
Length	30 m< LW <92 m	2 comp of at least 6 m	100 ft <LWL<300 ft.	2 comp
	92 m< LWL	Max {15%LWL/21m}	300 ft <LWL	15%LWL
Angle of list	$< 20^o$		$< 15^o$	
Area "A1"	> 1.4 Area "A2"		> 1.4 Area "A2"	
Area "A1"	$> A_{min}$			
	[$A_{min}=2.74*10^{-2}-1.97*10^{-6}x\Delta$ (m rad) ($\Delta<5000$)]			
	[$A_{min}=0.164*\Delta^{-0.265}$ (m rad) ($\Delta>5000$)]			
"GZ" at "C"	< 60 % "GZmax"		-	
Long. "GM"	> 0		-	
"GZmax"			0.25 ft < "GZmax" – "HA"	
Buoyancy	Longitudinal trim less than that required to cause downflooding		Margin line	

Damaged stability principles of the U.S. Navy are mainly based on the collection of data from experienced events. In 1947, BuShips (The United States Navy's Bureau of Ships) conducted a study of 24 warships that survived from weapon hits during World War II. This data was consisted of a minimum hit length which would result in the maximum survivability of 10 combatants and 14 auxiliaries. This study has offered the basic concept of the damaged length criteria. According to USN and RN damaged stability criteria; for ships less than 30 meters in length, damage of any compartment shall not submerge the ship more than the margin line. Ships greater than 30 meters in length and less than 92 meters must meet the same submergence criteria as those of two compartments. Ships greater than 92 meters in length should meet the submergence criteria in the case of a damage of 0.15 of LWL (at least 21 meters for RN) [7].

Sarchin and Goldberg stated that World War II damage reports recorded cases where a list of 20 deg. or more did not prevent damage control efforts and salvage of ships; therefore, in order to survive, an acceptable upper limit can be considered as 20 deg. list [8]. However, survival is rare in these important angles, and according to World War II damage reports, at the inclination of 15 degrees after damage, personnel begin to abandon ships (with or without order). As a result, for U.S. Navy ships, the criteria for designing equipment and machines to operate in a satisfactory manner up to

15 deg. has been introduced [6] (Figure 2). For Royal Navy ships the list criteria is 20 deg.

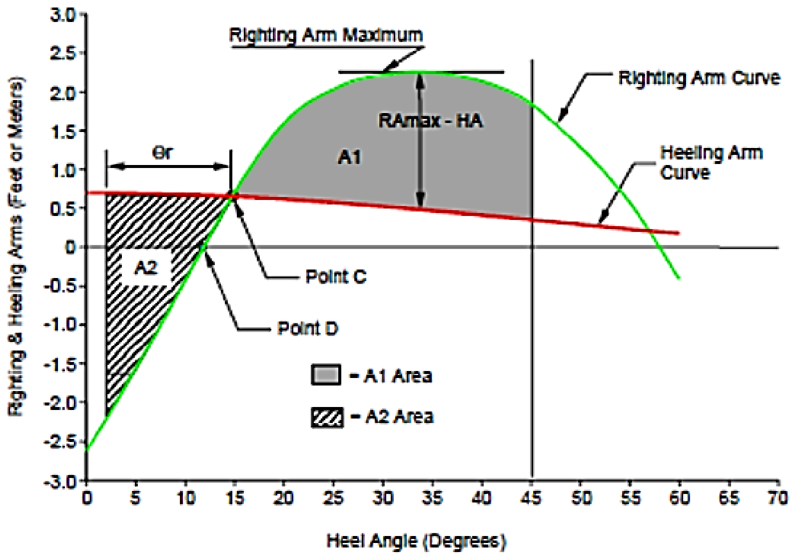

Figure 2. Damaged Ship Righting Arm and Heeling Arm (Source: [9])

4. PROBABILITY APPROACH

According to the basic concept of K.Wendel and the code of IMO A.265 (VIII), there are possibilities for the following events within the scope of damaged stability:

- Probability of flooding of a compartment or group of compartments under consideration, p
- Probability of survival of the vessel as a result of flooding of the relevant compartment or relevant bunch of compartment, s

The whole survival likelihood of the ship, defined as the "Attained Division Index, A", is equal to the total of pi and si values produced for every compartment and bunch of compartment, i, throughout the ship.

$$A = \sum_i (p_i \times s_i) \tag{1}$$

The code dictates that the gained division ratio must be higher than the "Required Division Index, R" (A > R), composition of the vessel's passenger carrying capacity and a function of the life-saving supplies on board. This is a measure of the acceptable risk of the ship not being able to survive from any damage and increases with the number of passengers on board.

Since the index A is acceptable as a true measure of the safety of ships, it is assumed that this index does not need to be supported by other deterministic conditions. On the basis of the probability approach; if same attained division index is calculated for two different ships with similar size and similar passenger carrying capacities, then these vessels will be equally safe.

5. ASSESSMENT OF THE SURVIVABILITY IN TERMS OF RISK METHODOLOGY

R.E. Ball, in 1994, introduced how to use the stochastic approach of survivability assessment in ship design and general definitions about survivability that were firstly introduced for aircraft combat survivability in 1985. When a warship is in operation, a precise prediction of the ship's survival cannot be made. The warship will probably return from the mission with success, perhaps not. Maybe she will be hit by the enemy, maybe she won't be. Maybe a fire will start when the enemy is hit, maybe it will not. If there is a fire, maybe it will cause the loss of the ship, maybe not.

In any task scenario, there are many random variables similar to those described above that will affect the warship's survivability. As a result of these uncertainties, there is no deterministic conclusion that the ship can survive in war; instead there is a stochastic result: the battleship will perhaps survive, maybe not.

As a result of the random nature of war, the survivability of a warship is likely measured. This probability is indicated as P_S, the survivability of a warship. The probability of survival ranges from 0 to 1; the closer the value is to 1, the more alive a ship is in question.

In this approach, killability, P_K, which is complementary of survivability, is expressed by the multiplication of the probability of occurrence of danger (probability of being hit, P_H) and the impact (probability of damage, $P_{K/H}$) in parallel with the classical risk methodology.

$$P_K = P_H \cdot P_{K/H} \tag{2}$$

A warship entering into the enemy environment will either survive or be killed. Given that there is no other way, survivability is complementary to killability and can be expressed mathematically with the following formula:

$$P_S = 1 - P_K = 1 - P_H \cdot P_{K/H} \tag{3}$$

After the approach which was introduced by Ball in 1994, the function of recoverability by researchers was included in the definition of survivability but not mathematically. The reason for this is the difficulty of developing a model to describe the adequacy of the training of the warship personnel, who are of great importance in the recoverability function. However, it should be kept in mind that there are measures to be taken by the design team regarding the decisions to be taken in the process of assembling damage control systems. If the risk reduction method (the probability of recoverability, P_R) is applied in a holistic manner; it is considered that the mathematical relationship between susceptibility, vulnerability and recoverability within the scope of the possibility of total ship survivability can be expressed as follows:

$$P_K = P_H \cdot P_{K/H} \cdot (1 - P_R) \tag{4}$$

$$P_S = 1 - [P_H \cdot P_{K/H} \cdot (1 - P_R)] \tag{5}$$

6. WARSHIP SURVIVABILITY ASSESSMENT BY STOCHASTIC APPROACH

In this part of the study, methods to assess the functions of survivability by a stochastic approach will be explained.

6.1. Susceptibility

Susceptibility is the inability of the ship to avoid damage in operation and can be expressed as the probability of being hit (P_H) [1]. It is based on the probability of the warship being identified by enemy detection devices (probability of detection, P_{DA}) and the probability of being hit by enemy threat weapons after detection of the warship (P_{HIT}) [10]. In addition to this approach, it is considered that the likelihood of threat suppression should be taken into account in calculating the probability of the susceptibility as a factor of reducing susceptibility. The probability calculation is shown in Figure 3.

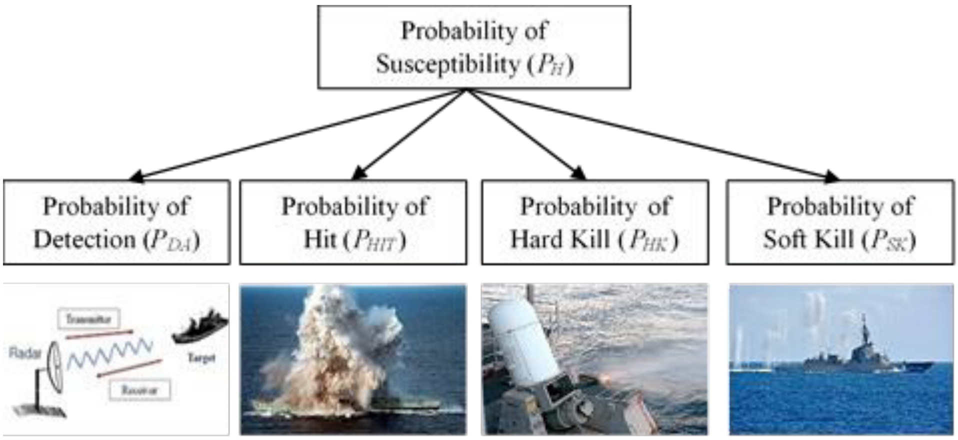

Figure 3. Probability of Susceptibility

The relationship between these probabilities can be expressed mathematically as shown in below:

$$P_H = P_{DA} \times P_{HIT} \times (1 - P_{HK}) \times (1 - P_{SK}) \tag{6}$$

The probability of a warship being detected by an active threat (P_{DA}) is a function of the ship's RCS. The ship's RCS affects how easily the ship can be detected. RCS is defined as the ratio of the power reflected back to the radar to the power density incident on the target and is a function of maximum radar range, R_{max} which is expressed by the following equation [11]:

$$R_{max} = \left[\frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 B F L \, (SNR)_{min}}\right]^{\frac{1}{4}} \tag{7}$$

According to Equation (7), the maximum detection distance of the radar is proportional to the ¼th force of RCS. For example, if we reduce the ship's RCS by 20%; the detection distance of the ship by the enemy radar will be reduced by approximately 5.5%.

The following formula is obtained when the Equation (7) is rearranged to find the Signal to Noise Ratios (SNR) which is a function of the minimum detectable signal power (S_{min}).

$$(SNR)_{min} = \frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 BFL R_{max}^4} \quad (8)$$

where,

Symbol	Description	Units
PT	Peak power	Watt
G	Antenna gain	dB
σ	Radar cross section	m2
λ	Wavelength	m
k	Boltzmann constant ($1.38 \times 10^{-23} J/K$)	J/K
T_0	Antenna temperature	Kelvin
B	Radar bandwidth	Hz
F	Noise figure	dB
L	Radar losses	dB
R_{max}	Maximum detection range	Km

The probability of a warship being detected by the active threat, P_{DA}, can be defined by the following equation [11]:

$$P_{DA} \approx 0.5 \times erfc(\sqrt{-lnP_{fa}} - \sqrt{SNR + 0.5}) \quad (9)$$

where, Pfa is probability of false alarm.

The probability of hit (P_{HIT}) is the probability of hitting the target area of the enemy threat weapon targeted to the friendly warship and is calculated depending on the characteristics and effectiveness of the threat weapon [12].

For naval surface ships, the hit of a threat weapon anywhere in the ship can be calculated by a probability function. The parameters of this function would be related to the properties of both the threat weapon and the target. This distribution is obviously related to susceptibility. Where there are no actual estimates for hit distribution along the ship, we can assume that the probability of weapon effects along the ship follows a basic mathematical distribution such as piecewise linear or normal distribution [13].

The normal (Gaussian) probability distribution is expressed by the equation given below:

$$p(x) = \frac{1}{\sqrt{2\pi} \times \sigma} \times exp\left[-\frac{(x-\bar{x}^2)}{\sigma^2}\right] \tag{10}$$

This distribution is symmetrical about the mean position and has a general bell curve shape as shown in Figure 4.

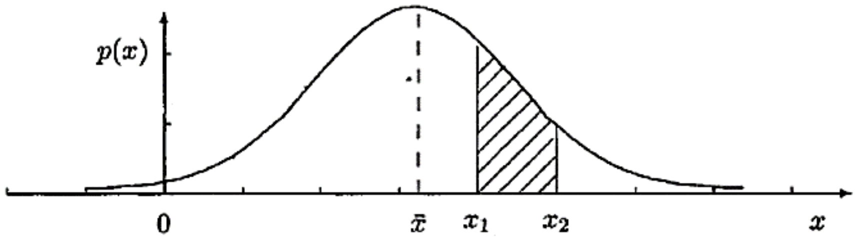

Figure 4. Probability of x Occurring Between x_1 and x_2

The area under the curve between x_1 and x_2 shown in Figure 4 reflects the probability that x occurs between x_1 and x_2, as expressed in Equation (11).

$$p(x_1 < x < x_2) = \int_{x_1}^{x_2} p(x)dx \tag{11}$$

Similarly, as shown in Figure 5, the area under the curve between x_1 and $x=\infty$ indicates the probability of occurrence of x between x_1 and $x=\infty$. This is expressed in Equation (12).

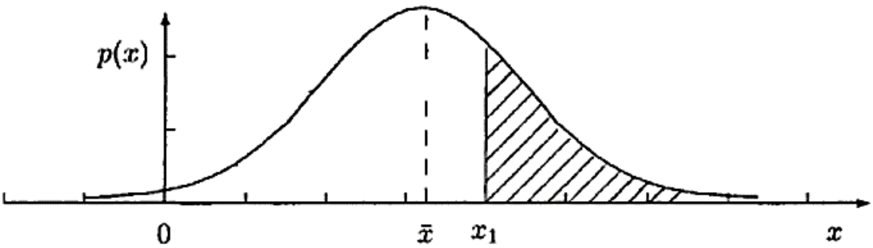

Figure 5. Probability of x Occurring Between x_1 and x=∞

$$p(x_1 < x < \infty) = \int_{x_1}^{\infty} p(x)dx \tag{12}$$

The full area below the curve which is the probability of occurrence of x between $-\infty$ and $+\infty$, of course, represents the certainty of a formation represented by 1 as shown in Equation (13).

$$p(-\infty < x < +\infty) = \int_{-\infty}^{+\infty} p(x)dx = 1 \tag{13}$$

In practical applications, Equation (13) is generally calculated in terms of standard variables (u), from the mean value ($\bar{x}$) as defined by:

$$x = \bar{x} + u \times \sigma \tag{14}$$

or,

$$u = \frac{x-\bar{x}}{\sigma} \tag{15}$$

Substitution of Equation (11) into Equation (12) and changing the variable x into u through Equation (15) with $dx = \sigma\, du$ finally leads to:

$$p(u_1 < u < \infty) = \frac{1}{\sqrt{2\pi}} \int_{u_1}^{\infty} e^{-\frac{1}{2}u^2} du \tag{16}$$

Equation (16) cannot be evaluated by known functions; therefore it is calculated numerically and available as special tables.

In many statistical studies and in the analysis of navigation errors, the convenient measure of error is standard deviation; however, in the weapon effect analysis usually uses the 50% error. This means that the end areas on both sides of the mean value ($\bar{x}$) must be equal to 0.25 as shown in Figure 6.

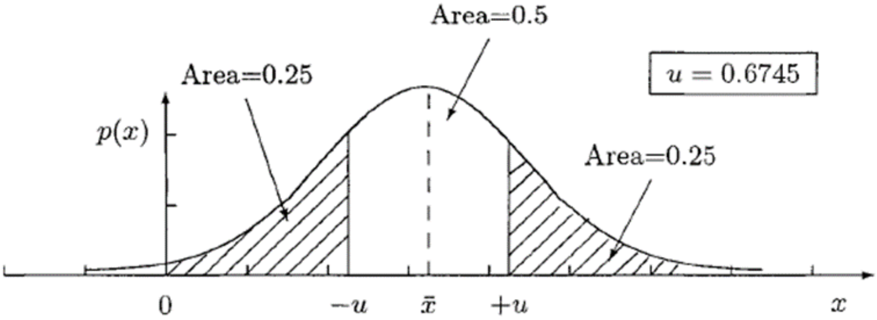

Figure 6. Linear Error Probable (LEP)

From the special tables for standard variables of normal (Gaussian) probabilities for this situation $u = \pm 0.6745$ is calculated, and because the total area below the curve is equal to 1, the center area is therefore equal to 0.50 and defines the possible linear error (LEP). Thus, by using the definition u in Equation (15), LEP as distance is expressed as follows;

$$LEP_{range} = 0.6745 \times \sigma \tag{17}$$

Accordingly, the probability of hitting a 11.8 meters length main engine room from the center point with a Harpoon Block II guided projectile which has a range error probable of 11.5 meters is calculated as follows;

$\bar{x} = 0$ (Hitting from the center point of main engine room)

$\sigma = 11.5/0.6745 = 17.05\ m.$

$x = \pm 6.4\ m.$

$u = 6.4/17.05 = \pm 0.375$

From the special tables for standard variables of normal (Gaussian) probabilities;

$P(u > 0.375) = 0.3538$

As a result, the possibility of the guided projectile hitting the main engine room from the center point;

$$P(-0.375 < u < +0.375) = P_{HIT} = 1 - 2 \times 0.3538 = 0.2924$$

6.2 Vulnerability

Warships must protect themselves against threats and asymmetric threats from enemy elements; but despite all its sophisticated defense systems, it is still vulnerable to attacks. In addition, they may also face dangers such as collision and grounding. In this context, in a most basic sense, the vulnerability ($P_{K/H}$) is the level of damage that occurs on board after being hit by an enemy or a damage.

Traditionally, the vulnerability assessment of a ship is carried out in the later stages of the design process. This is because the design must have reached a certain level of maturity in order to obtain sufficient information to do the needed analysis. In addition, because the design is often subject to change, it is not desirable to spend money and time on detailed damage analysis. However; this delay in the assessment means the placement of the bulkheads and the general arrangement. Because of that; combining the foundations of vulnerability reduction measures to the real sense of design can only be achieved when the vulnerability assessment is done at an early stage (concept design stage). Therefore, it is considered that the key to ensuring the survivability of a ship is the use of vulnerability measures in the early stages of ship design. These measures include;

- Structural strengthening of ship and sensitive spaces,
- Implementing a subdivision policy correctly,
- Providing as many redundancies as possible for critical systems, separation of redundancy systems and extra protection of systems if critical systems cannot be backed up,
- Using of shock absorbers to reduce shock wave effect,
- Providing of passive and active damage suppression.

Nowadays, some companies, which are supported by Defense Ministries, are involved in the design of warships. These companies examine the survivability of warships with the software they developed. These software provide support to some degree of integrated survivability analysis. However, these software are often unwieldy because they require a complete arrangement of the ship, including the superstructure, and do not evaluate trade-offs.

Within this scope, Boulougouris and Papanikolaou, developed a new method parallel to the method used to assess the survivability of passenger / Ro-Ro vessels based on the probability approach. In this method, as in the probabilistic approach, the attained division index, $A,$ is calculated by multiplying the probability of flooding of a compartment or group of compartments under consideration, p, which is calculated by probability density function (piece-wise linear distribution) with the probability of survival of the ship as a result of flooding of the compartment or group of compartment under consideration, s, which is calculated by a semi-empirical deterministic criterion.

Since both the radar profile of the ship and the machinery and exhaust emissions are highest at the amidships, this point is usually the target point of the projectiles (Figure 7) [14]. For this reason, the hit point probability density function is as follows:

$$imp(x)\begin{cases} 4x & x \leq 0.5 \\ -4x+4 & x > 0.5 \end{cases} \tag{18}$$

Regarding the "Damage Function" used in the literature of defense analysis, it is assumed that the missile has an effect within a radius r of the hit point which has the log-normal distribution [15]. This function can be represented in a slightly modified form as in below:

$$d(r) = 1 - \int_0^r \frac{1}{\sqrt{2\pi}\cdot\beta\cdot r}\cdot exp\left[-\frac{\ln^2(r/\alpha)}{2\cdot\beta^2}\right]dr \tag{19}$$

where,

$\alpha = \sqrt{R_{SS}\cdot R_{SK}}$, $\beta = \frac{1}{2\sqrt{2}\cdot z_{SS}}\cdot \ln\left(\frac{R_{SS}}{R_{SK}}\right)$,

R_{SS} , the absolute save radius meaning $d(R_{SS}) = 0.02$

R_{SK}, the absolute kill radius meaning $d(R_{SK}) = 0.98$

Z_{SS}, constant equaling 1.45222

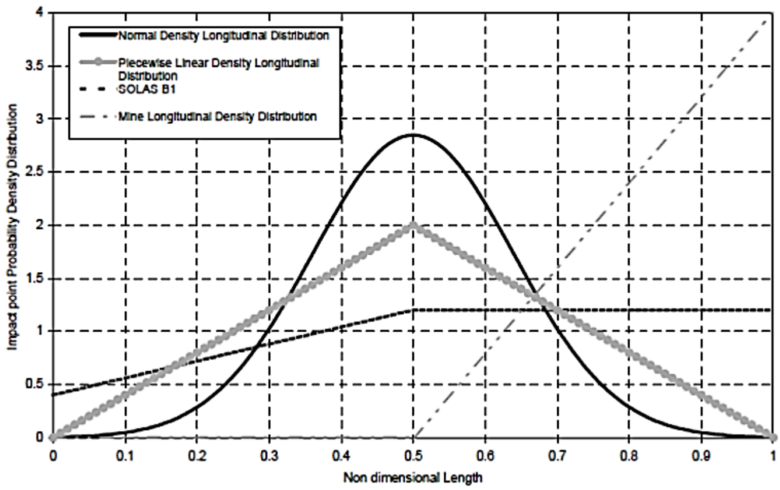

Figure 7. Longitudinal Damage Distributions

Boulougouris and Papanikolaou stated that as a first approach, R_{SS} could be taken as 0.15 LWL according to DDS-079-1 where R_{SK} can be assumed to be equal to 0.02 LWL.

Equation (19) can be simplified to the linear distribution in order to be easily solved by the known functions [16]:

$$Dam\ (y) = \begin{cases} 177.78y, & 0 \leq y \leq 0.075 \\ -177.78y + 26.67, & 0.075 < y \leq 0.15 \end{cases} \tag{20}$$

The hit point and the damage-length density functions can be combined to find the possibility of damage of a compartment or a group of compartment of a warship between x_1 and x_2 boundaries:

$$p_{i_{x_1}}^{x_2} = \int_0^y Dam(y) \cdot \int_{x_1}^{x_2} Imp(x)\, dx\, dy \tag{21}$$

The approach used to assess the probability of survival after damage is a quasi-static probability approach adapted to the currently valid, semi-empirical deterministic criterion used for warships. This approach assesses the probability of post-damaged recovery and is based on a semi- empirical survival criterion as used by USN and RN [1]. The equation of survival criteria to be used in quasi-static probability method to the survivability of warships is following:

Table 2. Survival Criteria (s_i) for Warships (source: [13])

$s_i = 1$	θroll = 25 deg.	Wind speed according to DDS-079-1
	A1 $\geq$ 1.4A2	Min Freeboard ≥ 3 in + $(H_S(0.95))$- 8 ft.
$s_i = P(H_S \leq 8ft)$	Ship meets DDS-079-1 damaged stability criteria	
$s_i = 0$	θroll = 11 deg.	Wind speed $\leq$ 11 knots
	A1 $\leq$ 1.05A2	Margin line immerses.

By applying this criteria; for naval surface ships operating in East Mediterranean $P(H_S \leq 8ft) = 0.90$ where for naval surface ships operating in North Atlantic $P(H_S \leq 8ft) = 0.56$ [17].

As an example the bulkhead arrangement of a Gabya class frigate is shown in Figure 8. The results of one compartment damage of a Gabya class frigate obtained by the Equations (18) to (21) are given in Table 3.

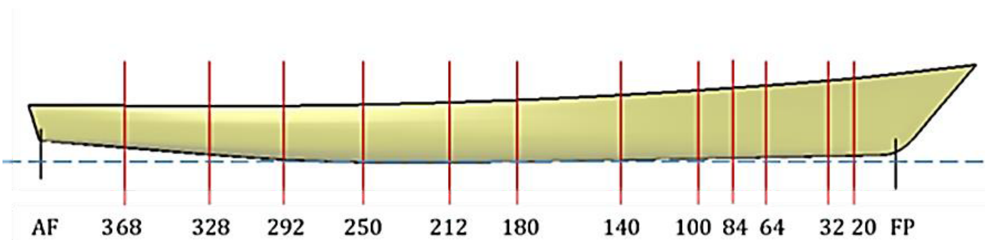

Figure 8. Bulkhead Positions of a Gabya Class Frigate

Table 3. One Compartment Damage Case

x_1	x_2	x_1u	x_2u	y	p_i
0	20	0.000	0.049	0.049	0.001
20	32	0.049	0.078	0.029	0.001
32	64	0.078	0.157	0.078	0.020
64	84	0.157	0.206	0.049	0.008
84	100	0.206	0.245	0.039	0.005
100	140	0.245	0.343	0.098	0.088
140	180	0.343	0.441	0.098	0.117
180	212	0.441	0.520	0.078	0.081
212	250	0.520	0.613	0.093	0.115
250	292	0.613	0.716	0.103	0.111
292	328	0.716	0.804	0.088	0.056
328	368	0.804	0.902	0.098	0.044
368	408	0.902	1.000	0.098	0.015

The calculations show that for the given bulkhead arrangement of Gabya class frigate 1 compartment damage case contributes about 0.37 to the attained division index, while 2 and 3 compartments contribute about 0.54 and 0.06 respectively. In this case, the attained division index for the given bulkhead arrangement of Gabya class frigates for is calculated as A = 0.97.

6.3 Recoverability

Recoverability is related to re-increasing the capacity of the ship's platform against time and is expressed as a partial or complete ability to rebuild ship's capacity and to maintain the recovered capability for a period of time [4].

Recoverability includes eliminating primary damage effects and controlling the secondary effects of damage. Secondary damages are elements that reduce the survivability of the ship starting after being hit over time. If fire / smoke, damage in to the components of the systems and flooding are not controlled over time, more vital systems will be disabled. If fire cannot be controlled, it can damage the power lines and disable the ship's control system, resulting in loss of movement and / or operational capability. In a more dangerous scenario, secondary damage can have fatal consequences if fire reaches the fuel system, tanks or ammunition.

At this stage, the effects of the systems on each other and the responses of the personnel in these systems should be taken into consideration. For example, the cooling system may be disabled due to the damage of the pumps, and combat central control stations can work for a while without cooling system, but before the ambient temperature reaches a level that would prevent the operation of the devices, the personnel must activate the system. As seen from the example, there is a need for a time-based methodology that takes into account both the interaction of the systems and components with each other and the personnel effects.

The most important issue in the calculation of recoverability is the consideration of personnel effects. Simulations, where personnel are classified according to their ability levels, where the starting positions are determined according to the scenarios, in which damage control functions are performed individually according to defined rules, are carried out as better damage control simulations.

7. CONCLUSION

Despite the fact that new methodologies have been used to assess the survivability of civilian ships, the empirical stability criteria adopted by Sarchin & Goldberg in 1962 continue to be used in assessing the survivability of military ships. These criteria, used by major Navies such as USN and RN, have changed little over time. In accordance with the developments in the assessment of the survivability of the passenger / Ro-Ro vessels, the concept of probability was also considered in assessing the survivability of military ships.

Although flag states do not have to obey the regulations of SOLAS; the countries comply with these regulations for warships of their own free will. In this context, it is considered that the importance of the deterministic stability criteria of Navies will be preserved in the design of warships, but the concept of probability will be used more as an alternative assessment.

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