Workshop 6

Damage Stability

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1 Introduction

This workshop focuses on damage stability calculations using NAPA and especially SOLAS 2009 calculation. The basic concept of SOLAS 2009 is introduced but the main focus is on the definitions of cross-flooding pipes, openings, A-class bulkheads and evacuation routes. The use of Flooding Simulation for calculating cross-flooding is also introduced. This workshop is aimed at users with basic knowledge of the calculation but who are perhaps new to the subject using NAPA.

2 SOLAS 2009

2.1 Ship types

Affected:

All passenger ships:
- o Pure passenger ships
- o RoRo passenger ships
- o Cruise vessels

Dry cargo ships (L ≥ 80m)
- o Container ships
- o RoRo cargo ships
- o Car carriers
- o General cargo ships
- o Bulk carriers having reduced freeboard and deck cargo (IACS Unified interpretation no. 65)
- o Cable laying ships

Not affected:

- o Offshore supply vessels (IMO Resolution MSC.235(82))
- o Special purpose ships (IMO Resolution A.534(13))
- o Special trade passenger ships "Pilgrim Trade" (1971)
- o High-speed crafts (HSC Code 2000)
- o Tankers (MARPOL 73/78)
- o Ships covered by Reg. 27 of the LL Convention
- o Ships carrying dangerous chemicals in bulk (IBC Code)
- o Ships carrying liquefied gases in bulk (ICG Code)

2.2 General

The harmonized revised SOLAS chapter II-1 was adopted and entered into force January 1st 2009.

The probabilistic concept is based on statistical data concerning what actually happens when ships collide, in terms of sea state and weather conditions; the extent and location of the damage; the speed and course of the ship; and whether the ship survived or sank.

The focus of the concept is to determine the probability that a ship will remain afloat without sinking or capsizing as a result of an arbitrary collision in a given longitudinal position of the ship.

By calculating the probability of the occurrence for each of the damage scenarios and then the probability of surviving each of these damages with the ship loaded in the most probable loading conditions, an overall probability of the ship in question surviving a collision can be evaluated. This probability is referred to as the **"attained subdivision index" A**.

By requiring a minimum value of A, we have a requirement for a particular ship.

The factors p, r, v and s depend on the watertight arrangement, the shape of the ship and the actual floating position according to the following:

- The probability that the damage occurs transversally only in and within the zone under consideration is represented by **factor p**.
- The probability that the damage has a transverse penetration not greater than the distance to a given longitudinal boundary is represented by **factor r**.

- The probability that the damage has a vertical extent that includes only the spaces below a given horizontal boundary, such as a watertight deck, is represented by **factor v.**

- The probability that the ship survives the flooding caused by the damage is represented by **factor s**.

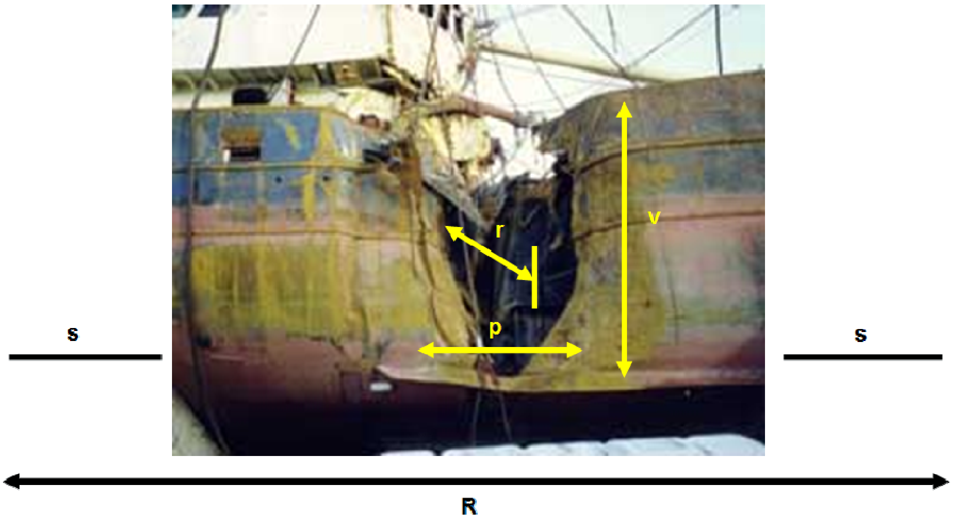

Figure 1. Calculation setup

The attained subdivision index A can be given by the formula:

$$A = p_1 * r_1 * v_1 * s_1 + p_2 * r_2 * v_2 * s_2 + ... + p_n * r_n * v_n * s_n$$

where A is equal to or less than unity.

The required minimum value of A, the **"required subdivision index" R**, depends on the ship's length and the number of passengers.

Compliance with the rules means that **A ≥ R**.

In addition, there are deterministic requirements imposed by Regulations 8 and 9.

The probabilistic damage stability calculations according to SOLAS 2009 can be performed with the PROB Manager application in NAPA.

2.3 Calculation of the survivability (s_i) of the ship

2.3.1 Survivability of cargo ships

$$s_{final} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right]^{1/4}$$

K = 1 if $\theta_e \leq 25°$

$K = \left(\frac{30 - \theta_e}{5} \right)^{1/2}$ if $25 < \theta_e < 30°$

K = 0 if $\theta_e \geq 30°$

2.3.2 Survivability of passenger ships

$$s_{final} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right]^{1/4}$$

K = 1 if $\theta_e \leq 7°$

$K = \left[\frac{15 - \theta_e}{8} \right]^{1/2}$ if $7 < \theta_e < 15°$

K = 0 if $\theta_e \geq 15°$

Calculations for **intermediate stages** of flooding should be performed whenever equalization is not **instantaneous** (equalization time > 60 s). The s factor for intermediate stages is

$$s_{int} = \left[\frac{GZ_{max}}{0.05} \cdot \frac{Range}{7} \right]^{1/4}$$

The s factor for moments is calculated for passenger ships. The moment used is the maximum moment of passenger, wind and survival craft moments:

$$s_{mom} = \frac{(GZ_{max} - 0.04) \cdot Displ}{M_{heel}}$$

$$M_{heel} = \max(M_{pass}, M_{wind}, M_{survivalcraft})$$

The s factor to be used for passenger ships is the minimum of intermediate, final and moment s factors:

$$s_i = \min(s_{int},\ s_{final} \cdot s_{mom})$$

2.4 Attained subdivision index

The summation of attained subdivision index is calculated by using different factors for different subdivision draughts. The ship is assumed to operate:

- 40% of its time at the deepest subdivision draught
- 40% of its time at the partial subdivision draught
- 20% of its time at the lightest service draught

The attained subdivision indexes A_s (service draught), A_p (partial draught) and A_l (lightest service draught) are multiplied with the percentage above to receive the total attained index A:

$A = 0.4A_s + 0.4A_p + 0.2A_l$

2.5 Required subdivision index

2.5.1 Cargo ships

$$R = 1 - \frac{128}{L_s + 152}$$ when $L_s > 100$ m

$$R = 1 - \frac{1}{1 + \frac{L_s \cdot R_{Ls}}{100(1 - R_{Ls})}}$$ when $80 \le L_s \le 100$ m.

R_{Ls} refers to the R in the upper formula.

2.5.2 Passenger ships

$$R = 1 - \frac{5000}{L_s + 2.5 \cdot N + 15225}$$

$N = N_1 + 2 N_2$
N_1 = number of persons for whom lifeboats are provided
N_2 = number of persons (including officers and crew) the ship is permitted to carry in excess of N_1

2.6 Compliance

Compliance with the rules means that **A ≥ R**. In addition to the overall A index, compliance also includes requirements for the attained index for each subdivision draught A_s, A_p and A_l:

A_s, A_p and $A_l \ge 0.5R$ for cargo ships

A_s, A_p and $A_l \ge 0.9R$ for passenger ships

3 Openings

3.1 General

An opening represents a location in the ship where water can enter or flow between rooms connected by the opening. Openings are mainly used for two purposes in a damage stability analysis: for progressive flooding calculation the openings spread water further around the ship, and in stability criteria analysis the openings provide the flooding angle and limit the range of the GZ curve.

Openings are normally defined in an opening arrangement table. Note, however, that all openings defined in the table are not automatically relevant, i.e. taken into account in calculations and output. The set of relevant openings is handled in the calculation arguments.

3.2 Relevancy of openings

An opening is considered relevant if:

- it leads from the sea to an undamaged compartment
- it leads from a damaged compartment to an undamaged compartment
- data about the connection is missing (no CONN given)

An opening is considered irrelevant if:

- it connects two already damaged compartments
- it connects two undamaged compartments
- it leads from the sea to an already damaged compartment

3.3 Opening arrangement table

A standard opening arrangement model table is stored in NAPADB as OPE*MODEL. The needed columns to define regular openings without any special purpose (specified later in this paper) are:

ID	Identification of the opening
DES	Description of the opening
WT	Watertightness of the opening and functionality
OTYPE	Additional definitions used in SOLAS II-1, not concerning the watertightness. Options: ESCAPE (vertical escape), ESCAPE and ROUTE (horizontal evacuation route), PIPE (cross-flooding pipe), PIPE and DUCT (cross-flooding duct without the pipe friction) or PUMP (used in Flooding Simulation).
GEOMOBJ	Geometric object defining the shape and position of the opening. The object may be a point, a curve or an object intersection.
REFX, REFY, REFZ	Alternative to GEOMOBJ, X-, Y- and Z-coordinate of the opening (check point for immersion).
CONN	Pair of compartments connected by the opening. The syntax *comp1, comp2* defines the connection in both directions, the syntax *comp1 -> comp2* defines a one-directional connection from comp1 to comp2. Comp1 can also be SEA to represent a connection out of the ship.

STAGE — Flooding stage where the opening is taken into account in calculation of SOLAS II-1. Options: ALL (also considered in intermediate phases) or FINAL.

4 Cross-flooding devices

4.1 General

Cross-flooding is calculated according to the IMO Resolution MSC.245(83) (previously A.266). The calculation of cross-flooding is carried out as a part of the damage stability analysis.

Cross-flooding devices are defined in an opening arrangement table (OPE*table). An opening arrangement model table for cross-flooding devices is stored in NAPADB with the name OPE*MODELCROSS. Besides the columns described above for regular openings, the table contains some additional columns to define the cross-flooding device properties:

AREA — Cross-sectional area (m2) of the opening. Area will be used in cross-flooding calculations and in progressive flooding calculations when time is present.

DIAM — An alternative way to give the cross-sectional area of the cross-flooding pipe. This data is needed in cross-flooding time calculations.

L — Length of the pipe. By default (if L=0) the length is the distance between the ends of the device. This data is needed to include the friction of the pipe.

KSUM — Sum of k coefficients

A cross-flooding device is defined using two lines in an opening table, one for each end of the device. The first line contains the details of the device and the coordinates of the first end. The second line is used for the second end location. Please see the example 1.

Note: OTYPE column must contain the word PIPE to activate the cross-flooding calculation.

A cross-flooding arrangement is a compartment connection table (CCONN*table), and it defines the compartments which are connected with each other. A model compartment connection table exists in NAPADB and it is named CCONN*MODEL. The columns needed for defining a cross-flooding device connection are:

CONN — Room where the inlet of the device is situated.

COMP — Room where the outlet of the device is situated. If the connection may be open in both directions, two rows are needed to define it.

OPEN — State of the connection. Options: Y (open) or N (closed).

STAGE — Name of the stage where cross-flooding time will be calculated (usually CROSS).

OPENING — Cross-flooding device that is connecting the rooms (defined in the cross-flooding device opening arrangement table).

4.2 KSUM factor

Colum KSUM defines the sum of k coefficients excluding the pipe friction 0.02*l/D. The value will be used for the calculation of the dimensionless factor of the reduction of speed F.

If the same flow crosses successive flooding devices of cross-section S_1, S_2, S_3… that have corresponding friction coefficients k_1, k_2, k_3…, the total k coefficient referred to S_1 is

$\Sigma k = k_1 + k_2 \cdot S_1^2 / S_2^2 + k_3 \cdot S_1^2 / S_3^2 \ldots$

Note that when the old IMO Resolution A.266(VIII) was renewed, the calculation of the factor F was modified. Thus, the losses due to outlet must be included in the sum of k's. This means that it must be KSUM>1.

The industry standard approximation for the discharge coefficient (WRCOEF in NAPA) is $C_d = 0.6$

→ $k_i = \frac{1}{C_d^2} - 1 \approx 1.778$ for each opening.

Note: For a single opening $C_d = \frac{1}{\sqrt{1+k_i}}$ in order to also account for the outlet in the k-factor. In principle, k=1 for outlet must be added to the final k-sum when entered into the opening table.

Note: NAPA adds the friction factor k[friction] = 0.02*l/D automatically to the KSUM unless the opening type OTYPE contains the keyword "DUCT" in addition to "PIPE". So, if you use, for example, PIPEDUCT as OTYPE, the pipe-friction is not added. The DUCT treatment is a new feature since Release 2010.2.

Example 1: The cross-flooding occurs through a series of structural ducts with one manhole (Figure 2). The area of a cross-section S_i of a manhole is default.

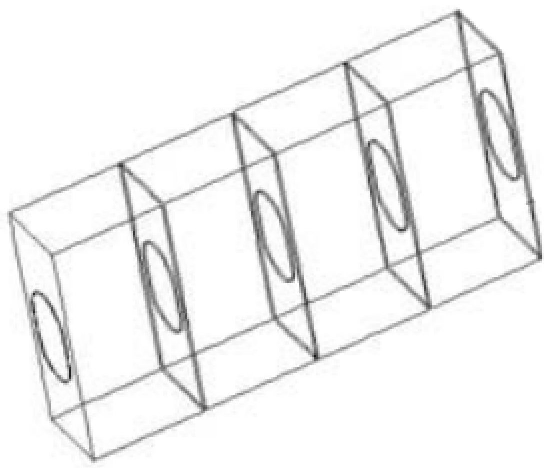

Figure 2. A series of structural ducts with one manhole

When the standard values of C_d are used, the sum of k coefficients is

$$\Sigma k = 1.778 + 1.778 \cdot S_1^2 / S_2^2 + 1.778 \cdot S_1^2 / S_3^2 + 1.778 \cdot S_1^2 / S_4^2 + 1.778 \cdot S_1^2 / S_5^2 + 1$$
$$= 1.778 + 1.778 \cdot 1 + 1.778 \cdot 1 + 1.778 \cdot 1 + 1.778 \cdot 1 + 1 = 9.89$$

Note: The added k=1 for outlet.

The cross-flooding pipe can be now defined in NAPA. First, the device definition is done in the cross-flooding opening arrangement table and then the connection is defined in the cross-flooding arrangement table by referring to the defined cross-flooding device.

	ID	DES	WT	OTYPE	FR [#]	REFX [m]	REFY [m]	REFZ [m]	CONN	DIAM [m]	AREA [m2]	KSUM	L [m]
1	DUCT1	STR.DUCT	UNPROTECTED	DUCTPIPE	100.00	67.920	5.000	0.800	ROOM1 ROOM2	0.357	0.1	9.890	10.000
2	DUCT1#2				100.00	67.920	-5.000	0.800		0.000	0.0	0.000	0.000
3													

Figure 3. Cross-flooding device defined in an opening arrangement table

	CONN	COMP	OPEN	STAGE	OPENING
1	ROOM1	ROOM2	Y	CROSS	DUCT1
2	ROOM2	ROOM1	Y	CROSS	DUCT1
3					

Figure 4. Cross-flooding connection defined in a cross-flooding arrangement table

4.3 Calculation of cross-flooding

The cross-flooding time through every single pipe is calculated according to resolution MSC.245(83). If one pair of compartments is connected by several pipes, the time of that pair is calculated using equation 1/time = 1/t1+1/t2+..., where t1, t2,... are times of single pipes. If there are many pairs of compartments, the cross-flooding time is the maximum of times of all pairs.

When the damages are generated and cross-flooding could occur, an additional stage CROSS is added to the damage definitions. The CROSS stage will damage the rooms through the cross-flooding devices according to the definition in the compartment connection table, and the CROSS stage is then considered to be the final equalisation stage for the cross-flooding and final s is applied.

For passenger ships: If the cross-flooding takes more than 60 seconds, an additional stage CROSS60s is added to the damage calculation. If the cross-flooding takes more than 600 seconds, an additional stage CROSS600s is added to the damage calculation. According to SOLAS 2009 the s factor for the additional stages will be calculated and it may affect the total attained subdivision index. If the duration of cross-flooding is less than 60 seconds, the s value of the first stage (prior to cross-flooding) is ignored assuming that the equalisation is instantaneous.

<u>Example 2:</u> ROOM1 is damaged in the damage definition DAMAGE1. The cross-flooding pipe is defined as in Example 1. Cross-flooding occurs but the duration is more than 60 seconds. s values will be calculated in each stage according to the formulas below. The final s value for the damage will be the minimum of the calculated s values.

```
DAMA, DAMAGE1
STA,  1
ROO,  ROOM1

STA,  CROSS
ROOM, ROOM2

STA,  CROSS60s
```

Optional stages defined after the cross-flooding

s according to the intermediate formula:

$$s_{int} = \left(\frac{GZ_{max}}{0.05} \cdot \frac{Range}{7} \right)^{1/4}$$

s according to the final formula:

$$s_{final} = K \cdot \left(\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right)^{1/4}$$

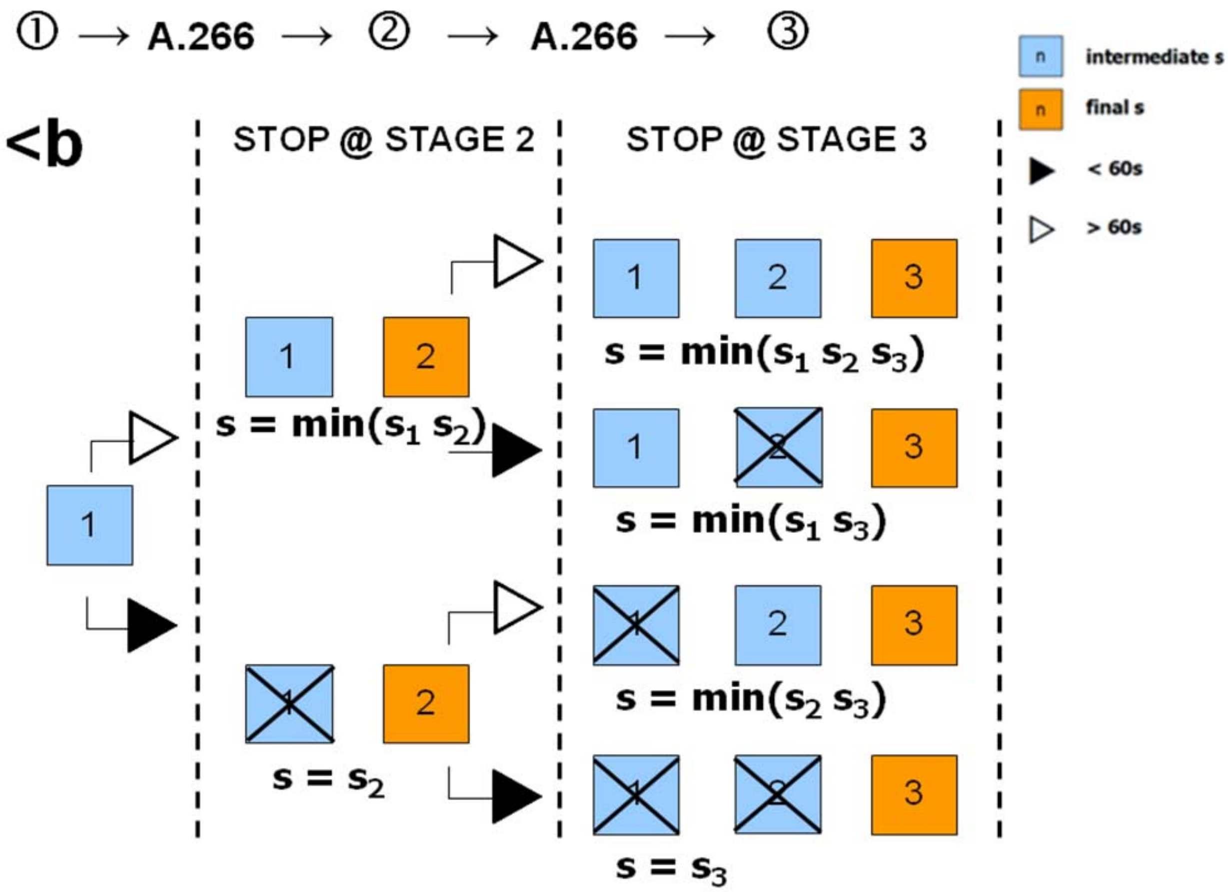

Figure 5. 60 second rule decides which s to pick

5 Evacuation routes

5.1 Vertical escapes

The vertical escapes ensure that evacuation from a compartment to the bulkhead deck will not be obstructed by water from above. In other words, the vertical escape may describe for example a hatch on the bulkhead deck.

Vertical escapes are defined in the default opening arrangement table. Vertical escape location can be given directly as opening coordinates or with a geometric object, i.e. with a curve describing the edges of a hatch.

Note: The OTYPE column must contain the keyword ‘ESCAPE’ for vertical escapes.

The watertightness (WT) of vertical escapes is usually defined to be WEATHERTIGHT to ensure that the escape is dry from above after the damage.

Example 3: Hatch on the bulkhead is defined to be a vertical escape. Because it is needed to check only whether water is flooding down from the hatch, the direction is set from the room R2002 (on the bulkhead deck) to R1002 (below the bulkhead deck):

	ID	DES	WT	OTYPE	GEOMOBJ	FR [#]	REFX [m]	REFY [m]	REFZ [m]	CONN
1	HATCH1	HATCH ON BH DECK	**WEATHERTIGHT**	ESCAPE		35.29	**30.000**	2.000	6.000	R2002 -> R1002
2										

Figure 6. Vertical escape definition in an opening arrangement table

5.2 Horisontal evacuation routes

A horizontal evacuation route means a route on the bulkhead deck connecting spaces located on and under the deck with the vertical escapes from the bulkhead deck required for compliance with SOLAS chapter II-2.

Horizontal escape routes are used for the evacuation of undamaged spaces. Horizontal evacuation routes do not include corridors within the damaged space. No part of a horizontal evacuation route serving undamaged spaces should be immersed. In NAPA, horizontal escape routes are defined in an opening arrangement table, and they are connected with the rooms in an evacuation arrangement table.

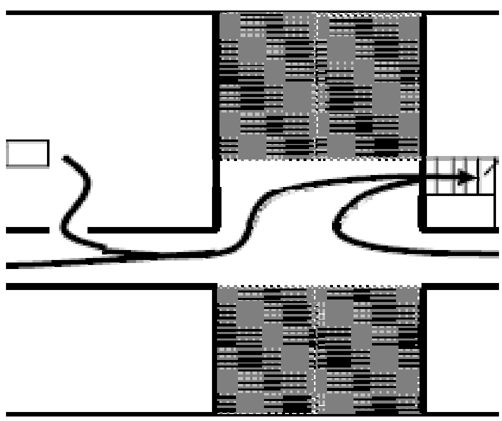

Figure 7. Horizontal escape route connecting a hatch (entry point) and a staircase (vertical escape from bulkhead deck)

Evacuation opening arrangement model table for evacuation route definitions is stored in NAPADB as OPE*EVACMODEL. It contains the additional columns needed for the definitions of horizontal evacuation routes.

ESCAPE	Entry point to vertical escape. Options: the name of a point object or coordinates given as x, y, z.
EVACARR	The name of evacuation arrangement table (normally TAB*) linked to this opening.

Note that OTYPE column must contain the keyword 'ROUTE' for horizontal evacuation routes.

The watertightness (WT) of horizontal evacuation routes is usually defined to be WEATHERTIGHT to ensure that the route is dry after the damage.

Evacuation arrangement model table is stored in NAPADB as TAB*EVACARRMODEL. It contains the following columns:

COMP	Compartment connected with the route
OPENING	The name of horizontal evacuation route definition in an opening arrangement table
FR, X, Y, Z	Location of the entry point to horizontal evacuation route

Example 4: Horizontal escape route on a bulkhead deck is serving room R1002 which is under the bulkhead deck and in the zone Z1. Horizontal escape connects the room with the vertical escape (from the bulkhead deck) which is located in zone Z2.

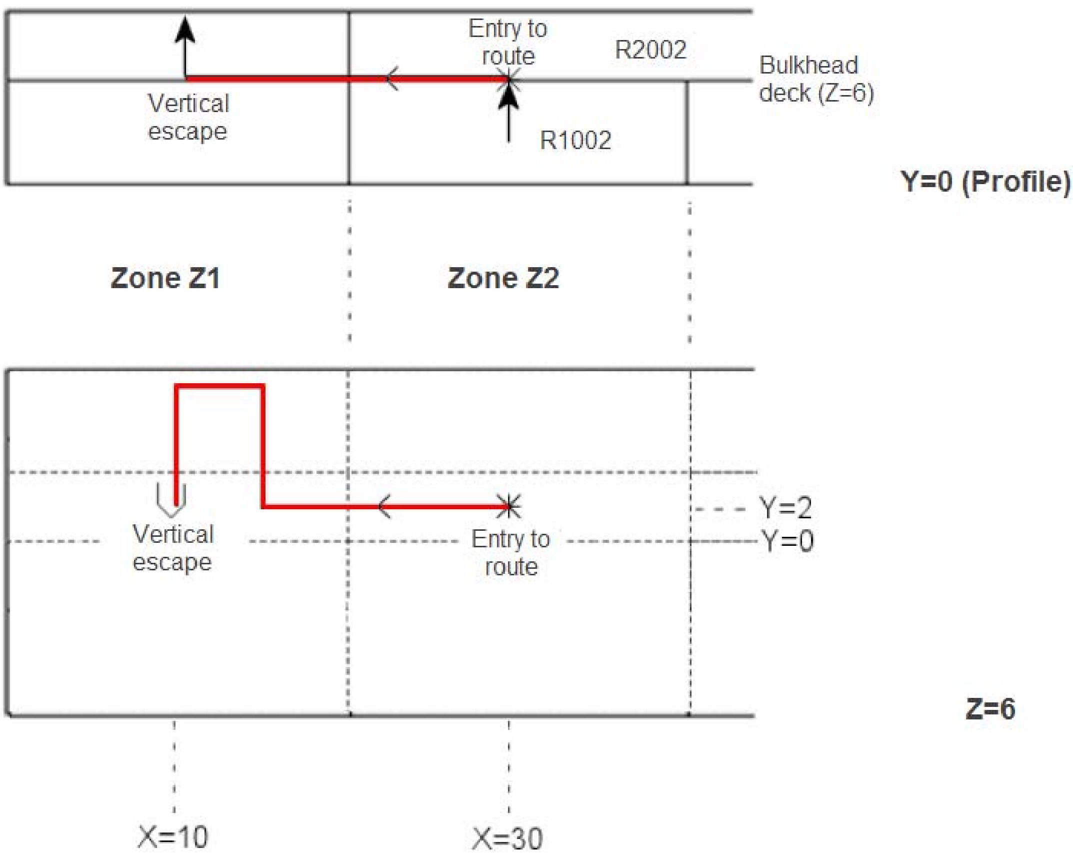

Figure 8. Horizontal escape route on the bulkhead deck serving the room R1002

	ID	DES	WT	OTYPE	GEOMOBJ	FR [#]	REFX [m]	REFY [m]	REFZ [m]	CONN	ESCAPE	EVACARR
1	ROUTE1	HOR.ESC.ROUTE	WEATHERTIGHT	ESCAPEROUTE	C.ROUTE1	0.00	0.000	0.000	0.000		10,2,6	EVACARR1
2												

Figure 9. Horizontal escape route definition in an opening arrangement table

	COMP	OPENING	FR [#]	X [m]	Y [m]	Z [m]
1	R1001	ROUTE1	35.29	30.00	2.000	6.000
2			0.00	0.00	0.000	0.000

Figure 10. Evacuation arrangement connecting room R1001 with the horizontal evacuation route ROUTE1

6 A-class bulkheads

6.1 General

SOLAS 2009 defines that if a compartment contains decks, inner bulkheads, structural elements and doors of sufficient tightness and strength to seriously restrict the flow of water, for intermediate stage flooding calculation purposes it should be divided into corresponding non-watertight spaces. It is assumed that the non-watertight divisions considered in the calculations are limited to A-class fire-rated bulkheads.

In other words, A-class bulkheads are the non-watertight boundaries between the compartments which restrict the flow of water.

Figure 11. A-60 double leaf hinged marine fire door leaking (FLOODSTAND – Integrated Flooding Control and Standard for Stability and Crises Management / CTO S.A.)

6.2 Method in NAPA

A-class boundaries divide the damage into several intermediate stages or several separate damages following the spreading of water. The last stage/damage is the largest one, i.e. it has the greatest number of damaged compartments. The selection between the intermediate stages and separate damages is made by the user. In PROB Manager, the selection is done in the item 'Damage Generation' (Generate 1 zone) under ADVANCED mode.

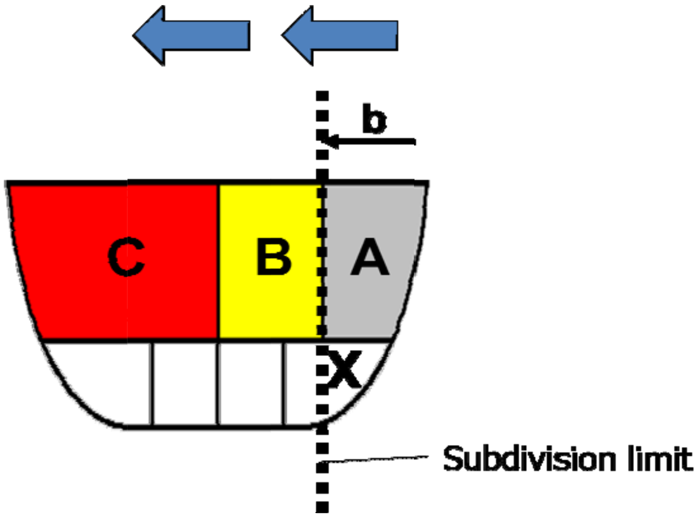

Figure 12. A-class bulkheads between rooms A, B and C

When the flooding through the A-class boundaries is divided into intermediate stages, the stages are named by using '#n' syntax. For example, the case which is described in Figure 12

```
DAMA, DAMAGE
STA, 1
ROOM, X, A
STA, #1          <-----------   A-class boundary between the rooms A and B is flooding.
ROOM, X, A, B
STA, #2          <-----------   A-class boundary between the rooms B and C is flooding.
ROOM, X, A, B, C
```

In the damage above, the final rule for factor s will be applied for the last stage and the intermediate rule for the preceding stages according to the normal practice.

When separate damages are used, the damages are named similarly as stages by using the '#n' syntax:

```
DAMA, DAMAGE
STA,  1
ROO,  X, A

DAMA, DAMAGE#1   <-----------   A-class boundary between the rooms A and B is flooding.
STA,  1
ROOM, X, A, B

DAMA, DAMAGE#2   <-----------   A-class boundary between the rooms B and C is flooding.
STA,  1
ROOM, X, A, B, C
```

The generated separate damages still have the same control number in the damage and result tables. As there can be only one control number for each damage in the final calculation, the one leading to the smallest s-factor will be chosen to be included for the final index.

6.3 Definition in NAPA

The A-class bulkhead definitions use a compartment connection table. The same model table is used with cross-flooding device definition (CCONN*MODEL). The additional column needed for A-class bulkheads is CLASS which is for marking the connection to be used as an A-class connection. The stage column includes the information when the connection is activated. With A-class connections the stage is ACLASS. No other definitions are needed.

The compartment connection table must contain two rows if the connection uses both directions, similarly as with cross-flooding connections. The opening definition is not needed with A-class bulkheads.

	CONN	COMP	OPEN	STAGE	OPENING	WTCOMP	CLASS
1	A	B	Y	ACLASS			A
2	B	A	Y	ACLASS			A
3	B	C	Y	ACLASS			A
4	C	B	Y	ACLASS			A
5							

Figure 13. The A-class boundaries in Figure 12 defined in a compartment connection table

Remember that all bulkheads (WT- and A-class) that seriously restrict the flow of water are always to be included in the subdivision table. In the case in Figure 12, the boundary between A and B, which defines the b-value for the basic damage, is included in the subdivision table. As the limit between B and C is the B/2 limit, it is not included in the subdivision table.

More information:

NAPA Online Manuals

IMO Resolutions MSC.245(83): 'RECOMMENDATION ON A STANDARD METHOD FOR EVALUATING CROSS-FLOODING ARRANGEMENTS'

RESOLUTION MSC.216(82): 'ADOPTION OF AMENDMENTS TO THE INTERNATIONAL CONVENTION OF THE SAFETY OF LIFE AT SEA, 1974, AS AMENDED'

RESOLUTION MSC.216(82): 'EXPLANATORY NOTES TO THE SOLAS CHAPTER II-1 SUBDIVISION AND DAMAGE STABILITY REGULATIONS'

CTO S.A.: FLOODSTAND FP7-RTD- 218532: 'Experiments with leaking and collapsing structures'