The Application of Goal Based Design for Passenger Ship Safety Improvement

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Abstract. SOLAS (International Convention for Safety Of Life At Sea) Chapter II-2/Regulation 17 and Chapter III/Regulation 38 allow for the adoption of "Alternative designs and arrangements" that deviate from the ones permitted by prescriptive regulations. The process to be used for the Alternative Design engineering analysis is documented by SOLAS by means of guidelines and requires a holistic and consistent risk assessment to demonstrate that the risk introduced by the novel design is less or at least equal to the one guaranteed by the prescriptive reference design. This activity de facto introduces the Goal-Based Design into the traditional design process by evaluating safety as a main goal in the ship design. This approach is possible thanks to the research activity aimed at improving the application of the simulation tools that are used to quantify the risk level of a specific design solution and its variants by evaluating the human element in the design. In this paper examples of shipbuilding application of goal based design are presented together with an overview of the new frontier in the adoption of these approaches for the improvement of safety and the maximisation of the ship payload.

Keywords. safety, goal based design, risk-based, risk-based design, risk-based approval, alternative design and arrangements risk assessment, evacuation simulation.

1. Introduction

The 1st of July 2002 marks the date of entry into force of MSC Res.99(73) and its comprehensive review of Chapter II-2 (Construction - Fire Protection, fire detection and fire extinction) of SOLAS. Such review not only modified format and regulation references but also introduced the instrument of "*alternative design and arrangements*": fire safety design or arrangements may now deviate from the prescriptive requirements provided that the design and arrangements meet the fire safety objectives and functional requirements indicated in the new chapter II-2.

The concept of deviation is not new in SOLAS: Reg.5 "*Equivalents*" in Chapter I (General provisions) states that any fitting, material, appliance of apparatus other than that required by SOLAS may be fitted or carried in a ship as long as the Administration "*is satisfied by trial thereof or otherwise that such fitting, material, appliance or apparatus, or type thereof, or provision, is at least as effective as that required by the present regulations*". What is new in the revised SOLAS II-2 is the detailing of a fire engineering methodology for the identification and determination of fire safety performances necessary for the comparison of the Alternative Design and Arrangement

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with the prescriptive one. The acceptance criteria of "*degree of safety not less than that achieved by using the prescriptive requirements*" is retained but the innovation is represented by the introduction of quantifiable and measurable performance criteria as opposed to the more generic "satisfaction" mention in Reg.5 of Chapter I.

The "*Alternative Design and Arrangements*" (AD&A) compliance approach of the revised SOLAS II-2 was also extended to Chapter II-1 (Construction – Structure, stability, installations) and Chapter III (Life-saving appliances and arrangements) by MSC Res.216(82) which entered into force on the 1st of July 2010. Reg.5 of Chapter I is still valid for the remaining SOLAS chapters.

2. Present Common Applications of Goal Based Design in Large Cruise Ship Design

Nowadays many shipyards design cruise ships offering arrangements and technical solutions, mainly challenged by Owners and new opportunities offered by technology and materials, which can be achieved only with an Alternative Design study. Owners requests are usually related to an increase of payload, to enhance comfort and architectural solutions, or to reduce ship weight increasing ship efficiency.

Some of the most frequent applications of goal based design made possible by the Alternative Design process are described below.

2.1. Main Vertical Zones exceeding the SOLAS prescriptive limits.

The adoption of Main Vertical Zones with a length of more than 48 meters and / or a surface area greater than 1600 square meters – limits set by SOLAS II-2 / Reg.2.2.1.2 - comes from different needs. This solution allows both to accommodate a larger number of passengers in the same fire zone and to allocate larger areas to public spaces - such as restaurants and atria - with greater accommodation capacity and greater appeal for increasingly demanding guests. At the same time, the aforementioned benefits are obtained by satisfying the always pressing need to increase the payload with more rational ship layouts and fire-resistant subdivisions.

2.2. Adoption of Lifeboats of Increased Capacity

The International Life-Saving Appliance (LSA) Code, aimed at providing standards for life-saving appliances required by SOLAS Ch.III, states that lifeboats with a capacity of more than 150 people cannot be used. In the last ten years, the gradual but continuous increase in the size of large cruise ships and the consequent increase in the maximum number of passengers embarked paved the way for the adoption of lifeboats with a capacity that exceeds this limit.

If no lifeboats with increased capacity were installed, the number of standard lifeboats (150 people capacity) required to meet the SOLAS minimum requirements would be such that not all lifeboats could be arranged on the ship sides due to lack of space.

2.3. Adoption of Large Sliding Fire Doors

In accordance with what requested by IMO MSC.1/Circ.1319, the goal of these studies is to demonstrate the equivalence in terms of safety of the adoption of large A-60 Class fire

sliding doors having sizes that exceed those of the specimens that can be fire tested in the standard IMO-FTP furnace. For large doors having a surface area that exceeds for more than 50% that of the corresponding fire-tested door, the circular recommends to perform a full analysis based on SOLAS regulation II-2/17, that is an Alternative Design study.
These kind of studies are not only focused on large A-60 fire doors with their mechanical and electrical systems – including all aspects related to the local and remote control and monitoring of the doors' status - but also deeply investigate all the safety-related aspects in the areas of the ship connected by these large doors.

2.4. Adoption of New Materials

The use of new materials on ships has become more prevalent in recent decades. Along with the improvements to materials, construction methods and applications, it comes an increased responsibility to ensure that vessels are safe for their passengers and crew and fire safety is part of that overall safety concern. An inherent problem with some promising materials is that they are "*not non-combustible*". Nevertheless, they prove good performance as far as fire resistance is concerned. This peculiarity makes these new materials very attractive in other engineering fields of application but not for the marine one as the "*non combustibility*" is mandatory within SOLAS for some applications (e.g. steel and insulated aluminum are the only materials allowed). The benefits of using such materials in shipbuilding can be valuable in terms of weight reduction, noise containment and, last but not least, energy saving. It is deemed there may therefore be scope, where appropriate and justifiable, to consider designs where a new balance between the "restriction" of the use of combustible materials and the usage of new technologies and materials can be reached. On the other hand at present SOLAS allows the use of furniture and furnishings without particular requirements - such as free standing furniture (sofas, tables, chairs, cabinets etc), bedding components, linings, carpets, decorations, etc. - as far the fire load amount is concerned. These Alternative Design studies are aimed at evaluating the performance, including those under fire conditions, of designs built with novel materials. Often these materials are already accepted and widely adopted in civilian engineering, where performance-based codes have already been adopted for a long time.

Being the installation of such materials not fully in accordance with SOLAS Chapter II-2, these innovative solutions must be the subject of a process of Alternative Design & Arrangements in order to demonstrate that the achieved level of safety is at least equivalent to the prescriptive one.

This engineering analysis does not rely on a comparison of the proposed AD&A with an existing prescriptive design solution. Although consideration is usually given to compare material performance and detail of construction of novel and prescriptive systems, the engineering analysis focuses on a "performance-based design" rather than a direct comparison between a prescriptive and an alternative solution.

3. Advanced Simulation Tools

Advanced simulation is nowadays a essential step in a performance-based design approach. The most common areas of application are pedestrian evacuation and fire & smoke modeling; often a combination of both techniques is adopted in the assessment of fire safety performance.

The mathematical models embedded in these tools allow to check a substantial set of parameters against the performance criteria to be met, including the duration of an evacuation process and the concentrations of fire pollutants capable of jeopardizing the tenability of the areas where the fire casualty takes place.

SOLAS requires that the tools used in performance-based studies are recognized by Flag Administrations and/or Class Societies for marine application and deemed capable of taking into account peculiar issues related to the marine environment and maritime operations. In this area, CETENA develops specific research activities aimed at identifying appropriate tools and methodologies to support the industry in the various design stages. For this purpose, two simulation tools have been identified as reliable and effective for Alternative Design studies:

- Fire Simulations: Fire Dynamics Simulator (FDS) developed by NIST (American National Institute of Standards and Technology) is used to simulate the development of fire and the subsequent production and spread of smoke and toxic gases. This software is developed and kept updated by NIST in the framework of a research project including testing activities [1].
- Evacuation Simulations: EVI (developed and distributed by Brookes Bell Group), used to perform evacuation simulations, is an agent-based software tool capable of reproducing the human behavior, in terms of interaction with other people and environment, during an evacuation process.

4. Future Applications of the Goal Based Design

An attractive application of goal based design currently under development consists in the definition, and subsequent evaluation, of design configurations aimed at maximizing economic opportunities - such as the increase of the payload - taking into account safety as one of the main design driver. An application under investigation is the revision of the means of escape design philosophy, in particular the sizing of the evacuation routes. At present evacuation routes, such as corridors and stairways, shall meet the prescriptive requirements reported in SOLAS II-2 Part D - Reg. 13 and in FSS Code. If such escape routes do not comply with these requirements, a review of the design related to ship evacuation can only be carried out in the framework offered by SOLAS Chapter II-2, Reg.17. This entails the implementation of a structured Alternative Design and Arrangements process aimed at demonstrating the equivalence of the alternative solution compared to the prescriptive one in relation to the satisfaction of the Fire Safety Objectives stated in SOLAS II-2 Regulation 2.1. In this regard, some industry research activities are underway aimed at achieving the following goals:

1. the definition of a set of standard ship layouts that offer the best compromise between an adequate level of safety (with particular reference to the flows of people in evacuation) and the payload increase;
2. the creation of industry design guidelines for enhancing design flexibility (i.e. increase of people load during ship contractual stage, change of ship layout, etc.).

4.1. Affected Regulations

The purpose of SOLAS II-2 Part D - Regulation 13 is to ensure the adoption of means of escape designed in such a way that people on board can quickly and safely reach the embarkation deck and then evacuate by means of lifeboats, liferafts and/or Marine Evacuation Systems.

A far as the design of the escape routes is concerned, Regulation 13 recalls Chapter 13 of the Fire Safety System Code (FSS Code) which gives detailed indications about the methodology to be adopted for sizing the evacuation routes.

In particular, for stairways designed as secondary means of escape one requirement is the minimum clear width of 900 mm regardless of the number of persons expected to use them. Stairways that are intended for the escape of more than 90 people must be aligned bow-stern or vice-versa) and shall not exceed 3.5 m in vertical rise without the provision of a landing. In addition, they shall not have an angle of inclination greater than 45°. The need for a landing is due to the fact that, in the event of a general alarm, people on each deck may enter the stairs at the same time. This means that people entering the stairwell can find it already occupied by those coming from other decks and will have to wait for a certain amount of time before channelling into the flow of people in transit. In any case, and regardless of the number of people entering the staircase, the landing must have at least 2 square meters of net area.

In general, SOLAS calculation procedure is intended to evaluate the minimum stairways width (eg. flights, intermediate landings and main landings) at each deck level taking into account all the flows of people entering the staircase (e.g. from cabins, corridors, public areas, service areas and work areas) [3].

5. Case Study - Review of the Evacuation Routes Design

5.1. Region of Analysis

The passenger ship analysed in this case study is a generic large cruise ship with a gross tonnage of about 170.000 GRT, more than 20 decks and a total number of embarked persons in excess of 6.500, 5.000 of which are passengers and 1.500 are crew members. The ship is longitudinally divided into 6 Main Vertical Zones (MVZ) having almost equal lengths. It is worth noting that a vessel with these characteristics will be divided into main fire zones that exceed, on all decks or on most of them, the prescriptive limits of length (48 m) or maximum area per deck (1600 m^2) set by SOLAS II-2 / Reg.2.2.1.2. This feature gives the project the additional peculiarity of being able to accommodate on any deck of any MVZ a number of people greater than what could be accommodated in any area with similar intended use of a fully SOLAS compliant ship.

Three passenger staircases are located in MVZ 3, 4 and 6 while other two service staircases are arranged in MVZ 2 and 5. It is also assumed that deck 7 is the embarkation deck.

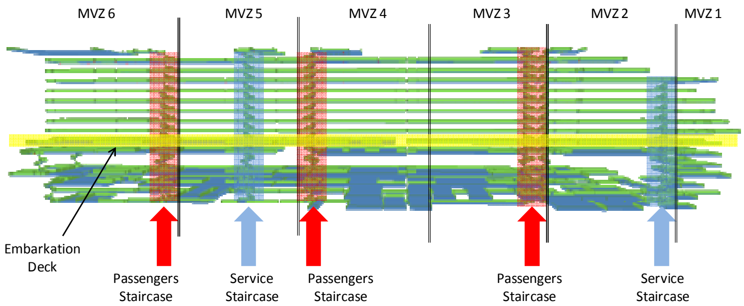


Figure 1. longitudinal view of staircases and embarkation deck layout (evacuation simulation model)

5.2. Ship model and People Distribution on Board

In order to proceed with the evaluation of the evacuation performance (i.e. time) related to this ship layout, the following activities have to be carried out:

1. ship mode layout setup;
2. distribution of people onboard definition;
3. population characteristics definition (e.g. speed distribution, gender distribution)

Evacuation performance must be evaluated in two SOLAS scenarios as referred in MSC.1 / Circ 1533, i.e. the night case and the case day.
These cases represent the two typical operational scenarios during a ship voyage. At night, passengers are sleeping in their cabins while crew is part at rest in cabins and part on duty. During daytime passengers are mainly accommodated in public spaces and crew are mainly involved in service operations or in their rest areas.
The distribution of passengers and crew in the two different scenarios are defined by ship contractual souls on board (SoB) and Chapter 13 of the FSS Code as a reference.

5.3. Analysis of Night Case scenarios - Worst Case Scenarios

Only the scenarios deemed worthy to be investigated by an evacuation simulation are selected, in particular:

- Night Scenario 1: simultaneous evacuation of MVZ 5 and MVZ 6 to the embarkation deck, with the maximum number of occupants (passengers and crew) at night-time, through the passengers staircase located in MVZ 6. Passengers staircases are considered designed in compliance with the FSS Code.
  The investigation of this scenario is aimed at providing a reference time and therefore a benchmark for the assessment of the following scenario 2.
- Night Scenario 2: as per scenario 1 but with reduced width passenger staircase.
  The resulting total evacuation time can be compared with the one obtained by the simulations of the Night Scenario 1.

The night case is judged to be the most hazardous as the number of people to be evacuated is very high and distributed on a number of decks greater than in the day case. Moreover, at night, the distances that people have to travel to get to the embarkation deck are larger than those that they should travel during the day.
The reduction of escape width may lead to:

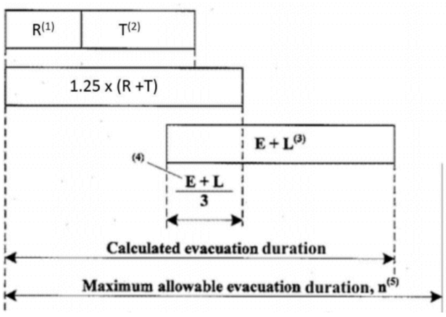
- increase of congestions and queues, both at the stairways entrance on each deck and inside the staircase itself and

- a general slowdown in the evacuation process.

5.4. Performance Criteria

Performance criteria are measurable quantities stated in engineering terms to be used to judge the adequacy of the Alternative Designs. These are usually set up taking into account SOLAS Safety Objectives and Functional Requirements; in particular for our case study they are derived from SOLAS II-2 and relevant IMO circulars:

- Reg. 2.1.1.1.5 states *".5 provide adequate and readily accessible means of escape for passengers and crew."*
- MSC.1/Circ.1533 Annex 1 par. 5.2 and 5.3 suggest the performance standard for total evacuation duration for a passenger ships:



$$1.25\,(R+T) + 2/3\,(E+L) \leq 80\ min \quad (1)$$

Where:

- R: Response duration for people to react to the situation;
- T: Total travel duration for all persons on board to move from where they are upon notification to the assembly stations
- (E+L): Embarkation and launching duration required to provide for abandonment by the total number of persons on board, starting from the time the abandon ship signal is given after all persons have been assembled, with lifejackets donned. This figure has not to be greater than 30 min.

For what above, according to SOLAS, a ship evacuation can be considered sufficiently safe if the total travel time (T) is lower than 48 minutes (solving equation 1 with E+L=30). In other words night case scenario 1 and 2 can be considered satisfactory if the time that people take to get to the assembly stations is lower than 48 minutes.

6. Results of the simulations

Since there are many uncertainties in the evacuation process (eg. people position onboard, people age, gender, walking speed, awareness time, etc.) simulations are carried out with a probabilistic approach. For each simulation all relevant figures are randomised around the average reference value (e.g. Gaussian distribution) and as a result, the travel evacuation time is not a single figure but comes as a statistical distribution.

The comparison among the considered night scenarios gives a very interesting picture of the ship evacuation performance. The variation of the escape routes size, expressed in term of total surface, plays an import role in the evacuation overall performance. As shown in Figure 3, an optimisation of the escape routes surface may provide an increase of area for extra payload up to 15 %, assuring at the same time the evacuation performance required by SOLAS. Conversely, Owners requirements lead to an increase of surface area for evacuation routes, driven by architectural choices, with a lower evacuation time with respect to what requested by SOLAS.

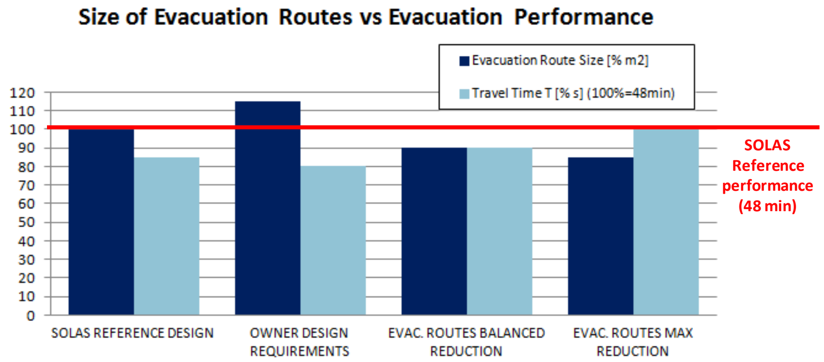


Figure 3. Scenario Performance Comparison

7. Conclusions

The introduction of Goal Based Design approach offered the designers new opportunities and challenges for ship design. In particular by evaluating the ship safety performances it is possible to redesign some layout of the ship out of SOLAS prescriptions. The results of the presented case study shows that for big passenger ship the size of escape routes has some safety margins. Some of these margins can be converted in payload without jeopardise ship escape capability.

Industry research activities in these topic are ongoing with the aim to constantly improve people safety by exploiting new technologies, materials and methodologies.

References

[1] MSC.1/Circ.1533, 6 June 2016 “Revised Guidelines On Evacuation Analysis For New And Existing Passenger Ships”
[2] IMO FSS Code
[3] V Bucci, A Marinò, G. Trincas and G. Zanutto, "Innovative tools for advanced evacuation analysis of passenger ships" 15 th International Conference on Ships and Shipping Research NAV 2015, Lecco, 2015, pp. 591-599.
[4] V Bucci, A Marinò, F. Mauro, R. Nabergoj and C. Nasso "On advanced ship evacuation analysis" 22nd International Conference Engineering Mechanics 2016, Svratka (CZ), 2016, pp. 105-112.
[5] Apostolos Papanikolaou (Ed.), Risk-Based Ship Design - Methods, Tools and Applications, Springer 2009
[6] SAFEDOR–The Implementation of Risk-based Ship Design and Approval
[7] IACS MSC 81/INF.6, “Goal-based new ship construction standards - linkage between FSA and GBS”
[8] IMO MSC/Circ. 1002, “Guidelines on alternative designs [and arrangements for fire safety”
[9] IMO MSC-MEPC.2/Circ. 12, “Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process”.