SOLAS Probabilistic Damage Stability – Past, Present and the Future

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Damage Stability

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Damage Stability

• Today regulated internationally
• Flooding accidents
• Ensuring a safety level by requiring that certain criteria are passed
• Measured deterministically or probabilistically
Damage Stability

After a flooding incident, we want
• The vessel to stay upright
• The vessel to stay afloat

Following this
• Passengers and crew can remain onboard safely (SRtP idea)
• The cargo is contained onboard
• Spills and pollution are reduced
History of Damage Stability Regulations

• The first attempts actually precedes the Titanic

“All vessels, whether propelled by steam or sail, should possess a margin of strength over and above that which is required to enable them to perform the work for which they were designed and built. A chain, a bridge, or any other structure, the failure of which would entail the loss of human life, invariably has a considerable reserve of strength provided; in other words, the admitted working load is always much less than the computed strength, or the strength ascertained by actual test; certainly it is no less important that the hull of a vessel should contain a similar reserve.

... 

“7. Ocean-going steam-vessels which carry passengers should be additionally protected by having efficient bulkheads, so spaced that, when any two compartments be filled with water, the vessel will still remain in a seaworthy condition and two at least of the amidships bulkheads should be tested by water pressure to the height of the deck next above the water-line.

International Marine Conference, Washington, 1889
Titanic, 1912

• Collided with an iceberg during her maiden voyage from Southampton to New York
• Sank in the North Atlantic on April 15th 1912
• >1500 of 2224 persons onboard lost their lives
• Largest ship afloat at the time, about 269m by 29m
• Capacity for about 3547 persons onboard, but a lifeboat capacity for only 1178 persons
SOLAS 1914

• “The International Convention for the Safety of Life at Sea”
• Signed by 13 countries on January 20th, 1914
• Ratified only by five
• Eventually interrupted by WWI and did not enter into force as intended on July 1st, 1915

• Floodable length, compartment and subdivision requirements
Empress of Ireland, 1914

• Crashed into by SS Storstadt during thick fog in the Saint Lawrence River, Canada
• Sank in the early hours of May the 29th 1914
• 1012 of 1477 persons onboard lost their lives
• Experienced a rapid list, no time to close WT doors and water entered through open portholes, some of them close to the waterline
WWI, 1914 - 1918

• Triggered by the shots in Sarajevo, June 28th 1914
• Listed ship disasters counts >53000 persons who lost their lives at sea during the war
• U-boats sank over 5000 allied ships

Source Wikipedia
SOLAS 1929

• "The New Convention for Safety of Life at Sea"

• Floodable length, compartment and subdivision requirements

• Assymetric subdivision to the satisfaction of the Administration
Jaakko Rahola

• Doctoral thesis accepted by the Technical University of Finland on May 36th, 1939
• Presented the minimum stability using curves
  • Upper curve – the GZ curve
  • Lower curve – the dynamic stability curve (integral)
WWII, 1939 - 1945

- Generally considered to start when Germany invaded Poland on September 1st 1939
- The deadliest conflict in history
- Listed ship disasters counts >270000 persons who lost their lives at sea during the war
- After WWI everybody expected submarines
- Importance of airplanes grew

Source Wikipedia
SOLAS 1948

• Floodable length, compartment and subdivision requirements

• *Minimum* damage extent
  • Longitudinal: 3.05m … 10.67m
  • Transverse: B/5
  • Vertical: top of double bottom to marginline
  • … or lesser, if it is found to be more severe

• Avoid assymetrical flooding, cross flooding acceptable to the Administration

• Deterministic criteria for
  • Maximum heel of 7deg (15deg if accepted by Administration)
  • No marginline immersion at final equilibrium
Andrea Doria, 1956

• Crashed into by SS Stockholm outside Massachusetts
• Sank on July 25th 1956
• Only 46 of 1706 persons onboard lost their lives
• Stayed afloat over 11h after the incident
• Widely covered in news media
SOLAS 1960

- First major achievement by IMO
- Signed on June 17th, 1960
- Entered into force May 26th, 1965
SOLAS 1960

• Floodable length, compartment and subdivision requirements
• Maximum damage extent
  • Longitudinal: 3.05m ... 10.67m
  • Transverse: B/5
  • Vertical: unrestricted
  • ... or lesser, if it is found to be more severe
• Avoid asymmetrical flooding, cross flooding in <=15min
• Deterministic criteria for
  • GM >=0.05m
  • Maximum heel of 7deg (15deg if accepted by Administration)
  • No marginline immersion at final equilibrium
Floodable Length

• How far apart can transverse bulkheads be placed, so that when the space in between is flooded the "margin line" remain dry?

• This question arose already in 1912, after the sinking of the TITANIC

• Included in the articles of the first SOLAS Convention, 1914

• Not relevant for current damage stability rules, but floodable length curves are still sometimes used during the initial design
• Different curves for different permeabilities
• Subdivision (transverse bulkheads) shown using triangles
Deterministic Damage Stability

- First regulations for damage stability were deterministic
  - Requirements for stability with a limited number of damaged compartments
  - Compliance measured with given criteria, you either pass or fail
- Clear cases and easy to present for the officers on the bridge
- Still used for additional requirements in SOLAS today, and in other regulations (e.g. MARPOL, IGC, IBC, etc.)
Lost Buoyancy or Added Weight

• Two methods used for damage stability calculations

• Lost buoyancy is when damaged rooms are removed from the buoyant hull while the displacement is kept constant

• Added weight is when the floodwater is loaded to the rooms and the displacement increases
A Probabilistic Idea

• The probabilistic approach for damage stability of ships was introduced by the German Professor Kurt Wendel in the late 1950s

• He described an alternative method for considering the damage stability of a ship based on damage statistics

• He aimed to introduce a more rational method for assessing the probability of survival for a ship in case of damage (a breach of the ship’s outer shell by collision or grounding)

• Additionally, he introduced a new assessment method that allowed the definition of a global ‘safety level’ (Sicherheitsgrad) through which the stability characteristics of ships of different size and type could be quantified
Making the Idea a Reality

The first attempt, IMO Resolution A.265(VIII), 1973

• The main purpose was to provide an alternative to the SOLAS 1960 regulations for RORO ferries with large holds below the bulkhead deck

• A deterministic provision was included on top of the probabilistic method due to political reasons  
  • Lack of confidence in the probabilistic method

• Resulted in significantly stricter requirements than under SOLAS 1960
SOLAS 1974

• A new type of convention, a convention which is amended instead of being replaced
• Entered into force on May 25th, 1980
• Use of SI units only decided at the 1975 Assembly, Resolution A.351(IX)
• SOLAS 1974, as amended, is what we still use today

• Passenger ships may, as an alternative, prove damage stability compliance using Resolution A.265(VIII) if applied in its entirety
SOLAS 1974

• Floodable length, compartmentation and subdivision requirements
• Maximum damage extent
  • Longitudinal: 3.05m ... 10.67m
  • Transverse: B/5
  • Vertical: unrestricted
  • ... or lesser, if it is found to be more severe
• Avoid asymmetrical flooding, cross flooding in <=15min
• Deterministic criteria for
  • GM >=0.05m
  • Maximum heel of 7deg (15deg if accepted by Administration)
  • No margin-line immersion at final equilibrium
Herald of Free Enterprise, 1987

- A RORO ferry that capsized just after leaving port
- Sank on a sandbank in the evening on March 6th 1987
- 193 of 539 persons onboard lost their lives
SOLAS 1990

- Resolution MSC.12(56), adopted in October 1988
- Entered into force April 29th, 1990
- 1, 2 or 3 compartment damages
- Criteria also for intermediate stages of flooding
SOLAS 1990

- Maximum damage extent
  - Longitudinal: 3m ... 11m
  - Transverse: B/5
  - Vertical: unrestricted
  - ... or lesser, if it is found to be more severe
- Avoid asymmetrical flooding, cross flooding in $\leq 15$ min
- Deterministic criteria for the final stage of flooding
  - Range $\geq 15$ deg ($\geq 10$ deg if the area is increased)
  - Area $\geq 0.015$ metre-radians
  - $Gz_{\text{max}} \geq 0.1$ m with external heeling moments
  - Maximum heel of 7 deg (12 for 2-3 comp, if acceptable to the Administration)
- Deterministic criteria for intermediate flooding stages
  - $Gz_{\text{max}} \geq 0.05$ m
  - Range $\geq 7$ deg
Francescutto, A. & Papanikolaou, A. 2010: Ship Buoyancy, Stability and Subdivision: From Archimedes to SOLAS 90 and the Way Ahead

(*) It can also be GM<0 provided the 7 deg rules is satisfied

- IMO’s regulations for dry cargo ships with a length of 100 meters or above came into force in February 1992
  - Introduced a new part B-1 into SOLAS Chapter II-1. Here the damage stability requirements were based on the probabilistic concept
  - Based on the probabilistic part of A.265 (1973)
- Extended to cover dry cargo ships with a length of 80 meters or higher in July 1998
Estonia, 1994

• A ROPAX ferry who capsized after the bow visor broke off in strong weather
• Sank on September 28th 1994 in the Baltic Sea
• 852 of 989 persons onboard lost their lives
SOLAS 1995 and Stockholm Agreement

- The SOLAS 1995 conference could not conclude on changing the SOLAS 1990 damage stability requirements to a worldwide standard
  - Seven northwest European countries concluded a regional agreement, the so-called **Stockholm Agreement**
- Fulfillment of the SOLAS 1990 damage stability criteria under the assumption of flooding of the ship’s main car deck with an amount of water of up to 50 cm height
  - The assumed amount of water depends on the ship’s damage freeboard and the significant wave height in the region of operation
Stockholm Agreement

• The first performance-based regulatory procedure by IMO was also adopted, allowing verification of the compliance through an equivalent model test procedure, Resolution 14

• Stockholm Agreement, even if referring to an outdated SOLAS Convention, is still in use today
  • E.g. in European waters through the EU 2003/25/EC directive
Express Samina, 2000

- A ROPAX ferry that crashed against the reefs outside Portes islets in the Agean Sea
- Main damage above the waterline, but a stabilizer fin cut through the hull below the waterline
- WT doors open
- Capsized and sank on September 26th, 2000
- 81 of 533 presons onboard lost their lives

- This event accelerated the implementation of the Stockholm Agreement throughout Europe

Image by Peter J. Fitzpatrick, Wikipedia
Harmonization (Cargo / Passenger)

- Started in the 1980s with the development of the probabilistic damage stability requirements for dry cargo ships
- EU project HARDER (2000-2003)
  - Damage statistics
  - Model tests
  - Verification
SOLAS 2009

- The proposed harmonized damage stability regulations were adopted by MSC through Resolution MSC.194(80) in 2005
  - Entered into force on 1st of January 2009
- Probabilistic damage stability requirements for both cargo and passenger ships
- Collision damages
Understanding a Regulation

• International regulations are compromises of many opinions, in few sentences

• Influenced by different political-, cultural-, and risk perceptions

• Background material is not provided in the regulation text
  • ... but they can be accompanied with Explanatory Notes

• IACS also issues interpretations and guidelines
Understanding a Regulation

• A regulation is mandatory – “shall”

• Explanatory Notes are recommendations – “should”

• Interpreted and approved by Class societies

• Final judgement by flag authorities
Understanding a Regulation

• The choice of words makes a difference

• Important to understand what is actually written…

• … and what is not

• Can sometimes be difficult to understand the first time you read it
Understanding a Regulation

• Application
  • Date
  • Ship types
  • Dimensions
  • etc.

• Definitions

• Cross references to other regulations, resolutions etc.
Definition Example, “Length”

- **Length** as defined in the International Convention on Load Lines in force (SOLAS)
- “**Length** (L)” means 96% of the total length on a waterline at 85% of the least moulded depth measured from the top of the keel, or the length from theforeside of the stem to the axis of the rudder stock on that waterline, if that be greater. In ships designed with a rake of keel the waterline on which this length is measured shall be parallel to the designed waterline. The length (L) shall be measured in metres. (MARPOL Reg 12A)
- **Subdivision length** (SOLAS)
Draught and Trim in SOLAS 2009

- Intentions might be good, but sometimes an update is not necessarily an improvement...

- **Draught** \((d)\) is the vertical distance from the keel line at mid-length to the waterline in question.

- **Trim** is the difference between the draught forward and the draught aft, where the draughts are measured at the forward and aft terminals respectively, disregarding any rake of keel.

- **Mid-length** is the mid-point of the subdivision length of the ship.

- **Terminals** are the aft and fore ends of the subdivision
• The deterministic approach in “SOALS 90” was eventually replaced by “SOLAS 2009”

• Unless expressly provided otherwise, do not apply to:
  • Ships of war and troopships
  • Cargo ships of less than 500 gross tonnage
  • Ships not propelled by mechanical means
  • Wooden ships of primitive build
  • Pleasure yachts not engaged in trade
  • Fishing vessels
SOLAS Damage Stability - Present

- Applicable to all passenger ships, and cargo ships >=80m not covered by
  - Annex I of MARPOL 73/78
  - International Bulk Chemical (IBC) Code
  - International Gas Carrier (IGC) Code
  - Offshore Supply Vessels (OSV) Code
  - Special Purpose Ships (SPS) Code
  - ICLL 1966 Regulation 27 damage stability
SOLAS Damage Stability - Present

- Probabilistic damage stability for both cargo and passenger ships
- Additional deterministic requirements for passenger ships (Regulation 8)
- Additional deterministic requirements for ships that do not comply with double bottom requirements (Regulation 9)
  - Even for some ship types that don’t need to comply with the probabilistic damage stability in SOLAS...
The outcome of the calculation is an indication for how likely a ship will remain afloat, without sinking or capsizing, as a result of an arbitrary collision in a given longitudinal position of the ship.
Probabilistic Damage Stability

- **Probability** – the likelihood that a ship is hit at a certain location, based on statistical data

PROBABILISTIC = PROBABILITY

- **Survivability** – capability of surviving the consequences after being struck by another ship
SOLAS Probabilistic Damage Stability

• The probability calculated is related to the extent and location of the damage
• Probability for a damage to occur is 1
• Old statistical data used has resulted in that the maximum vertical extent is to the next watertight deck after 12.5m above the deepest subdivision waterline
Benefits of a Probabilistic Approach Compared to Deterministic Principles

- Deterministic regulations describe a “black and white” world where you either pass or fail
- Non-survival cases are acceptable for some damage cases, as long as the required safety level is achieved
  - (as long as the likelihood for it to happen is low enough)
- Believed to give a much more realistic representation of the safety level for a ship in damaged situations
- Allows more freedom regarding e.g. placement of watertight bulkheads
The Probabilistic Method
Factors $p_i$, $r_i$, $v_i$, $s_i$

• $p_i \sim$ probability of a damage situation
  • Probability that **only** the compartment or group of compartments under consideration may be flooded

• $r_i \sim$ transversal extent of the damage
  • Probability that a longitudinal bulkhead **will not be breached** by the damage. For each longitudinal bulkhead inside the ship’s side, an $r$-value will be calculated.

• $v_i \sim$ vertical extent of the damage
  • Probability that a watertight deck above the waterline remains intact

• $s_i \sim$ probability of the ship surviving the damage
  • Based on the range and maximum value of the GZ-curve and the heeling angle in the final floating position
Subdividing and the “Zonal” Approach

• SOLAS 2009 is based on a “zonal” approach to probabilistic damage stability
  • Based on subdividing the ship (transversally, longitudinally and vertically), the probability of each damage is calculated inversely
• Damages are generated for a number of zones combined
• When N is increased, the cumulative probability approaches 1.0
• “What is the probability that a given damage extent occur?”
Additionally for Damages

• Calculate cross-flooding
• Consider the impact of non-watertight boundaries restricting the flow of water
Probabilistic Damage Stability Concept

\[
A = \text{Attained subdivision index} \\
\sum p_i \cdot r_i \cdot v_i \cdot s_i \quad \text{(over all damages)}
\]

\[
R = \text{Required index} \\
\text{Rule formula based on the subdivision length and the number of passengers}
\]
Required Subdivision Index

\[ R = 1 - \frac{128}{L_s + 152} \quad \text{if} \quad L_s > 100 \text{ m} \]

\[ R = 1 - \frac{1}{L_s \cdot R_{ls}} \quad \text{if} \quad 80 \leq L_s \leq 100 \text{ m} \]

\[ R = 1 - \frac{5000}{L_s + 2.5 \cdot N + 15225} \quad \text{if} \quad L_s > 100 \text{ m} \]

\[ N = N_1 + 2 \cdot N_2 \]

\[ N_1 = \text{number of persons for whom lifeboats are provided} \]

\[ N_2 = \text{number of persons} \]

\( \text{(including officers and crew) the ship is permitted to carry in excess of} \ N_1 \)
Survivability \((s_i)\) After Damage

- Level trim
- Level trim
- Saddle trim

\[ \text{Max flooding angle} \]

\[ \text{EQ heel} \]

\[ \text{Range} \]

0 \(\ldots\) \(s_i\) \(\ldots\) 1
The S Intermediate Formula

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

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

Note: \( s_{\text{int}} = 0 \), if the intermediate heel angle exceeds 15°.
The S Final Formula

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

\[ \theta_e = \text{final equilibrium heeling angle} \]

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<th>K</th>
<th>( \theta_e )</th>
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<td>( \theta_e \leq 25^\circ )</td>
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<tr>
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<td>25 &lt; ( \theta_e ) &lt; 30^\circ</td>
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<tr>
<td>0</td>
<td>( \theta_e \geq 30^\circ )</td>
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<th>K</th>
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<tr>
<td>1</td>
<td>( \theta_e \leq 7^\circ )</td>
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<tr>
<td>0&lt;K&lt;1</td>
<td>7 &lt; ( \theta_e ) &lt; 15^\circ</td>
</tr>
<tr>
<td>0</td>
<td>( \theta_e \geq 15^\circ )</td>
</tr>
</tbody>
</table>
The S Moment Formula

- For passenger ships

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

\[ M_{heel} = \max(M_{pass}, M_{wind}, M_{survival\text{aft}}) \]

The probability to survive heeling moments is taken into account together with \( s_{final} \).

\[ s_i = \min(s_{int}, s_{final} \cdot s_{mom}) \]
S Factor Criteria

In addition, several checks are performed, which if failed will set $s=0$

- Openings being submerged
- Vertical escapes
- Control stations
- Horizontal evacuation routes
Summation of the Attained Index

• 40% of its time at the deepest subdivision draught (ds)
• 40% of its time at the partial subdivision draught (dp)
• 20% of its time at the lightest service draught (dl)

\[ A = 0.4A_s + 0.4A_p + 0.2A_l \]

• These initial conditions are idealized, and the ship is “dry”
Summation of the Attained Index

• Additional requirements
  • $\text{As, Ap and Al } \geq 0.5R$ for cargo ships
  • $\text{As, Ap and Al } \geq 0.9R$ for passenger ships
Examples on Other Damage Stability Regulations

- MARPOL – Tankers
- IGC – Gas Carriers
- IBC – Bulk Carriers
- SPS 2008 – Special Purpose Ships
- Polar Code
MARPOL, IBC and IGC

- Deterministic criteria for a maximum damage extent
- For loading conditions
SPS Code

- Refers to SOLAS for the methods to be used in the calculations
- S formula according to passenger ships
- A reduced required subdivision index (R) is used
Polar Code

- Damages with a fixed extent
- Penetration measured normal to the hull
- $S=1$ criterion according to SOLAS
Some Stability Related Research

- HARDER
- FLOODSTAND
- GOALDS
- EMSA3
HARDER, 2003

• EU project HARDER (2000-2003)

• Assist the harmonization between cargo and passenger ships
• Update damage statistics
• Model tests
• Verification of calculations, and parameters used
FLOODSTAND

• “to increase the reliability of flooding simulation tools in design and onboard use”

• “to establish a method for instantaneous classification of the severity of ship flooding casualty”

• http://floodstand.aalto.fi/
GOALDS, 2012

Objectives were:
• Enhance collision and grounding casualties database
• Develop an improved formulation for the survival probability in case of flooding
• Develop a new survivability model for flooding following grounding accidents
• Validate the new formulations by experimental and numerical analyses
• Develop a new damage survivability requirement for passenger ships
Divided into 6 sub-studies

• Identification and evaluation of risk acceptance and cost-benefit criteria and application to risk based collision damage stability

• Evaluation of risk from watertight doors and risk based mitigating measures

• **Evaluation of raking damages due to groundings and possible amendments to the damage stability framework**

• Assessment of cost effectiveness or previous parts, FSA compilation and recommendations for decision making

• Impact assessment compilation

• Updating of the results obtained from the GOALDS project according to the latest development in IMO
SOLAS 2020

• MSC adopted the updated regulation in Resolution MSC.421(98), and the accompanying Explanatory Notes in Resolution MSC.429(98) in June 2017

• Restores the changed definitions on how to measure draught and trim in SOLAS
SOLAS 2020 – What Was Adopted

Damage stability related changes include e.g.:  
• A new R index  
• A different treatment of the Ai indexes when calculating multiple trims  
• A single envelope minGM curve for different trims  
• Cargo ships with cross-flooding devices also get an s intermediate criteria  
• Increased range and maxGZ requirements in the s final formula for RoPax ship damages concerning roro-spaces  
• Usage of an envelope waterline  
• ... to mention a few
SOLAS2020 – A New R Index

MSC 98/3, IMO
SOLAS2020 – Ai Indices

• The overall attained index is based on the smallest Ai value calculated for each draught
SOLAS2020 – A Single MinGM Curve

SDC 4/16, IMO

Trim = 0
Trim = 1% L aft
Envelope curve covering trim ranges from 0.5% L forward to 1.5% L aft
SOLAS2020 – Cargo S Intermediate

• For passenger ships and cargo ships fitted with cross-flooding devices the factor $s$ intermediate, $i$ is ... 
• ... $s$ intermediate, $i = 0$, if the intermediate heel angle exceeds $15^\circ$ for passenger ships and $30^\circ$ for cargo ships.
SOLAS2020 – RoPax S Final Formula

\[ S_{\text{final,}i} = K \cdot \left[ \frac{GZ_{\text{max}}}{TGZ_{\text{max}}} \cdot \frac{\text{Range}}{TRange} \right]^{\frac{1}{4}} \]

where:

- GZmax is not to be taken as more than TGZmax;
- Range is not to be taken as more than TRange;
- TGZmax = 0.20m, for ro-ro passenger ships each damage case that involves a ro-ro space,
- TGZmax = 0.12m, otherwise;
- TRange = 20º, for ro-ro passenger ships each damage case that involves a ro-ro space,
- TRange = 16º, otherwise;
SOLAS2020 – An Envelope Waterline

SDC 4/16, IMO

Reference waterline

Shell / Original waterline

X1 Zone X2

Figure 1

Centreline

Reference waterline

Shell / Original waterline

X1 Zone X2

Figure 2

Reference waterline

Shell / Original waterline

X1 Zone X2

Figure 3

Reference waterline

Shell / Original waterline

X1 Zone X2

Figure 4
Future

• Current regulations still not perfect, room for clarification and improvement
• Probability and reduction of risk more used
• Moving away from the zonal approach, leaving more room for designers
• Use of more advanced methods, such as time-domain simulation, increases
Modern Tools for More Accurate Calculations

- Use of time-domain flooding simulation for analyzing the progression of flood-water
- Impact of doors being open/closed on a large ship subject to extensive flooding (simulations)
Conclusions

• International regulations are compromises of different political-, cultural-, and risk perceptions
• The regulatory development has been largely accident driven
• The current SOLAS convention is from 1974, as amended
• Older regulations still used for existing ships
• Never forget the human factor – no design or regulation can completely prevent all accidents
• The forces of nature should not be underestimated