Emerging trends in ship design

D. Béghin
on behalf of Bureau Veritas, Paris, France

Abstract

After a brief review of the merchant fleet evolution over the past 30 years, the paper presents in a first part the emerging trends in ship structural design and emphasizes that a rational life-cycle design should be reliability-based and include maintenance and operational considerations. The paper reminds briefly the various probabilistic methods versus the share given to the probabilistic approach and, in conclusion of the first part, presents the integrated system VeriSTAR developed by Bureau Veritas as a first step toward a life-cycle ship design.

More generally, there are drastic foreseeable changes in the ship design philosophy, the most significant one being the move toward a Total Safety Concept. The second part of the paper gives an overview of these changes which will enable to develop more rationally-based Rules thanks to the use of risk analysis techniques for assessment of the ship safety.

1. Introduction

Development of the world economy from the second World War made necessary the design and construction of new types of ships such as VLCCs and ULCCs, LNG carriers, container ships, Ro/Ro ships, etc. The size of ships increased continuously up to the beginning of the seventies and, as an example, between 1955 and 1975 the deadweight of oil tankers was multiplied by a factor of 25...

However, the evolution has been modified in 1973 when the price of crude oil increased suddenly. At that time, the construction of tankers of one million tonnes deadweight was anticipated...

Such an evolution led to a complete transformation of the shipping industry and the crisis changed the pattern of the shipping market but did not stop the research which was, on the contrary, urged in many areas. For example, intensive research
has been devoted by engine manufacturers to reduce the fuel oil consumption of low or medium speed Diesel engines. Less spectacular but rather continuous improvements of the hull structural design have been made in the last decades.

In a first part, the paper presents some of the emerging trends in ship structural design with emphasis given to the use of probabilistic methods. In conclusion of the first part, the paper presents the integrated system VeriSTAR developed by Bureau Veritas as a first step toward a life-cycle ship design.

More generally, drastic changes in the ship design philosophy may be anticipated, the most foreseeable one being the move toward the so-called Total Safety Concept. The ship’s safety has to be considered as a whole and the objective of this new concept is to provide the shipping industry with comprehensive information on the ship condition, ship management and ship operation as well as on the crew competency. The second part of the paper gives an overview of these changes which will enable to develop more rationally-based Rules thanks to the use of risk analysis techniques for assessment of the ship safety.

2. Emerging trends in ship structural design

2.1 General

When considering the main areas of research, the following emerging trends in structural design philosophy may be noted:

- a move toward a rational life-cycle ship design,
- a move to include maintenance, repair and survey considerations as part of the integrated life-cycle approach,
- a move toward the use of probabilistic technologies, as part of design and maintenance,
- a move from prescriptive criteria to performance standards.

2.2 Rational life-cycle ship design

Life-cycle design means that all aspects concerning the design, construction, operation, ageing, maintenance and inspection are considered at the very beginning of the ship structural design.

By necessity, life-cycle design is to be based on first engineering principles, contrary to the past practice where the ship design was mainly based on experience, which was reflected in the Rules of Classification Societies.

A rationally-based structural design requires to assess the capability of the structure to withstand the loads to which it may be subjected during its life and, therefore, should be reliability-based due to the randomness of loads and resistance.
In the recent years, many efforts have been devoted to improve our knowledge of loads and, in particular, of impact loads such as slamming, sloshing and green waters. However, significant levels of uncertainties still exist and many research projects are under progress to improve the accuracy of loads considered to assess the structural reliability.

2.3 Maintenance considerations

Integration of maintenance, repair and survey considerations in the structural design is one of the important emerging trends. Strength criteria defined by the codes are generally determined for intact structures though the safety factors take into account effects of degradations resulting essentially from wear and tear, corrosion and fatigue, bearing in mind that the structural reliability is maintained over the ship's life thanks to a regime of periodical surveys (annual, intermediate and special). Corrosion and fatigue as well as loading and unloading operations are recognized as the main causes of structural damage occurring on ships in service. More and more, Rules of Classification Societies give necessary information to take into account these aspects at the very beginning of the design (e.g. Bureau Veritas\(^1\).)

It is worth mentioning that application of reliability methods to inspection and maintenance as well as to structural design should enable to optimize the intervals between surveys. To date, surveys carried out by Classification Societies occur at fixed intervals and do not depend on the foreseeable evolution of the structure as it might be determined from analysis of the results of previous surveys and expected corrosion rates. This present practice will evolve in the future and application of reliability analyses will certainly enable to optimize the inspection planning of ship structures.

2.4 Performance standards

Performance standards have been introduced in the automotive industry for many years. For example, cars are to be designed with a view not to exceeding a given deceleration at a given speed in case of head-on impact. Ship rules address the structural behaviour for intact structures and do not generally consider the residual performance in the case of accidents. International reactions to the latest accidents of ships emphasize that it is urgent to develop design tools enabling to assess the consequences of accidents on human life and/or environment.

In that respect, several research projects are under progress and, when completed, will give valuable information on the actual extent of bottom or side shell damage in the case of grounding or collision. It may be anticipate that, in a next future, design codes will include requirements on typical accidental scenarios and corresponding performance criteria. IMO Guidelines for determination of Oil Spill of Tankers may be considered as an example of that trend.
In conclusion, performance standards will be introduced in Rules of Classification Societies, in addition to prescriptive criteria, for assessment of the residual strength of the hull structure in accidental conditions. Moreover, this will lead to promote emergence of new designs all the more as it is frequently stated that "prescriptive criteria inhibit innovation and remove the incentive to advance the ship technology while performance standards tend to promote new developments and innovations in terms of structural design" (4).

3. Reliability-based structural design

3.1 General

An oceanic structure is a complex thin stiffened shell with randomly disposed fabrication imperfections due to material and workmanship quality. During its life, it has to withstand various loads resulting from the action of winds, waves, currents, ice, temperature, etc. It is clear that an objective evaluation of the strength of a given structure is an impossible task, all the more as there are many uncertainties in the design of marine structures, among which :

- blunders, which include neglects and events not previously considered as a possible cause of failure. Blunders are considered to be responsible for 86 % to 90 % of failures, mainly due to human errors,
- random and systematic errors : they can be divided into statistical uncertainties, like strength, for which statistical data are available, and approximational uncertainties for which much experience and judgement are required (e.g. Hughes).

Safety concepts are generally classified according to the share given to probabilistic calculation. But whatever concept is used, the designer must define the capability "C" of the structure or structural element, that is to say its ability to withstand the load or demand "D" it may be subjected to. Therefore a criterion must be chosen, representing the limit above which the structure is considered as having failed. This criterion should be independent of loads and should be a specific characteristic of the material and/or the geometry of the structure.

3.2 Probabilistic design methods

3.2.1 Full probabilistic methods

Though efficiency of the deterministic safety factors considered in the present Rules of Classification Societies is well proven, it is generally difficult to identify the type and nature of uncertainties which are taken into account and to be sure that the safety is optimum.
To take into account the randomness of loads and strength, it is necessary to base the structural design on a probabilistic approach. In that case, the risk of failure is defined as the probability of a load reaching or exceeding its limit value:

\[ risk = P_f = \Pr \{ Q > Q_l \} \]  \hspace{1cm} (1)

The more general probabilistic method consists in considering all the various random variables to calculate the risks associated to each mode of failure and to combine them to obtain the probability of failure for the structure. If the "joint" probability density function for the basic variables is known, the probability of failure is given by:

\[ P_f = \int_{g(x)<0} p_{X_1, X_2, \ldots, X_n}(x_1, x_2, \ldots, x_n) \, dx_1 \, dx_2 \ldots dx_n \]  \hspace{1cm} (2)

where \( g(x) = g(x_1, x_2, \ldots, x_n) \) is the limit state function which characterizes the condition of the structure and defines two domains of safety:

- \( g(x) < 0 \) in the unsafe domain,
- \( g(x) > 0 \) in the safe domain,
- \( g(x) = 0 \) on the limit surface.

However, the "joint" probability is generally unknown and approximate methods based on the safety index concept are used to assess the structural reliability.

### 3.2.2 Approximate probabilistic methods

#### 3.2.2.1 Hasofer and Lind safety index

This method enables to calculate the safety index \( \beta \) from a geometrical approach. The problem illustrated in Figure 1 is expressed into a standard space of normal, reduced and independent variables. Then, the safety index \( \beta \) is defined as the minimum distance from the origin to the failure surface.

![Figure 1: Geometrical definition of the safety index](image-url)
3.2.2.2 Cornell safety index  Assuming that the limit state function is given by 
\( g(x) = C - D \), Cornell proposed to characterize the structural reliability by its safety index defined as follows :

\[
\beta = \frac{\bar{g}(x)}{S_g} = \frac{\bar{C} - \bar{D}}{\sqrt{S_c^2 + S_d^2}}
\]

where :

- \( \bar{C}, \bar{D} \) : capability and demand for the structure, assumed normal and independent random variables,
- \( \bar{g}(x) \) : mean value of \( g(x) \),
- \( S_g \) : standard deviation of \( g(x) \),
- \( S_c, S_d \) : standard deviations of the capacity and demand.

Moreover, where the limit state function is a linear function of the random variables assumed normally distributed, the probability of failure is given by 
\[ P_f = \Phi(-\beta) \], where \( \Phi \) is the standard normal cumulative distribution function.

3.3 Semi-probabilistic methods

Semi-probabilistic methods which are based on the Partial Safety Factor (PSF) concept, consider characteristic or nominal values for the basic variables. The safety of the structure is expressed in terms of Partial Safety Factors (PSF) taking into account all the uncertainties which intervene in determination of the design variables and expressed as follows :

\[
\gamma_d \gamma_f F_k < \frac{C_k}{\gamma_m \gamma_c}
\]

\( F_k \) characteristic values of loads, corresponding to a specified percentage of the area under the probability curve,

\( C_k \) characteristic value of the capacity,

\( D(\gamma_f F_k) \) value of the demand calculated from the characteristic values of loads and weighed by the partial safety factor \( \gamma_f \),

\( \gamma_d, \gamma_f, \gamma_m, \gamma_c \) partial safety factors taking into account the various uncertainties which intervene in determination of the design variables.

Determination of the Partial Safety Factors (PSF) necessitates :
- the identification of the various modes of failure or limit states which may deteriorate the structure,
- the definition of a limit state equation for each mode of failure,
- the carrying out of reliability analyses for the various types of ships, structural elements and modes of failure, with a view to producing structures with the most consistent and uniform safety index.

4. Integrated systems

4.1 General

All emerging trends in structural design mentioned previously cannot be practically implemented without the help of integrated systems covering design and maintenance. Several systems, among which the VeriSTAR system developed by Bureau Veritas, have been distributed by Classification Societies in the recent years and represent a first skeleton of these future integrated systems.

4.2 Present status of Classification

Traditional classification consists in gathering technical information enabling an appreciation of the degree of confidence, or class, granted by the Society to ships. This mission is achieved through certification of compliance with Rules set up by the Society. In particular, this appreciation concerns the structural reliability and, to that end, Surveyors refer to the Rules in a sequential process which includes:

- **Design review** - The structural reliability with respect to the various limit states is verified and safety factors are calculated according to deterministic procedures.
- **Construction survey** - Carried out to ensure that the construction is made in accordance with the reviewed drawings and with the state-of-the-art.
- **In-service survey** - Aiming at verifying at each periodical survey that the structural reliability is adequate for the next five years period, subject to proper maintenance. If structural problems are detected, repairs are required prior to renewal of the class certificate.

One characteristic of this system is that each step is considered separately. This is appropriate to the linear scheme of the classification where the output required at each step is a statement of conformity with rules.

4.3 New classification concept

Keeping in mind the demand of the shipping industry for improved safety, a new classification scheme has been developed by Bureau Veritas. The main objective
is to offer shipowners and shipyards advanced techniques to improve the design and maintenance of ships, based on:

- direct engineering analyses, allowing for a better distribution of materials and more homogeneous definition of safety factors,
- issuance of a "hot spot map" for the hull structure,
- comprehensive and permanent computerized data base for each ship,
- computerized system for survey data acquisition,
- systematic evaluation of the hull condition.

To that end, two additional class notations (e.g. Bureau Veritas) are proposed:

- for design review : RSD "Rational Ship Design",
- for ships in service : STAR "System of Tracability and Analysis of Records".

To achieve this objective one fundamental feature is necessary:

**A complete and permanent database for each ship** permanently maintained and up dated. This database will include all the data gathered during the ship’s life and, in particular, the information obtained during the periodical surveys.

In conclusion, the VeriSTAR system integrates the design analysis techniques into the ship's in-service life, using survey data to assess at any time of the ship’s life the structural reliability and to judge whether repairs or structural renewals are necessary.

### 5. Emerging trends in ship design

#### 5.1 Total Safety Concept

##### 5.1.1 General

Recent accidents which occurred in the shipping industry as well as in other industries, reveal that the public is less and less prepared to accept risks to the human life and environment, inherent to the human activities. Therefore, the most foreseeable change in the ship design philosophy will be, in the coming years, the move towards the so-called Total Safety Concept.

Traditionally, Class Societies were more concerned by the ship safety while the Flag Administrations were more responsible for the safety of persons and protection of the environment. This distinction between the role of Flag Administrations and Class Societies is less and less meaningful as more attention is paid to the human life and protection of the environment. The ship’s safety has to be considered as a whole and the objective of the Total Safety Concept is to
to be considered as a whole and the objective of the Total Safety Concept is to provide the shipping industry with comprehensive information concerning the ship condition, ship management ship operation as well as the crew competency.

Application of the Total Safety Concept makes necessary not only to control the performance but also to provide for malfunctions from ship design to ship operation. Such an approach may be implemented thanks to the use of risk analysis techniques based on assessment of:

- **reliability**, i.e. capability of a system to fulfil its function,
- **availability**, i.e. ability of a system to ensure its primary role,
- **maintainability**, i.e. ability of a system to be inspected and repaired, and
- **safety of systems**.

### 5.1.2 Risk analysis
First, it may be useful to remind that risk is the danger which undesired events represent for humans, environment and economical values and may be defined as the product of:

- the probability of occurrence of an unexpected and undesired event, and
- the consequences that this unwanted event produces.

A complete risk analysis includes the following steps:

- definition of reliability objectives, i.e. acceptable risks,
- identification of hazards,
- identification of accidental scenarios,
- quantified risk assessment for evaluation of risks associated to these adverse events,
- identification of risk reduction and mitigation measures,
- analysis of costs and benefits, and
- recommendations for decision making.

### 5.1.3 Risk management
Basically, risk management necessitates to define a safety policy and risk targets. These targets are generally defined by observing what the Society tolerates for the individual risks (loss of life), societal risks (number of fatalities or environmental pollution) or financial risks (loss of property, production or insurance). Due to the dramatic consequences that accidents may have on human life or environment, levels of permissible risks have to be fixed by National Authorities. Since these risk criteria are not based on scientific calculations, they may vary from one country to another one. As an indication, the present target of individual risk is estimated to $10^{-4}$ per year (1 death due to an accident or fatality out of 10,000 people per year).
Finally, there is a need to develop a safety culture among the Society and the public which is less and less prepared to accept risks, must be aware of the impact on cost that improvement of safety represents. Moreover, emergence of the total safety concept urges the development of probabilistic methods for design, operation and maintenance of ships, with a view to being in a position to quantify the risks associated to the various adverse events.

5.2 Human element

Another important trend for the future concerns the move to address the human element as part the overall safety, bearing in mind that human action plays a part in more than 70 per cent of ship’s accidents.
To date, Human Error Analysis techniques are used to identify and reduce the likelihood of human errors. HEA has to start as early as possible during the design phase of a system in order to optimize the system from that point of view. Following areas can be interested by human errors:

- design of Man Machine Interface and Control & Command system,
- steering/manoeuvring activities,
- maintenance activities,
- organisational activities,
- training of the personnel.

The organisational activities are covered by the International Safety Management Code. From 1st July 1998 all passenger ships, oil tankers, gas carriers, high speed cargo craft of 500 gt and above have to comply with the ISM Code while other cargo ships, mobile offshore and drilling units will have to comply by 1st July 2002.

To cope with the training of the personnel, the STCW Convention has been amended in 1995 and all seafarers will have to comply with these requirements on February 2002.
Research is needed to design systems less and less dependent on the human judgment or for which consequences of accidents are minimized.

6. Conclusion

This review of the emerging trends in ship design shows that the structural design is more and more reliability-based. However, large efforts are yet needed prior to introducing reliability analyses as a standard design tool. This research concerns improvement of loads and strength calculation technologies as well as the development of reliability-based codes.
In the future, application of probabilistic methods should improve the structural reliability of ships thanks to:

- the distinction between applied loads and capacity of the structure,
- a better knowledge of uncertainties to be considered for scantlings,
- a better consistency of the calculations,
- the quantification of risks (determination of the probability of failure and comparison with experience).

More generally, design codes will have to address more and more all the aspects of safety, taking into account that the public is less and less prepared to accept risks on the human life and environment. Application of risk analysis techniques to ship design will enable to develop more rationally-based codes and to promote the move toward a Total Safety Concept.

References


