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GOALDS – Goal Based Ship Stability & Safety Standards

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Abstract

The new probabilistic damaged stability regulations for dry cargo and passenger ships (SOLAS 2009), which entered into force on January 1, 2009, represent a major step forward in achieving an improved safety standard through the rationalization and harmonization of damaged stability requirements. There are, however, serious concerns regarding the adopted formulation for the calculation of the survival probability of passenger ships, particularly for ROPAX and large cruise vessels. The present paper outlines the objectives, the methodology of work and intermediate results of the EU-funded FP7 project GOALDS (Goal Based Damaged Stability, 2009-2012), which aims to address the above shortcomings by state-of-the-art scientific methods and by formulating a rational, goal-based regulatory framework, properly accounting for the damage stability properties of passenger ships.

Keywords: Damaged ship stability; probabilistic assessment; goal-based design; risk-based design; passenger ship safety.

Nomenclature

A	Attained subdivision index
CDF	Cumulative distribution function
PDF	Probability density function
LRF	Lloyd's Register Fairplay
POB	People on board
SWD	Semi-watertight doors
TTC	Time to capsize, TTS Time to sink
WoD	Water on deck (flooding of deck)

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1. Introduction and Objectives

In January 2009 the new harmonized probabilistic rules for ship subdivision became mandatory, initiating a new era in rule-making in the maritime industry in line with contemporary developments, understanding and expectations. This was the culmination of more than 50 years of work, one of the longest gestation periods of any safety regulations. Considering that this is indeed a step change in the way safety is being addressed and regulated, "taking our time" is well justified (Papanikolaou, 2007).

One of the great achievements of this effort was thought to be the harmonization of standards for dry cargo and passenger vessels in a probabilistic framework which allows for a rational assessment of safety and design innovation. In this regard, the EU-funded R&D project HARDER (1999-2003) created history at IMO by being the first externally funded research project to support specifically the IMO rule-making process and to contribute massively to the successful development of the new rules.

However, with a number of ship owners opting to follow these new rules in advance, a number of issues have surfaced. These require urgent consideration, as they affect the most safety-critical ships, namely large passenger ships, which are currently one of the fastest growing ship sectors and, what is more important, constitute the core strength of the European shipbuilding industry. Also, great concerns were expressed by EU member states and the European Maritime Safety Agency (EMSA) regarding the abolishment of the Stockholm Agreement provisions for ROPAX ships, when the new SOLAS 2009 entered in to force; in fact, there was strong evidence that SOLAS 2009 does not satisfactorily cover water on deck effects on ROPAX survivability (e.g., HSVA, 2009). These concerns form the kernel of the rationale for the research reported in this paper. Furthermore, one of the top agenda items at IMO, namely Goal-Based Standards, is targeting in the longer term all ship types, with passenger ships being a main target. The implication of this is again the need to sort out the damage stability standard for large passenger ships.

This latter point provided the inspiration for the title of the present research project, namely "Goal-Based Damage Stability" – GOALDS: it aims to contribute to IMO regulatory work in a similar fashion to HARDER supported by a consortium of partners that essentially constitute the same core partnership.

The project addresses the above outlined challenges by undertaking research to improve the current survivability formulation, to integrate collision and grounding damage events, to proceed to a risk-based derivation of a new subdivision requirement and to conduct a series of concept design studies to ensure the practicability of the new formulation. Upon completion, GOALDS will submit key results to IMO for consideration in the rule-making process.

The key objectives of the project are to:

- Develop an enhanced formulation for the survival factor 's' accounting for key design parameters of passenger ships and for the time evolution of flooding scenarios – the formulation of the new survival factor will have to cater for the design differences between cruise and ROPAX ships;
- Develop a new survivability formulation for flooding following grounding accidents;
- Integrate collision and grounding survivability formulations into a single framework;
- Validate the new formulations by experimental and numerical analyses;
- Develop a new damage survivability requirement in a risk-based context;
- Evaluate the practicability of the new formulations by a series of ship concept design studies;
- Submit results for consideration by IMO upon completion.

The project consortium consists of eighteen (18) European organizations[1], representing all major

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[1] National Technical University of Athens-Ship Design Laboratory (coordinator), University of Strathclyde - Ship Stability Research Centre, Germanischer Lloyd, Det Norske Veritas, Safety at Sea, Lloyds Register, Hamburg Ship Model Basin, Vienna Model Basin, Danish Maritime Authority, Maritime and Coastguard Agency, University of Trieste, STX Europe-France, STX Europe-Finland, FINCANTIERI, MEYER Werft, Color Line, Carnival PLC, Royal Cruises Lines, http://www.goalds.org.

stakeholders of the European maritime industry (yards, class societies, operators and flag states), research institutes and universities. Also, an advisory committee has been formed composed of representatives of major public regulatory authorities and CESA, to the extent they are not already active partners in the project. The Advisory Committee is meant to be a sounding body for the consortium as well as a platform for early discussion of project results related to the preparation and consolidation of regulatory proposals to IMO[2] . More detailed objectives and work plan of the project may be found in the public domain area of the project's web site http://www.goalds.org.

2. Overview of Early/Intermediate Results

2.1 Damage statistics for collision and grounding

Some early work of the project has focused on an update of the collision damage statistics compiled in the HARDER project. These statistical data were also subsequently updated by a number of flag state delegations as part of the rule-making process at IMO. The aim of GOALDS is herein to collect and analyse latest damage data, available to the project, and to provide suitable probability distributions for collision damage characteristics pertinent to passenger ships. To this end the GOALDS database builds on the existing HARDER database, with additional data coming from all stakeholders participating in the project, as well as from other publicly available accident databases.

Whereas the earlier damage statistics were limited to collision damages only, in the present project we consider also grounding damages. This work was actually initiated but was never completed within the project HARDER. In this respect, emphasis will now be placed on the grounding damage characteristics of passenger ships, noting that grounding is a very serious hazard for passenger ships' survivability.

The HARDER database includes casualties from 1944 up to the year 2000. To identify the casualties in the last 10 years, the Lloyd's Register Fairplay database (LRF) has been used, whereas the characteristics of these damages were deduced mainly from class societies' records. A total number of 1587 casualties could be recorded in the updated database (349 GOALDS, 1238 HARDER). It was differentiated between collision, grounding and contact damages, as shown in Table 1.

The distribution of the ship types captured in the GOALDS database can be seen in Fig. 1 as a pie chart. The limited number of available damage data for passenger ships has led to the conclusion that all damage data, regardless of ship type and time period, should be considered. This was done likewise in previous relevant analyses (e.g., HARDER project). Some preliminary results of the data analysis are shown in Figs 2 and 3.

Collision:
A-1.1 non-dimensional damage position in longitudinal direction (f(x) = PDF; Nx=Number of casualties)
A-1.2 non-dimensional damage length (f(x) = PDF, F(x) = CDF)
Grounding:
A-1.1 nondimensional damage position in longitudinal direction (f(x) = PDF; Nx=Number of casualties)
A-1.2 nondimensional damage length (f(x) = PDF, **F(x) = CDF)**

The analysis of the updated collision damage data of the GOALDS database did not lead to significant changes in the resulting probabilitic distributions for the collision damages as laid down in SOLAS 2009.

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[2] Association of European Shipbuilders CESA, flag states: Maritime Administrations of Norway, Sweden, Netherlands, Finland, Germany and USA, noting that the Maritime Administrations of Denmark and United Kingdom are already regular members of the consortium.

Table 1: Overview of data sample

	Collision	Grounding	Contact
HARDER	832	312	35
GOALDS	184	160	4
database	**1016**	**472**	**39**

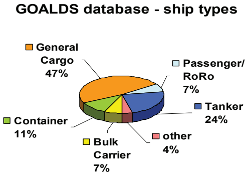

Fig. 1: GOALDS database – ship types

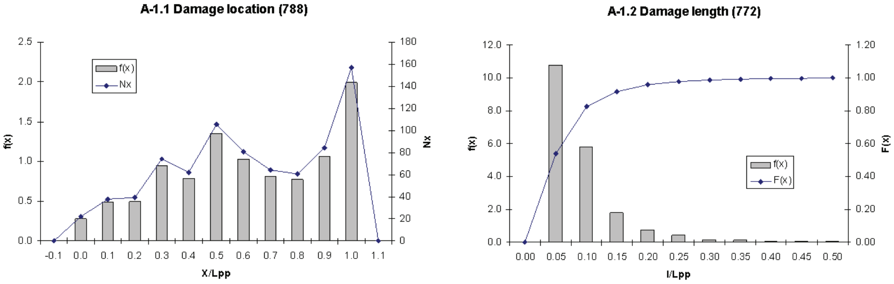

Fig. 2: Damage location and length for collision damages according to GOALDS database

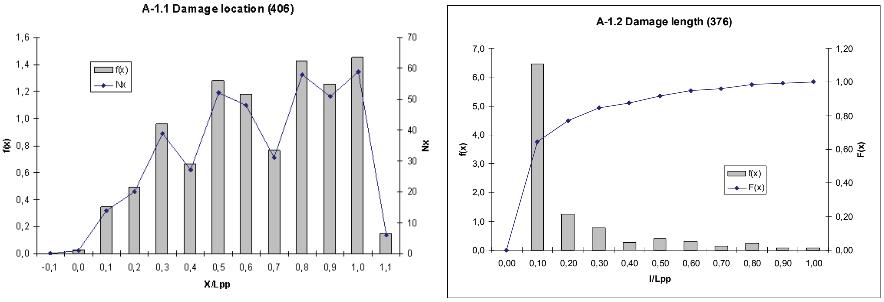

Fig. 3: Damage location and length[3] for grounding damages according to GOALDS database

Therefore, attention was focused on the the new findings related to the grounding damages and their impact on possible reconsideration of SOLAS Reg 9 (min. height of double bottom for passenger ships). Some background information associated with the original development of the requirements in Reg. 9 can be found in SLF47/INF.4, (2004), in which use was made of grounding data collected, but not analysed in detail. Herein, the enhanced GOALDS database was considered and data analysed aiming at:

- The quantification of the probability that bottom damage could penetrate the inner double bottom if constructed according to minimum standard;
- The quantification of the probability that bottom damage dimensions could be larger than those specified by SOLAS Reg.9;

The obtained results were also (approximately) compared with the probability levels which became known in the process of development of Reg.9 (SLF47/INF.4, 2004), and therefore to some extent agreed at IMO.

Table 2 shows the estimated probability of the inner bottom being penetrated as a consequence of a grounding accident, if constructed according to minimum SOLAS standards. In the table, L_z is the vertical

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[3] Regarding the recorded damage length of groundings, special attention was paid to the consideration multiple holes' damages by an equivalent damage length

damage extent (damage penetration), DBH_{S2009} is the minimum double bottom height according to standard requirements (Reg. 9.2) and $DBH_{S2009\text{-}LLH}$ is the increased minimum double bottom height relevant for passenger ships fitted with large lower holds (Reg. 9.9). In both estimations all available data for ships except tankers and fishing vessels have been used, although in principle for the estimation of the probability Pr $\{L_Z > DBH_{S2009\text{-}LLH}\}$ only passenger vessels should have been considered. This approach is however reasonable considering the fact that, in the exploratory data analysis, there was no evidence of significant differences in the distribution of bottom damage penetration between full ships and non-full ships (representative of passenger vessels).

Table 2: Probability of bottom damage penetration exceeding SOLAS minimum double bottom height

Event	Estimated probability with 95% confidence interval	Details of the sample of data
$\Pr\{L_z > DBH_{S2009}\}$	27.3% $[16.1\% \, , \, 41.0\%]$	Samples: 55 Exceeding: 15
$\Pr\{L_z > DBH_{S2009\text{-}LLH}\}$	14.5% $[6.5\% \, , \, 26.7\%]$	Samples: 55 Exceeding: 8

For what concerns the estimation of the probability of exceedance of bottom damage dimensions as specified by SOLAS Reg.9, the analysis considered different events. The probability was estimated that each single damage dimension specified in Reg.9 is exceeded in case of a grounding accident. In addition, the probability was estimated that all damage dimensions specified in Reg.9 could be exceeded as a consequence of a grounding accident. Finally, the probability was estimated that al least one damage dimension resulting from a grounding accident could exceed the values specified by Reg.9. Results from this analysis are reported in Table 3. In the table, L_X is the damage length, L_y is the damage width and L_Z is the damage penetration, while the subscript 'S2009' indicates the same quantities as specified by SOLAS Reg.9.8. It can be seen that the SOLAS dimension with the highest probability of exceedance is the damage length, followed by the damage penetration and finally by the damage width.

Table 3: Exceedance probabilities for bottom damage characteristics as prescribed in SOLAS

Event	Estimated probability with 95% confidence interval	Details of the sample of data
$\Pr\{L_x > L_{x,S2009}\}$	54.6% $[47.6\% \, , \, 61.6\%]$	Samples:205 Exceeding:112
$\Pr\{L_y > L_{y,S2009}\}$	18.2% $[11.5\% \, , \, 26.7\%]$	Samples:110 Exceeding:20
$\Pr\{L_z > L_{z,S2009}\}$	29.1% $[17.6\% \, , \, 42.9\%]$	Samples:55 Exceeding:16
$\Pr\left\{\begin{matrix}(L_x > L_{x,S2009}) \wedge \\ \wedge (L_y > L_{y,S2009}) \wedge \\ \wedge (L_z > L_{z,S2009})\end{matrix}\right\}$	11.1% $[3.7\% \, , \, 24.1\%]$	Samples:45 Exceeding:5

$\Pr\left\{\begin{matrix}\left(L_x > L_{x,\mathrm{S2009}}\right)\vee \\ \vee\left(L_y > L_{y,\mathrm{S2009}}\right)\vee \\ \vee\left(L_z > L_{z,\mathrm{S2009}}\right)\end{matrix}\right\}$	64.4% [48.8% , 78.1%]	Samples:45 Exceeding:29

Probabilities of exceedance of SOLAS bottom damage characteristics have been found to be, overall, quite in line with those estimated at the time of development of Reg. 9. Therefore, the present analyses would not call for immediate and significant revisions of Reg.9, unless different acceptable probabilities of exceedance are set. There are, however, some indications that the present Reg.9 requirements could be more conservative for large ships and less conservative for small ships, and this aspect deserves additional attention.

2.2 Development of the new survival s-factor

Capsize band

The capsize band, or more precisely the capsize transition, is one of the core concepts associated with ship survivability in seaways. It is the band of sea states within which the transition from unlikely to certain capsizes takes place. Capsize (failure) rate within the band follows sigmoid distribution. Obviously, the rate of observed capsizes depends on time of observation and in a limiting case of infinite exposure the capsize rate distribution will become unit-step function. Importantly, as observed during the GOALDS project, the capsize rate function will contract towards its lower boundary. Therefore, taking the capsize rate to be some small number, it can be assumed that the sea-state corresponding to that rate will not change significantly when the time of observation is observed. This has some important practical implications, namely that sea state corresponding to the small capsize rate can be established on a basis of relatively short simulations or experiments and would still remain valid (with some uncertainty) for much longer observations.

Water on deck

The problem of “water-on-deck”, WoD, derives its importance from observed correlation of the amount of accumulated water on deck and survivability of the vessel. The major difficulty encountered in attempting to address the WoD problem is the stochastic and non-ergodic character of the flooding process, which generally makes the analysis very complex and time consuming. In this context properties of the capsize band can be used to reformulate or, rather, address this problem in a more convenient fashion. In other words, the analysis of WoD accumulation can be based not on the cases within the capsize band but just outside its lower boundary, towards which the band contracts.

Such approach has certain advantages – firstly, long but finite observation time around the lower boundary practically guarantees infinite survival time (the lower boundary can be assumed time-invariant, as previously shown). Secondly, analysis of surviving cases allows relaxing the limitation with respect to ergodicity of the process – i.e. flooding, similarly to ship response, can be assumed (for engineering purposes) ergodic. This allowed formulating a procedure for analysing WoD (or floodwater accumulation in the general case) based on an averaged 95th percentile calculated within the cumulative time (i.e. within one wave period and its multiplications).

Although the technique adopted, i.e. time domain simulations and analysis based on a relatively small number of realisations, might be questionable, particularly the inclusion of the transient phase of the time history (non-stationary), it should be noted here that the main purpose was to visualise and qualitatively compare flooding processes without any attempt to draw quantitative conclusions. In spite of certain mathematical shortcomings, however, the analysis produced very important information. Firstly, it has been noticed that the 95th percentile in all the surviving cases reached an asymptote whereas lack of it indicated progressive flooding that would eventually result in a loss. Secondly, although the limiting amount of floodwater would vary with sea state, such variability proved to be statistically insignificant. Furthermore, should in any particular time realisation the floodwater amount (the asymptotic value) exceeded (by some statistically significant amount) the corresponding upper confidence limit, it would be a clear indication of subsequent loss.

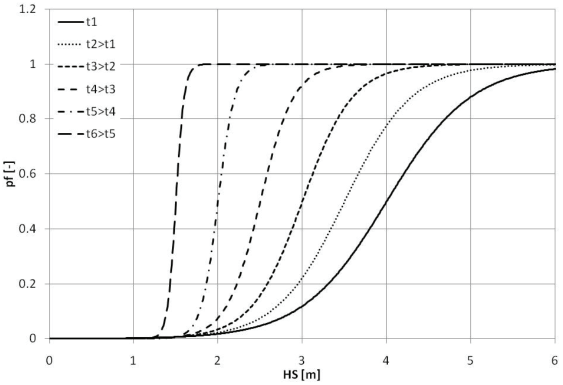

Fig. 4: Contraction of the capsize band with increased time of observation

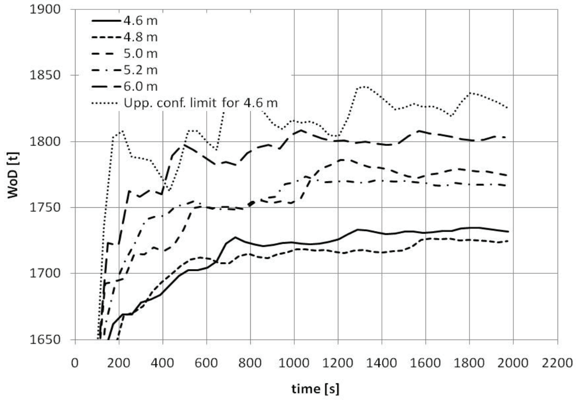

Fig. 5: Examples of accumulation of floodwater (total amount) for small ROPAX

The final outcome of the WoD analysis is that the flooding process of the surviving cases can be characterised by a statistically unique limit for any given damage, independent of sea-state and time of observation. It is important to note that the limiting amount of floodwater coincides with the quantity obtained for the highest sea state at which no losses were observed – lower boundary of the capsize band. Furthermore, as the analysis indicates, increasing the sea state further does not have an impact on the limiting value but increases the probability of exceeding it. This probability is time-dependent – in the extreme case of infinite time observation all realisations in sea states below the lower branch of capsize band would never exceed the limit whereas it can be expected that in sea states within the capsize band, the probability of exceeding the limit would approach unity. This is in essence an equivalent of the unit-step representation of the capsize band. Finally, the analysis has proved that in spite of differences in the underlying physics, both modes of gradual loss (i.e. capsize and sinking) can be successfully approached with the same model. Furthermore, consistency of outcome of WoD investigation with observed properties of the capsize band allowed reformulating the definition of a critical significant sea state. The critical significant wave height, HS_{crit}, is a sea state at which no more than 5% of realisations performed for at least 30 minutes resulted in ship loss.

The s-factor

Deriving from the original HARDER project and the outcome of the EMSA studies [4] EMSA/OP/08/2009, it has been decided in GOALDS to base the s-factor formulation on the concept of critical significant wave height, H_{Scrit}, and construct the probability of surviving collision damages by mapping the H_{Scrit} by IMO distribution of sea states encountered during collision incidents:

$$s_{i,j,k} = \int_{0}^{H_{S\,crit}} dH_S \cdot f_{H_S|coll}(H_S) = \exp\left(-\exp\left(0.16 - 1.2 H_{S\,crit}\right)\right) \qquad (1)$$

where, according to HARDER:

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[4] “Study of the specific damage stability parameters of Ro-Ro passenger vessels according to SOLAS 2009 including water on deck calculation”.

$$H_{S\,crit} = 4\frac{\max(GZ,0.12)}{0.12}\frac{\max(Range,16)}{16} = 4s^4 \tag{2}$$

According to sensitivity analysis (design of experiments, or DOE, technique) it has been found, however, that the parameters present in the formulation are insufficient to capture fully the relations between sea state and the damaged ship properties. Indeed, it has been found that, apart from the GZ_{max} and *Range*, ship size should also be taken into account. Furthermore, an effort was made to replace the statistical norms, i.e. 0.12° and 16° with generic parameters. Finally, the studies have shown that the following formula can be used to estimate the H_{Scrit} with satisfactory accuracy:

$$H_{S\,crit} = \frac{A_{GZ}}{\frac{1}{2}GM_f \cdot Range} V_R^{1/3} \tag{3}$$

where:

A_{GZ} - area under residual GZ curve up to the flooding angle [rad·m]
GM_f - metacentric height of the flooded ship [m]
V_R - residual volume (volume of the subdivided spaces not opened to sea) [m^3]
Range - range of positive stability up to the flooding angle [rad].

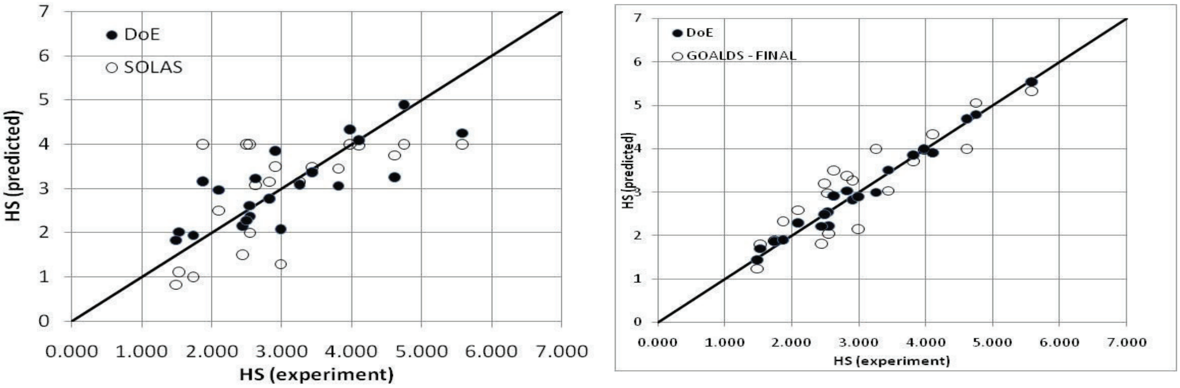

Fig. 6: Comparison of GOALDS prediction of H_{Scrit} and a regression based on response surface (DoE) with use of initial and final set of parameters. DoE fails to significantly increase correlation with experimental data in case of initial (SOLAS) parameters set; however, applying to the final formula parameters results in 99% correlation.

Although the formula may look quite complex, it can be seen that it has very simple interpretation. Specifically, using triangular approximation of the GZ curve, it is:

$$\begin{aligned} H_{S\,crit} &= \frac{A_{GZ}}{\frac{1}{2}GM_f \cdot Range} V_R^{1/3} = \frac{\frac{1}{2}GZ_{\max}\cdot Range}{\frac{1}{2}GM_f \cdot Range} V_R^{1/3} = \\ &= \frac{GZ_{\max}}{GM_f} V_R^{1/3} = \frac{\varphi_{GZ\max} - \varphi_0}{1} V_R^{1/3} = \varphi'_{GZ\max} V_R^{1/3} \end{aligned} \tag{4}$$

It means that the stability-related factor can be approximated by the ratio of the heel angle at the maximum GZ measured from the angle of static equilibrium to an angle of 1 rad, φ'_{GZmax}.

2.3 Experimental studies on survivability

One of the main objectives of the project is to provide an additional body of experimental data on passenger vessels in relation to the process of ship stability deterioration after typical hull breach from collision and grounding accidents. An exact match between the numerical results and experimental results on a run-by-run basis is neither desirable nor sought for, due to the probabilistic nature of the flooding phenomena. However, the accumulation of a substantial body of experiential and experimental data is essential in increasing the confidence in the methods and algorithms used to estimate the damage stability characteristics of vessels. The information sought for through the experimental studies includes the relationship between specific set of damage and environmental conditions and the probability of the limit state condition evolving and the time taken for the limit state to be reached. Experiments were designed and conducted so that the results could be used broadly for the verification of related numerical predictions of the survival factor (s-factor), as outlined in the previous section.

The experiments were undertaken for two representative large ROPAX and two cruise liner ships. Vienna Model Basin built and carried out experiments for cruise vessels and HSVA (Hamburg) was in charge of the ROPAX vessels. The main data of the sample vessels selected for the physical experiments are given in Table 4.

Table 4: Main data of GOALDS test ships

Ship	**Ropax (R1)**	**Ropax (R2)**	**Cruise ship (C1)**	**Cruise ship (C2)**
Number of passengers	1400	622	3840	2500
LOA	194.3 m	97.9 m	311.123 m	294.81 m
LBP	176.0 m	89.0 m	274.73 m	260.6 m
Breadth moulded	25.0 m	16.4 m	38.6 m	32.2 m
Deepest subdivision loadline	6.55 m	4.0 m	8.6 m	8.0 m
Depth to bulkhead deck	9.1 m	6.3 m	11.7 m	10.6 m
Displacement	16,558 tn	3,445 tn	62,459 tn	45,025 tn
Service speed	27.5 kn	19.5 kn	22.6 kn	22.0 kn

All sample vessels are ships designed in compliance with the deterministic SOLAS ’90 damage stability regulations. The decision to use SOLAS 90 ships as a basis for the development of the GOALDS damage stability standard was made so that a common baseline could be formed with comparable numerical and experimental data obtained in the HARDER project. Note that the harmonized probabilistic SOLAS 2009 was also developed on an equivalent basis with SOLAS 90.

Damage selection

The selection of the damage location and extent for the model experiments was more or less straightforward for the collision damages, in view of past experience with respect to the identification of the worst damages. However, it was less clear-cut with grounding damages for which less experience exists. Thus, the location of the grounding damages for the selected sample ships was specified on the basis of the statistical data collected by the project. For the critical grounding, it was assumed that 4 compartments of the double bottom were flooded, with the additional penetration of the centre watertight bulkhead above the inner bottom to allow up-flooding into the two central compartments (Fig. 7).

The critical location of the collision damage was derived based on the idea of the worst SOLAS damage (2-compartment damage up to B/5, within ±35%L from midship) with respect to the minimum area under the residual positive GZ curve, combined with the results of numerical time-domain simulations of the same damages. The impact of the damages at various locations assessed by applying SOLAS 90 provisions and numerical simulations was ranked in terms of their severity. The rankings from both methods were summed and the case with the lowest sum (or the highest ranking) was regarded as the most severe case and was chosen for testing. It should be noted that, for cruise vessels which were expected to exhibit very high survivability, a *3-compartment damage* of outer shell was used in order to

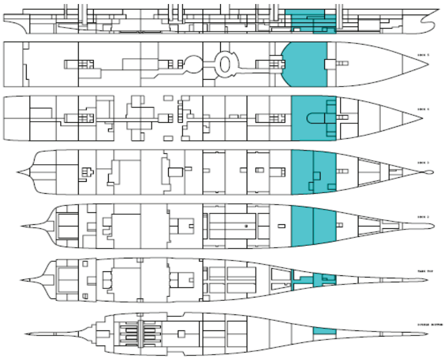

Fig. 7: Example grounding damage used (C2)

approach the survivability boundary. In general it was agreed that for verification purposes suitable statistical damages beyond SOLAS 90 standard (i.e. increased penetration) be included in the tests, to ensure that the formulation of the s-factor realistically captures the physics of related damages.

Summary of tests

Typical test matrix included testing of one collision and one grounding damage for each ship at a given displacement, initially with maximum KG values (SOLAS 90), but subsequently with higher KG values in an attempt to capture the survivability boundary, especially with the cruise vessels. Various significant wave heights of up to 4.0m were tested in most cases except when wave heights in excess of 5.0m were used in an attempt to ascertain the survivability limit.

The normal procedure of ‘equilibrium mode’ tests was followed in most cases, by allowing the damaged model to complete the flooding process in calm sea without any motions before waves were generated. In some cases, however, ‘transient mode’ tests were also used to discover the effects of transient flooding in spectral seas. The standard test time of 30 minutes full scale was used as a rule, except when some tests were conducted for up to 60 minutes in a few cases to investigate the effects of longer test time.

Overview of main results

The rate of capsize was obtained as shown in Figs 8 – 10. The survivability of the vessel C1 was found to be so high that it was not possible to establish a meaningful rate of capsize for this ship. Nevertheless, the sigmoid distribution of the capsize bands for the other tested ships is apparent.

Both cruise ships showed very good survival capability even for very high KG, well beyond the maximum KG allowed by SOLAS 90. Therefore, it was necessary to leave the semi-watertight doors (SWDs) open in order to make them capsize. The time to capsize is given in Figs 10 – 11.

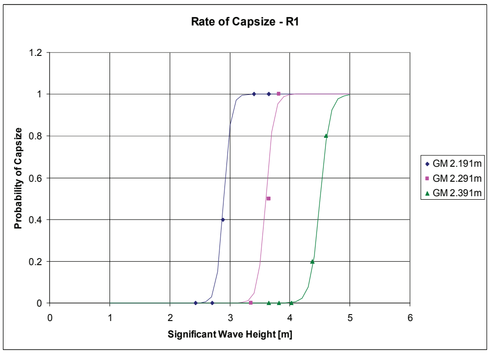

Fig. 8 Capsize rate of R1

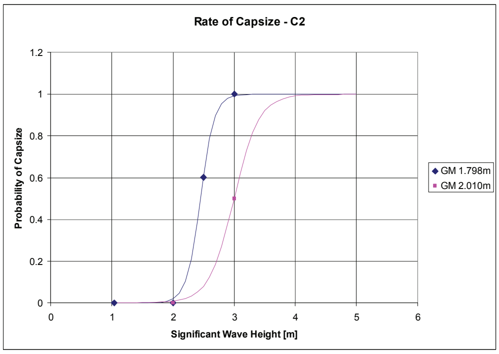

Fig. 9 Capsize rate of C2

Through this experimental study, the following observations have been made:

(a) Time to capsize has shown a very wide distribution for all models suffering collision damage.
(b) The most important parameter which determines the survivability of a damaged vessel is the intact stability characteristics, the most obvious of which is GM.
(c) In order to obtain experimental data of statistical significance many more tests have to be run for the same models.
(d) Tests carried out in 'transient mode' for sample ships C1 and C2 show that a large passenger vessel can experience excessive heel or roll motion in the intermediate stages of flooding soon after the breach of the hull. This aspect will require further investigative attention in the future.
(e) The importance of keeping semi-watertight doors closed even in harbour has been clearly demonstrated, as the large cruise ship models which did not capsize in most onerous conditions readily succumbed when the SWDs were left open. Both cruise models showed very good damage survivability, when the SWDs were kept closed.
(f) All four ships have exhibited very good survivability when grounding damage is inflicted, and no capsize occurred even in the transient mode tests.

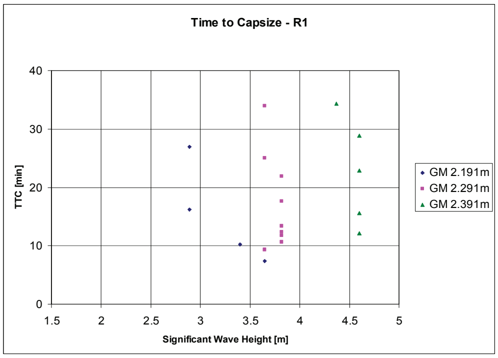

Fig. 10 Time to capsize for R1

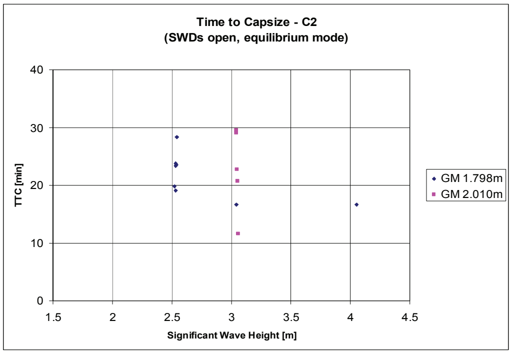

Fig. 11 Time to capsize for C2

2.4 Risk-based damage stability requirement

Statistical basis

In the GOALDS project the risk associated with collision and grounding events has been considered by collecting and statistically analyzing accident data. Accident data was deduced from IHS Fairplay Casualty database, LMIU and GISIS and only those collisions and groundings that were considered as 'serious' were included in the study. The initial collision and grounding frequencies for the period 1.01.1994 – 31.12.2010 were calculated for cruise/passenger ships and ROPAX/ROPAX-rail vessels using World Fleet Statistics. The following parameters were taken into account:

- GT ≥ 1000 – most ships below GT1000 operate on non-international voyages;
- length ≥ 80 m – most ships below 80m in length operate in non-international voyages;
- Built ≥ 1982;
- IACS class at time of accident – to reduce the potential effect of under-reporting;
- IACS class for determination of ship years;
- Froude No. ≤ 0.5 – to eliminate high-speed craft from the study.

Risk models – high level

The risk models of GOALDS are presented in the form of event trees covering grounding and collision accidents. The high level event trees are shown in Fig.12 and Fig 13, respectively.

Some important findings

The investigation into the statistics has resulted in updated frequencies for grounding and collision. The difference in initial frequencies between GOALDS and the SAFEDOR FSA studies are shown in Table 5. These variations may be explained by the different assumptions on the fleet at risk as well as the effect of utilizing the more recent data.

An interesting result has been obtained with respect to where the collisions take place. As can been seen in Fig. 14, when considering both ROPAX and cruise ships, the majority of collision takes place in terminal areas.

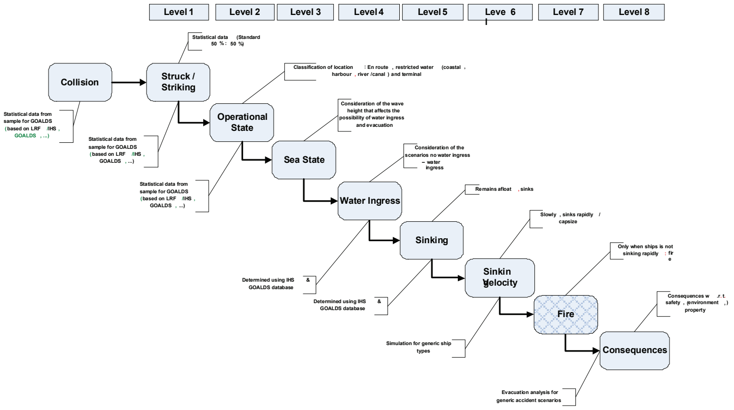

Fig. 12: High level event sequence for accident category collision GOALDS

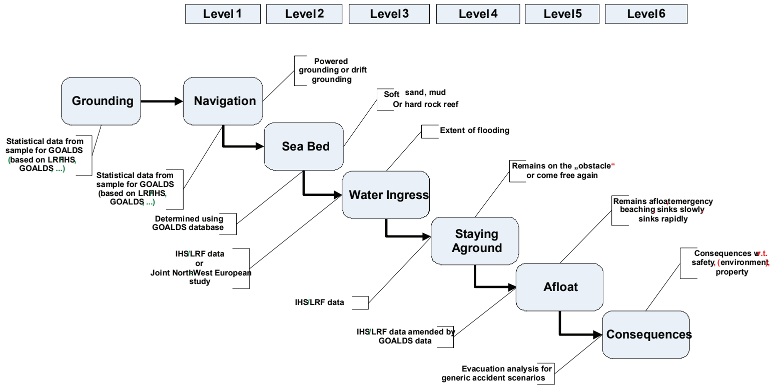

Fig. 13: High level event sequence for accident category grounding GOALDS

Table 5: Frequencies collision and grounding

	GOALDS		SAFEDOR	
	RoPax	Cruise	Ropax	Cruise
Collision	7.78E-3	6.99E-3	1.25E-2	4.6E-3
Grounding	4.88E-3	1.07E-2	2.11E-3*/3.73E-3**	9.8E-3

* Ships < 4000 GT ** Ships>4000 GT

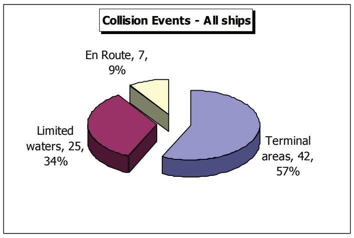

Fig. 14: Collision events

Sinking/capsizing

The probability for capsize or sinking is reflected through the attained index A, i.e. the probability for non-survival is equal to 1-A. As a part of the GOALDS project the factor s representing the probability has been developed and is currently subject to validation. The attained index A covering collision is calculated by the same method as in the current SOLAS:

$$A=\sum p * v * s \quad (5)$$

where the factors p and v represent the probability for damage extents and penetration. The conclusion from the analyses of the collision statistics updated in GOALDS is to keep these factors unchanged from the current SOLAS.

Potential loss of life

Initially, the basic assumption applied in the risk model was that if, following a collision or grounding damage, the ship sinks all lives of people onboard (POB) are lost. This is of cause an extreme scenario. In earlier related studies it has been assumed that any collision or grounding accident may lead to a certain number of fatalities and in case of sinking/capsize the fatality rates depend on how fast the ship sinks or capsizes. Even for known ship disasters in extreme conditions, e.g. the loss of ferry Estonia, the fatality rate was not 100 %. However, using again the Estonia accident as an example, it is noted that the survival of several POB was not the result of orderly evacuation. Therefore, the risk model should reflect the reality as close as possible and the assumptions on consequences in the risk model are subject to further validation and benchmarking before a final decision is made.

Comparison with results previously published and accident statistics

As already mentioned, there are, not unexpectedly, deviations in frequencies and probabilities used in the GOALDS model compared with the previously published results. When the results of applying the risk model to the sample ships are available, a comparison with causality data will be carried out. It is worth mentioning that present historical data do not include rare catastrophic events that may happen in the future. However, the developed risk model must also consider such likely events and, therefore, relevant provisions must be taken in the risk model development.

Handling of uncertainties

In the risk model each branch with its probability contains elements of uncertainty. The uncertainty depends on the sample size and the number of casualty reports. In some cases it is possible to quantify the uncertainty and calculate the low/high limits, for instance the 95% percentile. One example is the probability for the passenger ship to be the struck or the striking ship in the event of a collision. From the statistic we find the following probability for struck/striking for cruise: 38%/62%, while for ROPAX it is 69%/31 %. When following the above mentioned approach, the upper and lower limits for the 90% confidence interval are calculated to 4.5E-03 and 1.02E-02 for Cruise ships. Assuming that the distribution for this dependent probability can be approximated by a log-normal distribution and, when this is included in the risk model and treated by Monte Carlo simulations, the number of potential loss of lives (PLL) can be given as the mean value within the confidence limits.

New damage stability requirements based on cost/benefit assessment

The risks are quantified as Potential Loss of Lives (PLL) and Potential Loss of Ship (PLS). In the GOALDS project there are 5 sample ships available: large cruise ship, medium-sized cruise ship, large ROPAX, medium-sized ROPAX and small ROPAX. For each sample ship Risk Control Options (RCO), which are limited to design modifications that would improve the survivability, expressed as the attained index A, are proposed and checked by calculations. Possible design modification can be increase of breadth, increased freeboard, increased level of subdivision, etc. By using the generic risk model the improvement is quantified as a reduction in the PLL and PLS. The design modification can imply both costs and benefits.

In order to assess whether a design modification is cost-beneficial the methods and recommendations of the IMO SFA Guidelines are used, namely the GrossCAF and the NetCAF. At the final stage of this part of the project a number of sample ships and for each sample ship the result of the various design modifications (RCOS) will become available. The intention is to use these results as the basis for proposing the level of the required index R. This level should make risk as low as reasonably practical (ALARP). As the major contribution to risk is expressed as potential loss of lives (PLL), it is assumed that the level of the required index R should be a function of number of persons onboard only. Therefore, the basis for the proposed level R will be the sample ship modifications where the GrossCAF and NetCAF is less than the IMO criteria.

2.5 Innovative ship concept designs based on the new damage stability requirement

In order to investigate the impact of the new formulation for the probabilistic damage stability evaluation of passenger ships on the design and operational properties of characteristic ROPAX and cruise vessels, it is planned to produce conceptual designs and optimise innovative vessel layouts, meeting the new damage stability standard, whilst considering building cost and efficiency in operation.

An existing integrated design optimisation procedure (Zaraphonitis et al., 2003) of NTUA, encompassing the parametric design and optimization of ROPAX vessels, will be extended to account for cruise ship design layouts and adapted to the new damage stability standard. Industrial participants will be providing expertise and empirical data, as and when necessary, for the implementation of the developed procedure.

The resulting design concepts will be further elaborated to the preliminary stage by the participating shipyards, namely Fincantieri, Meyer Werft, STX Finland and STX France.

3. Summary and Expected Outcome

This paper presented the objectives and reviewed early and intermediate results of the EU-funded, FP7 project GOALDS. The main expected outcome of GOALDS is its contribution to enhanced safety of the maritime passenger transport and the facilitation of the application of rational, risk-based procedures to the design of ROPAX and cruise ships, a clear domain of the European shipbuilding industry. This will be achieved by delivering a rational, fully validated, robust and consistent method for assessing the safety of passenger ships in case of a collision or grounding.

In this way, the project aims at further developing and complementing past work of the successful HARDER project, which contributed decisively to the development and the adoption of the new harmonized damage stability regulations pertaining to all types of dry cargo and passenger ships. The outcome of this project is being sought not only by the European maritime community, but the entire international maritime community. In recent years it has been working on further improvement of passenger ship safety, especially in view of ultra large cruise ship designs and operations becoming a reality.

The results are mainly targeted to assist regulators in their work with new and improved regulations for passenger ships covered by SOLAS, with an expected time for exploitation of maximum three years. The main product of GOALDS, a rational probabilistic approach to assessing collision and grounding of passenger ships and the rational criteria derived from it as well as the consequence analysis tools, may of course be exploited by the maritime community on a worldwide basis. However, the detailed knowledge and understanding of the method remains within Europe, and will thus provide the European maritime community with a significant technological edge. This is especially valid for the shipbuilding industry, which will gain significant knowledge on how to apply the new approach on design of passenger ships following an improved probabilistic concept, better accounting for the special design features of ROPAX and cruise ships.

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