Advanced Evacuation Analysis considering the effects of fire using Computational Methods

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The analysis to verify the adequacy of escape routes for evacuation is mandated by SOLAS for new passenger vessels, w.e.f 1st January 2020. The analysis needs to consider several factors including the composition and walking speed of the passengers, location and geometry of the escape routes etc. It is thus beneficial to perform an advanced evacuation analysis considering the various influencing parameters for precise assessment of evacuation time for a given design/layout and effect due to change in the parameters. Advanced evacuation analysis helps in identifying the critical bottlenecks in the evacuation path and facilitate design improvement effectively.

The present paper presents description of performing advanced evacuation analysis with a practical example. Also presents description on coupling of advanced evacuation analysis with computational fluid dynamics (CFD) solver to compute the effects of fire (smoke, heat and toxicity) on the passenger walking speed with an example of fire inside a restaurant scenario.

KEY WORDS

Evacuation Analysis; Fire Dynamic Simulator (FDS); Fractional Effective Dose (FED); Heat Release Rate (HRR); Maritime Exodus; Ship accidents.

INTRODUCTION

Ships are subject to accidents which may culminate due to several causes; majorly due to capsizing/foundering, stranding, collision, fire/explosion, structural failure etc. Such accidents can typically lead to total loss or serious damage to the ship as well as injuries/fatalities of the crew and passengers. Based on the ship accident data from Papanikolaou et al., 2015; Butt et al., 2013 and AGCS, 2014, between the years 1990 to 2013 10841 serious ship accidents were recorded. Among these accidents, by foundering is predominant, i.e. between 40% and 50%. The next most important accident is stranding, followed by collision and fire/explosion. Fire accidents are between 10% to 15%. It is important to incorporate safety measures on board in terms of design and operations so as to prevent injuries/fatalities onboard consequent to the accidents. Evacuation is thus an important component of the safety measures especially for passenger and ro-ro passenger ships where there could be typically thousands of persons onboard. IMO has recognized the importance of evacuation and mandated evacuation analysis for all Passenger and Ro-Pax vessels w.e.f. 1st January 2020.

One of the important scenarios to be considered while designing escape routes is fire. There are various parameters which should be considered while investigating such scenarios. Recognizing the importance to understand the various parameters involved, the Association of Asian Classification societies (ACS) tasked a Project Team to study the study the same.

The present paper describes the ongoing project team work. Maritime Exodus - Smart fire and FDS - Evac analysis softwares were used by the project team. In both these softwares, the evacuation model is integrated with a CFD solver for performing fire simulations. For example, in FDS-Evac software the motion of each person is governed by an equation of motion. This approach is thus able to simulate the physical abilities of each person as well as his/her escape strategies, i.e., persons are treated as autonomous agents. In these softwares, it is possible to model and simulate fire related parameters, such as gas temperatures, smoke and gas densities, and radiation levels at each point in the computational grid. These quantities can be used to model the behavior of evacuating persons.

In this paper, two test cases have been analyzed:

1. Catamaran Ro-Pax Vessel of 55.0 meters length with four deck levels, Fig. 1. The Advanced Evacuation Analysis gives insights into the evacuation model, and its applicability.
2. A scenario for fire inside restaurant is developed for analyzing the effects of fire (smoke, heat and toxicity), Fig. 2. Fire and Evacuation Analysis gives the detail study on the passenger evacuation time considering the effects of fire.

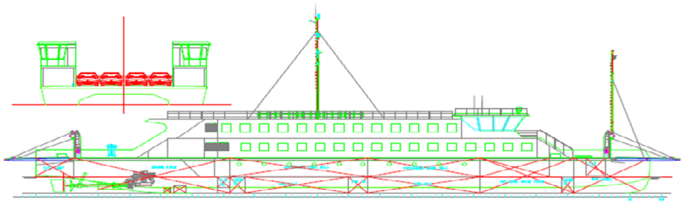

Figure 1 Catamaran Ro-Pax Vessel

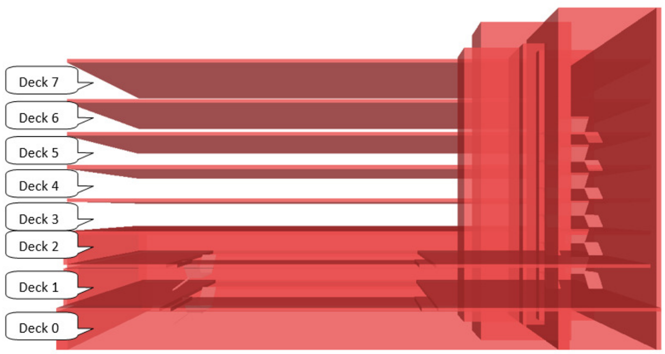

Figure 2 3D view of Restaurant Scenario (in FDS + Evac Software)

BACKGROUND

SOLAS Ch II-2 Reg. 13.3.2.7 regulates the maximum allowable total passenger ship evacuation time to be in the range of 60 to 80 minutes based on the following:

- 60 minutes should apply to ships having no more than three main vertical (fire) zones: and
- 80 minutes applying to ships having more than three main vertical (fire) zones.

This has now been further described by the IMO "Revised Guidelines on Evacuation Analysis for New and Existing Passenger Ships" (MSC.1/Circ.1533). Since this is mandated by SOLAS, evacuation analysis has to be performed during the design phase for all the Passenger and Ro-Pax vessels to be built after 1st January 2020.

The IMO Maritime Safety Committee approved MSC/Circ. 909 for evacuation analysis of ro-ro passenger ships in May 1999 and in June 2001 MSC/Circ. 1001 as interim guidelines for a simplified evacuation analysis of high-speed passenger craft, following a recommendation from the sub-committee on Fire Protection. Both of these guidelines were primarily driven by considerations of structural fire protection sustenance times onboard a vessel.

Based on these guidelines the IMO-Fire Protection sub-committee was tasked to develop further guidelines for passenger ship evacuations. This resulted in issuance of MSC/Circ. 1033 (Guidelines for a Simplified Evacuation Analysis for New and Existing Passenger Ships). This was intended to be used as an interim guideline. The interim guidelines had certain limitations. e.g, it did not consider that passengers would not necessarily respond immediately to a call to assemble during an emergency. This time lag between the announcement and passengers starting to move off to the assembly station is known as the response time and is a key to component of the evacuation process. Further, due to lack of adequate data relating to passenger response times in maritime environments, much of the data used for developing the guidelines was derived from measurements from buildings on land The committee recognised that there was a need for data and information to help further validate and enhance these guidelines.

The 'FIRE EXIT' project undertook drills on ship evacuation response times on board a ro-ro ferry Grimaldi during a voyage between the Port of Rome and Barcelona April 2005. While the data collected from these drill had its limitations, it was able to demonstrate that the response time data used in MSC/Circ. 1033 was not sufficiently detailed to provide a suitable basis for the modelling or validating evacuation simulation software. EU Framework 7 project 'SAFEGUARD', continued the FIRE EXIT work and acquired a large corpus of sea based data on passenger response times and assembly times of a sufficient size and richness to permit model calibration (in terms of response time distributions) and verification and validation (of the assembly process) and to serve as the basis for improved evacuation analysis protocols beyond MSC.1/Circ. 1238.

The data from these drills along with additional benchmark scenarios were reported to IMO in three information papers for possible incorporation into future modifications of MSC.1/Circ. 1238.

The revised guidelines provide for the possibility of undertaking either a simplified or a more advanced passenger ship evacuation analysis method. The guidelines recognised that the simplified "hydraulic" method, which considers passengers like particles moving in a liquid flowing through a pipe, can be useful in estimating total evacuation times during early ship design but is limited, as vessel complexity increases. The simplified method assumes all passengers and crew will begin the evacuation at the same time and will not hinder each other, walking speeds depend on the density of people, flow is only in one direction and there is no overtaking, passenger load and initial distribution are based on the safety system on chapter II-2 of SOLAS is known as Fire Safety System Code (FSS code) counter-flow is accounted for by a correction factor, effects of ship motion, passenger age and mobility, unavailability of corridors, effects of smoke, etc., are accounted for by a correction and safety factor.

Advanced evacuation analysis based on computer simulations seek to model the passengers and crew as unique individuals with specific capabilities and response times. The simulations assume that the crew will immediately be at the evacuation duty stations ready to assist the passengers and that the passengers follow the signage systems and crew instructions. The guidelines provide response time distributions, passenger sex and age distribution, walking speeds on flat terrain (including a statistical distribution) and on stairs. The MSC.1/Circ.1533 revised guidelines do not take account of family group behavior, effects of heat and smoke, effect of ship motion, heel and trim on the passenger/crew performance. The guidelines acknowledge the need for more information and data on full-scale tests on human behavior during ship evacuations, particularly for any future upgrading of the guidelines. The guidelines also describe a list of 12 test cases for checking the evacuation simulation software quantitative verification.

ADVANCED EVACUATION ANALYSIS

Introduction

Advanced evacuation analysis software tools help designer to test the design during concept and basic design stages and to verify the effectiveness of the planned escape routes and the location of muster stations. It is also aimed at identifying and eliminating potential congestion points and bottlenecks in the evacuation path.

In this paper the major features of the FDS - Evac software are described and advanced evacuation analyses are performed on a Catamaran Ro-Pax Vessel. The documentation of FDS - Evac is provided on the website of VTT Technical Research Centre of Finland: http://www.vtt.fi/fdsevac/.

Methodology

Advanced evacuation analysis software assigns each person an equation of motion. This approach allows each person to have his/her own personal properties and escape strategies, i.e., persons are treated as autonomous agents.

The movement of the occupant is simulated using two-dimensional planes representing the floors. The basic algorithm behind the egress movement solves an equation of motion for each occupant in a continuous 2D space and time, i.e., Evacuation software is doing some kind of an artificial molecular dynamics for the occupants. The forces acting on the occupants consist of both physical forces, such as contact forces and gravity, and psychological pressure exerted by the environment and other agents. The model behind the movement algorithm is the social force model introduced by Helbing's group (Helbing D 1995,2000,2002,2003).

The method of Helbing's group is used as the starting point of the occupant movement algorithm of the evacuation software, where a so-called "social force" is introduced to keep reasonable distances to walls and other agents, see Fig. 3.

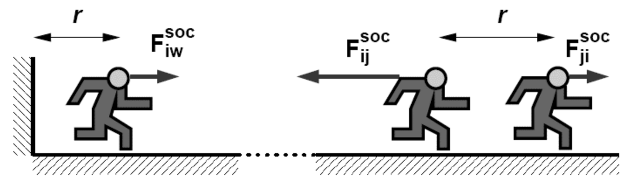

Figure 3 The concept of social force (Reference: FDS – Evac Technical Reference and User's Guide)

This software uses the laws of mechanics to follow the trajectories of the occupants during the calculation. Each occupant follows its own equation of motion (eq. 1):

$$m_i \frac{d^2 x_i(t)}{dt^2} = f_i(t) + \xi_i(t) \quad (1)$$

Where $x_i(t)$ is the position of the agent i at time t, $f_i(t)$ is the force exerted on the agent by the surroundings, m_i is the mass, and the last term, $\xi_i(t)$, is a small random fluctuation force. The velocity of the agent, $v_i(t)$, is given by dx_i/dt. The force on the occupant i has many components as shown in eq. 2:

$$f_i = \frac{m_i}{\tau_i}\left(v_i^0 - v_i\right) + \sum_{j \neq i}\left(f_{ij}^{soc} + f_{ij}^{c} + f_{ij}^{att}\right) + \sum_{w}\left(f_{iw}^{soc} + f_{iw}^{c}\right) + \sum_{k} f_{ik}^{att} \quad (2)$$

where the first sum describes occupant – occupant interactions (i.e., f_{ij}^{soc} represents the social force, f_{ij}^{c} represents the physical contact force and f_{ij}^{att} represent the attraction or repulsion between agents), the sum over ω describes agent – wall interactions, and the terms in the last sum, f_{ik}^{att}, may be used for other occupant – environment interactions, like the fire – occupant repulsion. The first term on the right hand side describes the motive force on the evacuating occupant. Each occupant tries to walk with its own specific walking speed towards an exit or some other target, whose direction is given by the direction of the field v_i^0.The relaxation time parameter τ_i sets the strength of the motive force, which makes an agent to accelerate towards the preferred walking speed.

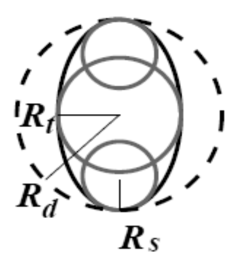

Figure 4 The Shape of human body is approximated by a combination of three overlapping circles (Reference: FDS – Evac Technical Reference and User's Guide)

Table 1 walking velocities and body dimensions in FDS - Evac software

Unimpeded walking velocities and body dimensions in Evacuation Simulation. The offset of shoulder circles is given by $d_s=R_d-R_s$, for the definition of the other body size variables, R_d, R_t, R_s, see figure 5. The body sizes and walking velocities of the agents are personalized by using them from uniform distribution, whose ranges are given below:					
Body Type	R_d	R_t/R_d	R_s/R_d	d_s/R_d	Speed
	(m)	(-)	(-)	(-)	(m/s)
Adult (Male + Female)	0.225 ± 0.035	0.5882	0.372	0.627	1.25 ± 0.30

Model description

A 55.0 m long Catamaran Ro-Pax Vessel with four deck levels is modeled with the population distribution as mentioned in the escape plan. In this paper, only the primary evacuation case is considered for a day scenario with full availability of escape routes.

The advanced evacuation analysis is done using the Numerical based computer evacuation tool FDS – Evac.

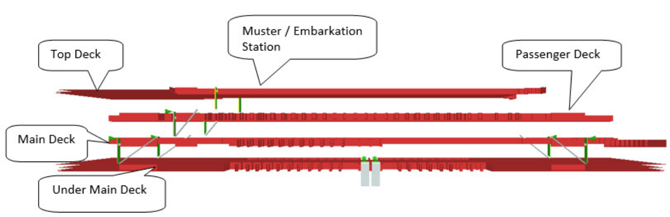

Figure 5 FDS Evac model of Catamaran Ro-Pax Vessel

A total of 503 passengers are considered in this analysis. The passengers are distributed according to the escape plan, while the demographic and response time distribution of the population are defined as specified in the IMO guidelines MSC.1/Circ.1533.

Analysis Result and Discussion

For primary evacuation day case as defined in case 2 of MSC.1/Circ.1533. A total of 50 simulation runs are performed and then the convergence criteria test is performed.

Convergence criteria definition

The distance between the maximum to the minimum of T_{95}^{i} obtained over the 50 last simulation increments should not exceed the distance (in absolute value) of the mean of T_{95}^{i} over the 50 last simulation increments, to the maximum allowable assembly time (T_{lim}):

$$|T_{lim} - T_{0.95}^{mean}| \geq T_{0.95}^{max} - T_{0.95}^{min} \quad (3)$$

Where:

$T_{lim} = \frac{n-\frac{2}{3}(E+L)}{1.25}$ with n, E, and L, as defined in Annex1 of MSC.1/Circ.1533,

$T_{0.95}^{mean}$=mean(T_{95}^{i}),with i between (N−49) and N,

$T_{0.95}^{max}$=maximum(T_{95}^{i}),with i between (N−49) and N,and

$T_{0.95}^{min}$=minimum(T_{95}^{i}),with i between (N−49)and N.

Convergence criterion test

T_{lim} = 32 min

T_{lim} = 1920 Sec (with n = 60', E+L = 30')

$T_{0.95}^{max}$=1182.3 sec

$T_{0.95}^{min}$=1048.5 sec

$T_{0.95}^{mean}$=1099.5 sec

According to the definition of the convergence criteria as mentioned above, the initial batch of 50 simulations satisfy the convergence criteria. Therefore there is no need to perform any additional simulations and , the travel time for the simulation (primary evacuation case, day) is $T_{0.95}^{mean}$=T_{case}=1099.5 sec.

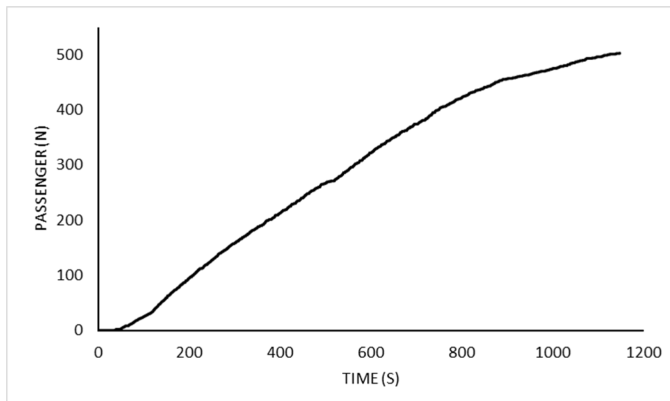

Figure 6 Evacuation time curve for one simulation

Calculation of Total Evacuation time

Total Evacuation Time = 1.25 (R+T) + 2/3 (E+L) (4)

Here,

R+T, Response time and Travel time = T_{case}

E + L, Embarkation and launching time = 30' (refer MSC Circ.1533)

The total evacuation time = 2574.4 sec (42 minutes 54 seconds)

Discussion

The total evacuation time for the Catamaran Ro-Pax Vessel using advanced evacuation analysis is less than 60 min. Congestion is observed at the landing area of the stair case at fwd. side of the passenger deck and also at the entrance of the stair case located at aft side of the passenger deck and queuing is identified on stair case connecting under main deck to the main deck at the aft side and also on the corridor of passenger deck as indicated in the fig 7.

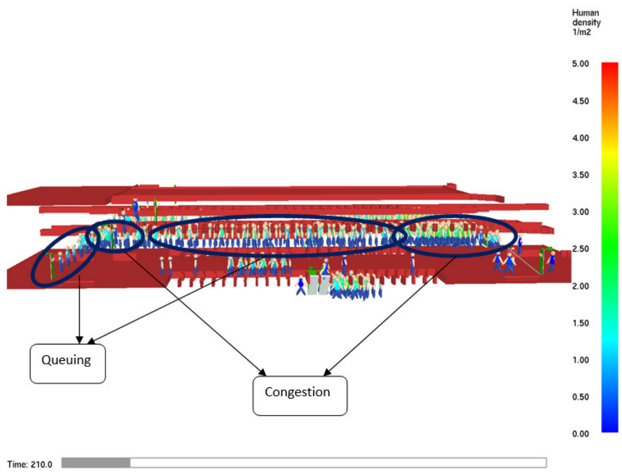

Figure 7 Passengers location with their density after 210 sec

FIRE AND EVACUATION ANALYSIS

Introduction and Methodology

Fire influences evacuation conditions, it may incapacitate humans and in extreme cases block major exit routes. On the other hand, humans may influence the fire by opening doors or actuating various fire protection devices. The effect of fire and smoke on the movement speeds of agents and the toxic influence of the smoke are implemented in movement algorithm of evacuation software.

In this paper, Fire and Evacuation analysis is performed using Maritime Exodus - Smart fire and FDS - Evac softwares as these softwares are able to account for parameters such as gas temperature, smoke and gas densities, radiation levels and their influence on the total evacuation time.

In the FDS – Evac software, each evacuee observes the locations and actions of the other evacuees and selects the exit through which the evacuation is estimated to be the fastest. Thus, the exit selection is modelled as an optimisation problem, where each evacuee tries to select the exit that minimises the evacuation time. The estimated evacuation time consists of the estimated time of walking and the estimated time of queueing. It is also assumed that people change their course of action only if there is an alternative that is clearly better than the current choice. Apart from the locations of exits and the actions of other people, there are also other factors that influence the evacuees' decision making. These factors are the conditions related to the fire, the evacuees' familiarity with the exits and the visibility of the exits. According to the three factors mentioned, the exits are divided to preference groups. Exits are rated by the familiarity, visibility and the smokiness of the exit route. The most important factor is the extent of smoke in the exit route. If there are lethal conditions on an exit route, the exit has no preference. The exit selection algorithm consists of the above described two phases. First the exits are divided to the preference groups and then an exit is selected from the most preferred nonempty preference group by minimising the estimated evacuation time.

Smoke reduces the walking speed of humans due to the reduced visibility, its irritating and asphyxiant effects. Recently, Frantzich and Nilsson (Frantzich, H 2003) made experiments on the effect of smoke concentration on the walking speeds of humans. They used larger smoke concentrations than Jin (Jin, T 1978) and they found the walking speed decreases with increasing smoke concentration according to the formula $v(K_s) = \alpha + \beta K_s$ to the experimental values, where K_s is the extinction coefficient ($[K_s]=m^{-1}$) and the values of the coefficients α and β are 0.706 ms^{-1} and -0.057 m^2s^{-1}, respectively.

The reduction of walking speed in smoke is considered in FDS - Evac along the lines given by these experiments conducted by Frantzich and Nilsson. It is assumed that the walking speed in smoke compared to the walking speed without smoke is same for all agents regardless of their different unimpeded walking speeds. Thus, FDS - Evac reduces the walking speed of agent i in smoke, $v_i^0 = (K_s)$, using the formula shown in equation 5

$$v_i^0 = (K_s) = Max\{v_{i,\min}^0, v_i^0(1 + \frac{\beta}{\alpha} K_s)\} \quad (5)$$

where the minimum walking speed of agent i is $v_{i,\min}^0 = 0.1 \cdot v_i^0$ by default, i.e., the agents are not stopping due to a thick smoke, they continue to move with a slow speed until they are incapacitated by the toxic effects of the fire products. The standard deviations are reported to be $\sigma_\alpha = 0.069$ ms^{-1} and $\sigma_\beta = 0.015$ m^2s^{-1}, but only the mean values are used in FDS - Evac, i.e., there is no variation between the agents.

The toxic effects of gaseous fire products are treated by using Purser's Fractional Effective Dose (FED) concept (Purser, D.A. 2003). The FED value is calculated as shown in equation 6

$$FED_{tot} = (FED_{CO} + FED_{CN} + FED_{NO_X} + FLD_{irr}) \times HV_{CO_2} + FED_{O_2} \quad (6)$$

Model description

A scenario for fire inside restaurant is presented in this paper for analyzing the effects of fire (smoke, heat and toxicity) on the passenger evacuation time.

Restaurant Specifications

The Restaurant has three decks, its dimensions are outlined below (refer fig. 2 and fig. 8):

- The length of each deck is 43.0 m excluding the staircase area located outside the restaurant.
- The deck 0 is 31.0 m wide and all other decks are 27.0 m wide.
- The height varies from deck to deck; deck 0, deck 1 and deck 2 are of 3.3m & rest all decks are of 2.7m. Deck thickness: 0.2m.
- Every deck has two 6x7m elevator blocks at the forward end located at 5.0m from boundary of each side.
- All the decks are equipped with one evacuation door, at the center of forward end of the area.
- The evacuation doors are 2.5m height and 2.0m wide.
- A 24.5x12m gap connects the deck 0 with the deck 1 and deck 2.
- The gap is located 8.0m forward to the aft wall.
- Stairs located inside the restaurant area are at the aft end of the gap, connecting deck 0 to deck 1 and deck 1 to deck 2.
- Stairs located outside the restaurant area are at the forward part of the area, this connecting all the decks to the embarkation deck.
- Embarkation station is located on the deck 7.

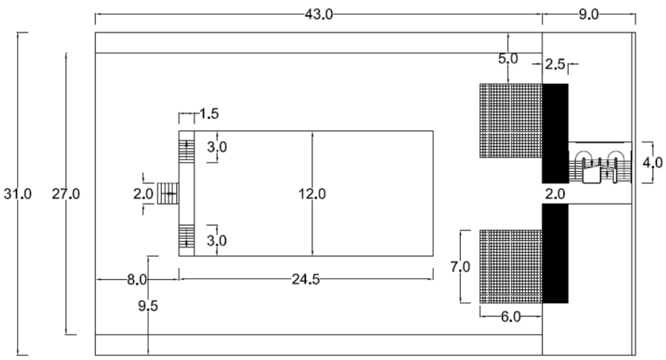

Figure 8 Plan View of Restaurant

Stairs Specifications

Stair dimension are outlined as below (refer fig. 2 and fig. 8)):

- Located inside the restaurant area, connects Deck 0 to Deck 1 and Deck 1 to Deck 2. The landing is 1.25m wide, 1.6m high and 6.0m long. They connect to the upper deck form both sides in a single lane as shown in fig.1 with riser height of 0.15m and thread depth of 0.20m respectively.
- Located outside the restaurant area, connects Deck 1 to Deck 2 and Deck 2 to Deck 3. The landing is 1.35m wide, 1.6m high and 1.9m long. They consist of two lanes with 10 risers (9 treads). The Landing is 1.8m wide and 6.2m long.
- Located outside the restaurant area, connects Deck 3 to Deck 4, Deck 4 to Deck 5, Deck 5 to Deck 6, Deck 6 to Deck 7 and Deck 7 to Deck 8. The landing is 1.35m wide, 1.5m high and 1.9m long. They consist of two lanes with 9 risers (8 treads). The Landing is 1.8m wide and 6.2m long.

It is to be noted that each stair width is measured from the inside of the handrail to the inside of the handrail and so represents clear stair width. The length of the stair also represents its horizontal length (i.e. it does not represent the length measured down the slope).

Material Properties

Single layer material is used for all the floor decks, the following material properties have been assumed:

Table 2 Material properties for the floor deck

Thickness [m]	Density [kg/m^3]	Thermal Conductivity [W/m K]	Specific Heat [J/kg K]
0.2	200	0.04	840

Heat Release Rate (HRR) and Fire load

Two HRR curves have been considered for this scenario. HRR1 curve represent the medium fire growth and HRR2 represent the fast growing fire. These two curves as show in fig. 9 are derived based on the literature Zalok, E (Zalok 2009).

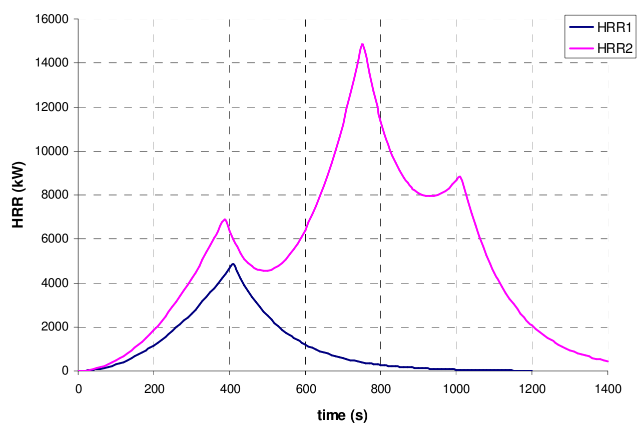

Figure 9 HRR Curve

The fire is located at the forward corner on the deck 0, 1m away from the side and forward wall as shown in fig. 10.

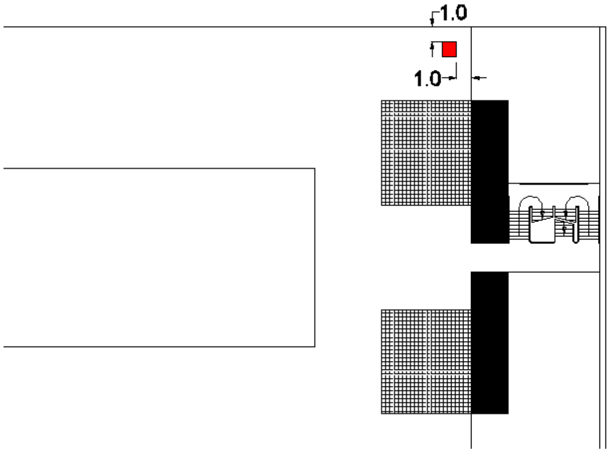

Figure 10 Fire Location

The reaction taking place during the fire is assumed to have properties similar to burning out of wood materials:
CO_YIELD = 0.013
SOOT_YIELD = 0.004

CO_YIELD is the fraction of fuel mass converted into carbon monoxide, and SOOT_YIELD is the fraction of fuel mass converted into smoke particulate.

Passenger distribution

The evacuation analysis is performed through the doors located on the deck 1 and deck 2 respectively.

Having assumed 2m^2 space for every person in the restaurant and near full capacity, the estimated persons for the evacuation scenario are as follows:
Deck 0: 600 persons
Deck 1 & Deck 2: 300 persons each.

Total of 1200 persons are assigned with the population attributes of age, gender and travel speeds according to those set out in the IMO guidelines MSC.1/Circ.1533.

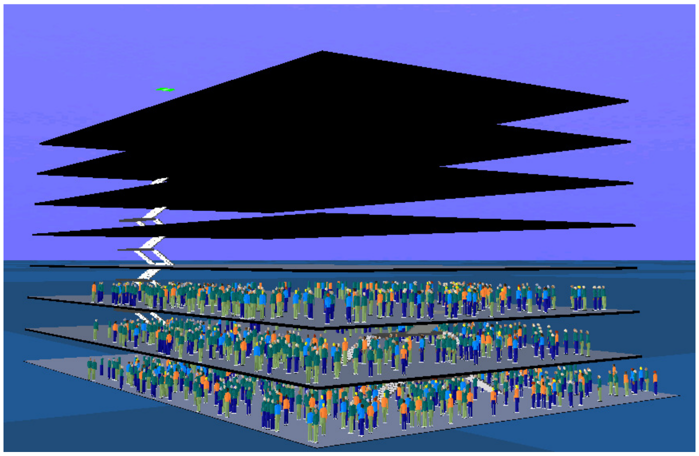

Figure 11 Restaurant model with passenger distribution in maritime exodus

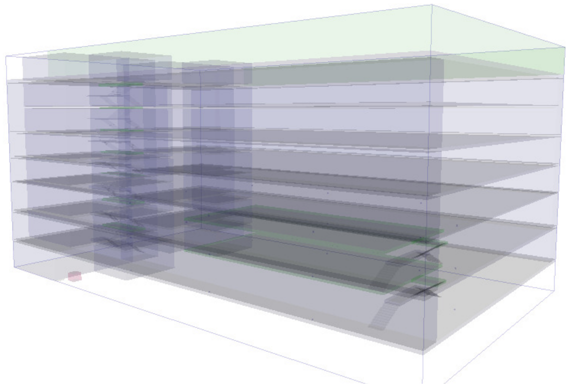

Figure 12 Restaurant model in smart fire

Analysis Result and Discussion

Fire and Evacuation analysis is performed by Maritime Exodus - Smart fire simulation software for two fire loads (HRR1 and HRR2). Following are the summary of the results.

Simulation Results for HRR1

The results from the fire and evacuation simulations for HRR1 are illustrated below.

1. Start Time of passenger evacuation: 82.99 sec
2. End Time of passenger evacuation: 1253.16 sec
3. Fatalities/Dead: 0 person

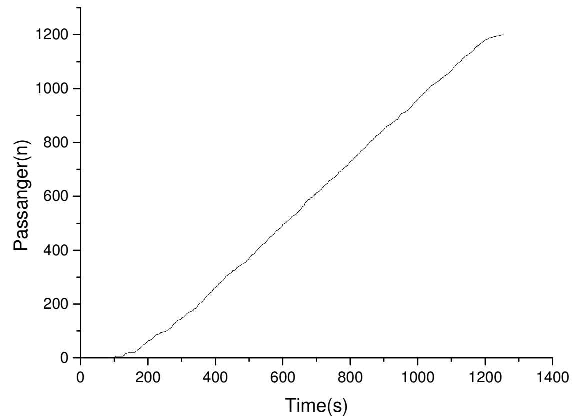

Figure 13 Evacuation time curve for HRR1

Simulation Results for HRR2

The results from the fire and evacuation simulations for HRR2 are illustrated below.

1. Start Time of passenger evacuation: 82.00 sec

2. End Time of passenger evacuation: 988.76 sec
3. Fatalities/Dead: 391 person

(Note: Start time and end time of passengers for HRR1 and HRR2 is obtained from mean of the 95th percentile of the total 50 simulation result values.)

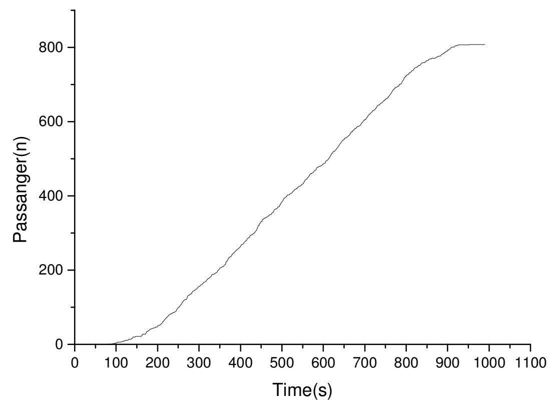

Figure 14 Evacuation time curve for HRR2

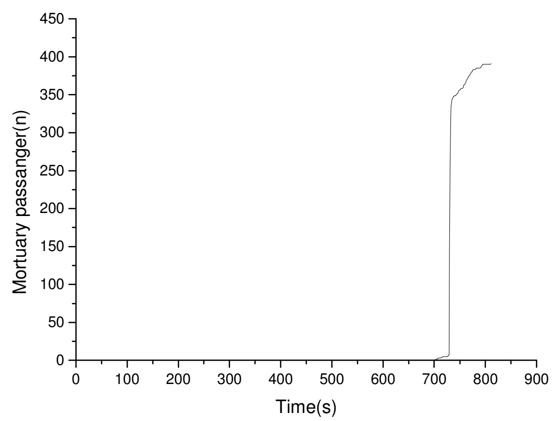

Figure 15 Fatalities/Death curve for HRR2

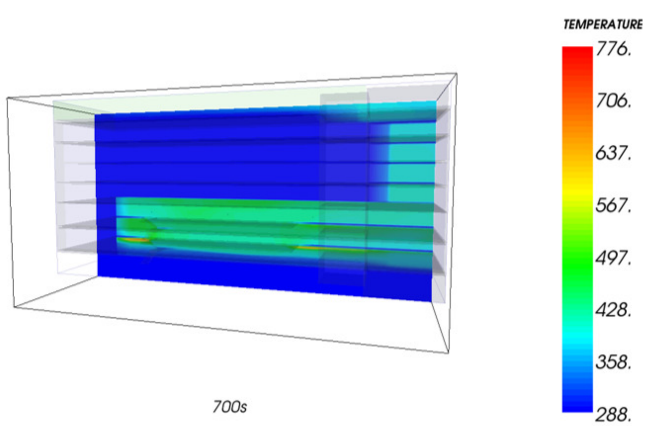

Figure 16 Temperature (K) contour plane at 700sec

Discussion

There is a significant difference in the total evacuation time if the fire effects are considered. We can summarize from the both HRR1 and HRR2 simulations, that as the heat load increases the number of deaths/fatalities suddenly tends to increase. The walking speed of humans is also related to heat, smoke, toxicity and visibility levels. We can observe that as heat load increases walking speed of humans decreases.

Future work

At this stage the direct co-relation between human walking speed to heat, smoke, toxicity and visibility levels have not been established, detailed study and research need to be carried out by appropriate domain experts for the same.

CONCLUSIONS

Advanced evacuation analysis simulation software's can model actual individuals and assesses their behavior and interaction with the surrounding environment of a ship. These analyses can be carried out efficiently throughout the design process to assess designs at an early design stage, to ensure safe and efficient evacuation, thereby avoiding costly redesign and can also to assess evacuation performance and identify corrective actions for existing vessels.

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