STABILITY AND SAFETY OF SHIPS: HOLISTIC AND RISK APPROACH

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Abstract

Present stability regulations developed over the years by IMO reached definite conclusion with the adoption of the Revised Draft of the Intact Stability Code. The criteria included there are design criteria of the prescriptive nature, based mainly on statistics of stability casualties. Currently IMO is considering development of criteria based on ship performance. Concept of such criteria is, however, at present not agreed. The criteria are working comparatively well with regard to the majority of conventional ships, however advent of very large and sophisticated ships of non-conventional features caused that those criteria may be inadequate. The author advances the idea consisting of application of safety assessment and risk analysis using holistic and system approach to stability. Safety against capsizing (or LOSA accident) is a complex system where design, operational, environmental and human factors have to be taken into account. Although this seems to be a very complex task, in the opinion of the author it may be manageable and could be applied for safety assessment of highly sophisticated and costly ships.

1. Introduction

One of the most important aspects of safety is safety against capsizing. In modern times capsizing is an accident that is not happening often, but if it happens, the consequences are usually catastrophic and ship is lost, quite often with all hands on board. When the number of lost lives is large, the public opinion reacts to such accidents acutely, almost hysterically, as for example in the case of ESTONIA disaster, and the consequences of the accident to the maritime world may be rather serious. That is why safety against capsizing is an important issue.

In order to avoid possibility of capsizing, criteria for ship stability were developed. Some simple criteria were proposed quite long time ago, in the middle of nineteenth century, but the most recent criteria were developed and recommended by the International Maritime Organisation (United Nations Agency) in late sixties and early seventies of the last century. Those criteria are used until this day in some countries; recently they were included in the Code of Intact Stability for All Types of Ships developed by IMO and they will become compulsory under the provisions of the SOLAS Convention in 2009.

The existing criteria are design oriented and their essence consists of specification of critical values of some stability parameters. In spite of the fact, that some ships satisfying those criteria capsized, the general opinion is that the great majority of ships are reasonably safe.

The existing criteria may be, however, not applicable to some types of modern ships incorporating novel design features. There is no previous experience in relation to safety and stability of those ships and to satisfy existing criteria may not assure required level of safety. Because of this, Marine Safety Committee of IMO recently included in its work programme the item requiring development of performance-oriented criteria for ships of novel ship type.

Performance oriented criteria according to this definition, but also according to the understanding of the majority of members of the IMO SLF Sub-committee, are criteria that take into account scenarios of capsizing of the ship in a seaway. However, forces of the sea are not the main hazard posed to the ship. Analysis of causes of stability accidents reveals that in more than 80% of casualties human factor is the principal cause, in the remaining accidents factors such as cargo shift, icing or other heeling moments are often initiating events. Therefore, the author proposed that instead of developing additional prescriptive criteria provision may be used, already included in the SOLAS Convention (Chapter II-1, Part B-1, regulation 25-1.3) allowing the Administration to apply, under certain conditions, alternative methods if it is satisfied that it least the same degree of safety as represented by the existing requirements is achieved.

If the formulation of this provision (rather often used in IMO instruments) is understood as such, that the objectives are specified, it opens the way to application of the holistic and risk-based approach. Chantelave [3] discussed this problem. Obviously, as the application of risk analysis is not an easy task, the provision should be supplemented by guidance to the Administration.

Full risk analysis for the particular ship or group of ships requires large resources that were not available to the author. Therefore risk analysis was executed on a limited scale, and in particular group of experts consisted of few persons. The purpose of the exercise was to investigate the possibilities of application holistic and risk approach to stability problems and create some basis for possible content of guidance such as mentioned above. In the paper only some parts of the analysis are referred; the other parts of the exercise will be published in other places.

2. Holistic and system approach

As mentioned above, existing criteria are design criteria intended to be applied during the design stage of a ship. However, even the preliminary analysis of stability casualties shows, that design features of the ship are not the most important nor most often cause of casualty. Casualty – it will be in the following called LOSA –(loss of stability accident) [16], is usually the result of a sequence of events that involve environmental conditions, ship loading condition, ship handling aspects and human factor in general. Therefore in order to make safety assessment holistic approach is needed to the ship stability system.

Ship stability system is rather complicated. However, in most cases it could be considered as consisting of four basic elements: ship, environment, cargo and operation (See *Figure 1*). The Venn diagram in this figure stresses strong interactions between the four elements. The use of the system approach to stability criteria was proposed by the author quite long time ago and it was partly applied in development of the Intact Stability Code [12], but in general until this day stability requirement remain basically design oriented. Analysis of LOSA casualties reveals that the causes of casualty may be attributed to:

- functional aspects resulting from reliability characteristics of the technical system, therefore stability characteristics of the ship
- operational aspects resulting from action of the personnel handling the system, therefore crew members but also ship management, cargo handling, marine administration and owners company organisation
- external causes resulting from factors independent from designers, builders and operators of the technical system therefore ship environment and climatology [4], [5].

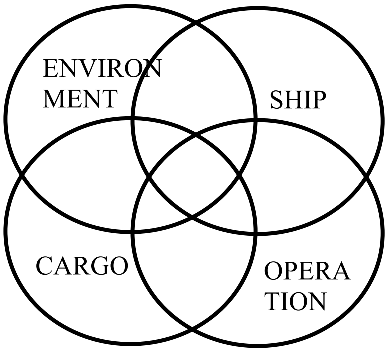

Figure 1. Four-fold Venn diagram for ship stability system

Human factor plays important part in all four elements of the system. Human and organisational errors, HOE, according to some authors, are responsible for approximately 80% of all marine casualties [17], other sources definitely stated that this percentage is 80% [23]. In order to achieve sufficient level of safety with respect of stability, all elements creating stability system have to be taken into account. Taking into account the fact, that less than 20% of all casualties are caused by faulty or bad design of the ship, the existing safety requirements that refer mainly to design features of the ship can not insure sufficient level of safety, in particular with regard to ships having novel design features. The only way out of this would be to use risk-based approach.

3. Prescriptive versus risk-based approach

In many fields of technology when planning highly sensitive and costly enterprises risk analysis is performed nowadays. The Marine Safety Committee of IMO recommended using this approach in IMO rule making process [11]. In spite of this recommendation, and in spite of the fact that risk analysis is performed, for example, as a rule in offshore industry experts on stability are hesitant to use this approach, still preferring development of prescriptive criteria.

Conventional prescriptive approach to the problem of safety that is used for a very long time is in the form of a recipe defining maximum or minimum values of some parameters. This approach is now substituted by safety assessment and analysis of risk. In place of rigid formulae, the disadvantage of which is insufficient flexibility to innovative of the system and that may be changed only using small steps, new risk based requirements are oriented on attainment of the target that is safety of the system.

Traditional regulations related to stability are of prescriptive nature and usually are based on deterministic calculations. They are formulated in the way where a ship dimension or other characteristic (e.g. metacentric height) must be greater (or smaller) than certain prescribed quantity. Prescriptive regulations could be developed on the basis of statistics, model tests and full-scale trials. In some cases probabilistic calculations might be also used as a basis of prescriptive regulations

The basic dichotomy in the conception of safety requirements consists of prescriptive approach versus risk-based approach. The main shortcoming of prescriptive regulations is that they are bounding designers and they do not allow introduction of novel design solutions. They are based on experience gained with existing objects and they are not suitable to novel types. Usually they were amended after serious casualties had been happened. The risk involved and the level of safety with the application of prescriptive regulations is not known [15].

At the opposite to the prescriptive regulations there is risk-based approach. In the risk-based approach the regulations specify objectives to be reached that is safe performance of an object. Risk-based approach could be described as a goal-oriented performance based approach utilizing, usually, probabilistic calculations. However, it is possible to imagine. The advantages of risk-based approach are obvious. They give free hand to the designers to develop new solutions, they actually allow taking optimal decisions from the point of view of economy and the risk to the public and to the environment is assessed and accepted.

All existing stability regulations are of the prescriptive nature. At present, however, the need to apply risk-based approach is recognized and actually recommended. However, up to now there are very few attempts to apply, at least partially, this approach to stability problems.

Risk-based approach according to IMO recommendation is formalized and includes the following steps:

1. Identification of hazards
2. Risk assessment
3. Risk control options
4. Cost-benefit assessment, and
5. Recommendations for decision making

4. Hazard identification

The first step of a risk analysis is to carry out hazard identification and ranking procedure (HAZID). Hazards could be identified using several different methods.

IMO resolution included general guidance on the methodology of hazard identification. With respect to stability, hazard identification could be achieved using standard methods involving evaluation of available data in the context of functions and systems relevant to the type of ship and mode of its operation. Stability is considered assuming that the ship is intact and accident evaluated is called LOSA (loss of stability accident) that is covering capsizing, that means taking position upside down, but also a situation where amplitudes of rolling motion or heel exceed a limit that makes operation or handling the ship impossible for various reasons -loss of power, loss of manoeuvrability, necessity to abandon the ship. In the last situation the ship may be salvaged [16].

According to general recommendation the method of hazard identification comprises mixture of creative and analytical techniques. Creative element is necessary in order to ascertain that the process is proactive and is not limited to hazards that happened in past. For this purpose a group of experts should be created consisting of specialists in design, operation, management and human factor.

Hazards identification was based on

1. Analysis of historical data on LOSA accidents.
2. Statistical analyses of cause of accidents available in various sources, *inter allia* in [1], [8], [9], [10]
3. Detailed description of LOSA accidents. For this purpose accidents of 20 described in detail casualties were analysed,
4. Analysis of the few accidents using TRIPOD methodology [22]
5. Evaluation by experts using DELPFIC method
6. Analysis by the group of experts

The group of experts was requested to evaluate the results of all the above analyses and to propose a list and ranking of hazards. Because of available resources to conduct engineering analysis was preferred in opposite to expert analysis as defined in [7].

The expert group recognized that the number of hazards defined as a potential situation to threaten the ship stability when considering all elements of the stability system is large and because of that decided to consider on the first level the following hazards

1. critical stability
2. forces of the sea
3. cargo shift
4. icing
5. human factor- management
6. external heeling moments
7. cargo and ballast operations
8. fire and explosion

Figure 2 shows fault tree for the first level. It shows all eight groups of hazards connected by "OR" gate; this however, does not preclude that two or more hazards may be present at the same time. The system is rather complex, because in further down levels of the fault trees there are strong interconnections between different factors. This is shown in the example of the fault tree (*Figure 4*).

In the above list, insufficient stability is defined as stability characteristics that do not meet IMO current requirements. Cargo shifting was singled out because in more than 300 LOSA casualties cargo shift occurred in about 40% cases. Fire is important because fire fighting water can reduce stability and cause capsizing (example: NORMANDIE in New York harbour in 1942). Forces of the sea include action of waves and wind. This may be the most difficult hazard to evaluate because of the complex hydrodynamic structural model of behaviour of the ship in a seaway. External heeling moments comprise different heeling moments apart of heeling moments caused by forces of the sea and shifting of cargo. In this category are heeling moment caused by water on deck, by centrifugal force when turning, fishing gear pull, tow rope forces etc.

Ranking for the frequency of hazards adopted in the application of Delphic method consisted of five groups (1 to 5) as proposed in [6]: (frequent, probable, occasional, remote and unlikely) that is different from the IMO recommendation [11]. Different ranking indexes are related to probabilities, but this was not revealed to participants of the exercise, because it seems that assessment of probability is very subjective and does not lead to reliable results. This is shown in *Table 1*.

Ranking, as proposed by the group of experts, that took into consideration all the above-mentioned results, differs in rather wide limits. That is understandable, because hazards probability is obviously different for different types of ships and for different modes of operation. For example, icing need not to be considered as hazard for ships operating in Mediterranean, and requires high ranking for ship s operating at high latitudes. The same applies to shifting of cargo, because in some ships there is no cargo that can shift.

Therefore no probabilities were attached to hazards at the first level. However an example of averaged ranking estimated by the group of nine experts is shown in *Table 2*.

Probabilities could be attached to different hazards when second and further down levels in fault trees are identified. Therefore the next step in the identification of hazards and estimation of their probabilities is construction of fault trees and event trees.

Table 1. Hazards classification

R	Description	Frequency per ship	Frequency per fleet	Probability (hourly)
1	Frequent	Likely to occur frequently – one or more times per year	Continuously	Greater than 10^{-3} do 10^{-4}
2	Probable	Several times per ship's lifetime – once every few years	Once or more times in a year	10^{-4} do 10^{-5}
3	Occasional	Likely to occur once during the lifetime of the ship	Several times during fleet's lifetime – once every few tears	10^{-5} do 10^{-7}
4	Remote	Unlikely, but possible during lifetime of the ship	Probable once during lifetime of the fleet	$<10^{-7}$
5	Extremely improbable	So extremely remote that it does not to be considered as possible to occur		Substantially less than 10^{-7}

Table 2. Averaged ranking of hazards as assessed by the group of experts

Hazard	Ranking			
	Ferry	Passenger ship	Container	Bulk carrier
Insufficient stability	1	4	2	2
Forces of the sea	4	4	3	4
Cargo shifting	4	1	3	3
Icing		4	4	
HOE	3	5	2	4
External heeling moments	2	3	3	2
Cargo and ballast operations	3		4	3
Fire and explosion	4	4	3	4

5. Risk evaluation

Risk is defined as a product of hazard probability and hazard severity (consequences):

$$\mathbf{R = P \cdot S}$$

To facilitate the ranking and validation of ranking IMO [11] recommended to define consequence and probability indices on a logarithmic scale. A risk index may therefore be established by adding the probability (frequency) and consequence indices. We have then:

$$\text{Log (risk)} = \text{Log (frequency)} + \text{Log (consequence)}$$

In order to assess risk, both quantities in the above equation should be evaluated. IMO recommended for the maritime safety uses–for the frequency of accidents ranking from FI=7 (frequent) to FI=1 (extremely improbable) and for consequences scale SI=1(negligible), SI=2 (marginal), SI=3(critical) and SI=4 (catastrophic). This classification is useful for the safety assessment in particular for the evaluation of risk control options.

With regard to safety against capsizing obviously we may consider only levels of frequency 1 to 4 and hazard severity of the category SI=3 (critical) and SI = 4 (catastrophic) because capsizing or loss of stability accident has always catastrophic or critical consequences and, on the other hand, probability of capsizing must be kept low. Catastrophic effect (Category SI = 4) would mean capsizing and loss of the ship, whether critical hazardous effect (Category SI =3) would mean dangerous list and loss of ability to sailing further, which, according to definition would mean loss of stability accident (LOSA).

Based on the above risk index matrix could be constructed (*Table 3*). The risk indexes applicable to stability (safety against capsizing or against LOSA accident) are grouped in the lower right corner of the matrix.

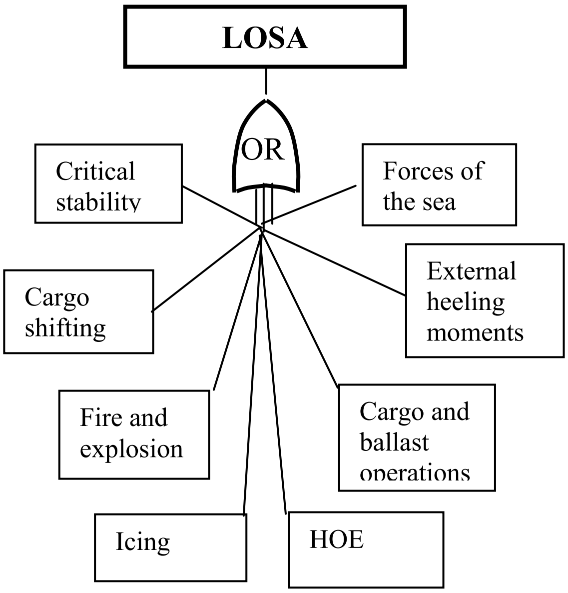

Figure 2. Basic events tree for stability

For assessment of risk index and in order to construct risk matrix, IMO resolution recommended using hazards and operability study (HAZOP). Frequencies of hazards could be assessed on the basis of risk contribution trees (RCT) being a set and combination of all fault trees and event trees as defined below [11].

A fault tree is a logic diagram showing the casual relationship between events, which singly or in combination occur to cause the occurrence of higher level event. It is used to determine the probability of the top event. Fault tree is to-down procedure systematically considering the causes and events at levels below the top event. The top events are events shown in the *Figure 2.*

Table 3. Risk matrix

Risk Index (RI)					
FI	FREQUENCY	SEVERITY			
		1	2	3	4
		Minor	Significant	Severe	Catastrophic
7	Frequent	**8**	**9**	**10**	**11**
6		**7**	**8**	**9**	**10**
5	Reasonably probable	**6**	**7**	**8**	**9**
4		**5**	**6**	**7**	**8**
3	Remote	**4**	**5**	**6**	**7**
2		**3**	**4**	**5**	**6**
1	Extremely remote	**2**	**3**	**4**	**5**

An event tree is logic diagram used to analyse the effect of an accident, a failure or an unintended event. The diagram shows the probability or frequency of the accident linked to those safeguard actions required to be taken after occurrence of the event to mitigate or prevent escalation. An event tree is down-top procedure starting from the undesired event and leading to possible consequences.

In the risk analysis of stability safety a number of risk contribution trees (RCT) have to be constructed, for each of the undesired event (hazard) in the first level hazard identification tree (*Figure 2*). Moreover, for some hazards require more than one fault and event tree to be constructed, because of possibility of different capsizing scenarios. Therefore, before RCT are constructed, different modes or scenarios of capsizing must be identified. This is particularly important with regard to forces of the sea, where more than twenty different capsizing scenarios could be identified.

Generally it appears that within risk analysis the system of RCT's may be quite complex, but in cases of risk analysis for concrete design it may by considerably simplified, because some of the hazards identified may be not applicable. As an example of this method risk contribution trees in the case of icing is shown.

6. A case study - icing

Icing was considered by the group of experts as one of the most serious hazards that may cause LOSA. Generally icing is considered dangerous for small ships and in particular for ships operating in high latitudes. However experts were of the opinion that icing is also dangerous for larger ships and not necessary operating in arctic water. As an example it was shown the photograph of icing that happened onboard M/S STEFAN BATORY in North Atlantic (*Figure 3*).

Figure 3. Example of icing in North Atlantic.(Photo: Kpt. Ż.W. Hieronim Majek)

Requirements concerning icing are currently included in the recommendatory part of the IS Code [12]. They are limited to the specification of amount of ice that has to be taken when calculating stability of ships sailing in certain areas. Those are general recommendations, the Administrations are encouraged to use different values of accrued ice if they have their own experience.

Te ice accretion is, however, o complex process. Not entering into details, it can be stated that ice accretion depends on several factors, of which the sea state, air and sea temperatures, wind velocity, ship speed and heading with regard to wind direction are of importance. In many cases ice accrued may exceed several times values recommended by IMO IS Code. Analysis of LOSA accidents reveals several casualties caused by ice accretion, some of them even in Black Sea [21].

The structural model for calculating effect of ice accretion is simple and it is identical to putting additional load onboard, but as the ice is accrued mostly on exposed decks, superstructures and rigging, the centre of gravity of ice accrued is positioned high. Therefore stability of the ship is impaired and the ship might be in dangerous situation.

The branch of fault tree for the case of dangerous icing must take into account

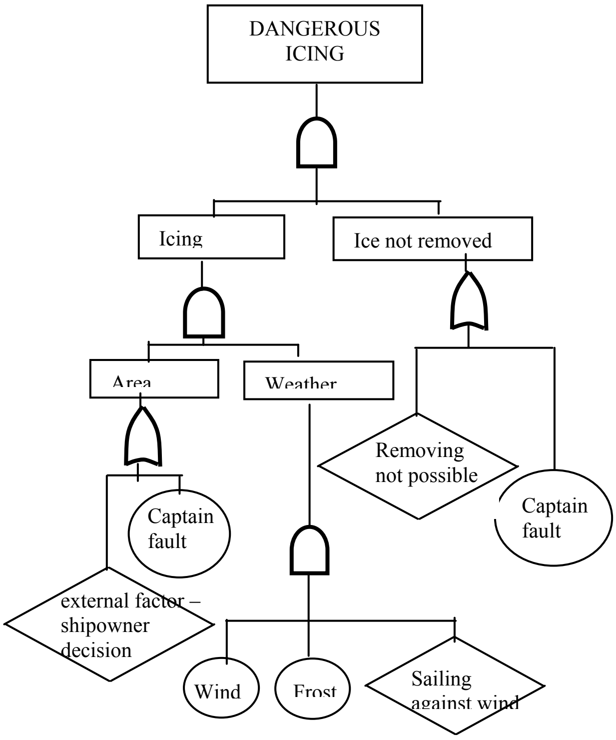

Figure 4. Branch fault tree for dangerous ice accretion

The branch of fault tree for the case of dangerous icing must take into account scenarios that may lead to LOSA accident. In all cases of icing the metacentric height and stability lever arms are reduced.

The simplest scenario is when the amount of accrued ice is so large, that the metacentric height becomes negative and the initial part of the stability lever arms curve is also negative. With the reduction of the stability characteristics probability of LOSA may increase even by two to three orders.

More complex scenarios, where human factor must be considered, are also possible. Accrued ice should be removed by the crewmembers. However it is not always possible. If the ship is sailing against the wind and waves in severe storm, when the conditions are most favourable for ice accretion in the bow quarters, it is not possible to send crew towards the bow in order to remove ice. It would be necessary to turn the ship to sail with the wind. Such manoeuvre is, however, dangerous and it may cause ship capsize, in particular if the removal of ice was started to late when the stability of the ship was already low.

Examples of fault tree and event tree for the case of dangerous icing are shown in *Figure 4* and *Figure 5*. It is obvious that two conditions are necessary for ice accretion: the ship must be in the area where icing is possible, and also weather conditions must allow that (negative temperatures, wind). Situation, where the ship is in the area where icing is possible and there are unfavourable weather conditions depends on sailing route, then on ship owner request or on decision of master who ignored the danger and makes no attempt to avoid the dangerous area.

Attaching probabilities to various events that appear in the fault tree and estimating on this basis probability of the top event should be accomplished mainly using expert's opinions. In some cases statistical data may be available in ship owners data bank. Review of the literature reveals that in case of icing such data were collected by some research institutes, but generally they refer to the amount of accrued ice in various conditions. Statistical data on effect of operational measures in case of icing are not available and probabilities could only be assessed o upon studying as many as possible real situations and accidents.

7. Risk control options and acceptability of risk

Considering risk control options three levels of action may be necessary if the risk index is over, say, grade 3.

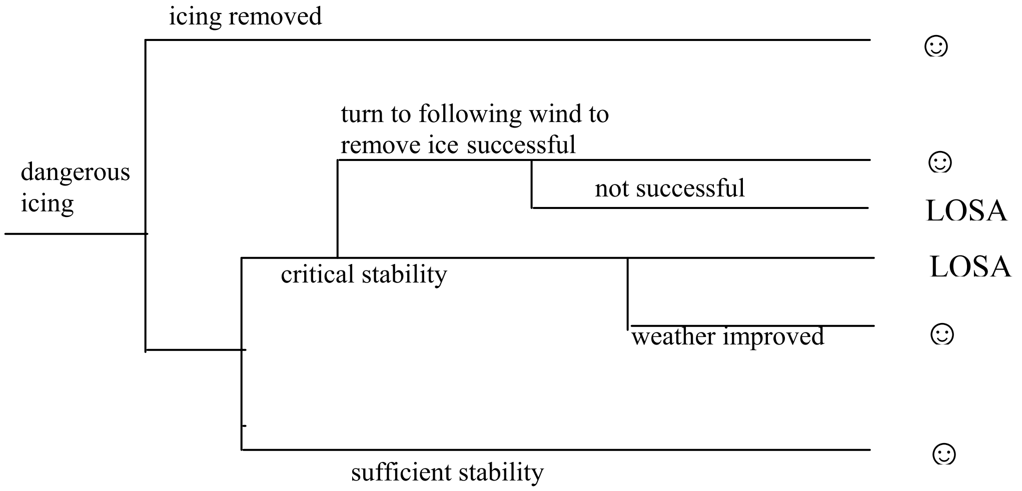

Figure 5. Event tree for severe icing consequences

Grade 8-9 – action to eliminate the hazard or hazardous situation (intolerable region)
Grade 6-7 – action to control or reduce the probability of the hazardous situation (tolerable region)
Grade 4-6 – action control the hazard, desirable, if cost effective

This problem is not elaborated because lack of space. Reference is made to [14] where risk acceptability and risk control options are discussed more widely.

8. Conclusion

Application of risk analysis may be quite complex task, requiring employment of large group of experts and analysts, nevertheless, is realistic. Risk analysis would reveal weak points in ship design, but also, which is more important, in management and operational procedures. It can also show where barriers have to be put in order to control risk. Risk analysis must be viewed as advantageous in comparison with the traditional prescriptive approach, although the last being much simpler, will certainly be used in majority of cases. Obviously, because of high effort and cost of performing risk analysis, in practice it could only be applied in cases of highly sophisticated large ships or ships with novel design features.

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