

DEVELOPMENT OF FACTOR-S: THE DAMAGE SURVIVAL PROBABILITY

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Abstract

The survival probability estimation has always been the most difficult element of the probabilistic damage stability assessment methodology. The proper account of all the effects, including dynamic effects of waves, on damaged ships ought to be included in assessing survivability. The consideration of the effect of waves for different types of ships is, however, the biggest step forward in damage stability assessment methods. The Ship Stability Research Centre (SSRC) originally developed the Static Equivalent Method (SEM) during the late 90's for the type of ships with a large undivided horizontal deck, which is close to damage waterline level. Later on, during the author's PhD study, the method was modified and developed further with the help of data available at SSRC. The data set includes results from survivability model experiments that were carried out primarily for EU funded research projects (in particular the HARDER project), as well as a great number of Ro-Ro ferry survival experiments carried out for Stockholm Regional Agreement upgrading projects. Although it never appeared to be the same capsizing mechanism for conventional vessels, the method is applied to both mono-hull passenger and cargo vessels. In this paper a methodology, in which the effect of waves as well as the other relevant effects on survival of a damaged ship can be combined, is demonstrated. As a result, a generalised survival factor is developed in a way suitable to adopt in subdivision and damage stability regulations.

1. INTRODUCTION

The final outcome of damage breaching the watertight integrity of the hull depends on many factors that are random in nature. Firstly the governing parameters must be identified, and then their effects on survivability must be modelled. Bearing in mind that, their influence may differ on ship type, it is very difficult to assess true survival probability of a damaged ship with a generalised methodology that utilises mostly deterministic criteria. In assessing survival probability, factor-s must be structured in a way making the best use of the

performance-based simulations and methods that are from the first principles. Nonetheless, a framework for survival probability, known as factor "s" can be developed with the help of state-of-the-art knowledge.

1.1. Development of The Probabilistic Based Regulations

The principles of probabilistic based damage stability assessment methodology were introduced in a paper by Kurt Wendel in 1960 [1]. In his paper, he outlined a procedure

intended to provide efficient subdivision for ships, by employing *probabilistic principles* for the systematic consideration of the risks of future accidents. During the 60's, it was taken further by a group of experts under the International Maritime Organisation (IMO). It was developed as the first probabilistic-based subdivision and damage stability regulations. By SOLAS conference of 1974, it was adopted as equivalent to, and a complete alternative to, the corresponding SOLAS regulations for passenger ships. These regulations are referred to as the *Equivalent Passenger Ship Regulations*, or more commonly as Resolution A.265 (VIII) [2].

Significant changes in IMO came in 1983 with a decision of taking the probabilistic principles for all future regulations on subdivision and damage survivability. As the first step, a draft set of probabilistic regulations for cargo ships were developed in 1987 and approved in 1988. IMO adopted these probabilistic based regulations as *the subdivision and damage stability regulations for cargo ships* [3]. They were then incorporated as a part of *SOLAS 90; Chapter II-1, Part B-1, as Regulations 24, 25, 25-1*, which became effective for all cargo ships over 100m in length constructed on or after 1 February 1992. Then it was extended to dry cargo ships of 80m in length and upwards but not exceeding 100m in length constructed on or after 1 July 1998.

1.2. Attained Subdivision Index

The probabilistic method is devised to obtain an index value - usually referred to as the *attained subdivision index* or *Index-A* - which is representing the mean survival probability. Special considerations are given to include factors for the likelihood of the damage scenarios as well as consequences of them. The philosophy behind the probabilistic concept is that two different ships with the same index of

subdivision are equally safe with respect to side collision damages.

There is a series of assumptions taken in order to apply the probabilistic damage stability principles. The most significant of all can be summarised as follows:

- The ship is damaged,
- The damage results in breaching of the watertight integrity i.e. causing flooding.

Under these circumstances the probability of surviving collision damages is given by the following summations:

$$A = \sum_j \sum_i w_j \cdot p_{i,j} \cdot s_{i,j} \quad (1)$$

Where, the index "i" is representing each possible flooding of a compartment or a group of compartments under consideration, and the index "j" is representing loading conditions while "w_j" is the weighting factor for each loading condition. The factor "p_{i,j}" is the probability that only the compartment or the group of compartments under consideration are flooded, while factor "s_{i,j}" is the probability of survival for the said damage flooding.

2. DAMAGE SURVIVAL ASSESSMENT

The assessment of the damage consequences should yield a survival probability that is the measure of ship being free from further dangers while maintaining her floatability. It is intuitive that the floating attitude of the ship changes as well as her reserve restoring capacity, which is usually associated with static stability characteristics only. Even though the majority of past accident data records demonstrates that accidents resulted in flooding of hull occurred in confined waters, the presence of external effects, such as waves and wind. Therefore any method developed to assess damage survival

ought to include these dynamic effects rationally.

2.1. Damage Survival Consideration

The floatability of a ship is simply measured by hydrostatic with the help of either lost buoyancy or added weight method in damaged conditions. If a damaged ship has hydrostatic stability (positive GM) in the final equilibrium stage, then traditionally the ship is regarded as safe. However, it requires more consideration than that to assign a damaged ship safe especially in waves. It is therefore of great interest to predict the survival probability by considering all the possible effects from the first principles. The well-known effects of waves on a damaged ship cannot be ignored in this respect. The probability of survival can directly be a function of the surrounding sea state, after realising this as one of the most important issues that are affecting the fate of the damaged ship. The probability of survival is associated to a critical sea state, where the damaged ship ought to be safe in wave heights up to this sea state. If wave height does not exceed the critical sea state, then the damaged ship is assumed to be free of risks of capsize or sinking.

The first probabilistic survival assessment was developed during the 60's, on the basis of findings from a series of systematic model testing [4], [5]. The model tests were conducted in order to establish a relationship between survival probability and the critical sea state. The critical sea state, characterised by significant wave height (H_s), was expressed as a function of effective freeboard after damage (F_e), metacentric height flooded (GM_f) and ship breadth (B) as follows:

$$H_s = f\left(\frac{GM_f \cdot F_e}{B}\right) \quad (2)$$

The survival probability factor “s” that a ship with a given damage and initial conditions will not capsize is equal to the probability that the critical significant wave height related to this condition is not exceeded. To this end, the distribution of wave heights at the time of collision has been derived from IMO casualty database [2]. Following this, the probability factor “s” is approximated in Resolution A.265(VIII) as the following:

$$s_i = 4.9 \left[\frac{GM_f \cdot F_e}{B} \right]^{\frac{1}{2}} \quad (3)$$

In the present cargo ship regulations, however, the above consideration is replaced by a static stability curve (GZ curve) based formulation. By assuming the GZ curve parameters GZ_{max} and *positive range*, as obtained in the final equilibrium stage, to be related directly with the survival sea state. In addition, there is restriction to the heel angle at the final equilibrium, which is introduced by the factor “c”. This is to provide safe launching of life rafts as well as to reduce the possibility of having large cargo shift. Without firm scientific grounds, however, the following formulation is adopted for the estimation of the survival probability pertinent to cargo ships [3]:

$$s = c \cdot \sqrt{0.5 \cdot (GZ_{max}) \cdot (range)} \quad (4)$$

where :

$$c = \begin{cases} 1 & ,if \quad \theta_e \leq 25^\circ \\ 0 & ,if \quad \theta_e > 30^\circ \\ \sqrt{\frac{30 - \theta_e}{5}} & , \quad otherwise \end{cases} \quad (5)$$

GZ_{max} = maximum positive righting lever, with in the range but not more than 0.1 m,
range = range of positive righting levers beyond the angle of equilibrium but not more

than 20°; however, the range should be terminated at the angle where openings not capable of being closed weathertight are immersed, θ_e = final equilibrium angle of heel.

The currently adopted both approaches for passenger and cargo vessels almost equally lack a rational basis for assessing the survival probability. Following a series of Ro-Ro ferry disasters, it became so obvious that the water on deck is a real threat to ships with large horizontal decks close to sea level after damage flooding takes place. The accumulation of water on deck due to dynamic effects of waves is widely recognised as the primary reason for capsizing of Ro-Ro ferries. Not only ships with large undivided inner decks but also conventional ships with low freeboard can be vulnerable to dynamic effects of waves. The latter has also been studied during the author's PhD research. The use of a suitable method in assessing dynamic effects of waves is developed in a way suitable for implementing in the probabilistic framework. The results will be shown later this paper.

3. A FRAMEWORK FOR FACTOR-S

In assessing survival probability all the relevant factors ought to be included. Therefore it is important to develop a framework where all factors effecting survivability can be identified and considered mutually to derive a generalised survival factor-s. To this end, the following framework is developed to obtain the probability of survival for a given damage case, as illustrated in Figure 1. Each factor included in the framework is selected and wired up to reflect the complex physical phenomena of survival in the best way possible. Admittedly not every effect can be modelled to the same degree of precision at this stage, due to lack of available knowledge. However, the framework is modelled in such a way so as to accommodate any future alteration or addition.

The following two risks are considered to be the primary causes for ship losses through collision damage; *the risk from dynamic effects of waves* and *the risk from other effects than waves*, as represented by factors “ s_a ” and “ s_w ” respectively. These two factors are combined to obtain a generalised survival factor-s for the damage case under consideration as follows:

$$s = s_a \cdot s_w \quad (6)$$

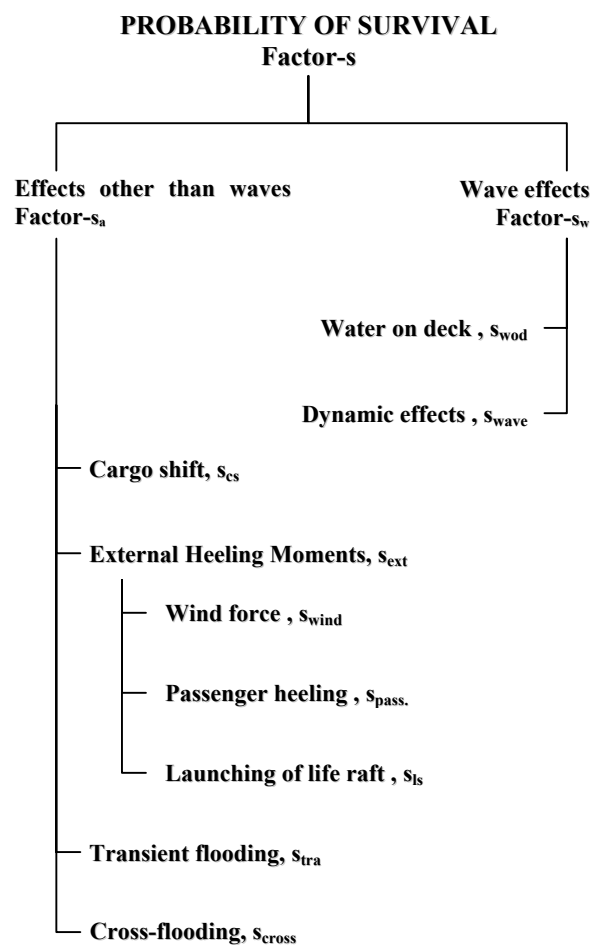


Figure 1: Combination of factors building up the survival factor-“s”

These two factors are assumed to be mutually independent; therefore product of the two directly yields the probability of survival, i.e. being free from any danger associated with them. Obviously each factor must be developed

while bearing in mind the possible interrelations between them. Thus, they are assumed to be independent, until it can otherwise be considered on a more scientific basis.

4. SURVIVABILITY IN WAVES

The probability that the ship will survive from the effects of waves is represented by the survival factor “ s_w ”. The survivability in waves is considered from two point of views, firstly survival from water on deck and secondly survival from dynamic effects of waves. The former consideration is given especially for ships that possess water on deck problem. The water on deck problem can be the primary source of capsizes for ships with large undivided decks that are close to the damage waterline. As this has been extensively confirmed in the cases of Ro-Ro ferry accidents, which happened during the 80s and the 90s. In the wake of these accidents a series of research efforts were initiated. A joint research program involving a number of North West European countries concluded in 1996, in which the Strathclyde University Ship Stability Research Group (SSRC, since 1997) developed the principles of the **Static Equivalent Method (SEM)**. The SEM is a quasi-static method to predict survival sea state of a damaged ship whilst accounting for progressive accumulation of water on deck.

4.1. The Static Equivalent Method

The SEM for ships with large undivided decks close to sea level assume that the ship capsizes quasi-statically as a result of accumulation of a critical mass of water on the deck. The deck is usually a vehicle deck with low freeboard, such as in a RoRo type of ships; therefore it is commonly referred as “*vehicle deck*”. The height of the critical mass of water which is above the mean sea surface uniquely

characterises the ability of the ship to survive a given critical sea state. This method was developed following the observations from behaviour of the damage ship models in waves, during the Joint Northwest European Project [6], the author’s PhD study and EU-FP5 funded HARDER project [10]. Among the most important observations from the model tests and subsequent numerical investigations are briefly:

1. As the ship reaches the “*Point of No Return*” (PNR), it behaves quasi-statically, with subdued roll motion and marginal transverse stability.
2. The PNR occurs at an angle ($\theta_{crit.}$), very close to (θ_{max}) of the GZ curve obtained at final equilibrium.
3. The critical amount of water on the vehicle deck can be predicted from static stability calculations by filling the vehicle deck with water until the ship lolls at the angle of (θ_{max}) while accounting for free trim and sinkage.
4. The unique measure of the ship’s survival capability is *the height of the water elevated above the sea level (h)* at PNR, as shown in Figure 2.
5. The model tests and numerical simulations indicate that this elevation of water on deck (h), can be directly correlated to the sea state, characterised by (H_s)
6. The higher the water elevation (h) at PNR, the higher the sea state needed to elevate the water to this level and capsize the ship.

The most valuable information that leads to development of the SEM was made during analysis of the model experiments, which is that: “*the damaged ship in waves behaves almost quasi-statically when it reaches the point of no return*” [6]. However reaching this point and the time to reach this point are determined by the dynamics of the ship and deck height as well as the sea state. In this respect, quasi-static behaviour of the ship at the point of no return designates lack of roll motion and restoring moment.

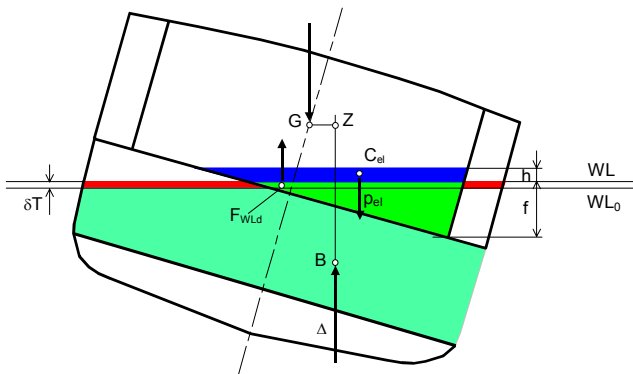


Figure 2: Damaged Ro-Ro vessel with water elevated on the vehicle deck at PNR

From the ship dynamics point of view, the vessel lacks roll motion while positive restoring capacity of the ship is reduced substantially with the presence of additional water on deck. The other ship motions like sway and pitch remain in practice unaffected by the quasi-static heel of the ship. Heave motion, however, remains particularly important, as ship tends to follow the incoming wave profile.

The most important effect of the elevated water on deck is to reduce the restoring capacity of the vessel to minimal, virtually to zero. Therefore, firstly one should identify the term “*elevated water on deck*” clearly. The reference must be the physics of the phenomenon, thus the model experiments. When the water volume on the vehicle deck is measured just before reaching PNR, it is clear that there is a layer of extra volume of water on top of the mean sea level, which is obviously elevated by the wave actions. That is why the water above waterline (WL) is called *elevated water on deck*. The whole mass of water on deck is then referred as the *added water volume on deck*, which includes water below WL together with the elevated water as seen in Figure 2. As a direct result of the added water volume on deck ship attains sinkage and heel.

It was found that the best way of calculating the SEM parameters (h) and (f) is the use of *constant elevated water* procedure with deck being included in the damage definition as usual. This is to put constant volume of elevated water on deck for each angle of heel considered for GZ curve calculations. The method then is most robust and applicable for all type of deck arrangements, whilst giving the most consistent and suitable results to the assumptions of the SEM method. The following steps are used in applying SEM:

Step 1: Determining the large undivided deck spaces, involved in the damage case, which holds elevated water due to waves. That is referred as “vehicle deck” here after. The GZ curve for the final stage of flooding should be like the one in Figure 3.

Step 2: Change the volume of elevated water in side the vehicle deck space, which is the water volume above the floodwater that might be present if the mean sea water level is above the vehicle deck. The GZ curve is reduces with the elevated water on deck as seen in Figure 4.

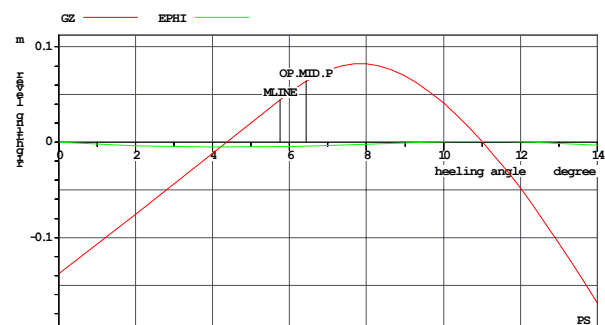


Figure 3: The elevated water on cardeck is 0m^3

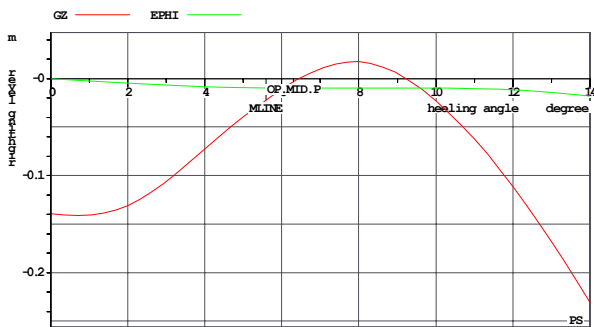


Figure 4: The elevated water on cardeck is 100 m³

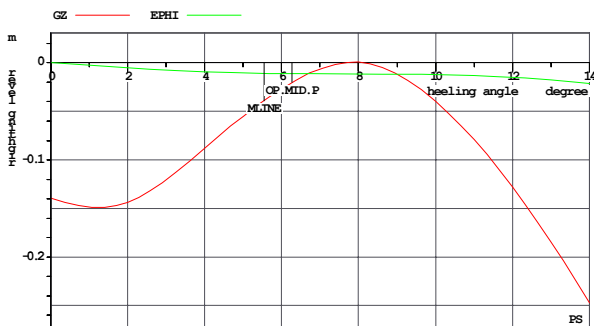


Figure 5: The *critical amount* elevated on cardeck is 127m³

Step 3: Perform iterations (i.e. repeat Step 2) until the GZ curve, which is calculated for free floating hull (i.e. free to sink and trim due to added water on the vehicle deck), virtually vanishes (i.e. maximum restoring moment is zero or near zero). When the GZ curve vanishes as seen in Figure 5, the elevated water on deck is then called *the critical amount of water*. Find the final floating position with critical amount of water.

Step 4: In the final floating position with critical amount of water, measure the height of elevated water in the vehicle deck; it is the vertical distance of two parallel surfaces, which are the elevated water surface and the water line surface (WL). This can be seen in Figure 2. The freeboard is measured as the vertical distance from waterline level (WL) to the edge of the vehicle deck at the mid point of the

damage opening or damage zone under consideration.

The SEM for Non-RoRo Ships

The SEM methodology has also been applied to vessels other than those with large undivided horizontal deck close to waterline level, i.e. low freeboard weather deck other than vehicle decks that are enclosed within the hull. Although the methodology has been originally modelled and validated by the results from model experiments that are conducted with RoRo type ships, the results of the model experiments for non-RoRo type vessels demonstrated similar behaviour at PNR. It is intuitive that reaching to PNR is very different, but non-RoRo type ships demonstrated similar quasi-static behaviour at PNR suggesting that the SEM methodology can be used for these types of vessel too.

There have been a limited number of survivability model tests conducted previously for non-RoRo ships. The observations from these tests have not been very revealing. Nonetheless, these earlier tests on non Ro-Ro models have reported similar observations to those obtained by the author based on three different non-RoRo type vessels (dry cargo ships) model experiments. A briefly summary of the observations obtained from the cargo ship tests conducted during HARDER project as follows:

1. The ships were highly damped in roll and the predominant motions were in heave and sway modes.
2. The dominant capsizing mechanism was from large heeling initiated by waves boarding onto the main deck.
3. There was no steady build-up or accumulation of water as seen in RoRo type ships since boarding sea water is free to flow off the weather deck. Capsizing was often

initiated by one or two large wave(s), and that occurs within a short period of time.

4. Ship with sufficient freeboard to stop most of the waves from boarding on to the main deck showed considerable resistance to capsize even with quite marginal stability.

Obviously there is no potentially water-holding deck like a vehicle deck in RoRo, instead the weather deck plays the similar role in a rather different manner. The boarding waves can accumulate in a very short instance of time, yet there are instances where more than one successive high waves can create the same effects as water on deck, and imposing upsetting heeling moment and sinkage.

Essentially the same SEM calculations can be used for conventional ships to determine (h) and (f), by assuming the ships sides were extended vertically above the open deck, as shown in Figure 6. This assumption enables one to apply the same principles for calculating the critical amount of water and SEM parameters; however, there is an obvious need for deploying new correlation between SEM parameters and the critical sea state for the prediction of survival sea state (H_s).

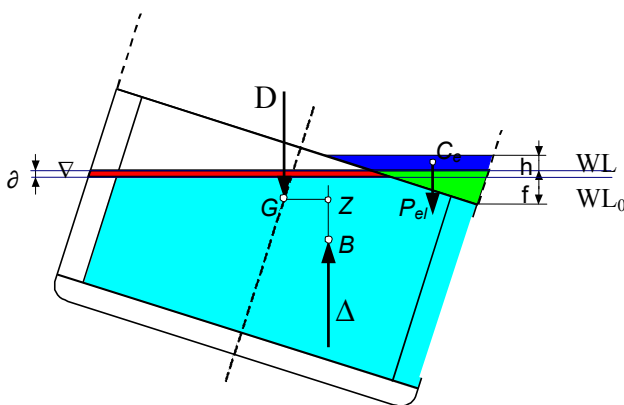


Figure 6: The SEM parameters for weather deck

Using the same methodology as the SEM for RoRo type ships, at the critical heel angle, the

SEM parameters, the dynamic water head (h), and the freeboard (f) are calculated. Then the only difference is the reference point for (f).

After thorough investigation and careful consideration of water accumulation on weather deck, the best longitudinal position is found to be the same longitudinal position of centroid of the additional water on deck. To this end, the freeboard (f) is the vertical distance between static water level and relevant deck edge at the longitudinal position where the centroid of additional water volume takes place. This is a unique definition for any kind of deck arrangement and volume formation.

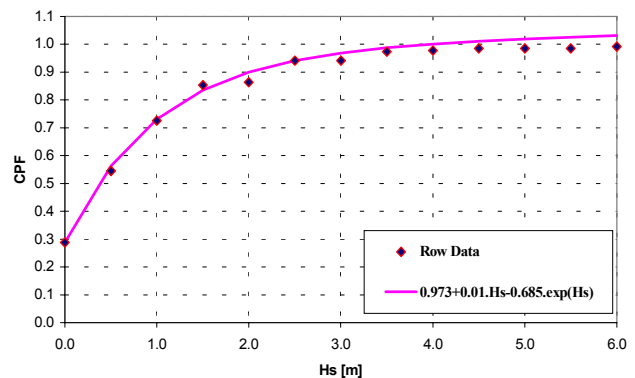


Figure 7: Cumulative probability function of wave height at the time of collision

4.2. Wave Height Distribution Function

The cumulative distribution of wave height at the time of collision, which is derived from the past collision data, can be used to determine the probability of survival.

The original IMO data on wave height distribution at the time of collision has been updated according to the additional collision data within HARDER project. From the collision accident database available, the following characteristics for the wave height distribution at the time of collision are taken into consideration:

- The wave height in which 90% of the collisions occurs; $H_{s90} = 2.00$ m
- The wave height in which 99% of the collisions occurs; $H_{s99} = 4.5$ m
- Fraction of cases with no waves; $y_0 = 0.288$

Considering the above and the updated statistical data, the Equation (7) is found one of the best fits, and it is reproduced in Figure 7.

$$CPF(H_s) = 0.973 + 0.01 \cdot H_s - 0.685 \cdot e^{H_s} \quad (7)$$

As there is no apparent correlation found between ship characteristics, consequences of the accident and the number of fatalities, however, the cumulative probability function (CPF) can directly be used to assess survival probability.

4.3. Statistical Correlation For Ro-Ro Type Ships

A sample of twenty-nine Ro-Ro vessels is utilised to form a sampling of 69 damage cases. The sample cases originally consisted of data from the model tests carried out at SSRC, an additional 3 cases extracted from the original series of tests conducted prior to A.265. Further data samples were gathered from the model tests that are available to SSRC. Some of these ships have been tested for only SOLAS'90 worst damage case, which is usually amidships case, however, some have been tested for two different damage cases; worst damage and an additional amidships case.

The statistical correlation between dynamic water head (h), freeboard to cardeck at damage opening (f) at the critical angle ($\theta_{crit.}$), and the mean significant survival wave height (H_s) has been modelled with a three dimensional regression. Several surface functions are tested to obtain the best fit, yet keeping it relatively easy for implementation within probabilistic calculation procedure. To this end, the

following surface fit is found statically good and relatively simple to implement:

$$H_s = 2.221 \ln(h) - 0.635f + 4.676 \quad [m] \quad (8)$$

The statistical data for the fit is as follows:

Residual Sum of Squares = 12.27
Standard Error of the Estimate = 0.476
Coef. of Multiple Determination (R^2) = 0.8245
Highest Overestimate = 0.904m
Lowest Underestimate = -1.064m
Mean Error = 0.378m

The Equation (8) is reproduced in Figure 8, together with the sampling data points. The prediction of the lower survival sea states are slightly underestimated while keeping the over all accuracy of the fitness of the data. The residuals plot, in Figure 9, shows comparison between the predicted H_s and the mean survival H_s measured from model experiments. The direct analytical solution resembles rather a complicated formula on hand. Therefore, the resulting "h" and "f" values from SEM is taken as variables, and regression analysis is carried out to fit a function to factor " s_w " which is obtained from the experimental results of survival (H_s) and with the help CDF as given in equation (7). The resulting regression function is given below by equation (9) that provides satisfactory fit to the sample data.

$$s_{wod} = \min \begin{cases} 1.02 \exp(-\exp(0.46 \cdot f - 7.9 \cdot h + 0.76)) \\ 1.0 \end{cases} \quad (9)$$

After considering some simplifications to above formulation of " s_{wod} ", the following expression is proposed for factor- s_{wod} :

$$s_{wod} = \exp(\exp(0.5 \cdot f - 8 \cdot h + 0.7)) \quad (10)$$

The statistical data for the fit is as follows:

Residual Sum of Squares = 0.1287
Standard Error of the Estimate = 0.0493
Coef. of Multiple Determination (R^2) = 0.847
Highest Overestimate = 0.140

Lowest Underestimate = -0.175
Mean Error = 0.03433

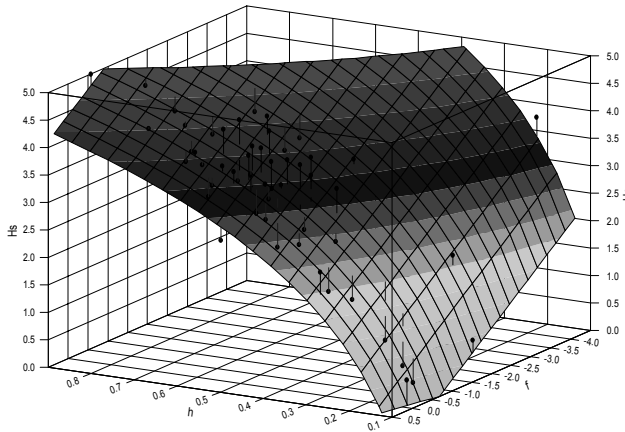


Figure 8: Regression for H_s as a function of (h) and (f) by a curved surface

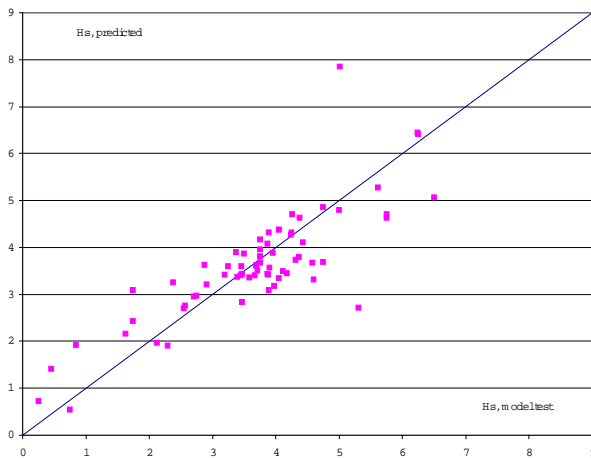


Figure 9: The residuals chart for survival prediction of RoRo type ships

4.4. Statistical Correlation For Non Ro-Ro Type Ships

The similar regression study was undertaken for SEM consideration of weather deck. There are 35 damage cases in the sample data set, which consist of the mean survival wave height in the form of significant wave height and SEM parameters (h) and (f), derived according to the

weather deck consideration as outline in section 4.1.1.

The best fit for the sample data from RoRo type ships, which is given in equation (8) is applied to sampling data for non-RoRo ships, as shown in Figure 10. Even though the behaviour at PNR is similar, it is obvious that the correlation between SEM parameters and critical (H_s) is not the same. It is clear that the sample data has a large scatter and cannot be correlated this way. After trying different correlation formulations it was concluded that the sampling size is simply far from a significant number to develop a regression formula of any sort in the form of a 3D surface.

As more test data added, the earlier correlations developed by using equation (11) [8] is not giving good correlation either, as can be seen from the residuals plot in Figure 11.

$$H_s = H_{sr}^{1/0.3} \tag{11}$$

Where,

$$H_{sr} = \frac{h}{(0.67 - 0.61x)} \tag{12}$$

$$x = 1 - \frac{1}{\left(1 - \frac{1}{3} \frac{f}{h}\right)} \tag{13}$$

To this end, the use of correlation model needs further consideration; perhaps additional data is required to develop a more robust correlation formula. Further studies are necessary in this direction to overcome this problem.

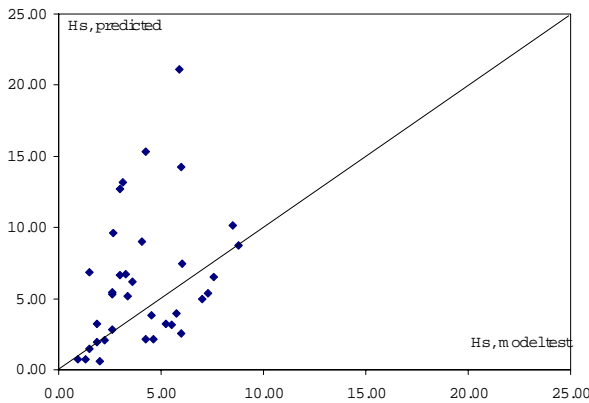


Figure 10: Survival boundary prediction for non-RoRos; $H_s = 2.221 \ln(h) - 0.635 f + 4.676$

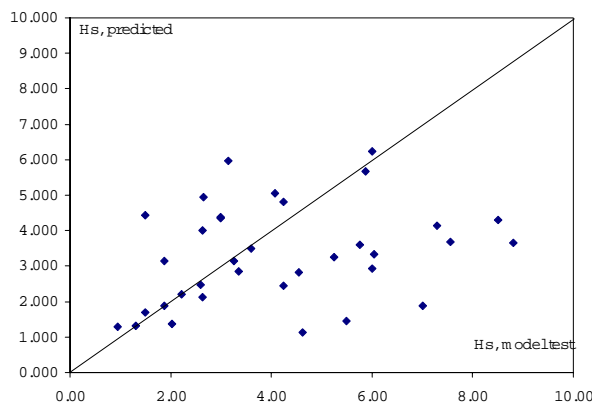


Figure 11: Survival boundary prediction for non RoRos with $h/H_{sr}=F$ (f/H_{sr})

4.5 Conventional Methodology For Non Ro-Ro Type Ships

After the poor results from SEM for non RoRo type ships, the conventional methodology of GZ curve related criteria is employed [9]. In the same way as the SEM formulation, the mean survival sea states are correlated to the stability parameters, with H_s limited to 4m:

$$H_s = 4 \cdot \left[\left(\frac{GZ_{\max}}{TGZ_{\max}} \right) \cdot \left(\frac{Range}{TRange} \right) \right] \quad (14)$$

Based on an examination of the best correlation with the model test results the following values of TGZ_{\max} and $TRange$ are proposed:

$$TGZ_{\max} = 0.12m$$

$$TRange = 16 \text{ degrees}$$

The statistical data for this fit is as follows:

$$\text{Sum of Squares} = 8.6$$

$$\text{Highest Overestimate} = 1.15m$$

$$\text{Lowest Underestimate} = -1.53m$$

$$\text{Mean Error} = 0.38m$$

At least within the 0 to 4m sea state range of interest, this formulation provides the prediction of the survival sea state with similar accuracy; with mean errors approximately equivalent to the SEM predications for vehicle deck considerations. Following the same assumption, the probability of survival is the probability that sea state will not exceed the critical sea state; the factor- s_w can be predicted as follows:

$$s_w = K \cdot \left[\frac{GZ_{\max}}{TGZ_{\max}} \cdot \frac{Range}{TRange} \right]^{\frac{1}{4}} \quad (15)$$

where;

$$K = 1 \quad \text{if } \theta_e \leq \theta_{\min}$$

$$K = 0 \quad \text{if } \theta_e \geq \theta_{\max}$$

$$K = \sqrt{\frac{\theta_{\max} - \theta_e}{\theta_{\max} - \theta_{\min}}} \quad \text{otherwise} \quad (16)$$

$\theta_{\min} = 7$ degrees for passenger ships and 25 degrees for cargo ships, and

$\theta_{\max} = 15$ degrees for passenger ships and 30 degrees for cargo ships

The factor “K” is introduced to restrict the heel angle after equilibrium. This is aiming at providing effective means of evacuation process and rescue efforts. By ignoring the cause of the factor “K”, for simplicity, the

resulting regression for the factor- s_w from Equation (15) is illustrated in Figure 12.

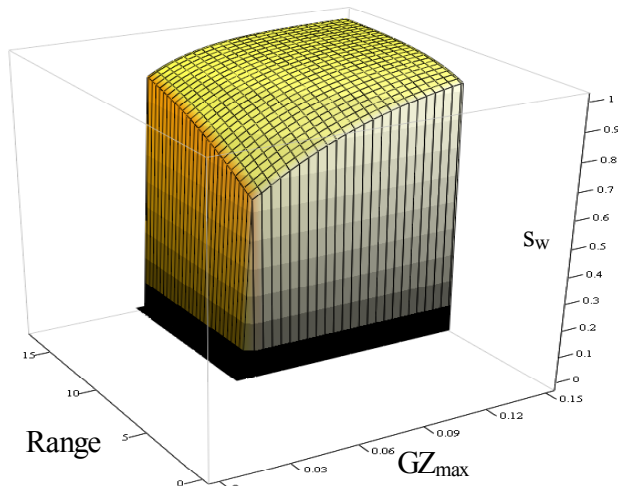


Figure 12: The survival factor- s_w based on GZ curve parameters GZ_{max} and Range.

The conventional methodology, GZ based assessment, may be used until further studies will be carried out with SEM for non-RoRo type ships, since the prediction accuracy is statistically similar for the range of interest. It can be used within the probabilistic assessment framework, as it is relatively simple to apply.

5. OTHER EFFECTS THAN WAVES

The survival probability from effects other than the dynamic effect of waves is combined within factor “ s_a ”. The factor- s_a consists of the following components:

- Cargo shift,
- External heeling moments,
- Transient flooding,
- Cross-flooding arrangements.

5.1 Survival Factor For Cargo Shift

A simplified model for the predictions of cargo shift effect was proposed based on the following assumptions:

- The ability of cargo to remain in place is characterised by the angle of repose (θ_R), an

angle of equivalent ship rolling motion leading to cargo shift due to gravitational forces.

- The forcing acceleration on cargo is composed solely of the gravitational acceleration resulting from mainly ship rolling.
- The effect of cargo shift is a heeling moment, which, regardless of its magnitude, is assumed to lead to imminent capsizing.

Furthermore, possible transversal force due to other modes of motions than roll is ignored. Based on these assumptions, the predictions of ship survivability due to cargo shifting, factor “ s_{cs} ” is equivalent to prediction of the likelihood that the onset of the conditions for cargo shift does not occur, i.e. the likelihood that the ship rolling does not exceed the angle of repose θ_R as given from the assumed linear cumulative roll angle distribution in equation (17). This can be seen in Figure 13.

$$s_{cs} = \frac{\theta_R - \theta_{mid}}{\theta_v - \theta_{mid}} \quad \text{if } \theta_{mid} \leq \theta_R \leq \theta_v \quad (17)$$

$$s_{cs} = 0.0 \quad \text{if } \theta_R < \theta_{mid}$$

$$s_{cs} = 1.0 \quad \text{if } \theta_R > \theta_v$$

Where:

θ_R = the angle of repose given according to the specifications of cargo and cargo securing devices,

θ_v = the angle of vanishing stability,

θ_{max} = the angle where maximum restoring occurs,

θ_{mid} = the angle measured in the middle between (θ_{max}) and angle of vanishing stability (θ_v), and can simply be calculated as follows:

$$\theta_{mid} = \frac{\theta_{max} + \theta_v}{2} \quad (18)$$

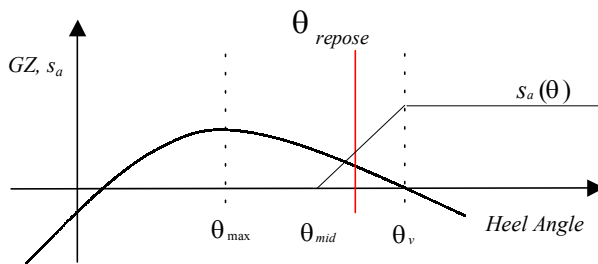


Figure 13: Probability of no cargo shift occurring as obtained from the GZ curve at the final equilibrium

5.2 External Heeling Moments

In accounting for additional heeling moments imposed to a damaged ship, the following categories can be identified as potentially hazardous:

- Wind force,
- Passenger crowding,
- Launching of life rafts,

It is obviously a serious problem for passenger ships with a large number of passengers on board, as well as ships with side profile resulting in a large windage area. There is highly debatable issue of how these individual moments come together and are to be applied. Perhaps, the best way to determine this is to carry out performance-based simulations to assess the movement of passengers through the evacuation process, together with changing wind pressure and direction to find a realistic heeling moment distribution.

Having no such method fully employed yet, in the light of the work undertaken by HARDER project and previous research programs, it can be suggested that the heeling moment can be imposed on the vessel by introducing shift of transverse centre of gravity (TCG) as follows:

$$TCG = \frac{M_{heeling}}{displacement} \quad [m] \quad (19)$$

With the current stage of knowledge, the following consideration of the external heeling moment is found to be a rational assumption:

$$M_{heeling} = [\text{Max.} (M_{passenger}; M_{LifeRafts}) - M_{wind}] \quad (20)$$

The external heeling moments under consideration depends on the number of passengers, relevant life raft arrangements and the windage area of the ship, as commonly used in SOLAS regulations. The above consideration of taking the maximum of passenger crowding and launching of life rafts holds the most suitable arrangement for a typical passenger vessel of today. As the wind gust can usually provide up righting force for the damaged vessel that heels towards incoming waves, therefore, it ought to be a reduction factor. These moments can be calculated, as proposed by the HARDER project, as follows:

Heeling moment due to wind force

$$M_{wind} = \frac{P \cdot A \cdot Z}{9806} \quad [t.m] \quad (21)$$

where:

$$P = 120 \text{ N/m}^2$$

A = projected lateral area above waterline

Z = distance from centre of lateral projected area above waterline to T/2; T is the draught under consideration

The wind pressure of 120 N/m² corresponds to a wind speed of around 13-14 m/s (gale), which is at the upper end of the statistical distribution of wind during collisions; hence it can be regarded as quite conservative.

Passenger heeling moment

$$M_{\text{pass.}} = 0.075 \cdot N \cdot (0.45 \cdot B) \quad [\text{t.m}] \quad (22)$$

It is assumed that the heeling moment arm is $0.45 \cdot B$, the average passenger weight is 0.075 ton, and the number of passenger is “N”.

Launching of life rafts

$$M_{\text{surv.}} = 0.075 \cdot N \cdot 0.5 \cdot B \cdot 0.55 \quad [\text{t.m}] \quad (23)$$

With today's requirements to lifeboat capacity, it is maximum 50% of the total life raft capacity on each side of the vessel. Furthermore, it is assumed that heeling arm to be $0.55 \cdot B$.

5.3 The Survival From The Effect of Transient Flooding

The survival from the effect of transient flooding stage can be determined from the method developed by The Technical University of Denmark within the HARDER project, as follows [10]:

$$s = \left(0.368 + 0.632 \cdot e^{-\sqrt{1-\frac{B}{A}}} \right) \cdot \left(\frac{GZ_{\text{max}}}{0.05} \cdot \frac{\text{Range}}{7} \right)^{\frac{1}{4}} \quad (24)$$

where:

GZ_{max} is not to be taken greater than 0.05m , and Range not to be taken greater than 7° .

A= maximum of the area under GZ curve from upright to equilibrium obtained by considering intermediate stages of flooding.

B= minimum of the area under GZ curve from equilibrium angle to the smallest vanishing angle of all the stages considered.

The first part of the equation (24) is derived by considering a distribution of flooding time from the damage database collected within the HARDER project. The second part is proposed from the current IMO standard for intermediate stages.

5.4 The Survival From The Effects of Equalisation Arrangements

The equalisation arrangements are introduced to reduce large heeling angles. Before the equalisation time elapses, a large heeling may possess the risk of capsize, therefore, such arrangements like cross-flooding ducts must also be incorporated in factor- s_a . The following consideration by DNV within the HARDER project [10] can be used to determine the safety factor for such equalisation devices, factor- s_{cross} , as follows:

$$s_{\text{cross}} = q + (1-q) \cdot s_w \quad (25)$$

$$q = 1 - e^{-\left(\frac{Q_e}{85}\right)^{0.7}} \quad (26)$$

where:

s_w = calculated as given based on GZ curve approach by equation (15).

q = the probability that the capacity of the equalisation arrangement or device will at least equal the inflow rate of the flood water.

Q_e = the capacity in $[\text{m}^3/\text{s}]$ of the equalisation arrangement, calculated assuming that all compartments on the damaged side are filled up to the level of the load line under consideration.

6. GENERALISED FACTOR-S

In assessing the survival probability, each factor determined in the framework must be

combined together to produce the survival factor “s”. The factor-s is then used within probabilistic framework to arrive with index-A. To this end, the proposed components of “s_w” and “s_a” are multiplied together to arrive at a final generalised factor “s”. In doing this it is assumed that two factors are independent as discussed in section 3. Generally speaking, the factor-s is relevant for both passenger and cargo ships, however, some components of the factor-s_a depend on the number of passenger, and ship arrangement.

There are still pending issues regarding the final wording of the regulations on factor “s_a” (Regulation 7-2) proposed by the HARDER project, therefore, depending on the outcome of the SLF 46 meeting, the matters will be settled. It is anticipated that the framework on factor “s” will be incorporated in the revised draft text of SOLAS Chapter II-1 Parts A, B and B-1, Regulation 7-2.

Nevertheless, for a given damage case and initial conditions following the equation (6), the following formula can be used to derive the survival factor “s”:

$$s = (\min. [S_w, S_{wod}]) \cdot (S_{cs} \cdot S_{tra} \cdot S_{eq}) \quad (27)$$

It is worth pointing out that in the above consideration, however, the factor s_{ext} is not used directly; instead the external heeling moment is introduced in the form of TCG shift while obtaining the factors “s_w” and “s_{wod}”.

7. CONCLUSIONS

Factor “s” represents a measure of the probability of survival of a damaged vessel in waves accounting for dynamic effects of waves and ensuring accumulation of water on deck, as well as other important effects namely; transient flooding, cargo shift, cross-flooding and additional heeling moments. All these contributions are assumed to be independent

until a rational method were developed for addressing the interaction between the various effects.

The framework introduced consists of all the relevant factors that influence the damage-flooding outcome. In this respect, the biggest step forward is the introduction of measures for the survival predictions in waves from the first principles. The identification of the problem with water on deck and setting a direct method for the prediction of the survivability are particularly important issues addressed.

Although the factor-s proposed in this paper represents state-of-the-art, there is room for further development on the components of the survival factor. Both factors are structured in the framework in such a way that any further improvements can be implemented easily.

8. ACKNOWLEDGMENTS

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