Damage Stability Making Sense

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ABSTRACT

Although aviation, nuclear, processing, etc. industries have long ago adopted and established preventative frameworks and procedures to safeguard against unwanted outcomes of daily operations, maritime industry still places the emphasis on the mitigation of consequences following an accident. Despite the widely expressed opinion that prevention is the way forward, curing occupies a central position not only in every day practice but in the underlying regulatory framework as well. Contrary to this approach, the work presented here aims to create the necessary momentum towards rationalisation of the fundamental choices made during the design process, thus attracting attention to areas where prevention strategies can find fertile ground and be fruitful and cost-effective. The methodology addresses the occurrence of a collision event and the crashworthiness capacity of a ship as prerequisites for its survivability assessment, with promising results to encourage further development.

KEYWORDS

Accident prevention; Collision; Crashworthiness

INTRODUCTORY INFORMATION FOR AUTHORS

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George Mermiris has graduated with MEng (2003) and PhD (2010) from the Department of Naval Architecture and Marine Engineering, University of Strathclyde. Currently he is a Research Fellow in the Ship Stability Research Centre (SSRC). The core of his work is on Risk-Based Design methodology and implementation with main emphasis on structural analysis and collision dynamics, advanced mathematical modelling and risk analysis. He has authored 10 journal and conference papers in this area.

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Dracos Vassalos is Professor of Maritime Safety in the Department of Naval Architecture and Marine Engineering of the University of Strathclyde and the Director of the Ship Stability Research Centre (SSRC), a world-leading centre of excellence on ship stability and safety. His motto is “safety enhancement through innovation”, an idea he has pursued single-mindedly in a career that spans over 30 years in industry and academia, promoting the use of scientific approaches in dealing with maritime safety. He has been instrumental in helping to create a critical mass in the research community on safety, through a series of initiatives that made SSRC the focus of active international collaboration. He travels the world over promoting maritime safety, lectures and publishes widely, with some 400 technical publications, 4 patents and 7 books/Conference proceedings to his credit and a string of prizes and awards, including some 100+ major research contracts amounting to over £20M. He served as Head of Department (1997-2007), Chair of the STAB Conferences and Workshops (1996-2006), Chair of the ITTC Stability Committee in Waves (1996-2002), Chair of WEGEMT (the European Association of Universities in Marine Technology 1999-2001). Currently, Professor Vassalos is Chairman of the International Standing Committee of the "Design for Safety" Conference, a theme instigated and promulgated by SSRC. He is also a long-standing member of the UK delegation to IMO for ship stability and safety.

INTRODUCTION

Traditionally, the damage stability and survivability performance of a ship are treated under the assumption that the hull is breached following a collision event. This approach has received considerable attention and significant effort has been spent in collating the required information for dimensioning the damage opening (SOLAS Ch.II-1).

Even though the probability of pertinent events that can compromise the watertightness of the hull, like collision and grounding, are consistently accounted for in quantitative risk analyses, the compulsory use of the Attained Index of subdivision, Eq. (1), discourages any focus on the associated causal factors and, in the particular case of collisions, on crashworthiness. As a result, accidents still happen, much more frequently than they should, and ships are lost with significant price for human life and the environment.

One key reason for this state of affairs relates to the fact that rule making in our industry focuses on damage limitation (cure) rather than damage prevention. Hence, the industry is pursuing happily a very ineffective means of sorting bad image and reputation. This being the case, the time for diverting attention towards an approach that makes sense of damage stability is long overdue but, fortuitously, ripe. More specifically, the emergence of the design for safety philosophy and the development of risk-based design methodology allows due attention on the risk pertinent to each vessel category in a scientific and all-embracing way, capable of balancing risk reduction and mitigation with other design objectives cost-effectively.

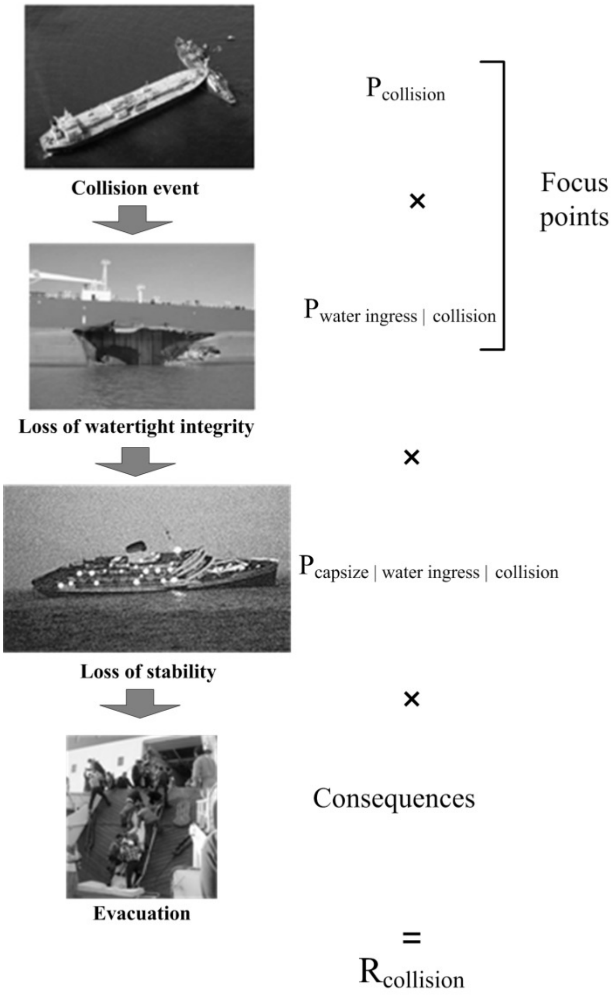

Fig. 1: Sequence of events in flooding scenario with the corresponding probability elements for the collision risk assessment.

The work presented here demonstrates that in order to integrate safety against collision in the design process, it is necessary to rationalise the survivability assessment as it is presented by Vassalos, (2004). This can be achieved by addressing the probability of collision occurrence, the probability of water ingress due to collision, the probability of capsize due to the ensuing water ingress and the consequential loss (Figure 1). Such an integrated approach has been the focus in SSRC over the past 5 years, reaching the stage where potential benefits from trying to make sense of damage stability are demonstrable. This offers new inroads for the integration of safety against collision in the design process by drawing information from and feeding knowledge to the ship operation in an unprecedented way.

THE REGULATORY FRAMEWORK

The assessment of the risk level following a ship collision event is presently performed according to Wendel's, (1960), probabilistic approach, which is practically implemented with the Attained Index of subdivision A, (IMO, 2009):

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j p_i s_{ij} \tag{1}$$

Where

j: the counter for loading conditions;

i: the counter for damaged compartments or groups of adjacent compartments;

J: the number of loading conditions;

I: the number of damaged cases (single of groups of adjacent compartments) for each loading condition;

w_j: probability mass function of the loading conditions;

p_i: probability mass function of flooding extent of a compartment or group of compartments for loading condition j ($\sum_i P_i = 1$);

s_{ij}: the average probability of surviving the flooding of a compartment (or group of compartments), for loading condition j.

Index A is the weighted average of the probability of survival, i.e. its expected value E(s), of all damage cases for a ship. As long as the value of A is greater than a prescribed threshold value (index R), the safety level of the ship is considered satisfactory, at least from a regulatory point of view.

A critique on the current approach

The philosophy of this regulation is attractive (due to its scientific foundation on probability theory) and special (as few precedent frameworks, if any, have ever adopted a similar approach). However, the framework is based on statistical analysis of past accidents and unavoidably builds on the fact that a collision has occurred and the watertightness is lost (otherwise the accident would not be considered). Instead of using statistical information for rationalising the choices of the damage scenarios and benchmarking the results of structural analyses, the regulation puts emphasis on the identification of all damage cases that would compromise survivability. That is, irrespective of how improbable 5-compartment damage would be, this scenario will still be considered in the assessment. Hence, the process changes into a vulnerability analysis.

A closer look at the provisions of the framework will reveal determinism and inconsistency, as it is explained next:

(i) The calculation of the probability of flooding is conditional on the collision occurrence, i.e. the probability of collision $P_{collision} = 1.0$. However, modern communication and IT developments in combination with improved training of the navigation officers contribute significantly towards the traffic management even in the most congested waters.

(ii) The probability of flooding is also conditional on the probability of water ingress due to collision, i.e. the ship shell is breached and the penetration is of sufficient size to cause large scale flooding of one or more compartments instantly. Therefore, $P_{water\ ingress\ |\ collision} = 1.0$. Yet, a collision occurrence does not mean that the watertightness of the hull is lost. Statistical data and computer simulations clearly indicate that the overall damage can range between denting and breaching of the side shell, with large variation of the damage opening (Figure 2). In any case, instant flooding is expected to be very remote.

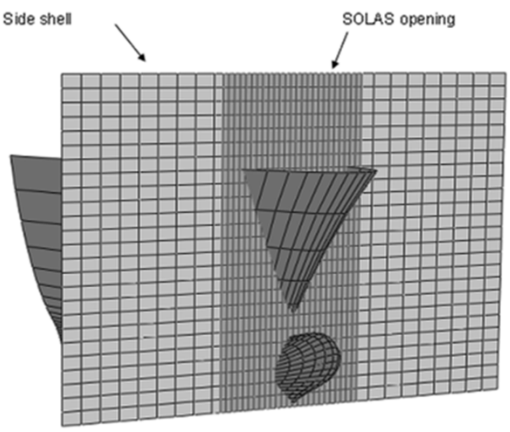

Fig. 2: Actual damage as opposed to SOLAS opening.

(iii) The calculation of the p-factor is solely based on the location of transverse and longitudinal bulkheads. At the same time, the crashworthiness of the side panel of each compartment, i.e. its capacity to absorb impact energy, (Vredeveldt, 2005), is ignored.

(iv) In the process of the above calculations, the operational profile of the struck ship should be taken into consideration for the following reasons: (i) in the case of $P_{collision}$, information on the traffic density and the geographical restrictions will indicate the level of congestion in a seaway, whereas (ii) in the case of $P_{water\ ingress\ |\ collision}$ it will offer an estimation of the available kinetic energy and bow geometries (as it will be explained in the next section) that can compromise the side shell. This way, a ship, which operates in coastal waters and in open sea, will experience different collision risk levels but because the operational profile is not accounted for in the regulation, the p-factor will remain the same.

As a result, the level of assumptions in the calculation of the p-factor renders the value of A questionable. More importantly though, index R is derived on the basis of a sufficient number of A-values of ships that have survived the elements over their life-cycle and represents an acceptable level of safety standard, (HARDER, 2003). But if R is based on values of A, the value of which is fraught with uncertainty, then R is also uncertain and the level of safety it represents is questionable.

THE PROPOSED MODEL

Conventionally, the environment (in terms of wind, waves, etc.) in which a ship operates largely defines its design characteristics with respect to hydrodynamic and structural performance. In addition to the imposed loading on the hull girder, the operational environment also provides information concerning the accidental loading on the ship (congestion levels, speed and direction of the surrounding traffic, etc.), which until recently was of secondary or no importance during design. With this information readily available, the calculation of the p-factor can be rationalised as it is briefly described in the following two sections and in more detail in (Mermiris, 2010).

Probability of collision

The assessment of the probability of collision is based on the concept of *ship domain*, as it was introduced in the late 70’s, (Goodwin, 1979), and treated in various contexts and studies, (Hansen et al., 2004), (Filipowicz, 2004), etc. It was initially defined as a circular area surrounding a ship and if an object entered this area then a collision was assumed.

In the proposed model, the shape of the domain is retained but its diameter varies as a function of operational and design parameters. When the domain diameter becomes equal to or less than the ship length then a collision occurs.

The elements of the model that define the ship domain are:

1. The ship length (L) is indicative of the size of the vessel in a seaway and it is inversely proportional to the diameter of the domain.
2. The response time (R) is the necessary time for the vessel to advance at 90 degrees and it defines how fast the ship will respond to a command for an evasive

manoeuvre (ignoring any depth effects). R is reciprocal to the size of the domain as well.

3. The speed of the vessel (V) is important from an operational point of view. Its value reflects the conditions (traffic density, visibility, time schedule, etc.) under which the vessel steams and its variation depends on the geography of the navigational area.
4. The traffic density (ρ), i.e. the number of ships per unit area, in a seaway can impose further restrictions to the speed range. Evidently, speed and traffic density are inversely proportional to the domain size as well.
5. The transverse channel width (C) defines the topological boundaries of the course of the ship in a waterway. It varies proportionally to the domain size and, according to Kriastiansen, (2005), it is related to the traffic density:

$$\rho = \frac{N}{V'C} \qquad (2)$$

Where N is the number of ship passages per unit time (e.g. annually), and V′ is the speed of the surrounding traffic.

6. Over the years, authors like (Fujii et al., 1974) and accident investigators, e.g. (MAIB, 2005), have stressed that collision accidents (i) never occur instantaneously and without the right initial conditions (low visibility, early morning hours, etc.), and (ii) can be attributed to miscalculations, over-confidence, lack of communication, etc. When everything is orchestrated properly, then there is always a critical *point of no return*, which is measured consistently in the range of a few minutes, (Cahill, 2002)!

The fact that ship collisions always occur for a very specific set of initial conditions suggests that existing methodologies are fragmented (attributing the accident to human factors and adverse weather conditions or bad maintenance of hardware) and inadequate (the irreversibility of the situation is ignored).

In the proposed methodology the “softer” aspects of an accident are accounted for as disorder or uncertainty, i.e. in the form of entropy of a situation (H), (Williams, 1997), which is expressed as:

$$H=\sum_{j=1}^{M}\sum_{i=1}^{N_j} P_{ij}\log_2\left(\frac{1}{P_{ij}}\right) \qquad (3)$$

Where:

i: counter for the number of states of each event,
j: counter for the number of events,
M: number of events,
N_j: number of states of event j,
P_{ij}: probability of occurrence of the state i and the event j, where $\sum_i P_i = 1$.

As the value of entropy increases, the more imminent a collision is. Examples of high and low entropy values are presented in Table 1.

Table 1: Examples of high and low entropy situations

High entropy	Low entropy	Remarks
Disorder, disorganisation, thorough mix-up	Order, high degree of organisation	Existence of a Vessel Traffic System (VTS) in the area of navigation
Great uncertainty	Near certainty, high reliability	Information about wind gusts, when close quarter manoeuvring is required.
Great surprise	Little or no surprise	The familiarity of the navigator with the area of operation and the dominant conditions

Establishment of threshold values for entropy is an ongoing development but this concept allows a broad range of critical information to be consolidated into a single number with widely accepted meaning.

In summary, the domain diameter is expressed as:

$$D = \frac{C}{V\,L\,R\,\rho}10^{-H} = \frac{V'\,C^2}{V\,L\,R\,N}10^{-H} \qquad (4)$$

The probability of collision per unit time can be obtained with Monte Carlo sampling of the entailed parameters.

With Eq. (4) the point of no return is substantiated (due to its non-linear character) since the contribution to the entropy level of each of the participating events can be determined at successive instances and the escalation of a situation can be quantified, thus providing better decision support to the navigator, the port authorities, etc. An example of this is the comparison between navigation in open and closed waters for a ROPAX ship (Figure 3). In the former case a collision event is guaranteed for values of entropy approximately equal to 4.0, whereas in the latter case the entropy levels will have to be doubled. The fact that space availability allows longer decision-making times is reflected in the proposed model and justifies the choice of entropy as an aggregate measure for quantitative and qualitative information.

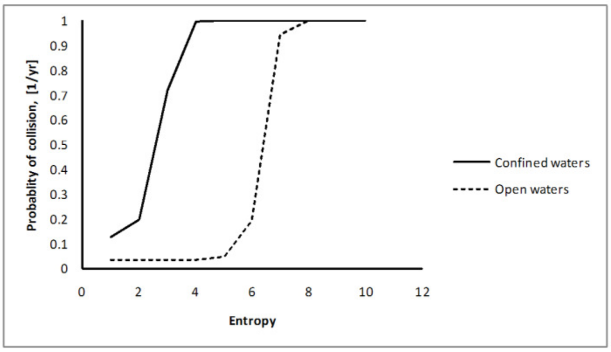

Fig. 3: Entropy variation for open, (Pedersen and Zhang, 1999), and confined waters, (Øresund, 2006).

It should be stressed that Eq. (4) is applicable when the ship is in sailing mode and when collision with other ships is considered; otherwise the element of speed of surrounding traffic (V′) becomes meaningless.

Probability of water ingress due to collision

The extent of the structural damage following a collision event is tightly connected to the crashworthiness of the side shell panels as it was stressed earlier. Although the highly non-linear failure of the structure intuitively calls for sophisticated analysis with the Finite Elements (FE) technique, the very nature of FE is prohibitive for early design application (where most of the main characteristics of a ship are decided) due to long modelling, processing and post-processing times, and because such results cannot be communicated easily to the rest of the design tools. This being the case, the designers can either consider a small number of selected damages (i.e. check the vulnerability of the hull) or ignore such input and resort to using damage openings as prescribed in SOLAS.

The proposed approach is founded on the absorption of the kinetic energy of the striking ship by a restricted portion of the structure of the struck ship. The phenomenon is governed by (i) the magnitude of the kinetic energy, (ii) the structural configuration of the struck panel, and (iii) the geometry of the striking bow (assumed rigid here). The first two aspects can be derived from the operational profile of the ship in terms of the surrounding traffic (i.e. the size and the speed of other vessels), and its structural configuration respectively. The latter complements the expectation of breach occurrence considering that the sharper the contact edge of the striking body is, the easier the panels of the side shell will rupture (i.e. with less expenditure of kinetic energy), as it is confirmed by numerical simulations and experiments.

The remaining factors, which affect the development of a collision event are related to the angle between the two ships (as the angle increases the sharpness of the striking bow is reduced), their inertia, i.e. their virtual (real plus added) mass before (striking ship) and after the contact (struck ship), and the friction during the penetration.

The link of the side structure deformation and the striking body geometry is the *principal radii of curvature* of the latter, which provides a measure of its sharpness at the contact points.

The radii of curvature of a three-dimensional surface can be obtained by its parametric definition:

$$x = x\,(\mathrm{p,t,w_0}),\ \ y = y\,(\mathrm{p,t,w_0}),\ \ z = z\,(\mathrm{p,t,w_0}) \qquad \mathrm{p,t} \in [0,1] \tag{5}$$

Where x, y and z are real, continuous and at least twice differentiable functions (with respect to either of the two parameters) in a right-handed coordinate system and w_0 is the indentation of the panel since in the current context interest lies in the necessary deformation to cause rupture. The geometry of the striking body is represented with a Bezier surface, whereas the struck surface deformation is modelled with the *Witch of Agnesi* function, which allows for explicit consideration of the deflection w_0 as a function of radii of curvature of the striking body:

$$\mathrm{u(x,y,w_0)} = \mathrm{C_x}\frac{\mathrm{w_0}}{\left(1+\left(\frac{\mathrm{x}}{\mathrm{r_1}}\right)^2\right)},$$

$$\mathrm{v(x,y,w_0)} = \mathrm{C_y}\frac{\mathrm{w_0}}{\left(1+\left(\frac{\mathrm{y}}{\mathrm{r_2}}\right)^2\right)} \tag{6}$$

$$\mathrm{w(x,y,w_0)} = \mathrm{C_{xy}}\frac{\mathrm{w_0}}{\left(1+\left(\frac{\mathrm{x}}{\mathrm{r_1}}\right)^2+\left(\frac{\mathrm{y}}{\mathrm{r_2}}\right)^2\right)}$$

Where:

- u, v and w are the deformation functions along x (longitudinal), y and z (vertical to its plane) directions of the stiffened panel.
- C_x, C_y and C_{xy} are constants accounting for the stiffening along the x, y and the x-y directions, respectively.
- r_1 and r_2 are the radii of curvature of the striking bow at the point of contact.

Because of the substantial deformations experienced by the stiffened panel, the accumulated strain energy is dominated by membrane action and is expressed as:

$$\mathrm{V_{mem}} = \frac{1}{2}\int_0^L\int_0^B (\mathrm{N_x}\varepsilon_\mathrm{x}+\mathrm{N_y}\varepsilon_\mathrm{y} + \mathrm{N_{xy}}\gamma_\mathrm{xy})\,\mathrm{dy\,dx} \tag{7}$$

Where N_x, N_y and N_{xy} are forces per unit length of the plate edge and ε_x, ε_y and γ_{xy} are the corresponding strains for large deflections, (Timoshenko and Woinowski-Kreiger, 1964).

The necessary energy for rupture initiation is obtained from the experimental work of Jones and Birch, (2006), where the diameter of the indenter is taken into account when measuring the responses of plates subjected to low speed (in the range of ships' speeds) collisions.

The above model is implemented in the CRASED (*CR*ashworthiness *AS*sessment for *E*arly *D*esign) program. Its results are compared with the statistical data obtained in HARDER for the case of a ROPAX colliding with a similar ship. The length and breadth of the damage opening is presented in Figure 4 as a function of penetration.

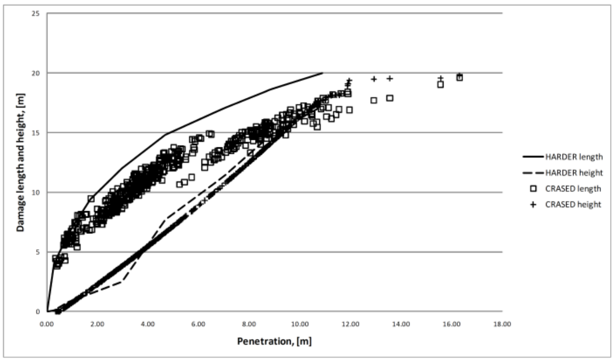

Fig. 4: Comparison between CRASED and statistical data

The integrated model

Putting the two elements of probability together (for a particular waterway or a set of routes) will provide a concise picture of the flooding probability and its extent due to collision and will highlight potential deficiencies (e.g. in structural arrangement and watertight subdivision) that need to be addressed at design level. This way, the operational profile of a new ship and its physical properties are mutually contributing to the derivation of the ship collision risk levels.

CONCLUSIONS

Although the probabilistic framework for damage stability is moving in the right direction for the quantification of safety levels of ships, its implementation is inconsistent as the weight is placed on the vulnerabilities of a ship. This way, any realistic treatment of the operational risks, and with it any serious attempt to build on prevention, is lost. The methodology proposed here aims to address this issue and, considering that accidents still happen despite the substantial effort spent for analysis and regulation, to create a momentum of thinking for rationalising the ship survivability assessment and the shipping operations in general.

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