# Aircraft carrier stability in damaged condition

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ABSTRACT: Building today's aircraft carriers is the culmination of science and the art of shipbuilding for maritime nations with this type of vessel in its naval fleet. The wartime role of aircraft carriers during the 20th century evolved rapidly, so in less than 50 years the aircraft carrier has changed from an auxiliary warship of limited combat value, into the most important and valuable genre of warship. As aircraft carriers grew in importance, so did the need to establish and improve the stability criteria, with special attention to determining the stability criteria after sustaining damage below the water line. Stability of aircraft carriers in damaged condition is vitally important from the standpoint of the retention of both operational and combat capabilities. The fundamental purpose of this paper is to verify the capability of an aircraft carrier after sustaining damage with regard to maintaining sufficient stability to be still operational and combat capable i.e. to withstand prevailing wind and seas in damaged condition. The results of these calculations were presented in the form of regression equations with an $R^2$ value of between 0.9 and 1, giving the possibility to use them for the fast and efficient prediction of the expected equilibrium position of the damaged aircraft carrier with a flooded compartment, or group of adjacent compartments.

## 1 INTRODUCTION

Aircraft carrier is the most important warship with high-speed and a large action radius. Hull is identical to the shape of any other type of large warship. It has a large and spacious deck with variety of devices and equipment for takeoffs and landing various types of aircrafts. Interior is organized in way that it can accommodate all aircrafts, equipment, weapons, fuel, and about 2,000 crew members. Aircraft carrier strike force is the main part of every major Navy's, especially those who have pretensions to control the waterways around the world's oceans. Aircraft carrier designs features results directly from the experience gained during the war operations, particularly the damage control ability which can be described with the following features:

- Watertight bulkheads must have the full integrity with as much as possible watertightness above the highest water line that the ship can reach after the damage occurs by hostile action. At the same time the watertight bulkheads must limit and prevent the spreading of fire, since from the war experience the fire is the second cause of loss.
- Longitudinal subdivision, with a rare set of transverse watertight bulkheads proved to be an extremely dangerous because it caused the occurrence of very large transverse angles after flooding, which has regularly provoked the abandonment of the vessel, although the danger of sinking due to loss of reserve buoyancy did not exist.
- Engine and power plants on aircraft carrier must be well protected and standardized, and marine electrical network capacity have to be significantly higher in order to enable the smooth supply of electricity of all equipment (e.g. radar, sonar).
- Uptakes and openings for ventilation must be designed as mutually separated independent systems. Systems must have simple and fast watertight closings to avoid that their openings became critical points.
- Experience gained during the war period revealed the need for serious consideration of the shock impact to hull caused by underwater no-contact explosion. Therefore, it is necessary to devote great attention to protection and elastic foundation for all important equipment, devices and machines.

## 2 RULES AND CRITERIA FOR AIRCRAFT CARRIER STABILITY IN DAMAGED CONDITION

Although the largest and most important ship in the fleet, an aircraft carrier is like the all other vessels exposed to the same external influences and risks that significantly affect her stability and buoyancy. Hazards to which the aircraft carrier is exposed are those that result with hull penetration, flooding the inner volume (grounding, explosion of torpedoes, mines, grains cannon, rocket projectiles), but also significant external influences such as an action of wind and waves.

After the flooding, according to Uršić (1991) we can observe penetrated water or as added weight or as lost displacement. Regardless of the observation method it is evident that the penetrated water affects the longitudinal and transverse stability that will increase ships draft, trim and heel.

In the case when one, two or more watertight compartments are flooded the ship will float on a new water line which must be less than the border line. Heel angle as a result of an unsymmetrical flooding must be less than the angles where new water line reaches points of progressive flooding i.e. when water line reaches openings which can not be water tightly closed. Also, heel angle must be not so large to avoid uncontrollable moving of various masses and to keep operability of machines and equipment as much as possible.

Besides all mentioned here the metacentric height (GM) and stability for large angles should be sufficient to prevent ship capsizing due to effects of winds and waves. All this implies that the stability of the aircraft carrier is one of the most important design requirements that the designers should dealt with.

As a result of testing the effects of explosives on structural models of war ships and war reports the specific models of damage have been developed which describe probability of survival of a warship. All of these results and the knowledge are the reason for leaving the concept of damage length and accepting the new concept of the allocating the watertight compartments (aircraft carrier has about 300 watertight compartments) as the basis for the determining capability of sufficient stability in damaged condition.

Parallel to the empirically established requirements most navy countries today slowly began to apply the most important parts of the IMO and SOLAS conventions regarding the safety and stability of damaged ships.

### 2.1 *About the stability of damaged ships*

According to Sarchin & Goldberg (1960) aircraft carrier belongs to the warship category that have side protection system which consists of several (usually five) longitudinal bulkheads. These, together with a number of transverse bulkheads form watertight compartments which are in the vertical direction bounded with strength deck (usually the hangar deck). This side-protective system extends to about 2/3 of the ship length and its main purpose is to minimize or to limit the flooded volume after damage.

As it will be explained later on this protection system increases the internal subdivision factor of aircraft carrier and secures operational characteristics when inner hull is flooded. Damage stability calculation has the purpose of determining minimum amount of intact stability that ship must have to survive damage. The new waterline should principally satisfy two basic considerations:

- Ship immersion should not exceed the border line with aim to prevent further flooding.
- Heel should not exceed certain values in order to keep the operating and seaworthiness characteristics.

When determining this new position i.e. the maximum allowable angle of heel after flooding (Russo & Robertson 1950) we distinguish symmetrical and unsymmetrical flooding of inner volume of the vessel.

#### 2.1.1 *Symmetrical flooding*

During the symmetric flooding, according to Uršić (1991) the basic problem with which the aircraft carrier is facing with, is primary change of metacentric height (GM). Particularly fatal for stability is reduction of the metacentric height which is as much dangerous as the centre of gravity of penetrated water is higher. It follows that for the stability aspects it will be particularly adversely the case of penetration above watertight compartment i.e. watertight deck.

This is particularly dangerous in the case of fire extinguishing, especially in the area of hangar deck where large quantities of water are thrown into. It is necessary to ensure the efficient drainage of this large quantity of inserted water because due to these large and highly placed free surfaces of water ship can easily capsize.

#### 2.1.2 *Unsymmetrical flooding*

Unsymmetrical flooding occurs when side longitudinal bulkheads are not damaged so the flooding occurs only at one side of the ship. Unsymmetrical penetration of water is particularly dangerous for ships with side-protective system (Sarchin & Goldberg 1960) since it cause the appearance of strong heeling moment and consequently a sudden and uncontrolled angle of heel with significant reduction of stability heeling levers (GZ).

This unsymmetrical flooding is extremely dangerous due to large angle of heel at which the side-protective system is in very poor position to resist further torpedo attack since the ship is exposed to damage below the side-protective system on the high side and above it on the low side. If this angle is not possible to remove rapidly it might lead to the abandonment of the ship much earlier than there is any danger of foundering or capsizing.

For this reason the aircraft carrier must be able to quickly and effectively reduce angle of heel and if possible completely neutralize it. This is usually done in such way that the ship is equipped with the system of cross-connected pipelines which are independent of the ballast system, and which connects side tanks, tanks in double bottom and flooding spaces within the side-protective system.

### 2.2 *Rules applicable to stability of aircraft carrier in a damaged condition*

Safety of aircraft carrier, and particularly the possibility that retains substantially for his operational and combat features after the damage, primarily depends on stability and the amount of reserve displacement.

Since internationally accepted rules for the stability of war ships do not exist (Sarchin & Goldberg 1960) like for civilian ships (IMO and SOLAS regulations) the navies had to determine, independently their own rules for stability in damaged condition. Rules considering damage standards are generally dealing with two basic requirements, i.e. design and operation.

Design requirements are based on an evaluation of the vessels ability to withstand major amount of damage and to continue to be sufficiently seaworthy and operational. Design requirements are established at the beginning of the process of designing and they significantly influence the selection of ships main dimensions, form, layout and number of watertight compartments.

Operational requirements are based on the minimum degree of offensive and defensive capability for continuing operations. These considerations include the capability of rapid list and heel corrections to the allowable value.

It is important to note that the rules for the stability of aircraft carrier in a damaged condition by no means guarantee that the vessel will not founder but its strict application can significantly increase the survival after being damaged.

When considering the damage stability rules for the aircraft carrier it is important to know standard loading conditions at which vessel can sail before damage occurs.

According to Sarchin & Goldberg (1960) loading conditions vary in the range from light conditions over the maximum loads in which the ship is departing from the port to the optimal combat load at sea. Standard loading conditions are as follows: basic condition, deep condition, light condition, light seagoing condition, light harbour condition and optimal combat condition. It is considered that the aircraft carrier is capable to survive several successive torpedo attacks.

Development of criteria regarding the size of damage that ship should survive it considered the range from flooding one, two or three adjacent compartments, based on a subdivision factor, while today the standard for aircraft carriers is based on a percentage length of a total length of the hull that can be damaged.

Therefore, the aircraft carrier should satisfy the following requirements for the extent of damage:

- For the vessels of waterline length greater than 92 m vessel must be able to retain significant amount of stability (defined as an area under the GZ curve) after damage occurs anywhere along its length extending 15% of the waterline length or 21 m whichever is greater the (MOD 2000, Brown & Chalmers 1989). This extent of damage usually affects 3-4 watertight compartments which is very similar to the request of the IMO (1974) Chapter II-1: Regulation 8.1.4., which applies to passenger ships.
- In the case of transverse propagation of damage, after the explosion (Keil 1961), it is allowed that the extent of damage comprises about 20% of the interior of the ship, and therefore aircraft carrier has a side-protective system.
- Vertical distribution of damage is not defined by standard but the according Keil (1961), it can be concluded that it should not exceed damage control deck, which is usually determined by the first deck above the constructive water line.

Based on these requirements and data from the Keil (1961) the extent of damage caused by a contact explosion creates an opening length of 9-15 meters depending on the power of explosives, structural design and the steel quality. It can be concluded that the aircraft carrier will be lost after receiving several consecutive explosive damages. With these requirements and data ship designer can determine the length and arrangement of the watertight compartments.

### 2.3 *Effect of wind and waves action on the ship in a damaged condition*

Standards of sufficient stability for the vessel in a damaged condition when exposed to the forces of wind and waves are based on comparison of righting lever curve and wind heeling lever curve.

Wind heeling lever curve moment caused by wind and waves for the ship in damaged condition (Sarchin & Goldberg 1960) is calculated by the following formula:

$$\text{Wind heel lever} = \frac{0.004 \times V_{Wind}^2 \times A \times l \times \cos^2\theta}{2240 \times \Delta} \qquad (1)$$

where $V_{Wind}$ = normal wind velocity which damaged ship should withstand in knots; $A$ = projected sail area in square feets; $l$ = lever arm from half draft to centroid of sail area in meters; $\Delta$ = displacement in tonnes; and $\theta$ = angle of heel in degrees.

Wind speed that damaged ship must sustain without risk of capsizing is (MOD 2000):

$$V_{Wind} = 22.5 + 0.15 \times \sqrt{\Delta} \qquad (2)$$

where $V_{Wind}$ = wind velocity in knots; and $\Delta$ = displacement (deep) in tonnes.

### 2.4 *Damage stability criteria*

Requirements for damage stability criteria are as follows (MOD 2000):

- Angle of list and loll must be less than 20 °.
- The amount of GZ at the intersection of righting lever curve and wind heeling curve must be less than 60% of the maximum GZ (point C).
- Area $A_1$ to be greater than the value given from:

$$A_{min.} = 0.164 \times \Delta^{-0.265} \text{ in mrad} \qquad (3)$$

- where $\Delta$ = displacement (deep) in tonnes.
- Area $A_1$ must be greater than the area $1.4 \times A_2$
- Longitudinal trim must be less than that required to cause downloading.
- Metacentric height must be greater than 0 and is calculated according to St. Denis (1966):

$$\overline{GM} \cong \left( \frac{100}{80000 + \Delta} \right) \times B^2 \qquad (4)$$

where $B$ = ship breadth in meters; and $\Delta$ = displacement in tonnes.

Figure 1 shows the requirements for damage stability criteria.

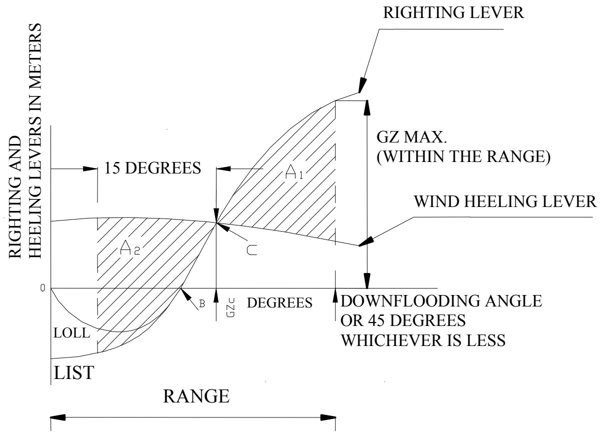

Figure 1. Damage stability criteria of aircraft carrier (MOD 2000)

### 2.5 *Operational criteria for aircraft carrier*

Sarchin & Goldberg (1960) give a basic criteria that aircraft carrier has to fulfil in the event of flooding one or more compartments. These operational criteria mostly determine the angle of heel where the vessel can be fully or partly operative:

- All installed equipment, regardless of the purpose must be so designed and installed to be able to be fully effective at a constant heel (transverse or longitudinal) of 15 °.
- All machines (main and auxiliary) must be fully operational at a constant heel (transverse or longitudinal) up to 15 °.
- To ensure survival of the vessel and to increase toughness, equipment and machines have to be able to function some time under the heel of 20 ° ÷ 25 °.
- Upper heel limit of 20 ° is allowed for withdrawing the damaged vessel from the zone of combat actions.
- The amount of heel angle of 5 ° is limit for conducting a full scale air activity (landing/take-off) while the heel angle of 8 ° stands for limited air activity.
- Exceptionally in the case of helicopter operations the heel angle to 12 ° may be allowed.
- Heel angle (transverse and longitudinal) up to 5 ° is considered to be safe. It is necessary that the aircraft carrier has such an arrangement of ballast tanks which allows rapid and effective correction of the inclination from 20 ° to 5 ° or less.
- Any angle greater than 20 ° is critical and in this case the order will be placed to abandon the vessel.

## 3 SELECTED AIRCRAFT CARRIER MODEL FOR CALCULATION

At the beginning of consideration of this issue, it was necessary to choose the kind and type of aircraft carrier for which the damage stability calculation will be carrying out. US aircraft carrier Yorktown (Essex class) from the period of the Second World War was chosen due to reasons of availability of data and literature since the necessary information about the newer generation of aircraft carriers is generally deficient and unavailable. It should be emphasized that the procedure applied in this paper can be applied to newer generation of aircraft carriers as well.

When the 1930th The U.S. Navy ordered the construction of a new type of aircraft carrier it was the first purpose built aircraft carrier class in history. Previously, the navies were mainly engaged with reconstruction of existing battleships or battle cruisers to aircraft carriers. This purposely built aircraft carrier class was given name Essex according to the first ship of the series of four completely identical units. The second ship of that class was the aircraft carrier Yorktown (CV-5).

Aircraft carrier Yorktown (CV-5) was armed with 8 guns of 127 mm for close defence, 16 guns of 28 mm anti-aircraft defence and 30 guns of 20 mm. She had anti-aircraft defend system, carried 71 aircrafts and the crew consisted of 2217 members. Figure 2 shows the general plan of the aircraft carrier York town (CV-5). On the picture it can be seen the interior layout with tanks, accommodation for crew, aircraft hangar, as well as the position and mutual distance of transverse watertight bulkheads.

### 3.1 *Analysis of selected aircraft carrier*

Selected aircraft carrier is one of the first modern aircraft carriers designed to carry a large number of different aircrafts. Analysis of the selected carrier shows the typical layout for this type of ship. The aim of this analysis is to briefly describe all vital parts of the aircraft carrier that are interesting for the damage stability consideration.

Table 1. Main particulars of aircraft carrier Yorktown CV-5

| | |
|---|---|
| Length over all | $L_{oa}$=247.00 m |
| Length between perpendiculars | $L_{pp}$=220.40 m |
| Length on WL | $L_{KVL}$=231.70 m |
| Length of flight deck | $L_{l}$=245.00 m |
| Breadth of hull | B=29.96 m |
| Breadth of flight deck | $B_{l}$=33.38 m |
| Draught | T=7.00 m |
| Height of hull | H=20.85 m |
| Total height of vessel | $H_{UK}$=34.75 m |
| Height of aircraft hangar | $H_{hangar}$=5.48 m |
| Displacement | $\Delta$=30375.36 t |
| Block coefficient | $C_B$=0.610 |
| Speed | $V_{max}$=32.5 kn |
| Action radius | N=12000 nm at 15.0 kn |
| Main engine | 4 x Parsons steam turbins |
| Main engine power | P=89500 kW |
| Longitudinal centre of gravity | LCG=106.162 m |
| Vertical centre of gravity | VCG=12.656 m |
| Longitudinal centre of buoyancy | LCB=106.162 m |
| Vertical centre of buoyancy | VCB=3.879 m |

#### 3.1.1 *Subdivision*

The main purpose of aircraft carrier watertight subdivision is to improve combat efficiency and reduce the risk of loss when the outer shell is damaged and interior been flooded. Watertight bulkheads contribute to a better use of space dividing the various vessel activities while in the same time they reinforce the structure. Watertight subdivision increases the ability of aircraft carriers to overcome the effects of underwater damages and thus to control the amount of flooding. Also, enables control of the vertical position of gravity of flooded water, quantity of water, moment of inertia of the free surface and spreading the fire and toxic gases.

Structure analysis shows that the selected aircraft carrier has 17 transverse and 4 longitudinal watertight bulkheads. Longitudinal watertight bulkheads are extending the entire length of the vessel and the transverse watertight bulkheads are extending the entire width from bottom up to hangar deck. In this way the carrier is divided into a number of watertight compartments which have the task to limit the flooding after damage. Strength of bulkheads is calculated to withstand the pressure load for deeper draft in damaged condition.

According to the MOD (2000) it is allowed to have a watertight bulkhead openings closed with watertight doors only above damage control deck while below this deck they must be compact. All horizontal communication between the watertight compartments is managed above the damage control deck while the vertical communication is provided for each compartment separately.

We have to keep in mind that the aircraft carrier combat effectiveness grows proportionally with the number of underwater hits that she can survive and resist but this is not the only measure of combat efficiency. Efforts that carrier can withstand most physically possible attacks can negatively affect her offensive striking power. Combat effectiveness is not satisfactory if it fails after the only one underwater hit. So, the all watertight subdivision does virtually no purpose. As a minimum allowable resistance standard it is considered when the vessel can withstand at least one successful underwater hit which crashes one watertight bulkhead that causes flooding of two adjacent sections.

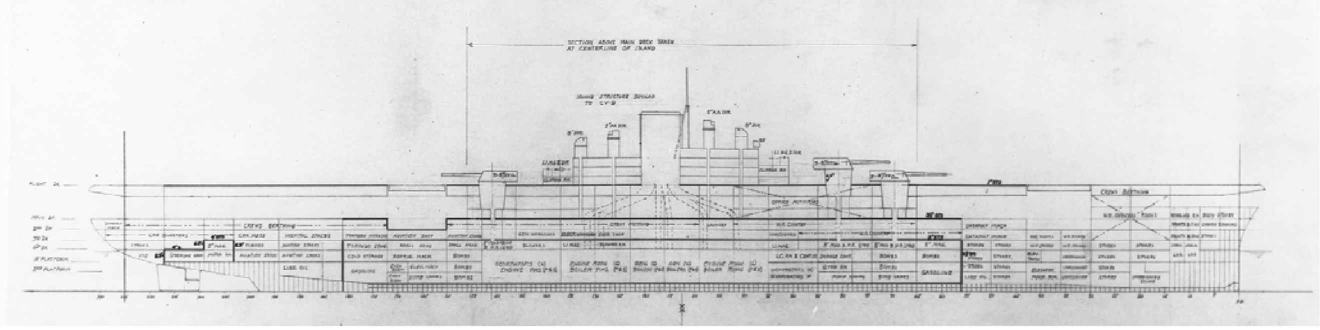

Figure 2. General plan of aircraft carrier Yorktown (CV -5 )

### 3.1.2 *Side- protective system*

Beside the densely set of watertight subdivision basic characteristic of aircraft carrier is the side-protective system which is located inside the hull on each side. Side-protective system consists of several (usually 4) watertight layers of which 2 outer are mostly kept empty and freely to flooding and 2, which serve as the internal tanks for various liquids (e.g. heavy fuel, kerosene, oil, water). This side-protective system extends to the 2/3 of the ship length and protects from the underwater damage vital parts of vessel (e.g. engine, power station, ammunition warehouses, fuel, supplies). Figure 3 shows the cross section of aircraft carrier while the Figure 2 shows the distribution of the length of the side-protective system in longitudinal direction.

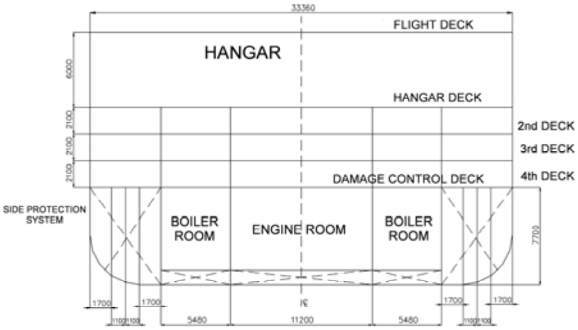

Figure 3. Cross section of aircraft carrier, Yorktown (CV -5)

### 3.2 *The equilibrium position of the aircraft carrier after flooding*

In this subsection the damage simulation of the selected aircraft carrier model is performed and a new equilibrium position after flooding of inner volume is determined. It is assumed that the explosion of torpedo or underwater mine in all examined cases does not cause the damage beyond the deck 4 i.e. damage control deck that vertically limits the amount of flooding.

Such damage causes sudden unsymmetrical flooding and the carrier emerges to the new water line so the total displacement is equal to the total weight of the aircraft carrier. But on this new water line direction of displacement and weight forces are not on the same line vertically placed on water line so the heeling moment appears and consequently vessel has certain angle of heel.

Damage stability calculation will be carried on taking into account the maximum allowed amount of wind that carrier must withstand. Area between GZ curve and the wind heeling moment curve indicated as $A1$ is calculated to a total heel of 30 °. Larger angle of heel will probable led to progressive flooding (Figure 1).

## 4 DAMAGE STABILITY CALCULATION OF AIRCRAFT CARRIER

Damage stability calculation of aircraft carrier with determining the new equilibrium is done using the program GHS (2005) (Figure 4). Simulation is performed for the damage of one, two, three and four adjacent compartments starting from stern to bow using the following commands (Figure 5): WIND, WIND HMMT, TYPE (compartment name) FLOODED, SOLVE, RAH and RAH/AREA.

The mechanism of damage in all cases of flooding is the same and it assumes that the explosion destroys completely side-protective system in adjacent compartments, damages transverse and longitudinal watertight bulkheads which leads to flooding of boiler room and the side ballast tanks in double bottom (Figure 6). It must be emphasized that this damage combination is valid for those compartments which have side-protective system while in the case of bow and stern compartments where there is no side-protective system, explosion penetrates longitudinal watertight bulkhead which leads to symmetrical flooding.

Figure 4. Geomteric model in GHS of Yorktown CV-5)

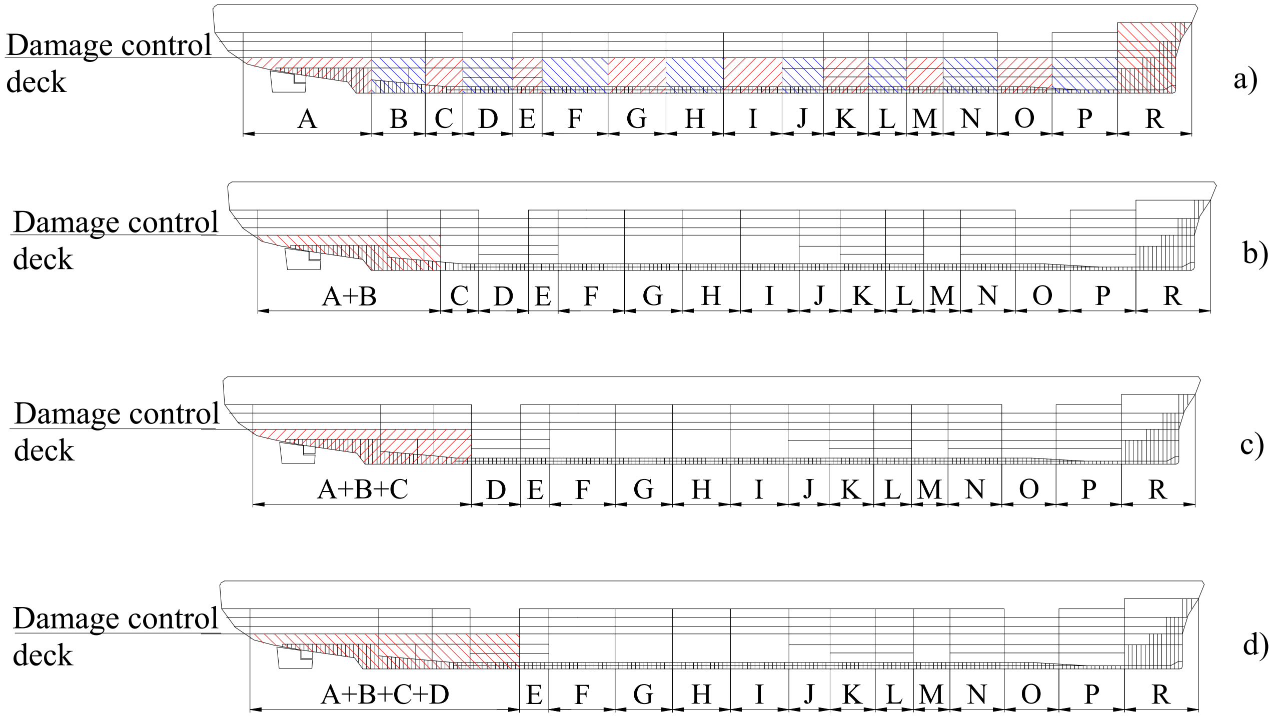

Figure 5. Longitudinal flooding sheme ( one (a), two (b), three(c) and four (d) compartments)

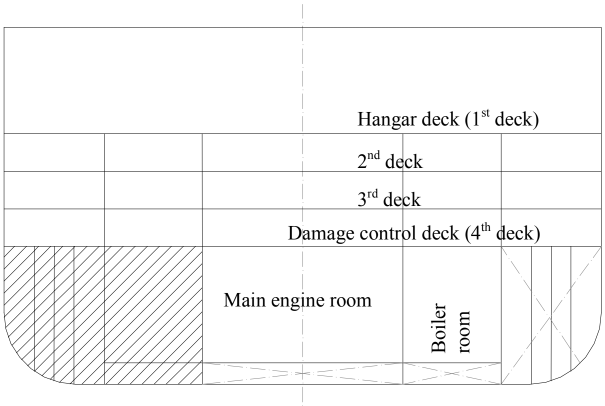

Figure 6. Transverse flooding scheme of compartments

The volume of damage assumes that the torpedo or mine explosion happens at the moment of contact with hull. For such definition of flooded compartments the new equilibrium position is determined taking into account the maximum amount of allowable wind that blows from the left side of the ship. Table 2 presents calculation results for the equilibrium for one compartment flooding depending on the longitudinal location of damage $x_C$.

### 4.1 *One compartment flooding*

Simulation of one compartment flooding is done starting from stern to bow (Figure 5 a). The basic assumption is that the aircraft carrier is hit by one torpedo which affects the considered compartment in the middle while surrounding transverse bulkheads are not damaged. Example of the one compartment flooding calculation is shown in the Table 2.

Table 2. Results for the equilibrium for one compartment flooding depending on the longitudinal flooded location

| Flooded compartment | $x_C$ [ m ] | $T$ [ m ] | $\psi$ [° ] | $\varphi$ [° ] | $LCB$ [ m ] | $TCB$ [ m ] | $VCB$ [ m ] | $GM$ [ m ] | $A_1$ [m-rad.] |
|---|---|---|---|---|---|---|---|---|---|
| *1* | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| A | 2.90 | 7.603 | 0.26 a | 1.28 s | 103.799f | 0.245 s | 3.966 | 2.418 | 0.2883 |
| B | 26.47 | 7.471 | 0.20 a | 3.10 s | 104.325f | 0.591 s | 3.971 | 2.488 | 0.3795 |
| C | 37.80 | 7.283 | 0.12 a | 3.52 s | 105.055f | 0.673 s | 3.952 | 2.441 | 0.3594 |
| D | 48.78 | 7.207 | 0.09 a | 4.83 s | 105.297f | 0.924 s | 3.966 | 2.416 | 0.3233 |
| E | 58.67 | 7.145 | 0.06 a | 4.48 s | 105.575f | 0.858 s | 3.953 | 2.397 | 0.3370 |
| **F** | 70.48 | 7.224 | 0.10 a | **8.19 s** | 105.155f | 1.552 s | 4.085 | 2.605 | 0.2854 |
| **G** | 85.97 | 7.123 | 0.04 a | **7.36 s** | 105.693f | 1.396 s | 4.051 | 2.540 | 0.1946 |
| **H** | 100.30 | 7.045 | 0.00 | **7.00 s** | 106.078f | 1.330 s | 4.037 | 2.510 | 0.2010 |
| **I** | 115.31 | 6.940 | 0.06 f | **8.56 s** | 106.539f | 1.618 s | 4.100 | 2.603 | 0.2803 |
| J | 127.59 | 6.946 | 0.05 f | 5.22 s | 106.556f | 0.997 s | 3.973 | 2.408 | 0.3230 |
| K | 138.51 | 6.897 | 0.08 f | 5.58 s | 106.796f | 1.065 s | 3.985 | 2.418 | 0.2187 |
| L | 149.43 | 6.889 | 0.08 f | 4.86 s | 106.829f | 0.929 s | 3.963 | 2.391 | 0.3203 |
| M | 158.30 | 6.842 | 0.13 f | 4.29 s | 107.220f | 0.816 s | 3.969 | 2.411 | 0.3375 |
| N | 169.89 | 6.710 | 0.23 f | 4.44 s | 108.065f | 0.840 s | 4.003 | 2.488 | 0.3475 |
| O | 183.54 | 6.642 | 0.29 f | 1.32 s | 108.597f | 0.249 s | 3.982 | 2.355 | 0.2916 |
| P | 198.21 | 6.890 | 0.08 f | 1.33 s | 106.862f | 0.256 s | 3.905 | 2.305 | 0.2834 |
| R | 214.11 | 6.960 | 0.03 f | 1.38 s | 106.399f | 0.265 s | 3.890 | 2.281 | 0.2757 |

### 4.2 *Two compartment flooding*

Simulation of two adjacent compartment flooding is done starting from stern to bow (Figure 5 b).

Following two assumptions were made for the calculation:

- Aircraft carrier is hit by one torpedo near the transverse watertight bulkhead which leads to its collapse and flooding of two adjacent compartments.

Two torpedoes independently hit two adjacent compartments at their centre which caused their flooding.

### 4.3 *Three compartment flooding*

Simulation of three adjacent compartment flooding is done starting from stern to bow (Figure 5 c). Following two assumptions were made for the calculation:

- Aircraft carrier is hit with two torpedoes, first one which hits the hull girder near the transverse watertight bulkhead which leads to its collapse and flooding of two adjacent compartments. Second one torpedo hits adjacent compartment to these two already flooded compartments in the centre making a group of three completely flooded compartments.
- Three torpedoes independently hit three adjacent compartments at their centres which caused flooding of three adjacent compartments.

### Four compartment flooding

Simulation of four adjacent compartment flooding is done starting from stern to bow (Figure 5 d). Following three assumptions were made for the calculation:

- Aircraft carrier is hit with two torpedoes, where each hits one non adjacent transverse watertight bulkhead. This leads to flooding of two pairs of adjacent compartments making a group of four adjacent completely flooded compartments.
- Four torpedoes independently hit four adjacent compartments at their centres which caused flooding of four adjacent compartments.
- One torpedo hits near the watertight bulkhead which collapses and causes flooding of two adjacent compartments and the other two torpedoes hit other two adjacent compartments at their centres which caused totally flooding of four adjacent.

Graphical presentation for all groups of flooding for heel and trim depending on longitudinal location of damage is shown on Figure 7 and Figure 8. The results of these calculations are presented in the form of regression equations with an $R^2$ value of between 0.9 and 1, giving the possibility to use them for the fast and efficient prediction of the expected equilibrium position of the damaged aircraft carrier. Equations are listed below where φ1 ( Equations 5 – 8) and ψ1 ( Equations 9 – 12) indicates the angle of heel and trim after damage respectively while the index refers to the number of adjacent flooded compartments.

$$\varphi 1 = 5*10^{-8}x_C^4 - 2*10^{-5}x_C^3 + 0.0019x_C^2 + 0.0248x_C + 1.1669,\ R^2 = 0.8797 \tag{5}$$

$$\varphi 2 = 10^{-7}x_C^4 - 4*10^{-5}x_C^3 + 0.0041x_C^2 - 0.0038x_C + 2.3237,\ R^2 = 0.9638 \tag{6}$$

$$\varphi 3 = 10^{-7}x_C^4 - 5*10^{-5}x_C^3 + 0.0046x_C^2 + 0.012x_C + 3.3837,\ R^2 = 0.9808 \tag{7}$$

$$\varphi 4 = 10^{-7}x_C^4 - 6*10^{-5}x_C^3 + 0.0061x_C^2 - 0.0263x_C + 5.2763,\ R_2 = 0.988 \tag{8}$$

$$\psi 1 = -3*10^{-9}x_C^4 + 10^{-6}x_C^3 - 0.0001x_C^2 + 0.0087x_C - 0.3017,\ R2 = 0.914 \tag{9}$$

$$\psi 2 = -7*10^{-9}x_C^4 + 3*10^{-6}x_C^3 - 0.0004x_C^2 + 0.0222x_C - 0.6655,\ R^2 = 0.9588 \tag{10}$$

$$\psi 3 = -6*10^{-9}x_C^4 + 3*10^{-6}x_C^3 - 0.0003x_C^2 + 0.0213x_C - 0.8046,\ R^2 = 0.9775 \tag{11}$$

$$\psi 4 = -6*10^{-9}x_C^4 + 2*10^{-6}x_C^3 - 0.0003x_C^2 + 0.0224x_C - 1.0013,\ R^2 = 0.9923 \tag{12}$$

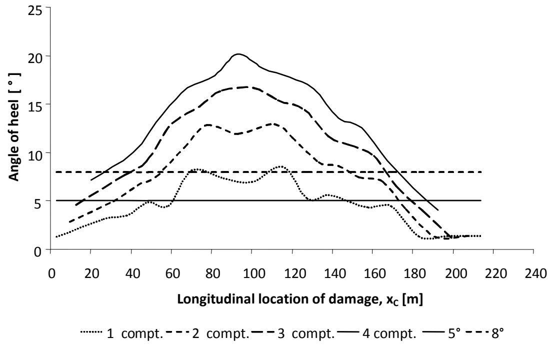

Figure 7. Angle of heel diagrams for the equilibrium position

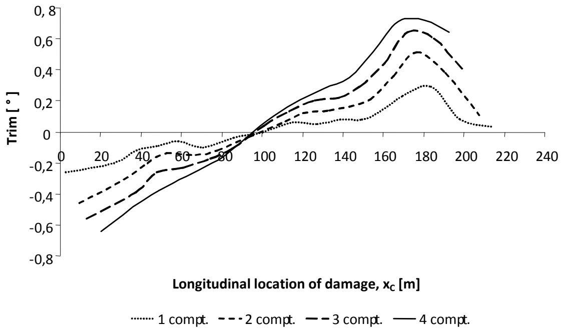

Figure 8. Trim diagrams for the equilibrium position

## 5 CONCLUSION

In this paper damage stability calculation was performed for the selected aircraft carrier using the program GHS (2005) for the new equilibrium position after the flooding was caused by underwater damage.

At the very beginning the assumption was taken into account that the aircraft carrier as warship has side-protective system capable to keep operating and combat features after received at least one straight underwater hit to any part of hull that causes flooding of one or two adjacent sections.

Required damage simulation was conducted for four different flooded groups (groups with one, two, three and four adjacent flooded compartments), (Figure 5). The obtained results are presented graphically for the heel and trim in equilibrium position (Figure 7 and Figure 8).

Obtained results shows that the aircraft carrier has the highest angle of heel after the flooding of the central compartments while flooding the compartments at the bow or stern gets mostly a high trim. These results are logical because the sections in the bow and stern are symmetrically flooded.

Also, it can be noticed that in the case of flooding only one compartment the results generally correspond with the results stated in Manning (1967), (2 ° - 3 ° angle of heel after one compartment flooding) except the results for the case of flooding the compartments F, G, H and I (midship compartments), which are somewhat higher. These higher results do not represent problem since the angle of heel is about 8 ° which still allows limited air operations.

It is necessary to note that the obtained angles of heel are higher because of the allowable maximum wind that is taken into account for calculation. Only when two adjacent compartments are flooded angle of heel becomes significant but in no case exceeding an angle of 15 °, which is limit for the smooth and safe functioning of lifesaving equipment. Flooding three and four adjacent compartments in the central part of the aircraft carrier the angle of heel becomes more serious and generally significantly restricts the seaworthiness of vessel with the loss of operational and combat capabilities. With such flooding combination the careful and rapid ballasting is needed to correct the angles of heel and trim to the allowable values.

Although the values of angles of heel in the case of three or four flooded compartments are significant review of the area between the GZ curve and the curve of wind heeling moment shows that the capsizing is not the imminent risk since the values are considerably higher than the minimum allowed. Therefore it can be concluded that this aircraft carrier will be in stable equilibrium even when the angle of heel is greater than 20 °.

With this fact, placing the order for leaving the vessel it can be postponed and the crew can concentrate on the vessels rescue operations. Also, the obtained results confirm the assumption stated in Manning (1967) that the aircraft carrier can withstand more than one direct underwater hit and under the equilibrium angle of heel it could still continue to sail but with limited combat activities.

As the aircraft carrier is warship it is assumed that the main cause of underwater damage will be primarily due to hostile activity. Having this in mind for the presented results (Figure 7 and Figure 8) the regression analyses was performed and we got corresponding equations. These equations can be used for fast and efficient prediction of the expected equilibrium position for the damaged aircraft carrier depending on flooded compartment or group of adjacent compartments.

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