Alternative assessment of passenger ship safety – Early results from the EU project FLARE

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Abstract. Mitigating flooding risk through passive and active measures is a key step in further increasing the safety of shipping, reducing loss of life and damage to the environment. This paper presents key findings from the EU Horizons 2020 project FLARE (**FL**ooding **A**ccident **RE**sponse) that introduces a novel risk-based methodology beyond the state-of-the-art for "live" flooding risk assessment and control, with potential application to new and existing ships. The project develops a flooding accident model - based on statistics and first-principles tools - that aims to assess the frequencies of flooding events whilst accounting for pertinent environmental conditions and design parameters including ship crashworthiness. Cost-effective risk control options are under evaluation and possible recommendations and/or amendments to the regulatory framework will be submitted to the IMO.

Keywords. Risk, passenger ship damage stability, crashworthiness analysis, safety in design, operation and emergencies, practical recommendations

1. Introduction

Current IMO regulations on ship damage stability are based on a static assessment of damage stability without due consideration on the design flooding risk per se, while the effects of on-board operations are often averaged and implicitly considered (if at all). Static stability models can be used to identify potential risk reduction/mitigation measures without directly quantifying their risk reduction effects, e.g., calculating instead the influence of watertight subdivision for flooding protection in so far as damage stability is concerned. Considering this, there are two basic problems that are being addressed in project FLARE namely: (i) "indices", which do not contain or convey the right risk information and (ii) passive solutions to address the flooding risk problem.

This is because, traditionally, ship safety has been addressed as a fundamental design problem that relies on passive design measures for safety improvement. This is actually the right approach, in so far as the residual risk, to be managed by operational and emergency response measures is small. However, this is not the case with ships of all sizes and, in particular existing ships, which have been designed many years ago to what

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we regard today as inferior standards. As a result, active measures to address damage stability following collision or grounding have not been pursued in a way that provides measurable, and hence auditable, safety improvements. Flooding risk assessment should rather be "dynamic", based on the actual ship operation and environmental conditions, introducing dynamic risk reduction/mitigation measures - such as damage control measures and passenger evacuation systems - making them more quantifiable and accountable, linking risks to real-time conditions and parameters.

In shipping, and specifically for passenger ships, risk levels are determined by the impact/consequences of an accident - which could be catastrophic - rather than by the frequency of accidents which is relatively low. In several cases, it is impossible to quantify statistically the effect of risk mitigation measures on risk. Appropriate and timely actions taken following a maritime accident can greatly reduce loss of life or damage to the environment. This is of paramount importance, considering that flooding due to collision, grounding and contact is the most significant contribution to the overall risk [1]. Flooding may lead to loss of stability and limit the functionality of essential safety systems, thus failing to evacuate large numbers of passengers.

Over the last 30 years the development of a framework to facilitate life-cycle flooding risk management has been thoroughly pursued by many studies and EU research projects [2]. Activities are now progressing to target risk prevention, reduction, mitigation and control, especially in emergencies, and to provide tools and a guided process to the end users, i.e., shipyards and ship owners (see Table 1). Risk control measures can be split into design and operational measures and further categorized as pre-incident, during incident and post-incident. Implicit interrelations exist between these categories, but they are not direct and are to be verified in terms of cost-effectiveness with different applications on new and existing ships. The ambition of the risk-based approach is to exploit the maximum risk reduction potential of all measures in these categories whilst ensuring the most appropriate risk balance in a quantifiable way and bridge the big gap in the current regulatory framework.

The EU Horizons 2020 project FLARE (**FL**ooding **A**ccident **RE**sponse) contributes to the ongoing efforts to increase the safety of shipping by developing and validating a flooding risk assessment model, which can be used to evaluate the safety level in the design phase and in real time operations. This platform offers to the crew the opportunity for fast evaluation of any impeding emergency. It, therefore, can serve as a decision support during emergency situations and as invaluable feedback to designers that aim to evaluate the effect of active and passive flooding mitigation measures. Fundamental to this is the accurate modelling of flooding risk with the ultimate aim to increase the reliability of predictions in ship safety assessment, risk mitigation and control.

This paper reviews the project and its relevance on Risk Control Options (RCOs), including susceptibility to flooding accidents (pre-accident phase) and risk estimation beyond existing statistics considered by IMO SOLAS [3]. The susceptibility model is linked to a flooding accident model to assess - based on statistics and first-principles tools - the frequencies of flooding events whilst accounting for pertinent environmental conditions and design parameters, including such novel concepts as the crashworthiness of the ship.

2. Initial data collection

Work in this section uses sample passenger ships and focuses on the potential use of operational data for better understanding of design for safety of cruise liners and Ro-pax vessels. Two major topics are addressed namely (i) permeabilities and their comparison
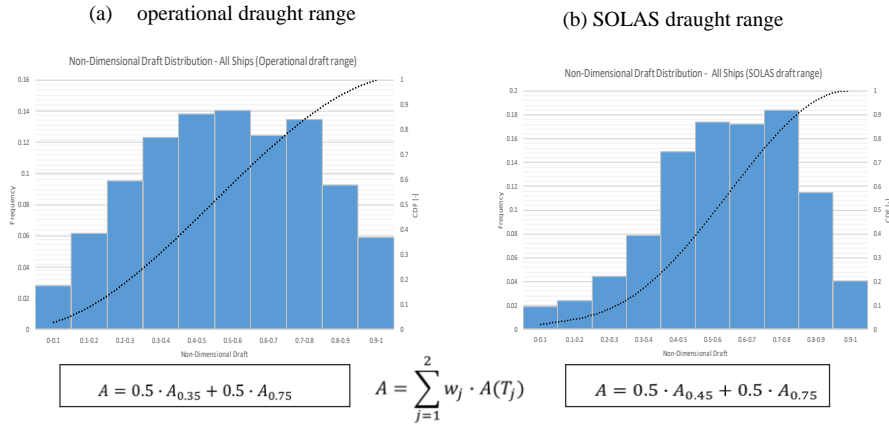
Table 1. Past versus present and future measures of relevance to ship flooding accident response

Past	Present (and future)
Safety improvements achieved through regulations driven by accidents. Focus on post-incident damage limitation by passive measures on new ships.	Focus on passive and active risk reduction pre/post-accident. Safety treated as measurable objective in a risk-based regulatory framework. Target both new and existing ships.
Flooding accidents classified as collision, grounding and foundering. No unified approach to cost-effective flooding risk reduction.	Adequate accident database, with data collated over the past 20+ years. Unified approach for improved flooding risk models and cost-effective RCOs.
Susceptibility to flooding models used to evaluate accident probabilities in fairways, but not the ensuing scenario post-accident.	Quantification of pertinent parameters post-accident (e.g., extent of damage). Fast and accurate flooding risk estimation, effective crisis management and control.
Few flooding simulation tools – Lack of rigorous verification.	Rigorous verification of tools by model experiment and CFD results. Development / verification of a "toolset" to support ship design and operation,
Flooding risk models address collision and grounding separately, the latter simplistically.	Holistic risk model for any serious flooding event. Cost-effective risk management and post-flooding control.
"Static" flooding risk addressed only by design measures	Real-time "live" risk estimation in actual operational conditions. Cost-effective risk-management in flooding emergencies.
Post-flooding incident response based upon arbitrary phases.	A holistic approach to mustering and abandonment in extreme scenarios. DSS for effective crisis management.
Crashworthiness unexploited. No emphasis on active risk measures.	Use cost-effective measure for flooding risk mitigation and post-flooding accident control. Influence of crashworthiness, watertight door management, buoyancy.
Rule-based approach Average but unknown level of damage survivability.	Risk-based integrated active and passive measures to control serious flooding risk. Quantifiable risk level for each design.

against values currently incorporated in SOLAS; (ii) the analysis of ship operational patterns using big data. Five cruise ships (11,800-230,000 GT) and three Ro-pax ships (28,500-70,000 GT) have been designed and selected as sample ships. The analysis of onboard data included ship operational loading condition histories and optimal draft / weight factor distributions relative to IMO SOLAS ranges (Figure 1).

The assessment of impact of passenger vessel loading behaviour encompassed 2 years of operational data and considered 36 passenger vessels, comprising 27 cruise ships, 6 Ro-pax and 3 cruise ferries with age range between 2 and 38 years and capacity between 19,800– 227,000 GT. Consequently, a new proposal for weighting of draughts, for operational loading conditions and for SOLAS draught range was developed. The analysis showed that passenger vessels, in general, operate within a much narrower draught range as compared to SOLAS assumptions and hence existing regulations are not optimal in terms of assuring safety in operations. Since passenger vessels rarely operate at their extreme draft range hence two calculation draughts should be considered at intermediate locations within the vessel draught range. The optimal non-dimensional calculation draught values for vessels in operation, relative to the operational draught range, were estimated between 0.35 and 0.75. For vessels at design stage, the optimal non-dimensional calculation draughts were found to be 0.45-0.75 as compared to the

currently SOLAS range. In both cases the optimal weighting factors applicable to the calculation was 0.5.

(a) operational draught range

(b) SOLAS draught range

$$A = 0.5 \cdot A_{0.35} + 0.5 \cdot A_{0.75}$$

$$A = \sum_{j=1}^{2} w_j \cdot A(T_j)$$

$$A = 0.5 \cdot A_{0.45} + 0.5 \cdot A_{0.75}$$

Figure 1. Non dimensional distributions of operational versus SOLAS draft distributions for passenger ships.

Analysis of the permeability of cargo holds for one year confirmed SOLAS default values. On the other hand, the analysis on the permeability of engine rooms and cabin areas of existing ships indicated that mean permeability value should be set at 0.9 (Table 2). This was also confirmed by a similar type of analysis on the permeability of stores (42 stores analysed on a cruise ship and a Ro-Pax vessel). Analysis of the tank permeability confirmed that cruise ship draught change is dominated by the range of filling in consumable tanks and therefore the SOLAS approach is not realistic (Table 3). Key results have been included in a document which will be submitted to the IMO SDC (Ship Design and Construction) sub-committee, proposing amendments to improve SOLAS Chapter II-1.

**Table 2.** Summary of permeability values for cargo holds

Description	Permeability value
Machinery spaces SOLAS.	0.85
Main Engine room #1	0.92
Main Engine room #2	0.916
Main Engine room #3	0.91
Aux. Engine room #1	0.91
Aux. Engine room #2	0.933
Mean value	0.918
Cabin area SOLAS	0.95
Cabin area #1	0.93
Cabin area #2	0.894
Cabin area #3	0.924
Mean value	0.916

Serious flooding accident response may be sensitive to hydrometeorological conditions and the area of operation. With the later in mind, work concentrated on understanding operational risks associated with passenger and Ro-Pax vessel encounters by collecting and analysing big data from wave statistics, ship routing and traffic patterns. With reference to vessel encounters that may lead to grounding or collisions, special

emphasis has been attributed to three key risk areas of operation namely Gulf of Finland, English Channel and Gibraltar Straight. Weather mapping accounted for global environmental conditions such as sea states, currents, wind and swell for which real operational data were made available by commercial providers at 180 min intervals and 1.25^0 grid resolution in 8 global areas of operation (Figure 2). Vessel positioning data were made available by AIS (Automatic Identification System) messages within 2 minutes interval sampling from all the cruise and Ro-Pax vessels of interest in the three risk areas. GEBCO bathymetry data and weather data were interpolated for each AIS data point location and time. The information was statistically analysed. It was concluded that big data analytics may lead to improved recommendations in terms of the impact of the hydro-meteorological conditions on passenger or Ro-Pax vessel encounters. These recommendations could be used for the development of grounding and collision probabilistic risk models.

Table 3. Summary of proposed permeability values for tanks (Standard Deviation – SDV based on 1,000 loading cases considered under FLARE)

Description	Formulae	SDV
SOLAS	0 to 0.95 (most onerous value to be selected)	0.42
FLARE (linear regression)	$0.59 - 0.11 \dfrac{T - T_{min}}{T_{max} - T_{min}}$	0.06
FLARE (mathematical formulae)	$1 - \dfrac{0.96 \times Disp - LWT - 0.5 \times HCap}{\rho \times TCap}$	0.04
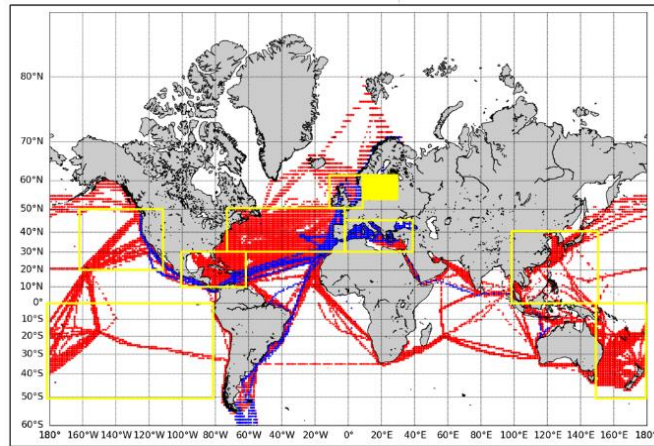
Figure 2. Weather data patterns (Red and blue patterns show the trajectories of passenger and Ro-Pax ships with weather data; Yellow boxed areas represent 50 areas of interest based on BMT GWS; Blue boxed areas represent 8 areas of interest namely North Sea, Baltic Sea, Caribbean, Mediterranean Sea, North Atlantic, Northeast Pacific, South-East Asia, South Pacific).

3. Damage breach modelling beyond current statistics
Waterway traffic complexity is one of the main reasons behind collision and grounding accidents. In FLARE existing gaps in statistics concerning frequencies of serious flooding accidents following collision and grounding events as well as their impact on

novel Risk Control Options (RCOs) were addressed by a rapid assessment tool for modelling grounding and collision accidents relevant to cruise and Ro-Pax ships and by establishing the macro-relation between crashworthiness and design [3]-[5].

The analysis considered accidental scenarios that may lead to serious flooding beyond those considered by current statistics. Traffic analysis accounted for the area of operation, which influences the probability of having a flooding accident, as well as the ship survivability after flooding. The analysis made use of big data records accounting for environmental conditions (weather, sea states, visibility) relevant operational scenarios and as applicable bathymetry records. On this basis a method for the evaluation of the probability of collision and grounding was developed and validated for the case of a Ro-Pax ship operating over a three - year period in the Gulf of Finland (Figure 3).

MMSI	276829000
Length	212 m
Breath	30.6 m
Draught	6.9 m
Gross Ton.	49,134 t

Figure 3. Weather data patterns (Red and blue patterns show the trajectories of passenger and Ro-Pax ships with weather data

Solvers accounting for the influence of surrounding water in way of contact and evasiveness of relevance to collision and hard grounding accidents (pure racking cases) were thoroughly tested and developed throughout the project. In order to be able to simulate large amounts of accident scenarios as required in risk analyses in a limited computation time, the developed solvers were based on the Super-Element method.

To validate the method special attention has been attributed to breach validation by comparisons against LS-DYNA. A benchmark study accounting for different scenarios of collision between the NAPA D-RoPax passenger ship and Floodstand Ship B cruise ship demonstrated good agreement between different methods developed by different project partners irrespective to modelling simplifications [4]. For both collision and grounding cases comparisons showed good correlation. Yet, the breach size resulting from analytical grounding simulations appeared to be quite sensitive to the failure strain values adopted to model the rupture of the ship bottom floors.

Two independent methodologies, namely direct and comparative methods, albeit accounting for the influence of grounding and collision accidental loads on dynamic response, have been developed. The comparative method [5] enables scaling of the SOLAS damage distributions by comparison between two ship designs (the reference ship and her modified version). The case study using Floodstand ship B considered various reinforcement strategies and demonstrated that the most effective strategies in terms of damage breach reduction over the whole range of SOLAS damages were reinforcement of decks (increased thickness of deck plating and stiffeners) but especially the addition of a double hull. For the double hull design studied, an average reduction of 30% of penetration and 15% of damage length was obtained. In order to quantify the impact of such damage reduction in terms of increase of A-index, an adaptation of the non-zonal Monte Carlo method has been proposed and implemented. The direct method [6] employed scenarios directly obtained by AIS data post-processed using a collision detection model. The damages obtained (by simulation only) were different from the

SOLAS approach (using real accidents statistics). Thus, the method has proved by nature sensitive to the accuracy of the models used and it is therefore deemed to be better suited as an operational tool for relative evaluation of the navigational risk (influence of route) on-board estimate of the most probable damage size following a collision event.

4. Lessons learnt from crashworthiness

Risk Control Options (RCOs) were proposed to (i) leverage on operational aspects (operational procedures, speed reduction, situation awareness, navigation equipment, DSS for collision avoidance, crew training), influencing both frequencies and consequences, (ii) improve structural solutions and (iii) introduce crashworthiness criteria to minimise the accident consequences. This concept has already been applied in the form of prescriptive requirements (e.g., Polar Code [6]), assuming that the hull areas subject to more severe damage are to be adequately strengthened.

Work demonstrated that crashworthiness is a cost-effective RCO, to be properly evaluated and measured. This is because a resilient ship will have a reduced extension of damage, less water ingress, and will gain more (or infinite) time before sinking / capsizing. Crashworthiness is also part of a blueprint for dynamic vulnerability screening, aimed at:

- identifying the most vulnerable compartments and internal layouts (watertight subdivision, cross-flooding, outfitting distribution) ranking a subset of breaches resulting in ship loss
- implementing a crashworthy design by parametric optimization (scantlings, arrangements, double hull extension, structural weight, etc.) to minimise the water ingress
- estimating the risk reduction, as residual average local s-factor in any hull section
- calculating the corresponding cost variation

Throughout the project the evaluation of crashworthiness correlated to an increased ship survivability index. This reduced risk of flooding/capsizing/sinking could lead to a standard "design crash test" and could help identify an internal "safe area" assumed to remain largely unaffected in case of long raking damages.

Operational RCOs are effective in minimising frequencies (preventing accidents by speed reduction, situation awareness, e-navigation, DSS for collision avoidance, crew training…) as well as consequences (fast and accurate damage detection and assessment, accurate measure of progressive flooding, emergency response, active/passive mitigation systems) to prevent the loss of the ship. Design RCOs are effective to minimise the consequences: improved structural solutions, crashworthiness, strengthening of hull elements exposed to higher risk. Active and passive RCOs are time-dependent, pre- and post-accident.

5. Other essential studies in progress

A flooding risk model under development focuses on risks related to sinking/capsizing due to collision, contact and grounding. Whereas the model identifies the main factors triggering the consequences (event sequence) from casualty reports it addresses "real" risk (not only historical data) and will measure risk in terms of fatalities (PLL) and environmental pollution. It is envisaged that ongoing work will lead to forming a new basis for a better quantification of the risk and a better basis for the assessment of probabilities of flooding events for passenger ships on the basis of sound numerical models, including near misses.

6. Future IMO Recommendations

It is envisaged that FLARE results will be grouped in three main categories for possible proposals or submissions to IMO, namely:

- Recommendations to change/amend IMO regulations, or recommendations to introduce new regulations, requiring a Formal Safety Assessment (FSA).
- Recommendations proposing alternatives to current regulations, without changing the safety level. In this case FSA is not required, and a submission as INF paper or proposed IMO Circular may be possible.
- Recommendations to amend IMO "explanatory notes" or IMO "unified interpretations".

Along these lines, the following clusters of topics have been identified and are under discussion by the consortium partners:

- The suitable use of damage stability calculation methods - namely non-zonal approach, direct methods instead of statistical approaches, use of improved data (revised permeability and draughts).
- Further development, evaluation and implementation of crashworthiness methods for use in damage stability analysis, following collisions and groundings leading to serious ship flooding.
- A flooding risk assessment framework, with focus on passenger ships.
- The suitable use of RCOs in Decision Support Systems (Emergency response / Emergency assessment / Operational information) and for Monitoring flooding risk in operations

7. Conclusions

Current IMO regulations on ship damage stability are based on a static assessment of damage stability without due consideration on the design flooding risk. In an attempt to address this problem, the EU Horizons 2020 project FLARE introduces a novel risk-based methodology beyond the state-of-the-art for "live" flooding risk assessment and control, with potential application to new and existing ships. The project develops a flooding accident model - based on statistics and first-principles tools - that aims to assess the frequencies of flooding events whilst accounting for pertinent environmental conditions and design parameters including ship crashworthiness. Cost-effective risk control options are under evaluation and possible recommendations and/or amendments to the regulatory framework will be submitted to the IMO.

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