MODELING THE EFFECT OF THE USE OF FIBER REINFORECED PLASTICS ON THE EVACUATION OF A RO-PAX PASSENGER DECK

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Abstract:

Modern ship design and construction is striving to make sea transportation more fuel efficient and more environmentally friendly. One of the possible solutions is to make the ships lighter by reducing the weight of the superstructure, constructing it completely or partially with lightweight materials such as Fiber Reinforced Plastics (FRP), like glass fiber composites or carbon fiber composites. However, the use of these materials would have an impact on the acceptance criteria for safe evacuation in case of fire, mainly due to the differences on the thermal, chemical and physical properties that have a direct effect on the smoke production and fire development. The evacuation module of FDS is used to couple the fire development with its influence on the evacuation process in 12 fire scenarios, including four design fires and three material set-ups. The unprotected FRP set-up proved to be the most critical one, hence passive fire protection must be provided. Performance-based design can be applied for ship evacuation, however, with close support of literature and prescriptive IMO codes. Implementing FDS EVAC simplifies the coupling of fire development with the evacuation process, allowing the user to model this interaction in an easier way.

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Summary/Abstract

Modern ship design and construction is striving to make sea transportation more fuel efficient and more environmentally friendly. One of the possible solutions is to make the ships lighter by reducing the weight of the superstructure, constructing it completely or partially with lightweight materials such as Fiber Reinforced Plastics (FRP), like glass fiber composites or carbon fiber composites. However, the use of these materials would have an impact on the acceptance criteria for safe evacuation in case of fire, mainly due to the differences on the thermal, chemical and physical properties that have a direct effect on the smoke production and fire development. The evacuation module of FDS is used to couple the fire development with its influence on the evacuation process in 12 fire scenarios, including four design fires and three material set-ups. The unprotected FRP set-up proved to be the most critical one, hence passive fire protection must be provided. Performance-based design can be applied for ship evacuation, however, with close support of literature and prescriptive IMO codes. Implementing FDS EVAC simplifies the coupling of fire development with the evacuation process, allowing the user to model this interaction in an easier way.

Resumen

El diseño y construcción de barcos está actualmente esforzándose para hacer el transporte más eficiente en términos de combustible y más amigable con el ambiente. Una de las posibles soluciones es hacer los barcos más ligero a través de la reducción del peso de la superestructura, construyéndola parcial o totaltmente con materiales ligeros Plásticos Reforzados con Fibras (FRP por sus siglas en inglés), como por ejemplo compuestos de fibra de vidrio o de carbon. Sin embargo, el uso de estos materiales tendría un efecto en los criterios de aceptación para tener un proceso de evacuación seguro en caso de incendio, básicamente debido a las diferencias en las propiedades térmicas, químicas y físicas, las cuales tienen consecuencias directas en la producción de humo y en el desarrollo del fuego. El módulo de evacuación de FDS es utilizado para acoplar el desarrollo del fuego y su influencia en el proceso de evacuación en 12 escenarios que incluyen cuatro fuegos-desiño y tres combinaciones de materiales. La combinación en la que el FRP no está protegido, resultó ser la más crítica, por ende, protección pasiva debe ser instalada. El diseño basado en desempeño puede ser aplicado en el caso de evacuación en barcos, no obstante, con apoyo cercano de literatura y de códigos preceptivos de la IMO. La implementación de FDS EVAC simplifica el acoplamiento del desarrollo del incendio con el proceso de evacuación, permitiendo al usuario modelar esta interacción más fácilmente.

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LIST OF ABBREVIATIONS

ASET	Available Safe Evacuation Time
DBI	Dansk Brandteknisk Institut (Danish technical institute of fire safety)
DFDS	Det Forenede Dampskibs-Selskab (The United Steamship Company)
FED	Fractional Effective Dose
FEC	Fractional Effective Concentration
FDS	Fire Dynamics Simulator
FDS EVAC	Evacuation module of FDS
FRP	Fiber Reinforced Plastics
HRR	Heat Release Rate
HRRPUA	Heat Release Rate Per Unit Area
IMO	International Maritime Organization
RSET	Required Safe Evacuation Time
SOLAS	Safety Of Life At Sea

1. INTRODUCTION & OBJECTIVES

Fire safety has been gained more and more importance due to the big impact that a fire accident has on people, therefore the fire regulation field has become an active sector creating more thoroughly rules and demanding higher standard. However, these regulations can indeed limit the design and the materials used in a project just because they are not covered in the law.

Nowadays, with an industry sector that is moving towards greener technologies and processes, the effective use of the energy sources is one of the main focuses of scientific investigations. The transportation segment is one of the main developers of new technologies in this field due to the higher demand of these services.

Modern ship design and construction is striving to make sea transportation more fuel efficient and more environmentally friendly. One of the possible solutions is to make the ships lighter reducing the weight of the superstructure, constructing it completely or partially with lightweight materials such as aluminum or Fiber Reinforced Plastics (FRP) for example glass fiber or carbon fiber composites.

However, the use of these materials will have an impact on the acceptance criteria for safe evacuation in case of fire onboard the ship. Differences in the thermal, chemical and physical properties have an impact on the smoke production and fire development. These changes could make the ship not safe in terms of fire, unless extra safety measures are taken. Reason why several studies have been done in order to provide solutions that are economically feasible with a significant weight reduction and, more importantly, that comply with the SOLAS regulations, including fire safety. Within these investigations, an important number of them are related to the field of FRPs, typically used in load-bearing elements and lightweight materials used as wall linings. A list of some of these studies that cover structural, chemical and fire reaction of the FRPs, is shown in the following section.

1.1 Background

One of the first studies by Adrian Coman is a structural feasibility study has been done to compare the use of steel or FRPs in the superstructure of a ship [1]. The main objective of this investigation was to design the superstructure of the Ro-Ro ship Tor Magnolia, using composite materials, specifically, fiber reinforced plastics. This work was motivated by the interest of making the ship lighter and thus, making it more fuel-efficient and more environmentally friendly. However, the fire safety issue was not considered, since it was outside of the scope of the mentioned dissertation.The S-LÄSS **Error! Reference source not found.** is a network that aims for the development of new lightweight constructions at sea, especially aluminum, carbon and glass fibers that have an accepted safety level. S-LÄSS gathers important information from various sources about the Swedish industrial development of lightweight constructions at sea.

The BEEST Project [2], a European initiative which goal was to increase the competitiveness of European ships by diminishing the life cycle cost, drastically reducing environmental impact and improving safety. The solutions include the implementation of lightweight materials in ships. Another related investigation is SAFEDOR [3], another European initiative that focuses on providing risk-based regulation that can lead to solutions to further increase the safety of water-borne transports that use lightweight materials.

Also, in 2009, fire safety engineering begins to be used as a tool to design composites for ships building. An example of this, is a paper included in the 11th International Conference and Exhibition of Fire and Materials organized by Gutierrez et al. [17]. This study was aimed to develop a methodology that complies with the SOLAS and IMO regulations for alternative design, validating numerical tools comparing them with results gotten from experiments. The safety of the passenger and the ship is studied by performing evacuation and thermo-mechanical simulations to afterwards, propose risk-control measurements to improve the safety for example, installing air curtains and water film system.

An effort to couple fire and evacuation simulations is being done, as an example is the work of Azzi et al [24] where a link between FDS (fire tool) and EVI (evacuation) is done. In the project the IMO standards are followed and the Fractional Effective Dose (FED) is taken into account to evaluate the evacuation performance. The design fire is taken from the real scale cabin fire experiments done by SP [9]. Azzi et al concluded that the fire effects on the people must be taken into account during the evacuation process to have more realistic and, therefore, safer designs; the investigators also concluded that crew assistance is crucial throughout the evacuation.

Based on the number of investigations and projects that can be found about the use of lightweight materials on ships, it is clear that further investigation on these materials is of great importance for the ship industry. Moreover, little tests have been done on the effect of FRPs on evacuation using coupled fire-evacuation simulations, reason why this project becomes important as to give a start research on this subject.

1.2 Objectives

The aims of the project is to determine the influence of the FRPs on the fire safety, however, it’s limited to study the evacuation process and the fire behavior.

1.2.1 General objective

1. Investigate the performance-based design method to determine the fire safety level of the 7th deck of the DFDS owned Ro-Pax ship ***Victoria Seaways*** for three different material set-ups of one passenger deck, with focus on fire and evacuation modelling.

1.2.2 Specific objectives

1. Assess the viability of applying performance-based methodology for ship safety and check the prescriptive guidelines for using software tools.
2. Determine the design fires relevant for the 7th deck of the Victoria Seaways and the input to them.
3. Determine the influence of the selected design fire on the evacuation process and the fire behavior.
4. Determine the influence of the material set-up on the evacuation process and the fire behavior.

2. METHODOLOGY

Traditionally, ships like ferries are designed according to prescriptive design codes (SOLAS) [4]. For safe evacuation SOLAS defines a minimum geometry width depending on the number of passengers. The safety level in relation to the evacuation is therefore quantified as "above minimum". In this thesis a comparison will be made between the construction materials on how safe they are or not using performance-based design, using the guidelines proposed by SFPE [7].

The assessment is made on both prescriptive and alternative designs using the same performance criteria for evaluating all the cases. The calculations are made using FDS 6.0.1 and FDS EVAC 2.5.0 to determine if the evacuees have enough time to abandon the deck safely.

The safety assessment takes into account mainly the FED, however, with the purpose of comparing with the methodologies proposed by Gutiérrez et al [17] and Azzi et al. [24], the following variables are considered for one example case as well: Smoke layer height, radiation to the floor, smoke layer temperature, fire propagation and visibility. If a zone and/or material are considered as critical, improving solutions are proposed.

The geometry was built based on blue prints given by the manufacturer. Then a mesh sensitivity analysis will be made in order to find the optimal size of the mesh's elements for the main simulations of the investigation. Four design fires are taken into account to evaluate the performance of the three material set-ups.

2.1 Software selection

From the many available CFD and evacuation simulation software, FDS is selected as the tool to be used in this project due to the fact that FDS has been tested already on its capacity to model the fire behavior of FRPs onboard a ship [9], [21] Another argument is the free availability of the software, motivated its choice. Furthermore, FDS (v 6.0.1) comes with an evacuation module called FDS EVAC (v 2.5.0), which has been verified using the cases proposed by IMO for verification of evacuation simulation tools. According to the developers of FDS EVAC, the software successfully passed all IMO's tests [19], making the program just ideal for the case in hand: Evacuation in a Ro-Pax ship.
The IMO tests for verification of evacuation software include component test and a series of functional, qualitative and quantitative verification tests. There eleven in total and go from elementary scenarios such as an agent maintaining a specified walking speed, to case where the exit choice of the evacuees is checked with informed expectations. However, this is not to be considered a validation of the model but just a verification that it can be used to study ship evacuation.

The validation of FDS EVAC has been already done by the developers, who compared FED EVAC's results with the ones of other evacuation software (SIMULEX and EXODUS) and experimental data of pedestrian traffic flow study done by Daamen [8]. The results of the validation are that FDS EVAC can reasonably reproduce the experimental data and other model's results. More information can be found in Chapter 6 of the User's Guide [19].

2.2 Geometry

The geometry used in this study has been adapted from the plans of the 7th passenger deck of DFDS' ship ***Victoria seaways,*** taking only into consideration the relevant geometry and dimensions. This deck is constructed in FDS and shown in Figure 1, where the walls are shown in white with a black outline and in blue; the floor and the ceiling are present but were set to be invisible for the sake of a better visualization of the results of the simulations.

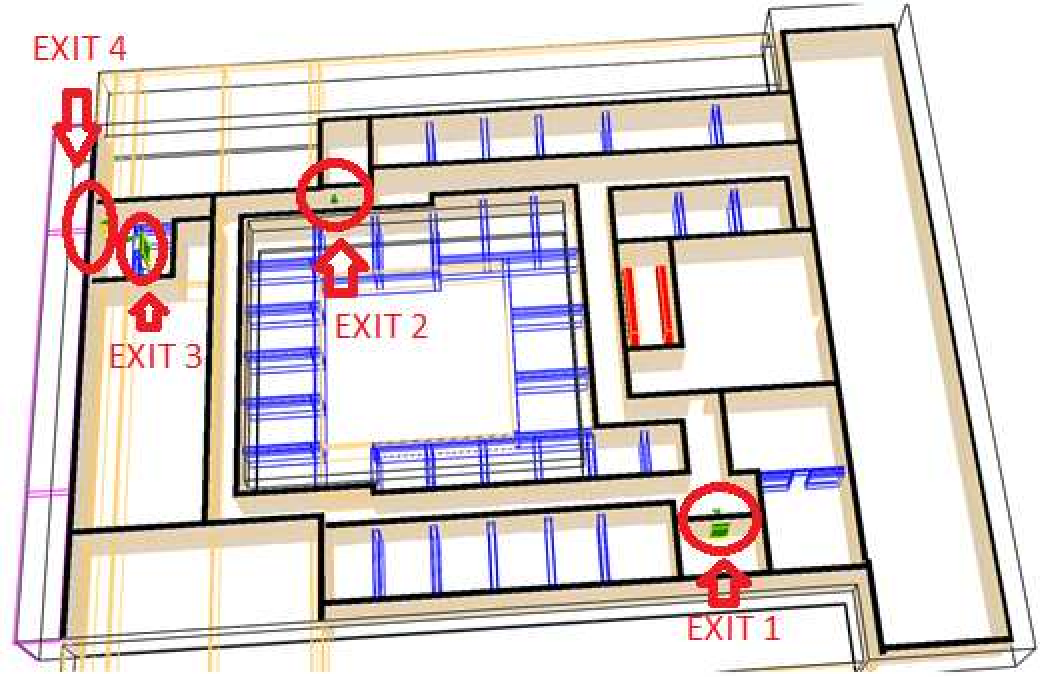

Figure 1 Geometry of the deck in Smokeview® showing the 4 exits of the deck

In the previous figure, the walls and holes in blue color are only taken into account for the evacuation calculations, whereas the rest of the walls are taken for both fire and evacuation simulations. The blue walls represent mainly the passenger cabins and the inner divisions that, because of their location, do not affect the development of the fire nor the movement of the smoke. In Figure 1, the location of the evacuation doors is marked with a green rectangle and a green cone. These openings aren't considered by FDS when calculating the fire behavior.

2.3 Evacuation simulations

The evacuation simulations are done using the evacuation calculation module of FDS: FDS EVAC. This software makes the coupled calculation of the fire behavior and the evacuation process, taking into account the effects of the smoke on the evacuees. The simulations use as input data for walking speed, pre-movement times and the population distribution the values proposed by IMO in its guidelines [5]. IMO requires that 50 evacuation simulations are done to account for uncertainty, the results of these simulations are treated and analyzed according to guidance given by the IMO.

This regulation requires that for the evacuation of the whole ship, the following relation should be fulfilled:

$$1{,}25 \cdot T + \frac{2}{3} \cdot (E + L) \leq n \tag{1}$$

and

$$E + L \ \leq 30 \ min \tag{2}$$

Where T is the travel time, E is the embarkation time, L is the launching time and ‘n’ is consider 60 min for Ro-Ro ships.

However, since this project consists on the analysis of only one of the passenger decks, the above criterion given by equations (1) and (2) cannot be used since it is only valid if the evacuation of the whole ship.

According the blueprints of the ship, the deck has a capacity of 73 people of which 22 are passengers and 51 are crew. The IMO guidelines propose the population distribution that should be used when performing the evacuation simulation. Table 1 shows the population’s composition suggested by IMO and the subsequent simplification that is done to input the data in FDS EVAC.

Table 1 Population's composition

Population group-passengers [5]	**Percentage of passengers (%) [5]**	**Person class to be introduced in FDS EVAC**	**Number of passenger within each class**	**Avatar color in FDS EVAC**
Females younger than 30 years	7	Children	2	Blue
Females 30-50 years	7	Adult Females	5	Black
Females older than 50 years	16			
Females older than 50 years, mobility impaired (1)	10	Elderly	4	Yellow
Females older than 50 years, mobility impaired (2)	10			
Males younger than 30 years	7	Children	2	Blue
Males 30-50 years	7	Adult males	5	Green
Males older than 50 years	16			
Males older than 50 years, mobility impaired (1)	10	Elderly	4	Yellow
Males older than 50 years, mobility impaired (2)	10			
Population group-crew [5]	**Percentage of crew (%) [5]**	**Person class to be introduced in FDS EVAC**	**Number of passenger within each class**	**Assigned color in FDS EVAC**
Crew female	50	Modified female	26	Sepia
Crew male	50	Modified male	25	Sepia

An important factor when evacuation simulations are done, is the pre-movement time of the evacuees. For this, IMO makes the difference between the response time at day and the time at night; in this project only the day case is studied. The following equation is the time distribution used to model the pre-evacuation time of the passengers.

$$y = \frac{1{,}00808}{\sqrt{2\pi}\,0{,}72\,x} exp\left(-\frac{(ln(x) - 4{,}562)^2}{2 * 0{,}94^2}\right)$$

Where, ‘y’ represents the probability density at response time ‘x’.

To introduce this distribution in FDS EVAC four values are required: minimum, maximum, mean and standard deviation. The following table summarizes these values.

Table 2 Pre-movement time input values [5]

Case	Minimum [s]	Maximum [s]	Mean value [s]	Standard deviation [s]
Day	0	300	4,562	0,94

Subsequently, once all the 600 evacuation simulation are carried out, these are compared with a base case, modeled as an evacuation drill in FDS EVAC, disregarding the fire data. Then, the effect of the location of the fire and the material set-up can be assessed by a comparison using the evacuation time, maximum FED value and average fatalities. In the cases where fatalities occur, the evacuation time is taken as the time when the last alive evacuee leaves the deck.

2.4 Design fires. Size and location

Fire 1, Fire 2 and Fire 3

The first three design fires are equal in size (HRR) and growth to the fire measured experimentally by SP [9] where an exact replica of a passenger cabin was set to fire and its development was recorded. This fire is located in three different cabins within the ship’s 7th deck; the locations, shown in red in the following figures, were selected according to its proximity to the means of evacuation, therefore, challenging the evacuation design of the deck and are shown in Figure 3, Figure 4 and Figure 5.

However, to perform the mesh sensitivity study, the fire will be limited to 1000 s as seen in Figure 2, the decay phase won’t be considered. People are supposed to evacuate during the initial stages of the fire and, after the fire goes beyond its maximum HRR, the effect on the composite material won’t be as large as on the growth and flashover phases. These assumptions are checked and confirmed in the 3. Results’ section. The following figures show the actual HRR curve and the simplification, because of the noise present in the experimental curve, of the cabin fire in order to introduce it as an input in FDS to calculate the fire behavior.

An important note is that the cabin door is assumed to be open and the suppression systems are to be not operational, making these combinations extreme scenarios.

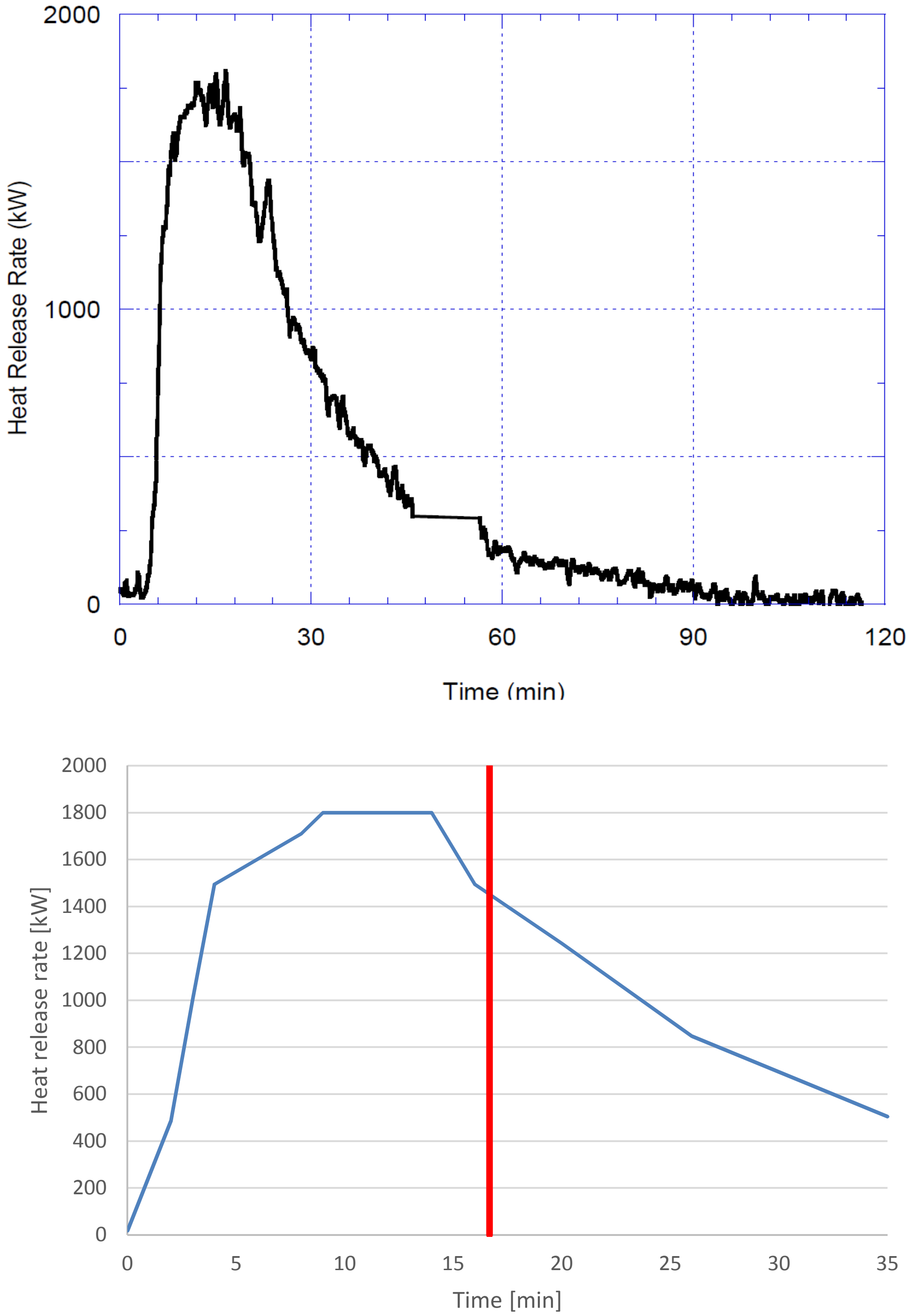

Figure 2 Actual (above) and simplified (below) Cabin fire [9]

As stated above, the design fire shown in Figure 2 is put in three different cabins within the deck. The first location, shown in red on Figure 3, is chosen due to its proximity to one of the staircases used as a mean of evacuation in the deck. To differentiate it from the other cases, in this scenario the window of the cabin is assumed to be open during the whole simulation, this opening provides with more oxygen to the fire in the initial phases delaying the under-ventilated conditions that occur in the other three cases.

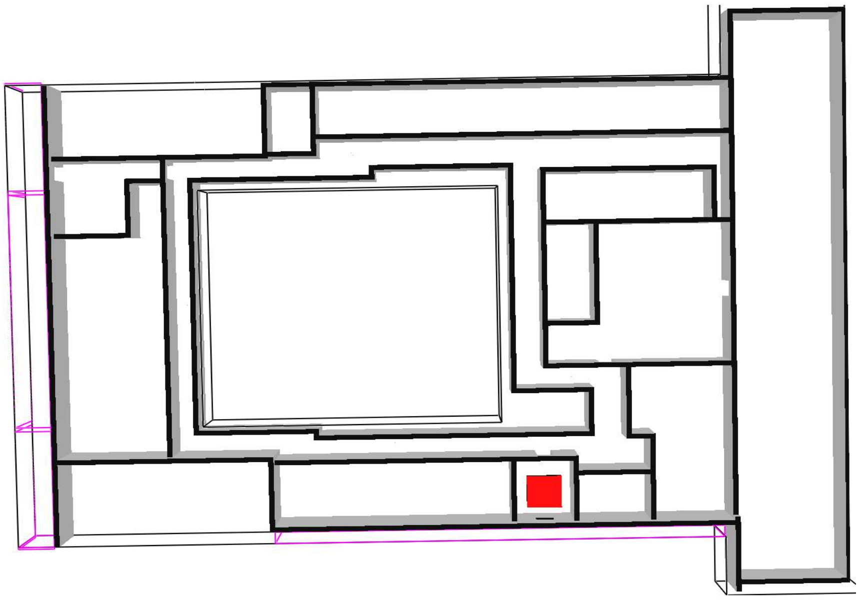

Figure 3 Location of fire 1

The location of fire 2 is thought to have an effect on two cabin corridors almost at the same time while also filling with smoke the area leading to one staircase and to the helipad in the exterior of the deck, shown in leftmost part of Figure 4.

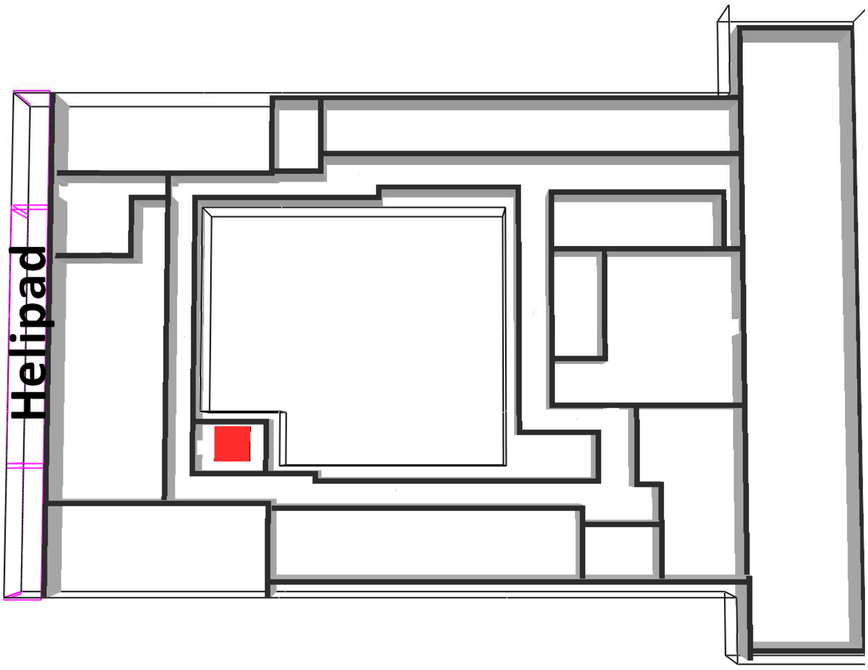

Figure 4 Location of fire 2

The location of fire 3 is thought to be the most challenging to the evacuation design. Being at this position, it easily fills with smoke the staircase located to its front and the smoke spreads to the corridor leading the leftmost staircase, thus, two exits will be filled with smoke at the beginning stages of the evacuation.

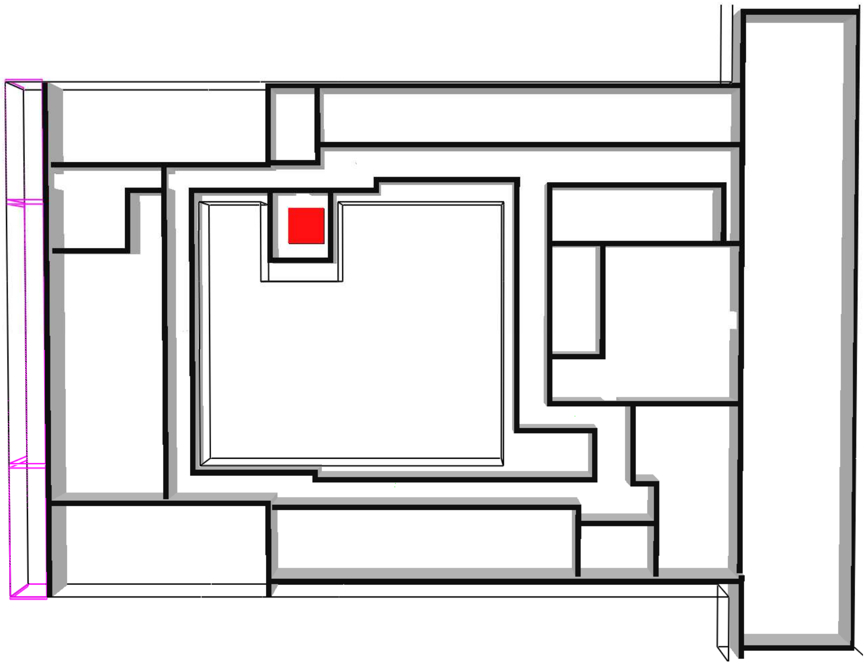

Figure 5 Location of fire 3

Fire 4

In this case, a fire starts in the converter room due to a short circuit. As a consequence of the large quantity of cables coated with PVC, the fire develops quickly. A t-squared fire is assumed with a fast growing rate [13]. Two data cables and one medium voltage cable are assumed to be involved in the fire; and average of each peak HRRPUA [12] is taken to calculate peak heat release rate of the fire.

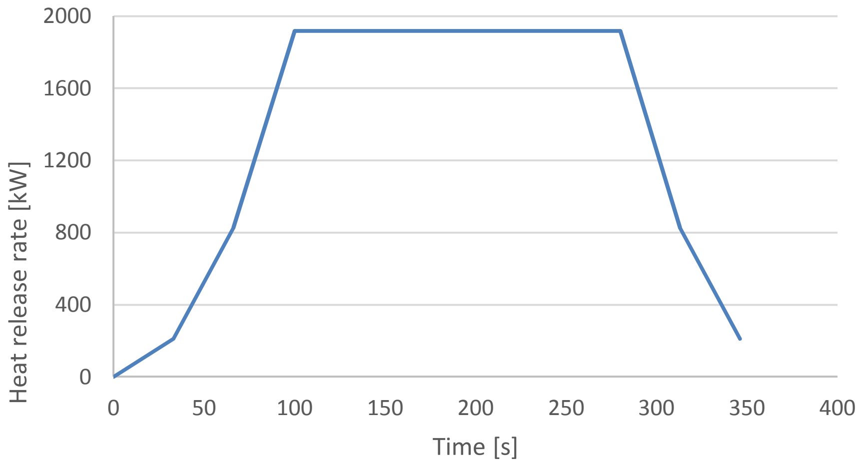

Figure 6 Cable fire in converter room

The location of this fire endangers the staff that is in charge of steering and navigating the ship inside the wheelhouse, while also filling with smoke the corridor leading to one of the main staircases.

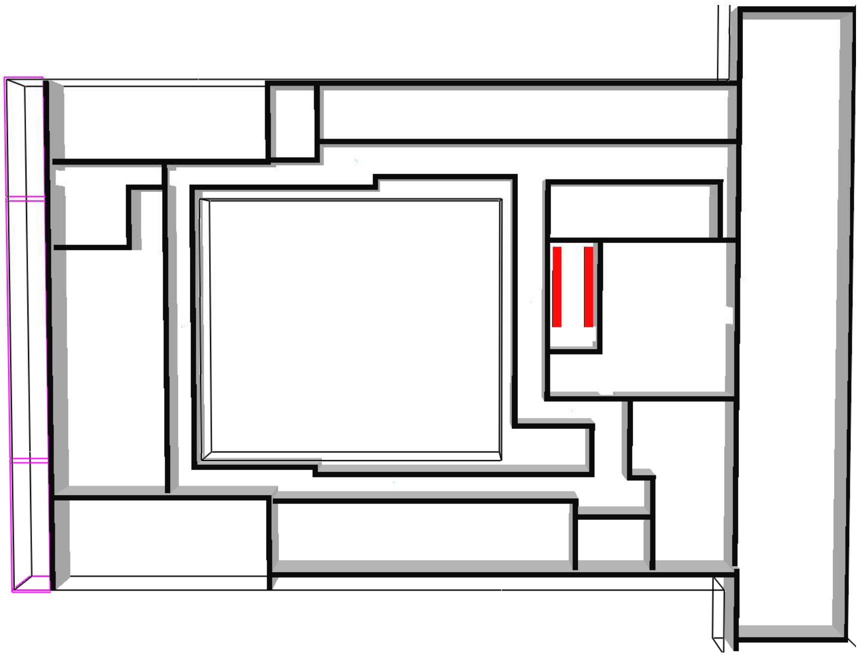

Figure 7 Location of fire 4

2.5 Material set-ups

In this project, three material combinations are used. In the first one steel is used, this is the original construction of the ship. The second one consists of a composite sandwich layout without passive fire-protection and the last one involves the same composite sandwich arrangement but, this time with passive fire-protection layer.

The original set-up consists of a sandwich set up with plaster board on each side of a steel core. The boards have thickness of 12,5 mm, whereas the steel core has a thickness of 100 mm.

The composite sandwich is made of Divinycell® H80 as core material and fiber glass as the external layer with a polyvinyl-ester as resin polymer. No thermal protection is provided for this configuration. Each layer of fiber glass has 2 mm of thickness and the core has 50 mm.

Since the PVEST resin used is ignitable, the unprotected walls are considered to be ignitable when they reach 397 °C [16] and to follow the HRRPUA curve shown in Figure 8. This figure shows the HRRPUA of a glass fiber-PVEST laminate once it reaches its ignition temperature. The experimental curve was taken using a radiation of 50 kW/m^2 to ignite the composite, this condition is not added to the combustion model of the laminate. This issue it is discussed later on in section 4.1.

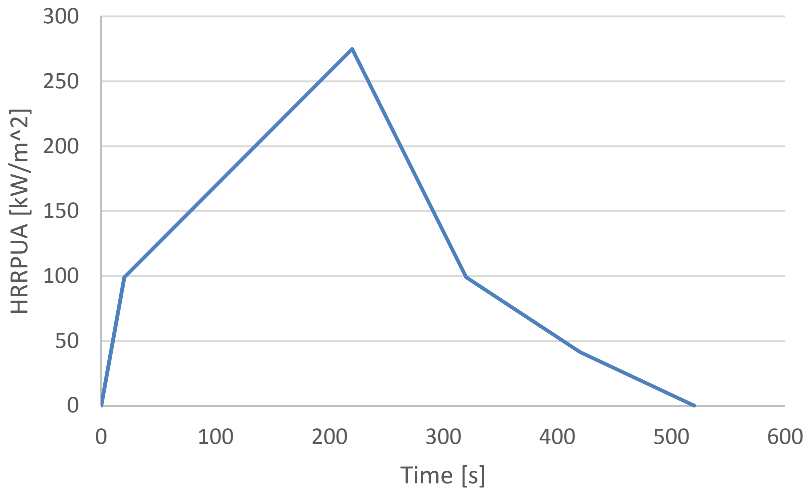

Figure 8 HRRPUA of the laminate [16]

The third set-up takes the same sandwich of the previous configuration but with an extra layer of 10cm of thermal protection on each side of the sandwich. The insulation material used as a passive fire protection is Fire Master ®, whose properties are shown in Table 3.

The relevant properties of all the materials used in the simulations are grouped in the following table:

Table 3 Material properties

MATERIAL	Density (Kg/m^3)	Conductivity (W/m*K)	Specific heat capacity (kJ/kg*K)	Thickness (mm)
Divinycell H80	80 [14]	0,031 [14]	1,92 [15]	50 [12]
Glass fiber laminate [15]	1870	0,047	0,89	2
Insulation [15]	100	0,08	0,80	100
Steel [23]	7850	45,8	0,46	100
Plaster board [23]	1440	0,48	0,84	12,5

2.6 Performance criteria

In this project, four criteria are studied to assess the safety of the passenger deck; FED being the principal one as it gives the chance to measure to some extent, the interaction of the people with the fire while evacuating. Nevertheless, for one example case the other three criteria are evaluated as well, thus having a better picture of the evacuation process during the fire, being this one of the advantages of applying performance-based design in fire safety [7].

2.6.1 FED (Fractional Effective Dose)

This value is measured taking Purser's definition of FED (Fractional Effective Dose) [10], shown in equation (3). Even though an FED value lower than 1,0 is consider as non-lethal, the limit of the FED for safe evacuation is taken as 0,3 as suggested in ISO/TS 13571 [20]. This document takes into account the variability among humans to withstand the toxic effects as there are people more sensitive and others more resistant.

One of the limitations of FDS EVAC is that it takes only the narcotic effects of CO, CO_2 and O_2 to calculate the FED as follows [19]:

$$FED_{tot} = FED_{CO} \times HV_{CO_2} + FED_{O_2} \tag{3}$$

As noted at the beginning of the Methodology, FDS EVAC does not take into account the influence of HCN or HCL in the FED and, furthermore, only takes the hyperventilation effect of the CO_2 that increases the breathing rate and therefore the quantity of inhaled gases. This is further explained in the User's guide in chapter 2 [19].

2.6.2 Visibility

The measurements of this quantity have a big deal of uncertainty. The main values, used to quantify visibility, are derived from a study made by B.F. Clarke, which is summarized in the SFPE Handbook [10]. The experiment used the psychological state of individuals moving in smoke with increasing extinction coefficient, as a measurement of the minimum visibility needed to escape safely. Despite a big range of values for visibility (from 1,2 m to 20 m) the selected value for this performance criterion will be the one derived from the data of the above-mentioned experiment. For this case the chosen value for this criterion is 10m. Visibility is assessed 2m above the floor level.

2.6.3 Radiation

Certain values of heat may lead to incapacitation. According to D.A. Purser, exposures to a flux of 2,5 kW/m^2, equivalent to a smoke layer temperature of 200 ℃, can be tolerated by a person for no more than five minutes. Greater values can be bared for only few seconds. These values can be found in the table 2.6-19 of the SFPE Handbook [10]. For the purpose of this project, the tenability limit for heat flux exposure is a value less than 2,5 kW/m^2 at floor level.

2.6.4 Smoke layer temperature and height

The smoke layer temperature is related to the amount of permitted radiation to the floor (2,5 kW/m^2). This amount limits the temperature of the smoke layer to approximately 200°C. The height that the smoke layer will be allowed to descend should not be less that 2 m above the floor; however, this value might be increased due to the limiting factor of the radiation. Thus, the radiation will dictate the temperature and the height above ground that the smoke is allowed to descend [11].

2.7 Mesh sensitivity analysis

An important part of ensuring the error of the results generated by the simulations is acceptable, is proving that they are independent of the mesh being used. The FDS' developers provide guidance on how to estimate the size of the mesh to be used based on the magnitude of the fire and the ambient conditions. This is measured by the non-dimensional expression D^*/δ_x, where D^* is the characteristic fire diameter (given below) and δ_x is the size of a mesh cell, this ratio has been validated in the range of 4 to 16 [18]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \tag{3}$$

The bigger the ratio D^*/δ_x is, the finer the mesh is. Table 4 summarizes the relevant values of the meshes used for the 4 fires.

Table 4 Mesh cell size and number of cells

		$D^*/\delta_x = 4$	$D^*/\delta_x = 8$	$D^*/\delta_x = 10$	$D^*/\delta_x = 12$
Fire 1	*Cell size (cm)*	30	15	12	10
	Number of cells	196944	1246560	2402460	4207140
Fire 2	*Cell size (cm)*	30	15	12	10
	Number of cells	198624	1260000	2429460	4252500
Fire 3	*Cell size (cm)*	30	15	12	10
	Number of cells	198960	1255968	2428710	4233390
Fire 4	*Cell size (cm)*	30	15	12	10
	Number of cells	196944	1246560	2402460	4207140

Due to the fact that the design fires have almost the same peak HRR, the selected mesh cell sizes are the same for all the fires and just varies depending on the ratio $D^*/\delta x$.

The mesh independency is evaluated both qualitatively and quantitatively by measuring temperature, smoke layer height and temperature and radiation in 5 points of the ship shown in white in Figure 9. These points remain unmoved for all the simulations regardless of the fire location.

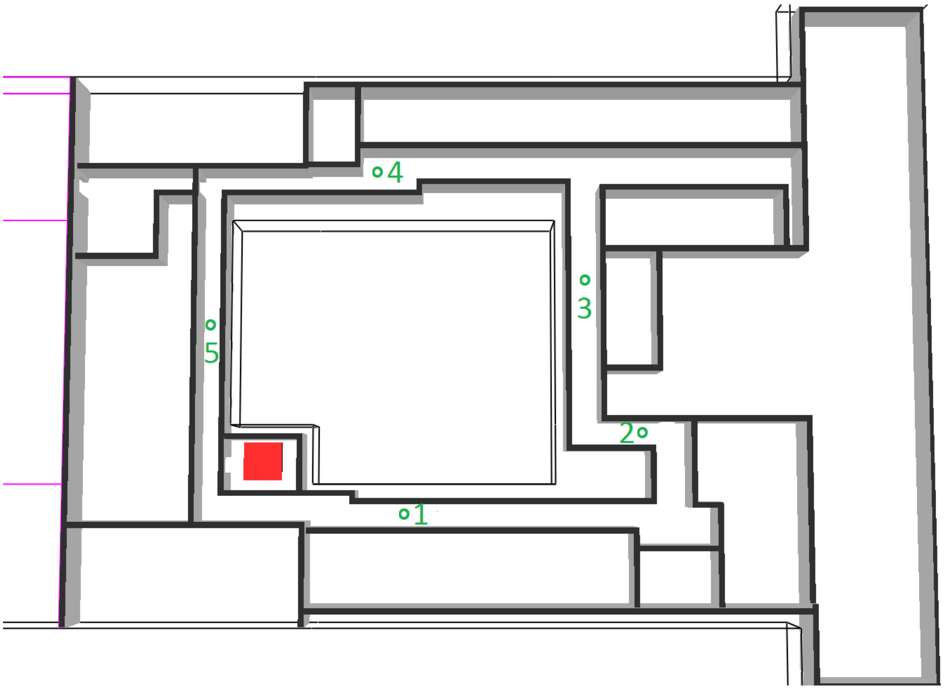

Figure 9 Measuring points for mesh sensitivity (in green)

The optimal mesh cell size will be the coarser one that starts the trend of not affecting the simulation's results, for the measured variables.

2.8 Input data FDS and FDS EVAC

In order to carry out the simulations, FDS and FDS EVAC require certain data, that due to their effect on the final result, must be well supported and the selection has to be motivated. The simulations with unprotected FRP walls have two fuels that will be involved in the fire. However, these do not start burning at the same time; the FRP combustion is conditioned to start when its surface temperature reaches 397 °C [16]. This circumstance makes the selection of the heat of combustion, soot yield and CO yield not trivial since FDS only allows one reaction line for these cases. The approach to this issue is to take a weighted average between the properties of the materials involved in the fire. The proportion is taken as 60% of the laminate (Glass fiber and polyvinylester) with a soot yield of 0,076 g/g [10] and a heat of combustion of 22 kJ/g [10] and 40% of Polyurethane foam with a soot yield of 0,23 g/g [13] and a heat of combustion of 17 kJ/g [13]; this results in an average soot yield of 0,14 and a heat of combustion of 20 kJ/g. The carbon monoxide yield of polyurethane is used and it has been estimated to be 0,031 g/g [10]

Fire number 4 is a cable fire in the converter room as shown in Figure 7. The HRR curve is built averaging the data from three different types of cables gotten from Grayson et al. [12]. Two data cables and one medium voltage kind of cables are involved, all of them with PVC cover which is taken as the dominant combustible. The peak average HRRPUA is 417 kW/m^2 and an ultra-fast growth coefficient of 0,19 kW/s^2 [13] is used. The duration of the developed phase of the fire is assumed to last 3 minutes.

One case of fire number 4 includes unprotected FRP walls, which is combustible as well. In this case the same approach of weighted average is taken with the same proportions used for fire 1 to 3. The soot yield of PVC is 0,17 g/g [10] and has a heat of combustion of 16 kJ/g [10] which combined with the ones of Polyvinylester (0,076 g/g and 22kJ/g [10]) result in a soot yield of 0,11 g/g and a heat of combustion of 19,6 kJ/g.

On the other hand, the evacuation section of the simulations requires data related to human behavior in order to get the agents to act as realistically as possible. Despite the control that FDS EVAC has over the human behavior variables, some modifications were done to some of them to comply with the IMO guidelines when software is used to estimate the evacuation time.

The pre-evacuation time, walking speed of the crew and the density of smoke at which any agent will detect the fire, are modified and added to the FDS input files. The values of the first two are given by IMO and explained in section 2.3 of this document; the latter has a value of 0,65 g/m^3, a value that according to Gann, “At this mass density of smoke, people 10 m away would begin to have difficulty seeing a reflecting exit” [22]. Hence, this value will be taken as enough for evacuees in FDS EVAC to realize there is a fire somewhere in the deck and prevent them to stand waiting in thick smoke for the assigned pre-movement time to be reached.

An example of the FDS input file used for the simulations can be found in APPENDIX A.

3. RESULTS

This section comprises the results of the mesh sensitivity study, the evacuation simulations with the different material configurations and design fires, and the example case. Firstly, the results of the mesh sensitivity are presented followed by the principal simulations of the project, finalizing with the example case taking into account all the performance criteria mentioned in section 2.6. It is important to bear in mind that in the cases where fatalities occur, the evacuation time is taken as the time when the last alive evacuee leaves the deck.

3.1 Mesh sensitivity

In order to estimate the optimal element size for the fire calculations, four meshes were built according to the guidelines in the FDS' user guide [18]. The meshes, as seen in Table 4, were tested with the same scenario, namely case fire number 2 with the steel walls. The curves for the mesh resolution D/dx=12 (in red) are incomplete due to several issues with the Restart function in the Linux cluster where the simulations were done.

In Figure 10 the HRR curves generated by each mesh are plotted as a function of the time and compared with the simplification of the experimental curve specified by SP [9], shown in black. As expected, the higher the resolution, the closer the results are to the experimental curve and less different the curves are between them. The figure also depicts an increasing difference in relation to the experimental data from 200 s onwards. Despite that, the difference between using 10 or 12 as mesh resolution is not considerable.

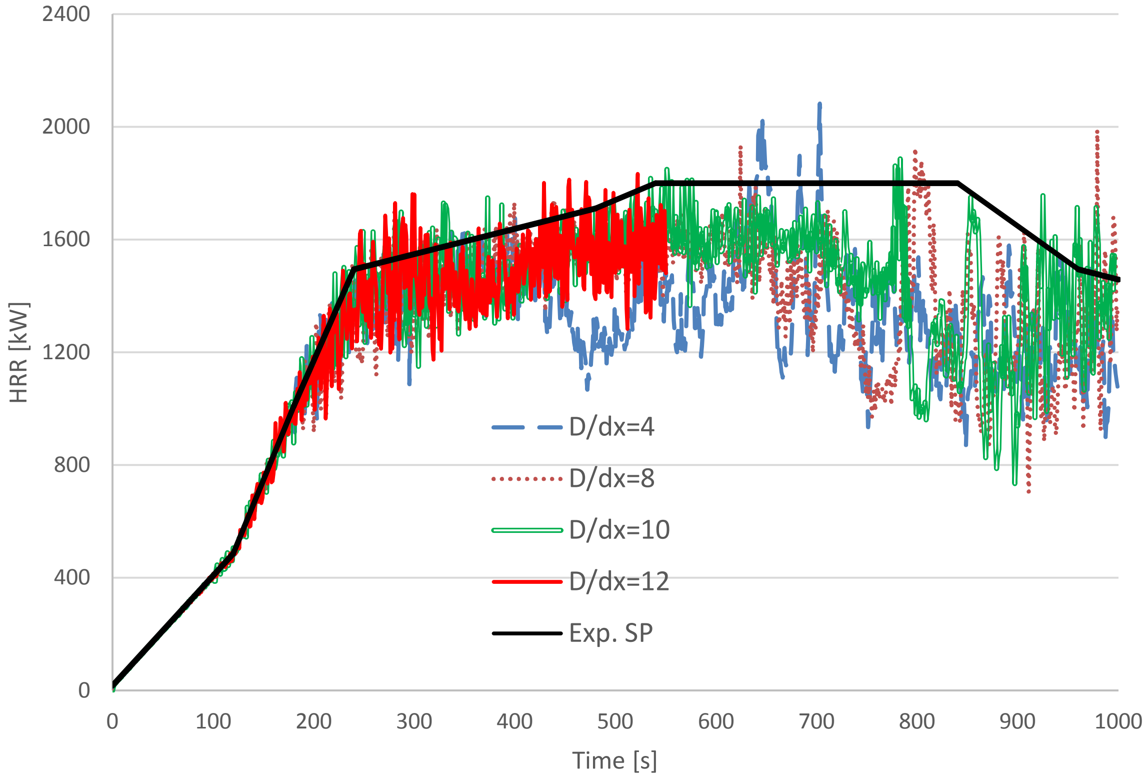

Figure 10 HRR curves for all the mesh resolutions

The following figure shows the gas temperatures as a function of the time for the measuring point 3 for the different mesh resolutions. The higher the mesh resolution is, the lower the differences between the curves are.

The data of D/dx=4 and D/dx=8 show appreciable differences between them, with a maximum of 36%. Whereas the curves corresponding to D/dx=10 and D/dx=12, present no big differences with a maximum of 10% in an otherwise good match.

The remaining graphs of the gas temperatures have a similar behavior as shown in Appendix B. The mesh resolution of 10 is the most efficient one giving almost the same results as using a resolution of 12 and noticeably better results than using the other lower resolutions.

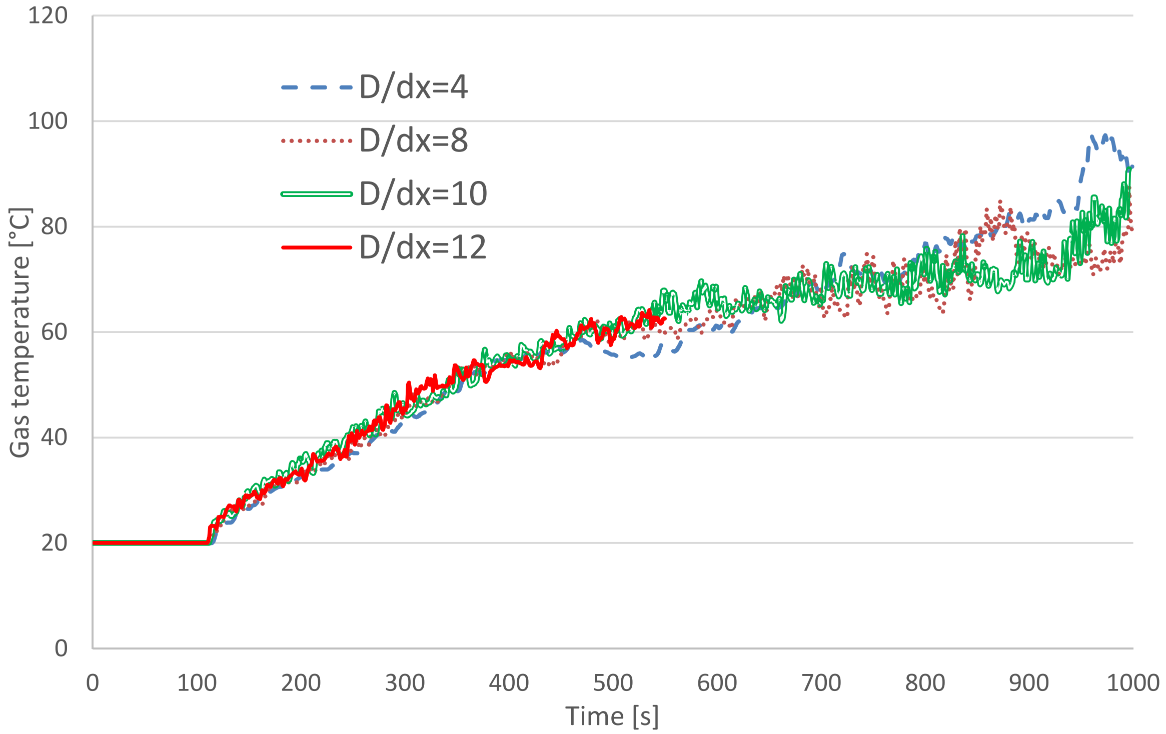

Figure 11 gas temperatures at point 3 for all the meshes

Radiation to the floor is the next variable to be analyzed, since is one of the performance criteria used to evaluate the scenarios.

The following figure shows radiation to the floor in time for measuring point 3 with different mesh resolutions. This quantity was measured in FDS as Incident Heat Flux since it's the relevant quantity for the specified performance criterion of radiation to the floor.

The higher the mesh resolution is, the lower the differences between the curves are.

The data of D/dx=4 and D/dx=8 show appreciable differences between them with a maximum of 25%. Whereas the curves corresponding to D/dx=10 and D/dx=12, present no big differences with a maximum of 2% in an otherwise good match.

The remaining graphs of the radiation to the floor have a similar behavior as shown in Appendix B. The mesh resolution of 10 is the most efficient one giving almost the same results as using a resolution of 12 and noticeably better results than using the other lower resolutions.

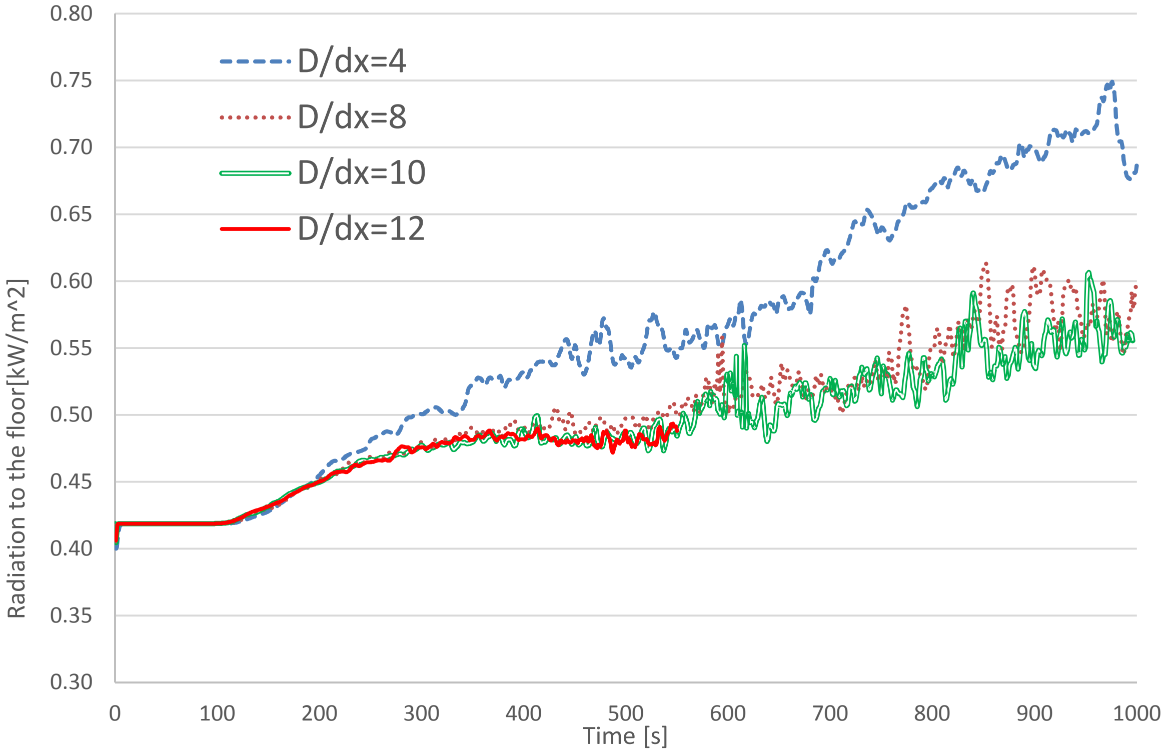

Figure 12 Radiation to the floor at point 3 for all the meshes

3.2 Effect relative to the design fire

The results of the effect of changing the design fires for each material set-up are presented. Each one is analyzed focusing on the influence that it has on the evacuation process of the passenger deck. The evacuation time, average fatalities and average maximum FED are compared with a base case modelled as a fire drill in FDS EVAC, which are calculated to be 393 [s] (taken as the RSET), no fatalities and zero FED, respectively.

Even though fatalities are understood to be a whole number, decimals are shown in order to have a display that in at least one evacuation simulation fatalities occurred, thus having a better comparison between the cases.

The quantity of Average Fatalities per simulation, is a measurement of how many evacuees died, in average, in each of the 50 evacuation simulations done for the correspondent scenario. A similar approach is taken for the Average Maximum FED, for each of the 50 simulations, the maximum FED among the evacuees that are still alive is taken for the calculations. If there is at least one agent that dies, the maximum FED for the run is taken as 1,0.

3.2.1 Original set-up (steel)

Table 5 summarizes the results of the studied variable when the steel set-up is used. This case has no combustible walls.

Table 5 Results relative to the original steel set-up

Design fire	**Evacuation time [s]**	**Average fatalities per simulation**	**Average maximum FED**
1	578	0	0,17
2	586	0,06	0,39
3	591	0,08	0,48
4	505	1,30	0,90

In the values of Table 5 it can be observed that the maximum evacuation time is for the design fire 3 being more than 50% larger that the drill time. Whereas for the fatalities and the maximum FED, fire number 4 has the largest values despite having the lowest evacuation time.

Studying the average max FED, the only case in which it is lower than the 0,3 (taken as the threshold for safe evacuation) is for fire 1; all the other cases present a value higher than the safety limit, being fire 4 the one presenting the highest values.

An average maximum FED value of 0,9 for fire 4, suggests that there is at least 1 fatality in almost all the evacuation simulations, as shown in APPENDIX C and with an average of fatalities per simulation of 1,3 it is clear that the most critical case for the steel set-up is design fire number 4.

3.2.2 Unprotected composite set-up

Referring to the set-up that is expected to be the most critical due to the presence of combustible fiber-glass walls, Table 6 summarizes the results of the studied variable when the unprotected composite set-up is used.

Table 6 Results relative to the unprotected FRP set-up

Design fire	**Evacuation time [s]**	**Average fatalities per simulation**	**Average maximum FED**
1	465	0,40	0,46
2	459	0,46	0,61
3	462	1,26	0,89
4	249	4,48	1,00

In the values of Table 6 it can be observed that the maximum evacuation time is for the design fire 1, being more than 18% larger than the drill time. Whereas for the fatalities and the Maximum FED, fire number 4 has the largest values despite having the lowest evacuation time.

Studying the average max FED, none of the cases has a value lower than the 0,3. Furthermore, fire 4 again gives the highest value when compared to the other design fires.

An average maximum FED value of 1,00 for fire 4, means that there is at least 1 fatality in all the evacuation simulations, as shown in APPENDIX C and APPENDIX D, and with an average of fatalities per simulation of 4,48 it is clear that the most critical case for the unprotected composite set-up is design fire number 4. This means so far that design fire 4 is the most critical for two material configurations.

3.2.3 Protected composite set-up

Table 7 summarizes the results of the evacuation process when the protected composite set-up is used.

Table 7 Results relative to the protected FRP set-up

Design fire	**Evacuation time [s]**	**Average fatalities per simulation**	**Average maximum FED**
1	625	0,02	0,21
2	557	0,06	0,47
3	507	0,70	0,77
4	524	1,26	0,92

In the values of Table 7 it can be observed that the maximum evacuation time is for the design fire 1 that is more than 59% larger that the drill time. Whereas for the fatalities and the maximum FED, fire number 4 has the largest values despite having the second lowest evacuation time.

Studying the average max FED, the only case in which it is lower than the 0,3 is for fire 1; all the other cases present a value higher than the safety limit, being fire 4 the one presenting the highest value.

An average maximum FED value of 0,92 for fire 4, means that there is at least 1 fatality in all the evacuation simulations, as shown in APPENDIX C and APPENDIX D, and with an average of fatalities per simulation of 1,26 it is clear that the most critical case for the unprotected composite set-up is design fire number 4. For all the material configurations, the general trend is fire 4 to be the most critical case.

3.3 Effect relative to the material set-up

The results of the effect of changing the material set-up for each design fire are presented. Each one is analyzed focusing on the influence that is has on the evacuation process of the passenger deck, following the same methodology of the previous section.

3.3.1 Fire 1

In the following table the results for the evacuation runs for design fire 1 are presented in relation to the material set-up.

Table 8 Results relative to design fire 1

Material set-up	Evacuation time [s]	Average fatalities per simulation	Average maximum FED
Steel	578	0	0,17
Unprotected FRP	465	0,40	0,46
Protected FRP	625	0,02	0,21

In the values of Table 8 it can be noted that the maximum evacuation time is for the protected composite set-up that is more than 59% larger that the drill time. Whereas the fatalities and the Maximum FED are related to the unprotected FRP set-up, despite having the lowest evacuation time.

Studying the average max FED, there are two cases with an average maximum FED lower than 0,3 which is the safety limit; the steel and the protected FRP set-up fulfill this criterion. On the other hand, the unprotected FRP case, having an average FED of 0,46 exceeds the limit becoming not safe for the evacuees.

An average maximum FED value of 0,46 for the unprotected FRP case, means that there is at least 1 fatality in half of the evacuation simulations, also as shown in APPENDIX C and with an average of fatalities per simulation of 0,40 it is clear that the most critical case for design fire 1 is the unprotected FRP configuration.

3.3.2 Fire 2

In the following table the results for the evacuation runs for design fire 2 are presented in relation to the material set-up.

Table 9 Results relative to design fire 2

Material set-up	**Evacuation time [s]**	**Average fatalities per simulation**	**Average maximum FED**
Steel	586	0,06	0,39
Unprotected FRP	459	0,46	0,61
Protected FRP	557	0,06	0,47

In the values of Table 9 it can be noted that the maximum evacuation time is for the steel set-up that is more than 49% larger that the drill time. While the fatalities and the maximum FED are again related to the unprotected FRP set-up, despite having the lowest evacuation time.

Studying the average maximum FED, none of the cases presents a FED value lower than 0,3 making them all not safe for evacuation. The highest value of this variable appears with the unprotected FRP set-up.

An average maximum FED value of 0,61 for the unprotected FRP case, means that there is at least 1 fatality in almost three quarters of the evacuation simulations, also as shown in APPENDIX C and with an average of fatalities per simulation of 0,46 it is clear that the most critical case for design fire 2 is the unprotected FRP configuration.

3.3.3 Fire 3

In the following table the results for the evacuation runs for design fire 3 are presented in relation to the material set-up.

Table 10 Results relative to design fire 3

Material set-up	**Evacuation time [s]**	**Average fatalities per simulation**	**Average maximum FED**
Steel	561	0,08	0,48
Unprotected FRP	462	1,26	0,89
Protected FRP	507	0,70	0,77

In the values of Table 10 can be noted that the maximum evacuation time is for the steel set-up, being more than 42% larger that the drill time. Whereas the fatalities and the Maximum FE, are again related to the unprotected FRP set-up, despite having the lowest evacuation time.

Studying the average maximum FED, none of the cases presents a FED value lower than 0,3 which is the safety limit. The highest value of this variable appears with the unprotected FRP set-up.

An average maximum FED value of 0,89 for the unprotected FRP case, means that there is at least 1 fatality in more than three quarters of the evacuation simulations, also as shown in APPENDIX C and with an average of fatalities per simulation of 1,26 it is clear that the most critical case for design fire 3 is the unprotected FRP configuration.

3.3.4 Fire 4

In the following table the results for the evacuation runs for design fire 4 are presented in relation to the material set-up.

Table 11 Results relative to design fire 4

Material set-up	**Evacuation time [s]**	**Average fatalities per simulation**	**Average maximum FED**
Steel	505	1,30	0,90
Unprotected FRP	249	4,48	1,00
Protected FRP	524	1,26	0,92

In the values of Table 11 can be noted that the maximum evacuation time is for the protected FRP set-up that is more than 33% larger that the drill time. Whereas the fatalities and the Maximum FED are once again related to the unprotected FRP set-up, despite having the lowest evacuation time.

Studying the average maximum FED, none of the cases presents a FED lower than 0,3 which is the safety limit. The highest value of this variable appears with the unprotected FRP set-up.

An average maximum FED value of 1 for the unprotected FRP case, means that there is at least 1 fatality in all of the evacuation simulations, also as shown in APPENDIX C and with an average of fatalities per simulation of 4,48 it is clear that the most critical case for design fire 4 is the unprotected FRP configuration.

This results make the unprotected FRP set-up the most critical configuration, especially when related to the design fire 4. Hence, the worst scenario by location and by material configuration is the design fire 4 combined with the unprotected FRP walls.

3.4 Example case

As an example case, the scenario comprising the protected composite set-up and the design fire 1 is selected. The reasons for this selection are based on the material configuration of most interest for this research and is one of the cases that has a FED below the threshold of

0,3. Thus, it becomes important to further analyze the other performance criteria. As explained in the methodology, the scenario is evaluated taking the performance criteria exposed in section 2.6.

The first performance criterion to be taken into account is the FED. Its value has to be lower than 0,3 for the evacuation process to be carried out safely [20]. The present scenario has a FED value of 0,21 which fulfills the first performance criterion.

The second criterion is the visibility. This parameter has to be larger than 10 m to be considered as safe [10]. Nevertheless, in Figure 13 Visibility slice at 48 [s]and 14 it can be noted that the visibility at exit 1 and exit 2 is below the threshold at 48 and 112 seconds respectively. In this case this criterion is not fulfilled.

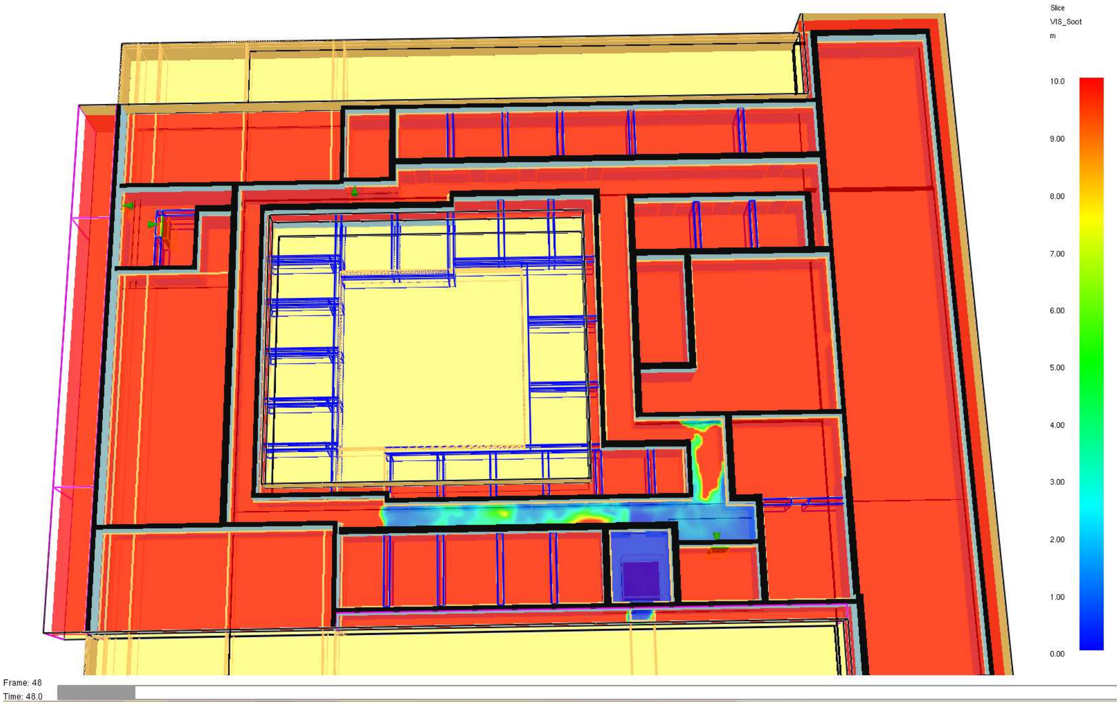

Figure 13 Visibility slice at 48 [s] for design fire 1 with protected FRP walls

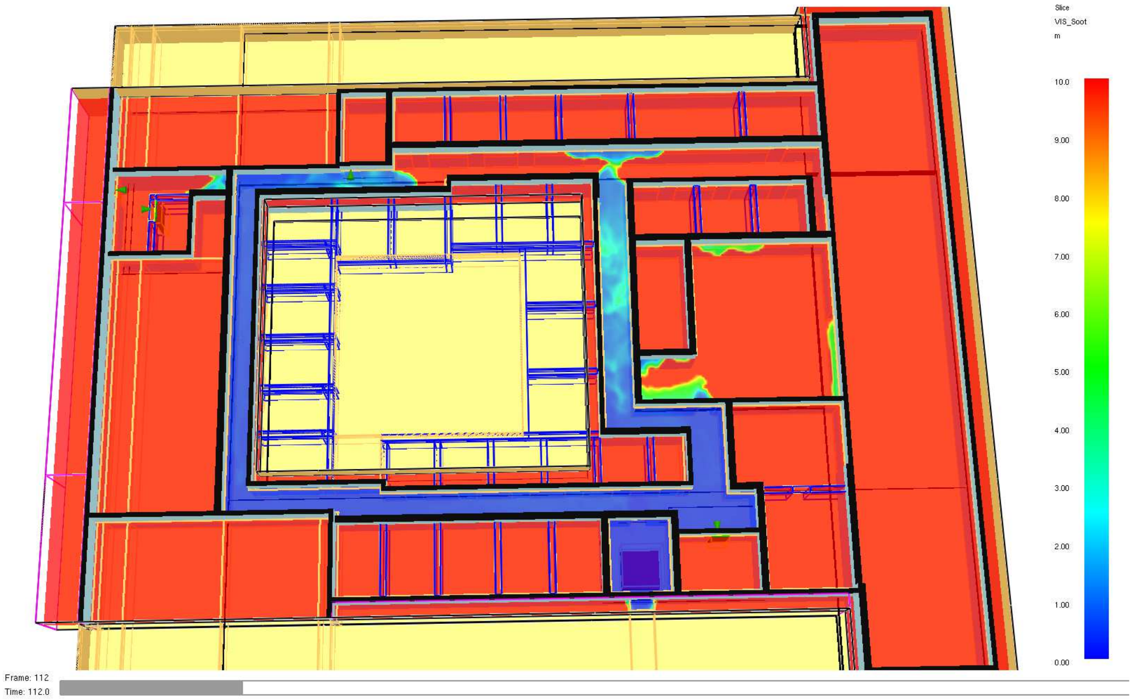

Figure 14 Visibility slice at 112 [s] for design fire 1 with protected FRP walls

When analyzing the next criterion, radiation to the floor, the accepted limit is 2,5 kW/m^2 [10] for safe evacuation. Figure 15 shows that for this case the criterion is fulfilled as the radiation to the floor is well below the limit at all the measuring points.

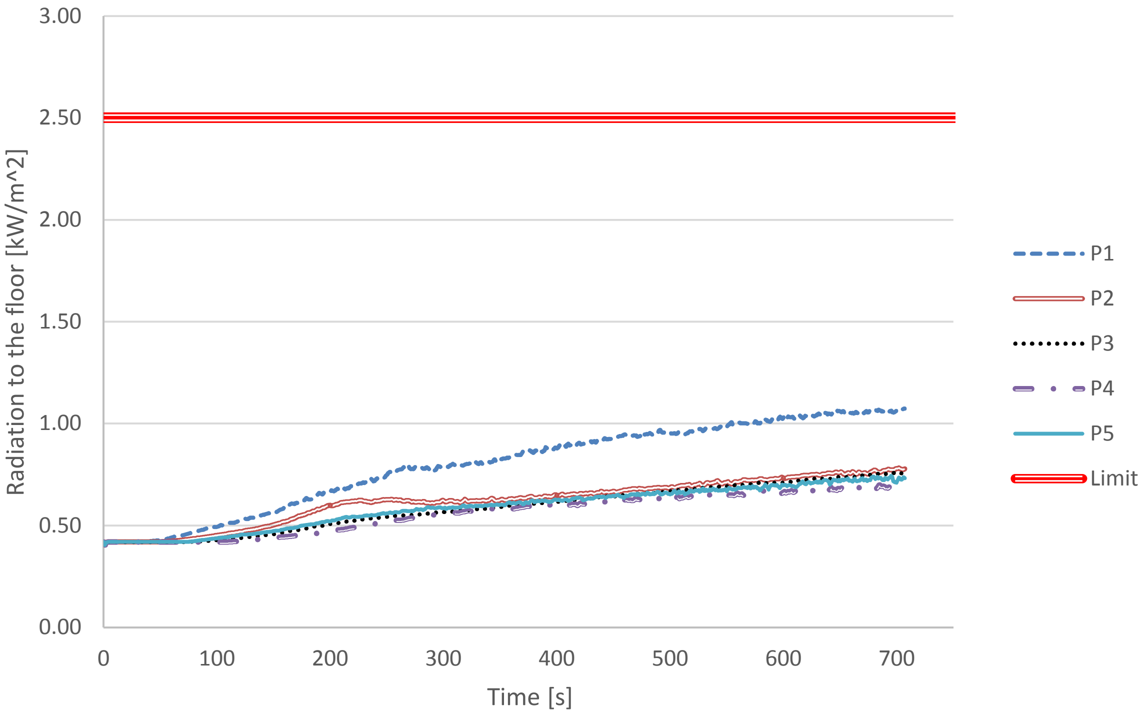

Figure 15 Radiation to the floor for design fire 1 with protected FRP walls

The last criterion to be assessed is the smoke layer height and its temperature. The limits for these quantities are 2 m above the ground and 200 °C [11], respectively. In Figure 16 Gas temperature at 2 m to Figure 18 Upper layer temperature, the results of the gas temperature at 2 m, the smoke layer height and the smoke layer temperature as a function of time are shown. For all three variables the criteria are not met, being the smoke layer height the first to exceed the accepted value at 40 [s], followed by the gas temperature at around 250 [s] and the upper layer temperature limit is exceeded at 300 [s]. The latter, being a condition for the radiation criterion, overrides the acceptance of the scenario for both criteria at the time previously mentioned. Hence, this case doesn't fulfill the criterion of the smoke layer properties.

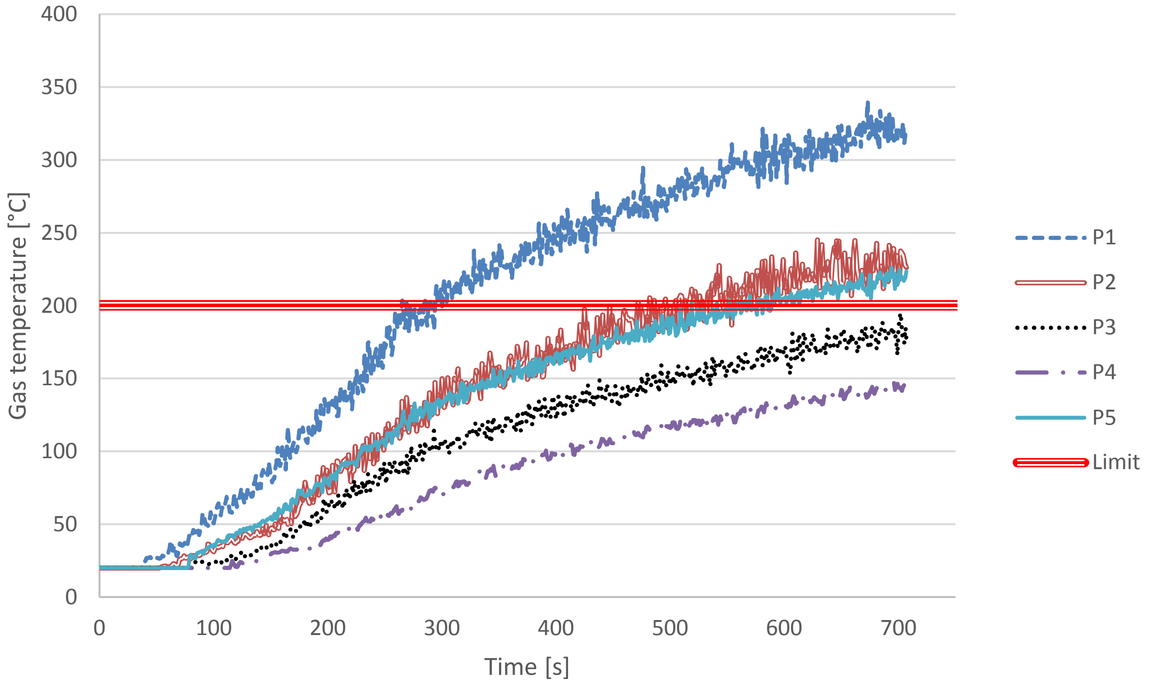

Figure 16 Gas temperature at 2 m from the floor for design fire 1 with protected FRP walls

In the previous image the gas temperature for each measuring point is plotted vs time, along with the performance safety limit. It's clear how point number 1 exceed the limit first at around 250 seconds.

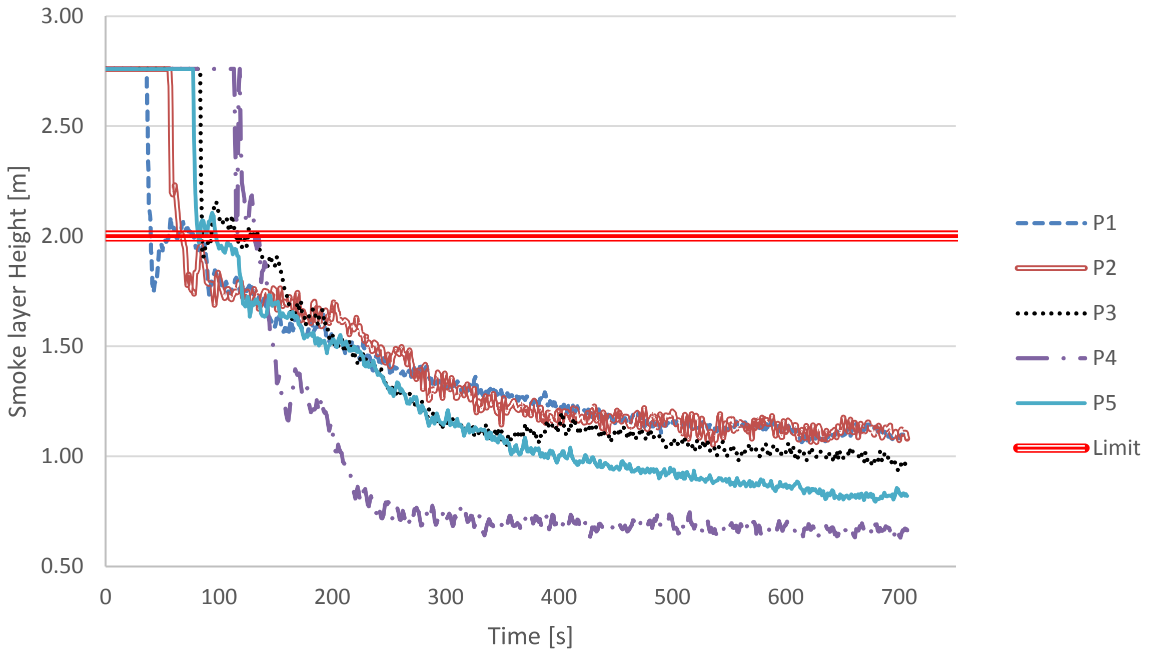

Figure 17 Smoke layer height for design fire 1 with protected FRP walls

The smoke layer height in time is plotted in Figure 17. The smoke layer height varies from point to point, however, the safety limit is first exceed in the measure point 1.

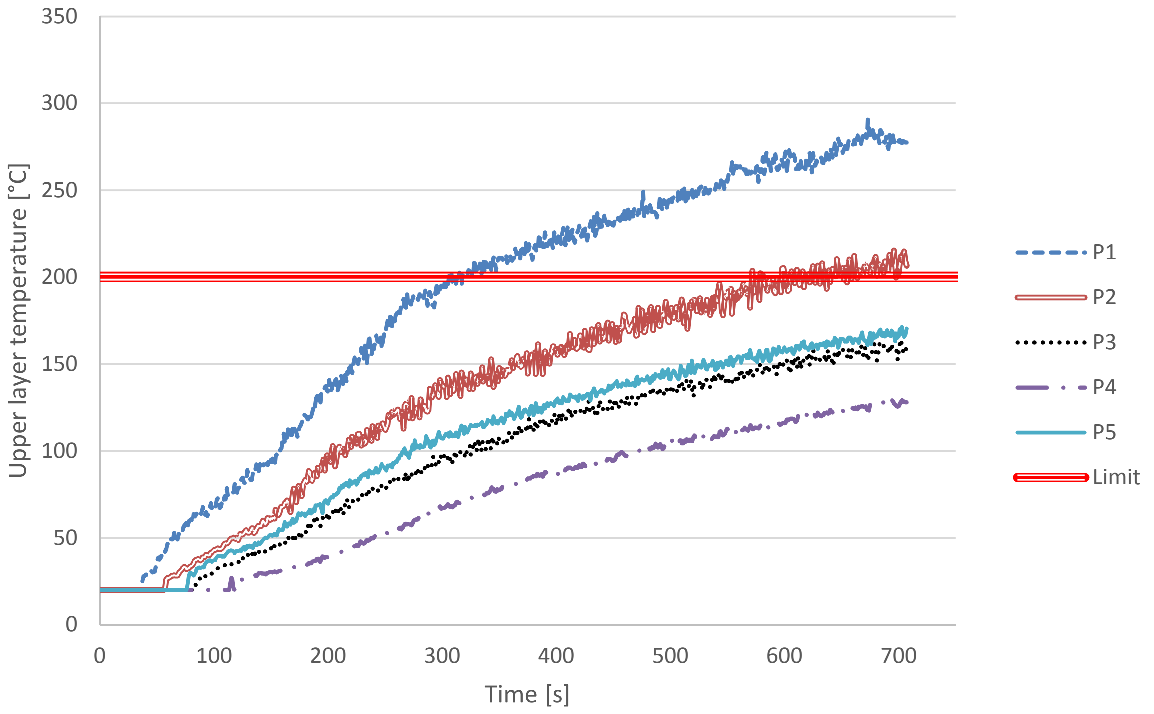

Figure 18 Upper layer temperature for design fire 1 with protected FRP walls

Figure 18 shows the temperature of the smoke layer as a function of time. It’s calculated in FDS using the 2-zone model approximation, still this quantity gives a good image of the smoke temperature to assess the correspondent performance criterion.

Despite the fulfillment of the FED criterion, the analyzed case does not meet the other performance criteria. Hence, the scenario cannot be considered as safe for the evacuation process. Additionally, solutions must be proposed since the RSET for this case is 625 [s] and the ASET is only 40 [s].

4. DISCUSSION

The results of the simulations are explained thoroughly in order to find relations, trends and the causes and the consequences of them. First, the mesh sensitivity is argued, followed by the results of the fire-evacuation simulations, then the example cases is analyzed and a comparison with the methods proposed by Gutiérrez [17] and the one by Azzi [24] are performed. The chapter finalizes with an assessment of the difficulty of applying a performance-prescriptive method for fire safety design in ships.

4.1 Mesh sensitivity

The mesh sensitivity analysis gave the optimal cell size as 12 cm. This result is derived from the behavior of the measured quantities whose plots are increasingly similar to each other. The observed differences between the calculated HRR and the experimental curves in Figure 10, are due to the difference in the ventilation conditions between the simulations and the experimental set-up; it is well known that the ventilation conditions can significantly affect the development of a fire [9][13][23].

In the original experiment done by SP, the cabin was not confined within a deck but was in an open space with unlimited air supply, hence well-ventilated conditions were present thought-out the complete experiment. On the other hand, in the simulations the cabin was confined within the deck with openings to fresh air relatively far from it, consequently limiting the available oxygen for the fire. This situation is well illustrated in Figure 19 where a slice of the oxygen mass fraction is shown for design fire 2 with the steel wall set-up. The image is taken at 400 s and in the fire area the oxygen mass fraction is around 7%. According to Drysdale [23], a fire in an environment with a low O_2 concentration due to inadequate ventilation can either self-extinguish or continue burning but at a slower rate, depending on the quantity of oxygen that is available. This explains why at the beginning, the simulations follow exactly the experimental results and then differ from them when under-ventilated conditions are in place. Furthermore, Azzi et al [24] encountered a similar situation using the same experimental data where big fluctuations in the HRR curve, appeared around 900 s of the simulated time due to the drop on the oxygen levels and to avoid fuel burning far from the cabin, only the first phenomenon was seen in the present project as shown in Figure 10.

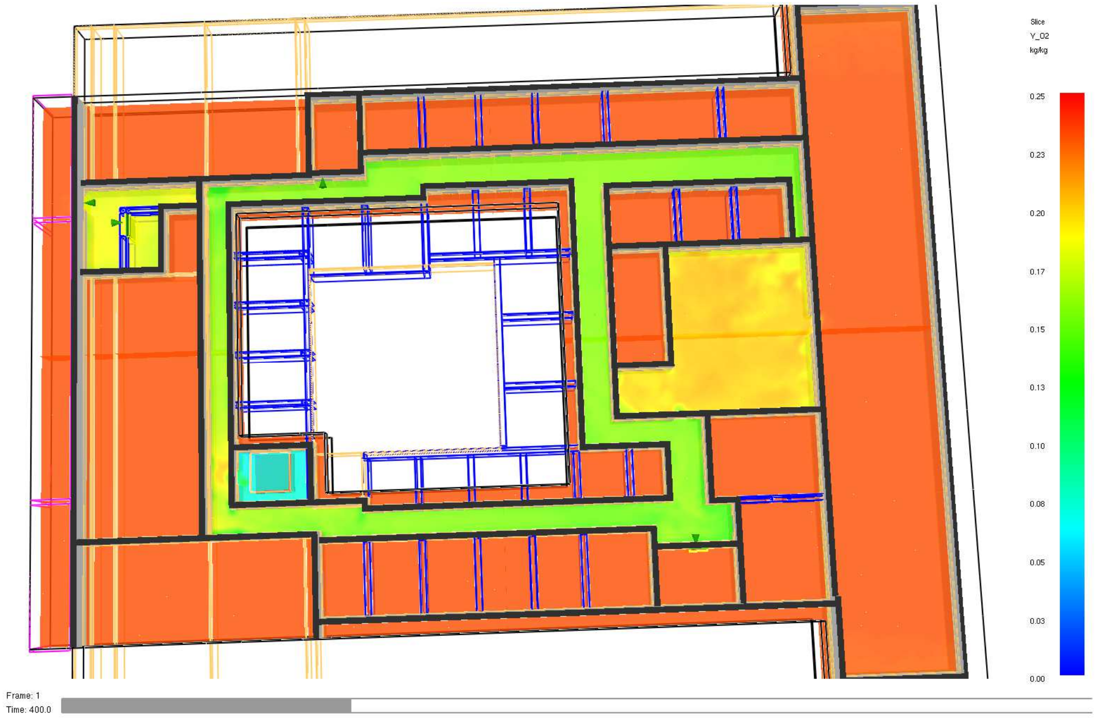

Figure 19 Oxygen mass fraction

Another phenomenon that usually accompanies under-ventilated conditions in a fire is external flaming [23]. This also happens in the simulated fires as shown in Figure 20 where the lack of enough oxygen in relation to the volatized inflammable vapors inside the deck, causes they cannot ignite inside, but outside the compartment.

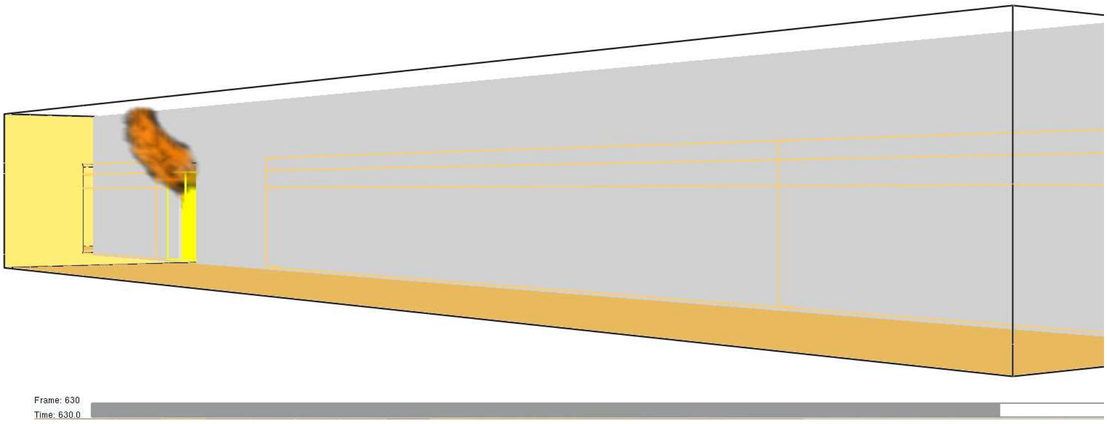

Figure 20 external flaming caused by under-ventilated conditions inside the deck

As it was mentioned in section 2.5, the HRRPUA curve of the laminate was got from an experimental set up were a radiation flux of 50 kW/m^2 was used to ignite the composite. This heat flux has an influence on the measured peak heat release rate. This is better seen on Figure 21, adapted from Mouritz et al, chapter 3, page 75 [16], where the peak heat release rate of four glass fiber laminates with different resins is plotted against the heat flux from the cone calorimeter apparatus.

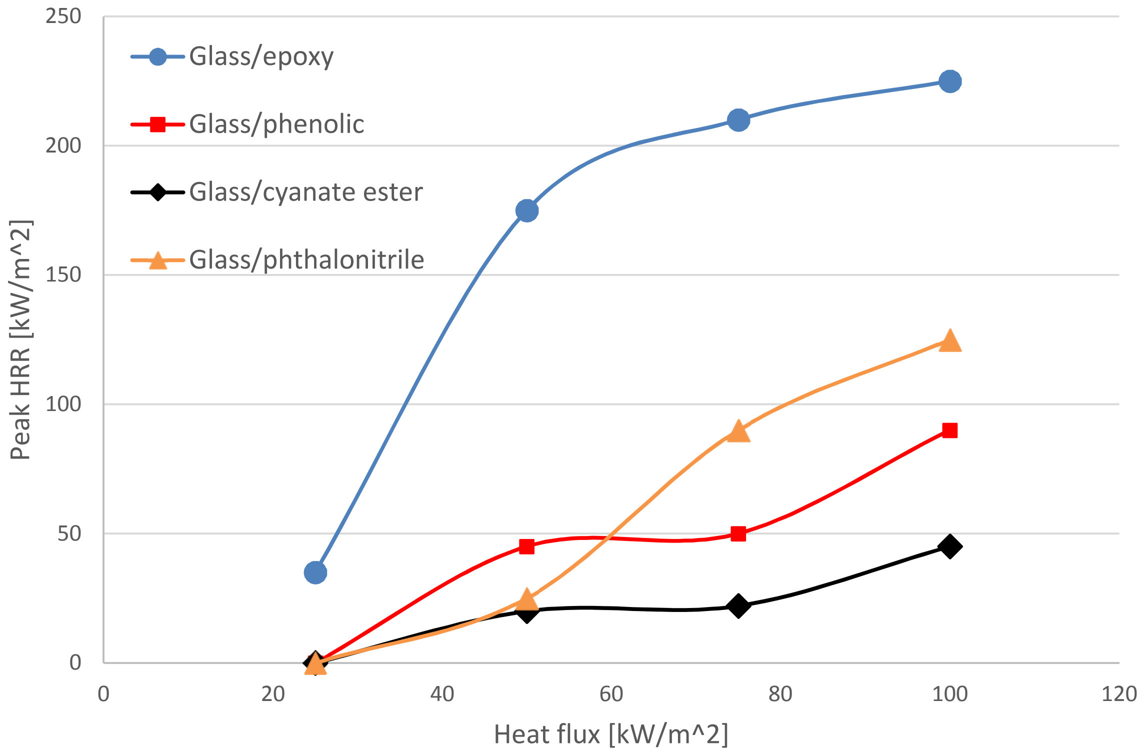

Figure 21 Effect of heat flux on the peak HRR for various glass polymer laminates

The influence of the heat flux on the peak HRR is high when epoxy and phthalonitrile are used as resin and not as important when phenolic or cyanate ester are implemented. Despite having no information when PVEST is used, which is the resin used in the laminate that´s being studied in this thesis, it can be said from the behavior of the other resins, that the peak HRR will be affected and the value taken in this study could be not the best one. More data is needed in order to have a closer look at the influence of the heat flux used in the cone calorimeter test, on a laminate made of glass/vinyl ester.

4.2 Effect of the fire location and material set-up

The following figure is taken from the evacuation simulations for design fire 4 viewed in Smokeview®, where the long distances that some evacuees located in the wheelhouse have to walk to get to an exit are clear. Furthermore, these evacuees have to walk through smoke most of the time in their path to an exit, which explains the high numbers of fatalities and the large average max FED. Another reason for the high number of fatalities is the rapid development of hazardous conditions in the corridors even before the passengers emerge from the cabins, suffering this way a rapid increase on the FED and lowering their walking speed almost instantly.

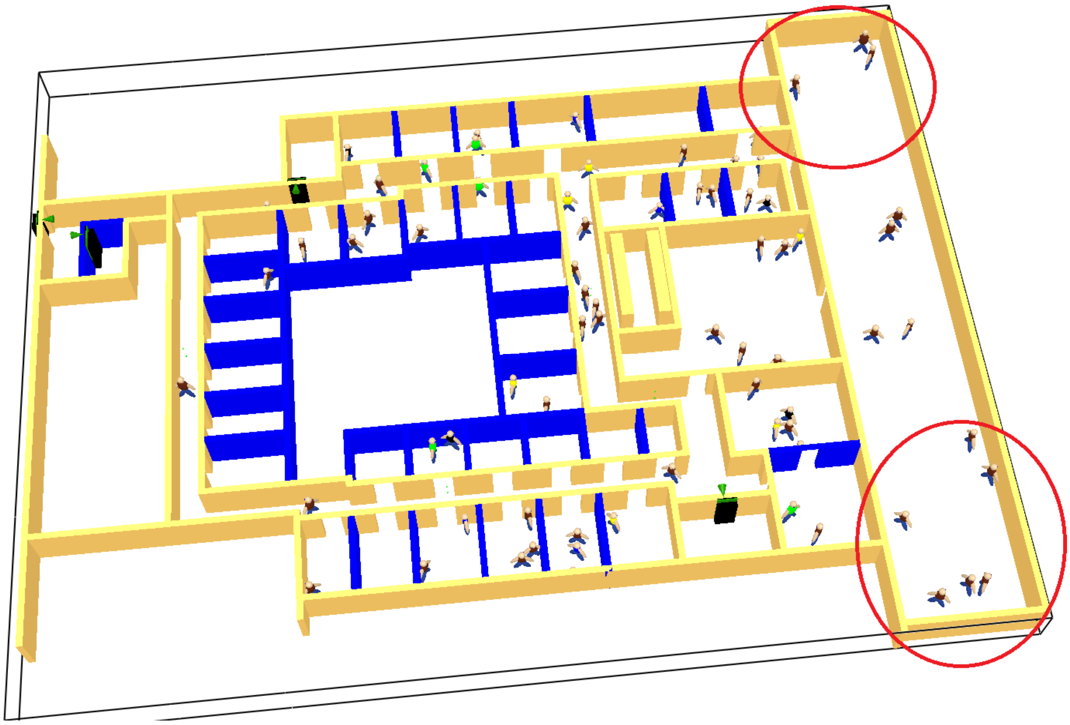

Figure 22 Farthest areas of the deck to an exit

If the different material set-up are considered, the worst case is when the walls are unprotected FRP. Despite of the under-ventilated conditions that the main fire area is subjected to, outside of it there is more oxygen available. Therefore, when the glass-fiber laminate reaches its ignition temperature it contributes to the heat and smoke production, thus the overall evacuation conditions become harsher for these cases. The significant contribution to the HRR of the cases with the unprotected FRP wall can be observed in Figure 23, where the calculated total HRR of the design fire 1 is plotted with the three different material set-ups. Immediately after 200 seconds the unprotected FRP curve abruptly separates from the others peaking up to more than 10 MW. The large area of the walls is the main reason for the huge difference between the curves, once they reach 397 °C [16], they burn with a curve similar to the one shown in Figure 8 reaching more than 250 kW/m^2 at its peak.

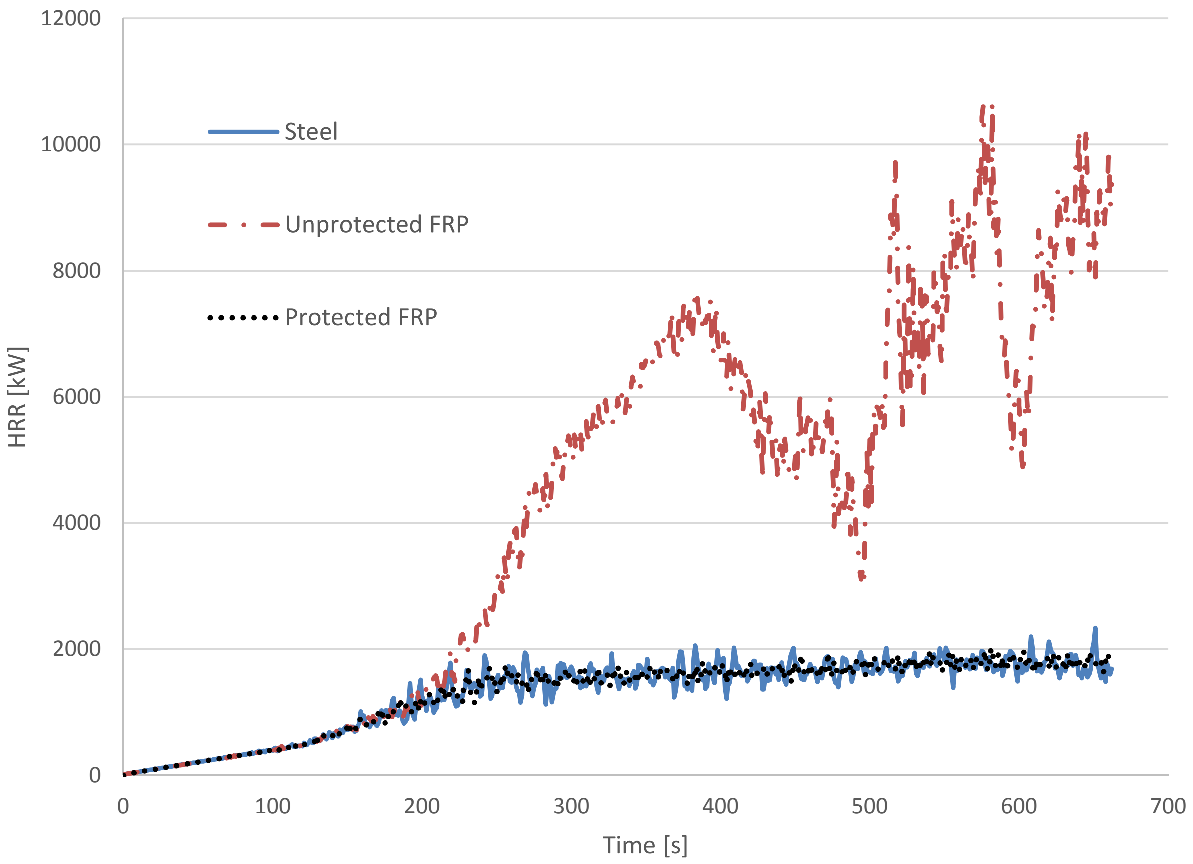

Figure 23 Difference in the HRR depending on the material set-up

However, when using a passive protection for the FPR walls, the HRR curve remains practically unchanged when compared with the original steel set-up; the outcome of utilizing passive protection is highly positive reducing the total HRR of the fire.

The material of the walls also has an influence on the temperatures inside of the compartment. Figure 24 shows the gas temperature at point 2 for the different materials. Once again, and in correspondence with the HRR curve, the case with unprotected FRP has the highest temperatures. However, this time there is a noticeable difference between the other two set-ups. The curve of the protected FRP is higher than the one of steel. The differences on the thermal properties is the factor making them differ. According to Drysdale [23] and Karlsson [13], the conductivity, density and specific heat capacity of the wall material, have a significant influence on the gas temperatures inside of a compartment. Since the passive protection applied on the FRP has a lower thermal conductivity than the plasterboard applied on the steel, the heat transfer is slower, hence the higher gas temperatures. Also, the thermal inertia of the plaster board is higher by 2 orders of magnitude making easier the heat transfer from the gas to the material, hence the lower temperatures.

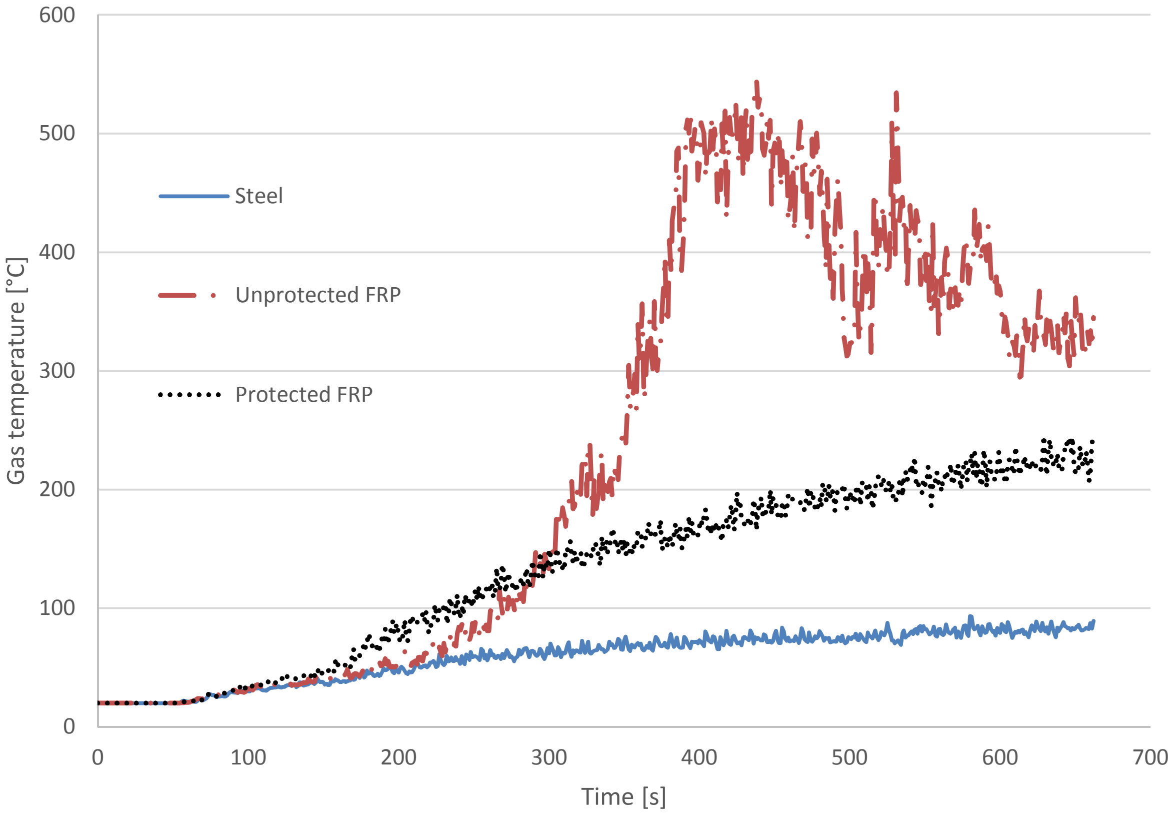

Figure 24 Temperature at point 2 for the different material set-ups

As a consequence of this, a closer look must be made when evaluating the temperature performance criterion since the temperatures will be higher and the ASET could become smaller.

The radiation to the floor has a similar behavior as shown in Figure 25 where the radiation to floor is plotted in time for point 2. Again the unprotected set-up give the highest values even exceeding greatly the performance limit of 2,5 kW/m^2, which is not surpassed by the other two material configurations. The higher temperature in the compartment using the protected set-up, is the reason of having a higher radiation to floor than in the steel set-up.

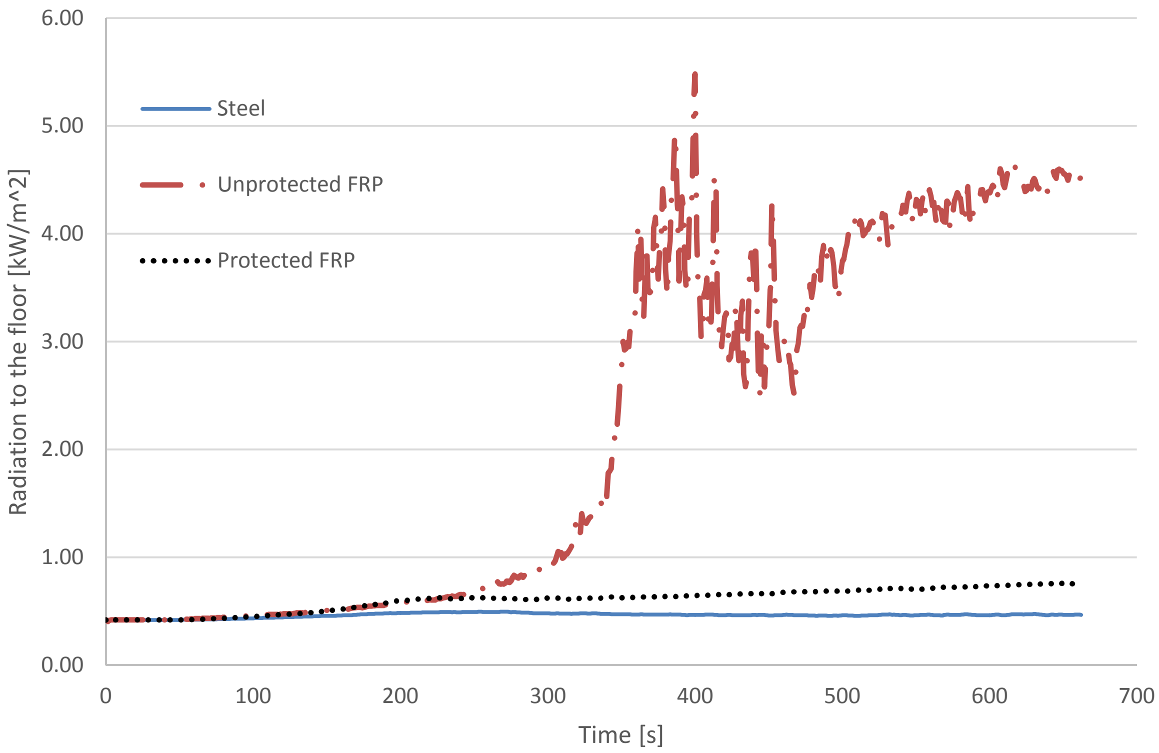

Figure 25 Radiation to the floor for the different material set-ups

The other variable to take into account is the smoke layer height, plotted in Figure 26 in time; the influence of the material does not show until 200 seconds have passed, point to which the three curves behave practically the same way, surpassing the performance limit for safe evacuation of 2 m at the same moment. After this time, they start to differ more and more with the highest criticality shown for the unprotected FRP set-up, which also present a huge jump around 500 seconds that is also shown in the HRR curve in Figure 19. These abrupt changes are due to the under-ventilated conditions that hinder the combustion of the volatile gases but then, when enough oxygen comes into the compartment, the combustion process reinitiates, causing the smoke layer to drop back again and the HRR to increase.

For this criterion, the use of passive protection for the FRP walls doesn’t make any difference regarding the safety of the evacuation process since, regardless of the material, the performance criterion is exceed at the same time. However, it will certainly avoid the extra smoke production due to the combustion of the laminate.

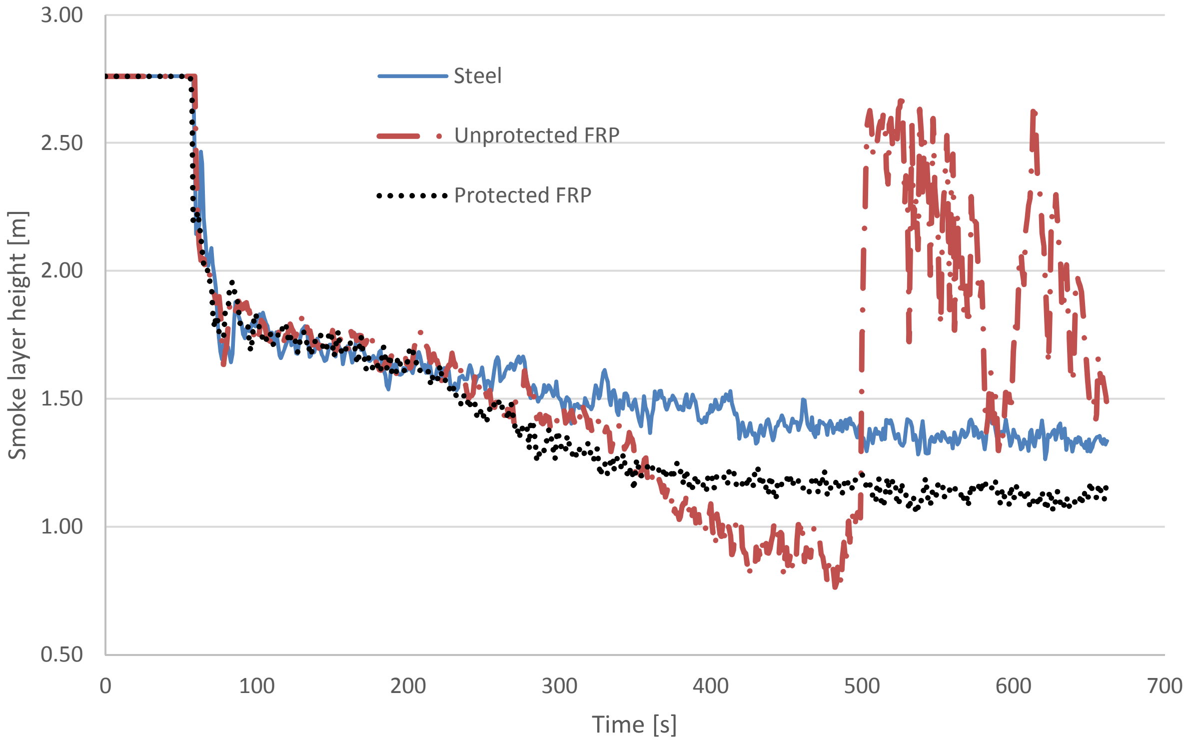

Figure 26 Smoke layer height for the different material set-ups at point 2

When evaluating the influence of the design fire, the worst case for the evacuation is design fire 4. Its location causes that a considerable amount of evacuees have to walk through smoke causing the highest fatalities and the FED regardless of the material set-up being used. The reasons for this to occur are explained taking a look to the relevant data of the fire and smoke behavior. Firstly, the HRR of design fire 4 is higher than the other design fires, see Figure 27, and it is also reached faster; producing more smoke and heat at the initial phases of the evacuation which accompanied with a higher CO yield, has a bigger impact of the evacuees' speed, reducing it due to the decreasing visibility and the increment of the FED value.

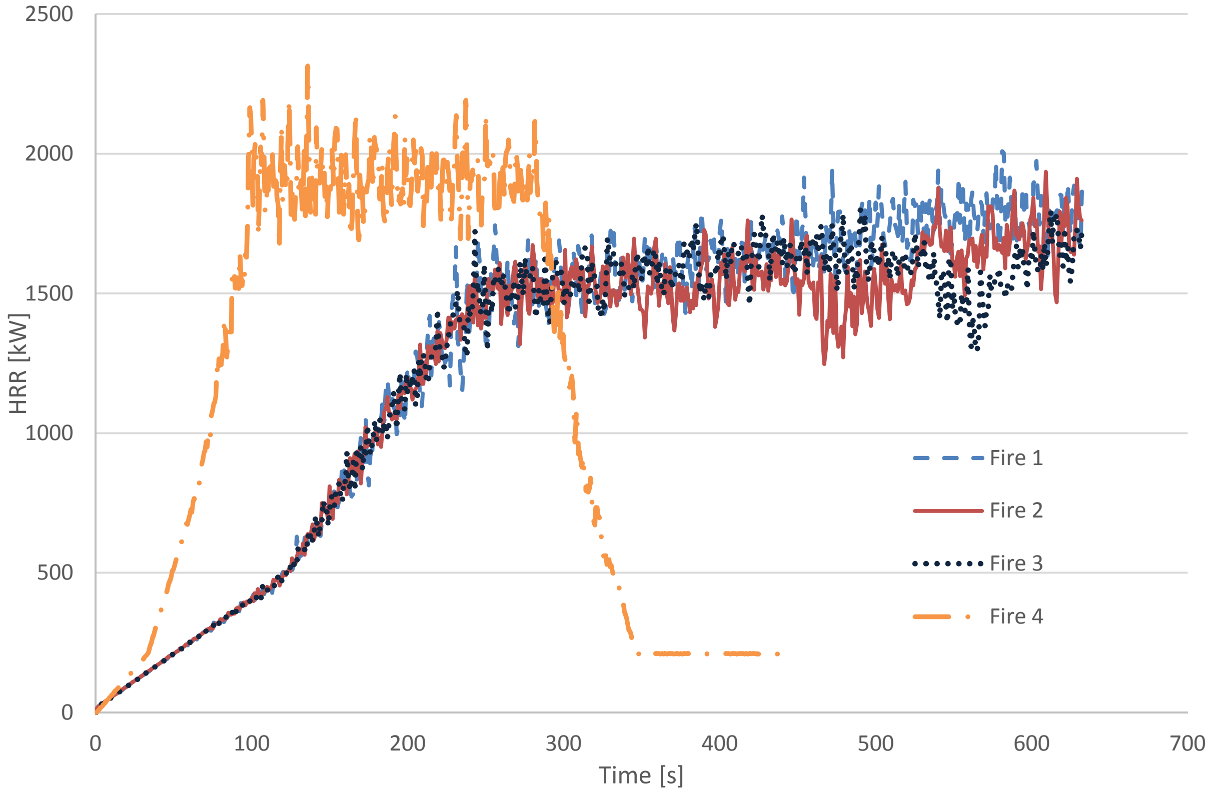

Figure 27 HRR for the different design fires

As shown in Figure 28, the gas temperatures are higher for design fire 4 at the initial stages of the evacuation. It is important to point out that the location of fire 4 is the farthest one to the measuring point 2, hence the smoke produced by this fire has to fill first the room of origin, then the bigger room around it to only then reach the location of the gaging point. Despite this, fire 4 presents the highest temperature at the initial stages of the evacuation. Hereafter, the temperatures inside of the wheelhouse of the deck are expected to be higher, which is confirmed when looking at Figure 29 that shows the maximum temperature reached inside the mentioned room through which a considerable number of evacuees have to walk in smoke at more than 300 °C, in order to get to an exit.

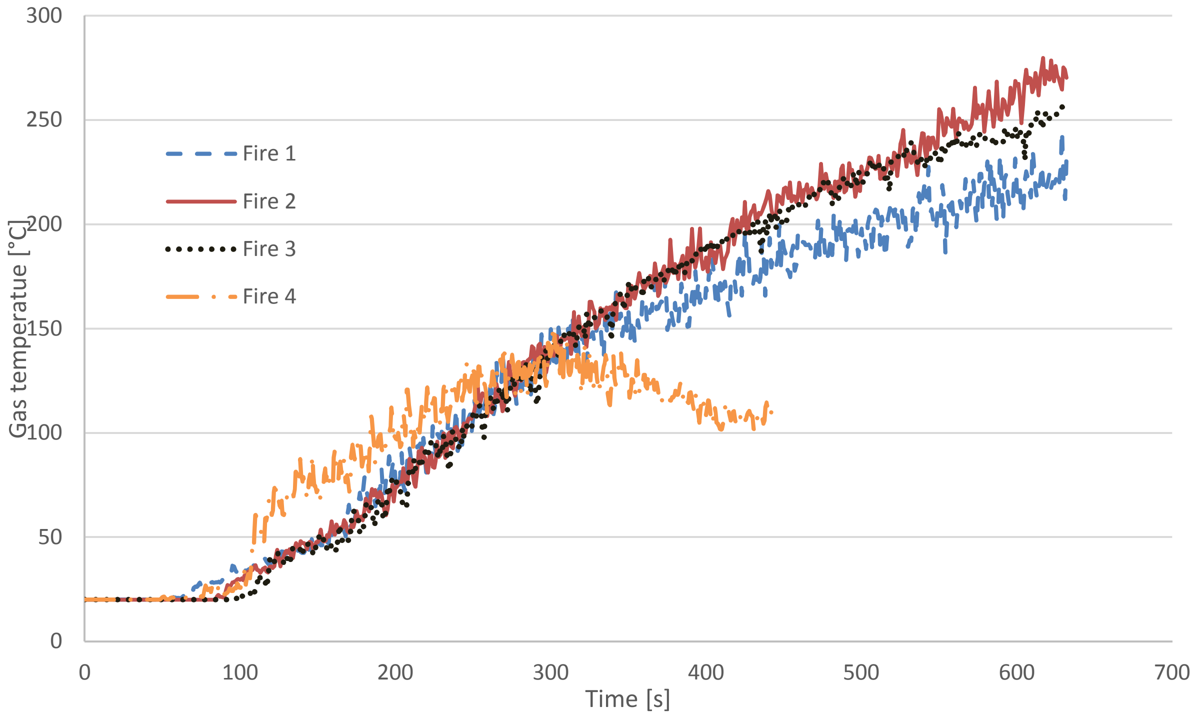

Figure 28 Gas temperature for the different fires at point 2

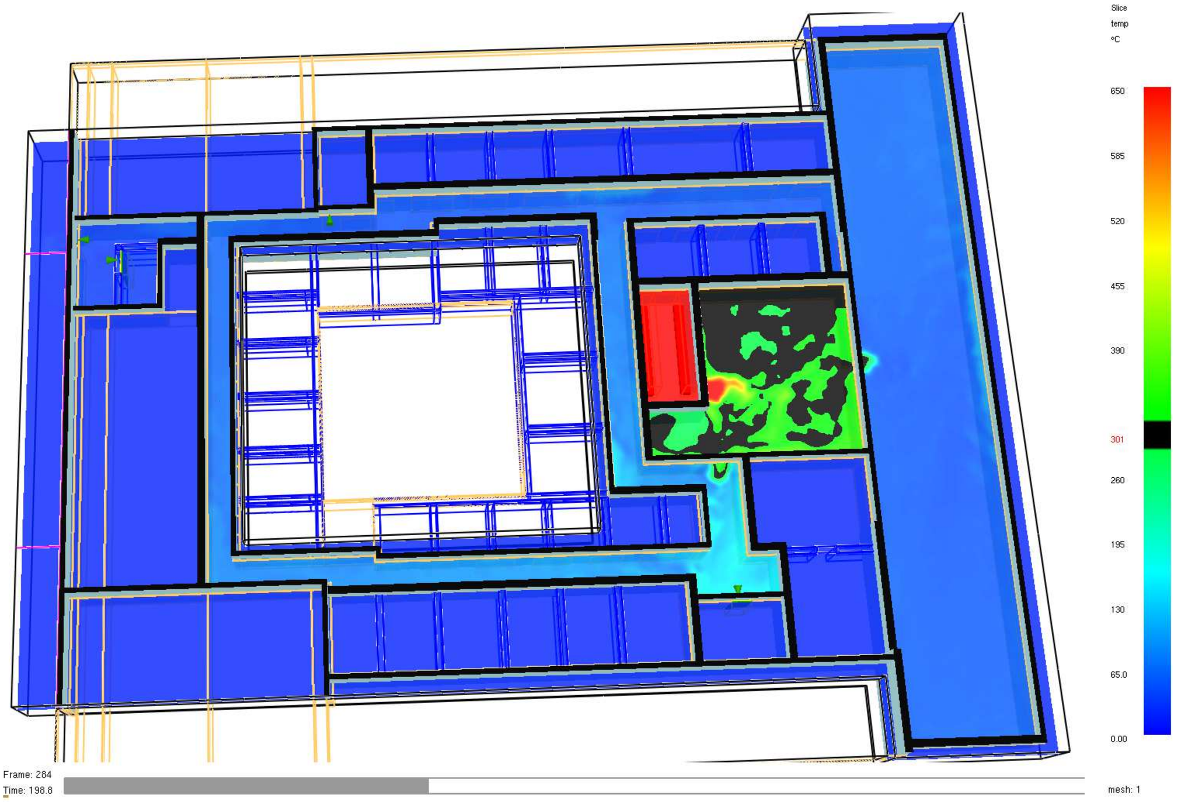

Figure 29 Maximum temperature reached at the wheelhouse for design fire 4

The radiation to the floor is plotted in time in figure 26. Having a performance limit of 2,5 kW/m^2 makes it clear that none of the design fires exceeds this criterion, nonetheless, fire 4 presents the highest values during the evacuation process, which falls in relation with the high HRR at the same time frame.

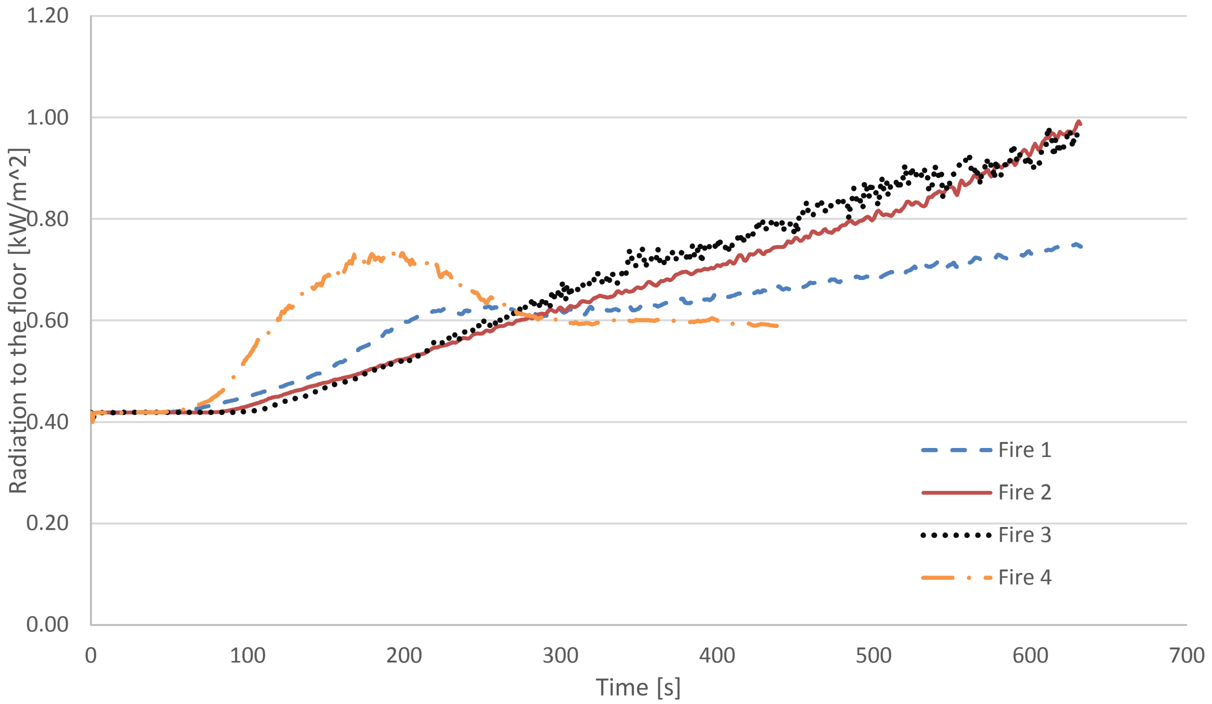

Figure 30 Radiation to the floor for the different design fires at point 2

The last variable to analyze is the smoke layer height, shown in Figure 31, as a function of the time. At that measuring point, all of the fires exceed the criterion of 2 m within 100 seconds of the simulations, being fire 1 the first to do so. In this case, fire 4 is the last one to surpass the criterion but, as mentioned before, the distance of it to the gaging point has an influence.

This is more clearly seen in Figure 32, where the smoke has already filled the wheelhouse compartment but still hasn't reached the area (shown in red) where the measurements are made, reason why the correspondent values of smoke layer height exceed the criterion later than the other three design fires. However, in the wheelhouse the situation is more critical since the criterion is surpassed before, forcing evacuees in FDS EVAC to walk through thick smoke to get to an exit.

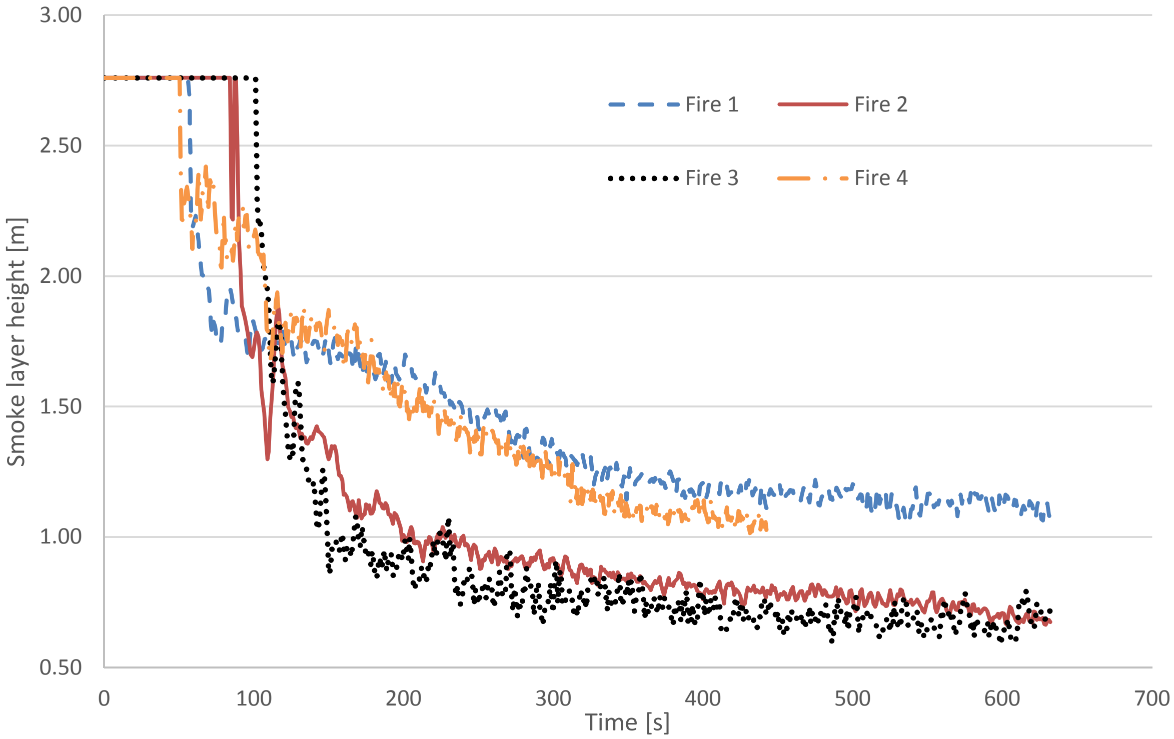

Figure 31 Smoke layer height at point 2 for the different design fires

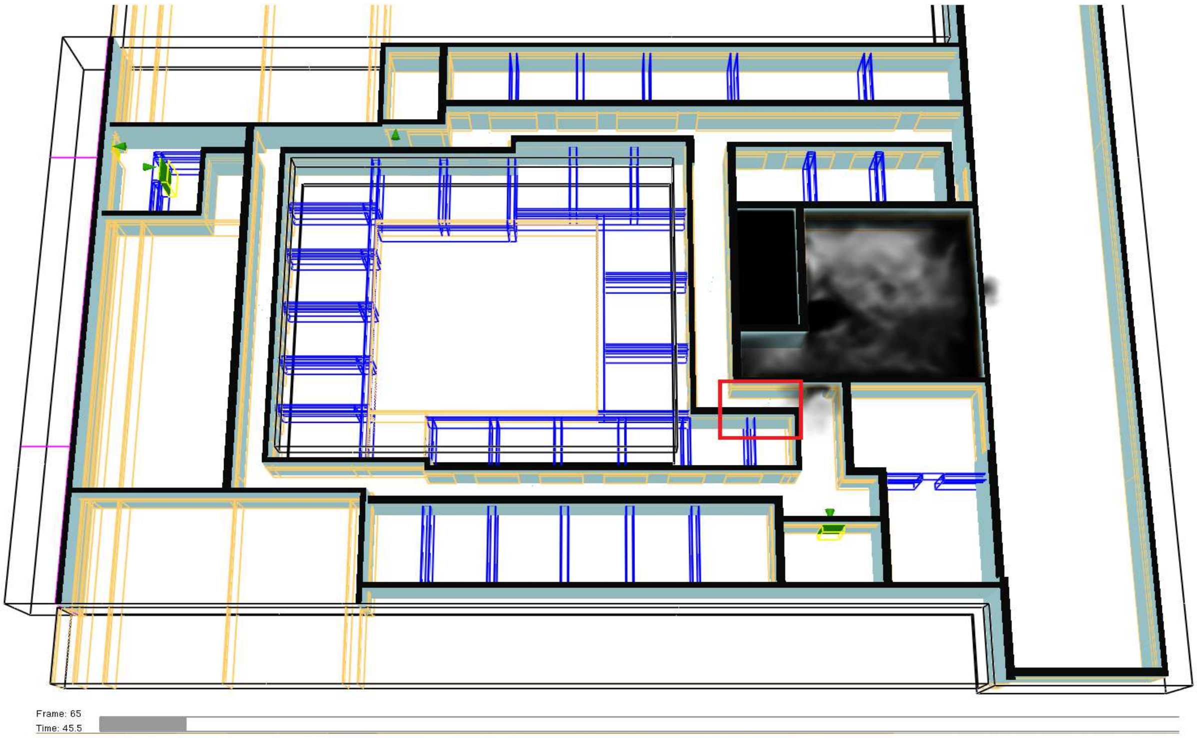

Figure 32 Smoke filling of the wheelhouse for design fire 4

It is also interesting to see that the lowest evacuation times appear in the most critical cases, namely when the unprotected FRP or design fire 4 are present, being its combination the worst scenario. This case has a high average fatalities per run (4,48) but an evacuation time of 249 s which is even less that the time whit no fire influence on the evacuees. This happens due to the way the evacuation time is measured. Regardless of the number of deaths, the egress time is estimated when the last living agent leaves the deck, therefore in a scenario where fatalities occur, the time to evacuate will be lower since fewer agents have to move through the narrow corridors of the deck.

The opposite situation occurs for the safer scenarios with an average FED lower than 0,3 and with average fatalities close to zero, since all or most of the 73 evacuees are able to leave the deck, resulting in a longer evacuation time.

4.3 Example case

As explained before, the case taken as an example only fulfils one of the performance criteria, namely having an FED value below 0,30. Yet, this fulfillment must be treated with care since the FED calculation in FDS EVAC only takes into account the asphyxiating effects of CO and low O_2 concentrations and the hyperventilation effect of the CO_2. As a consequence, cases with FED values close to 0,3 may exceed this limit if more toxic gases are taken into account, for instance, the ones produced by the combustion of polyurethane, one of the dominant fuels used in this project, also produces isocyanates [10] that will increase the FED value and therefore affects negatively the evacuation process, also the FEC should be taken into account due to the production of nitrogen oxides

When looking at the prescriptive side, IMO regulations are in place to limit the concentrations of toxic gases like halogenated acids, hydrogen cyanide and nitrogen oxides [6]. These gases, if present, will increase the FED value in the simulations. This suppose a limitation on the model and it should be taken with care

Another issue worth mentioning is that of the requirement IMO has on the number of evacuation simulations that must be done per scenario. A total of 50 evacuation runs should be done per scenario, this in order to account for the stochastic variables that affect the models of human behavior and, therefore, the evacuation process. However, this number of simulations may be the correct one, according to Ronchi et al. [25], the presence of distributions and probabilistic variables creates a set of values of the human behavior variables that are changed from one simulation to another, thus introducing an additional uncertainty that seems affected by the number of simulations done of the same evacuation scenario. Ronchi et al. propose a method to quantify and to diminish this so called “behavioural uncertainty”, using functional analysis.

Applying this method will certainly improve the calculations, since it gives the optimal number of runs to obtain convergence of the results and a better image of how each run affects the overall evacuation results. Therefore, the number of 50 runs proposed by IMO might not be enough to ensure the convergence of the evacuation time and the other variables, it may be that more or even less than 50 are needed to correctly analyze the evacuation.

4.4 Comparison with other methods

As mentioned in section 1.1, there are other available methodologies to assess the influence of having FRP (protected and/or unprotected) in fire safety; they have points in common and certain differences between each other. In this section, a comparison of the present method with the ones proposed by Gutierrez et al. and Azzi et al, is done. The comparison is made on the basis of the scope, software, regulations, complexity of the procedure and the results gotten by each one.

Azzi's work and the present project, have a similar scope that is to measure the effect of using FRPs on the evacuation process, whereas the scope of Gutierrez's project includes not only the safety of life (evacuation), but also the structural safety of the ship, which required them to also take into account the thermo-mechanical behavior of the composite.

Software wise, the three methods use numerical tools to get the final results and to try and make their own method as accessible and general as possible. Despite the lack of information about the software used by Gutierrez, in Azzi's work these are mentioned and bring a common point with the present project: the use of FDS as a fire calculation tool and the coupling of fire-evacuation simulations.

One common feature between the three methodologies is that, despite applying performance-based design, they also strive to be compliant with the SOLAS and IMO regulations, which have important data about human behavior that is not easy to model or assume.

Gutierrez et al, propose a method strongly based on experiments using cone calorimeter and thermo mechanic tests to get the relevant data to be used as an input to the models. On the other hand Azzi et al, offer a procedure that relies on the available literature to obtain the necessary data to be used in the models. This feature is common with the present project that also turns to the literature to get, for instance, the fire behavior of the laminate when exposed to high temperatures.

Gutierrez's method implies the availability of testing equipment in order to procure the fire data to perform the simulations. This makes the method more accurate but more time and resource consuming, that compared with the other two methods that may not be as accurate but they can deliver faster results at a fraction of the time, with the observation that literature data can be scarce about the fire behavior of the newest material combinations, in which case experiments should be performed to obtain the desired data.One point in which the present methodology differentiates itself from the other methods is the direct coupling of the fire and evacuation simulations. They are done simultaneously by one software (FDS) where only one input file per scenario has to be done, this way avoiding the process of exporting the fire data to another software that first, has to be modified in certain ways so it'd be able to read this data correctly.

5. CONCLUSIONS

The mesh sensitivity analysis resulted in a cell size of 12 cm. The differences between the calculated and experimental HRR curves are due to the appearance of under-ventilated conditions in the simulations.

The effects of having unprotected FRP walls are negative in terms of the evacuation process and the fire and smoke development.

Adding passive fire-protection to the FRP walls, greatly improves the fire safety performance of the glass-fiber laminate, with the only drawback of having higher temperatures inside of the compartment reducing the ASET, consequently, extra measures must be taken to reduce the RSET.

FDS EVAC doesn't allow assigning objectives to the evacuees, for instance the required IMO feature of counter-flow of crew members searching in the passenger cabins.

IMO also requires that a night case should be done. This has a larger pre-movement time, however, as shown in this thesis, the day case already failed; hence there is no need to study the night case.

Implementing FDS EVAC simplifies the coupling of fire-evacuation process allowing the user to model this interaction in a faster way than exporting the fire data to another software previously prepared to use it correctly.

Performance-based design can be applied for ship evacuation design, however, with close support of literature and prescriptive codes, the latter especially for critical human behavior parameters.

Since ventilation can have a great impact on the fire and smoke development, it would add value to include the effect of the ship's ventilation system on the fire, since in this thesis it was assumed to be turned-off during the fire scenarios.

In future works other design fires and material set-ups can be considered. Aluminum is also another lightweight material that can be used in ship building.

The use of functional analysis to study the convergence of the evacuation results is advised and a comparison with the present results can prove its convergence or not. A method to perform this is already at hand to be applied for these cases. See Ronchi et al. [25]

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APPENDIX A: EXAMPLES OF FDS INPUT FILE

```
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&MESH IJK = 328 , 54 , 30 , XB = 19.5, 58.86 , 27.2, 33.68, 0 , 3.6 /

&MESH IJK = 168, 120 , 30  , XB = 46.5, 66.66 , 12.8, 27.2, 0 ,3.6  /

&MESH IJK = 65, 90 , 30  , XB = 58.86, 66.66 , 2 , 12.8, 0 ,3.6  /

&MESH IJK = 65, 96 , 30  , XB = 58.86, 66.66 , 27.2, 38.72 , 0 , 3.6  /

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

Evacuation meshes

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CONDUCTIVITY = 0.04

SPECIFIC_HEAT = 0.9/

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&OBST XB= 50.8,54.8,9.4,9.7,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 17

&OBST XB= 54.8,55.1,6.5,9.7,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 18

&OBST XB= 54.8,55.1,9.7,11.6,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 19

&OBST XB= 53.5,55.1,11.6,11.9,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 20

&OBST XB= 53.5,53.8,11.9,16,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 21

&OBST XB= 48.9,59.4,16,16.3,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 22

&OBST XB= 48.9,49.2,16.3,28.3,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 23

&OBST XB= 59.4,59.7,6.8,16.3,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 24

&OBST XB= 49.2,58.7,28,28.3,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 25

&OBST XB= 49.2,59.7,24.8,25.1,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 26

&OBST XB= 58.4,58.7,25.1,28,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 27

&OBST XB= 59.4,59.7,25.1,33.4,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 28

&OBST XB= 36.5,59.4,30.2,30.5,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 29

&OBST XB= 33.8,36.2,29.2,29.5,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 30

&OBST XB= 36.2,36.5,29.2,33.4,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 31

&OBST XB= 27.8,28.1,10.7,29.2,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 32

&OBST XB= 29.3,29.6,12.2,28,0.3,3,  SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 33

&OBST XB= 29.6,39.4,27.7,28,0.3,3,  SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 34

&OBST XB= 39.4,39.7,27.7,28.3,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 34 con 35

&OBST XB= 39.4,47.4,28.3,28.6,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 35

&OBST XB= 47.1,47.4,14.6,28.6,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 36

&OBST XB= 47.1,51.7,14.5,14.8,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 37

&OBST XB= 51.4,51.7,11.8,14.5,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 38
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&OBST XB= 36,51.4,11.8,12.1,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 39

&OBST XB= 36,36.3,12.1,12.5,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/ Wall 39 con 40

&OBST XB= 29.6,36,12.2,12.5,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 40

&OBST XB= 51.8,52.1 ,18.9,24.8 ,0.3 ,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 41

&OBST XB= 49.2, 52.1, 18.6, 18.9,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 42

&OBST XB= 21.8, 26.1, 24.4 , 24.7 ,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 43

&OBST XB= 25.8, 26.1, 24.7 , 28 ,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 44

&OBST XB= 26.1, 27.8, 27.7, 28 ,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/  Wall 45

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Floor and ceiling

&OBST XB= 21.8,33.5,10.7,29.5,0,0.3, SURF_IDS='COMPOSITE_WALL','INERT2','COMPOSITE_WALL', COLOR='INVISIBLE'/

&OBST XB= 21.5,33.5,10.7,29.5,3,3.3, SURF_IDS='COMPOSITE_WALL','INERT2','COMPOSITE_WALL', COLOR='INVISIBLE'/

&OBST XB= 33.5,59.4,6.5,33.7,0,0.3, SURF_IDS='COMPOSITE_WALL','INERT2','COMPOSITE_WALL', COLOR='INVISIBLE'/

&OBST XB= 33.5,59.4,6.5,33.7,3,3.3, SURF_IDS='COMPOSITE_WALL','INERT2','COMPOSITE_WALL', COLOR='INVISIBLE'/

&OBST XB= 59.4,66,2.5,37.7,0,0.3, SURF_IDS='COMPOSITE_WALL','INERT2','COMPOSITE_WALL', COLOR='INVISIBLE'/

&OBST XB= 59.4,66,2.5,37.7,3,3.3, SURF_IDS='COMPOSITE_WALL','INERT2','COMPOSITE_WALL', COLOR='INVISIBLE'/

============================================================================

Vents

&VENT XB= 16.5,21.5, 2,38.3, 3.6, 3.6, SURF_ID='OPEN'/

&VENT XB = 16.5 , 16.5, 2 , 38.3, 0 , 3.6, SURF_ID='OPEN'/

&VENT XB = 16.5 , 21.5 , 33.8 , 33.8, 0 , 3.6, SURF_ID='OPEN'/

&VENT XB = 16.5 , 21.5 , 5.6 , 5.6, 0 , 3.6, SURF_ID='OPEN'/

============================================================================

Doors

&HOLE XB= 27.5,28.4,28,28.9,0.3,2.4/

&HOLE XB= 21.4,22,28,28.9,0.3,2.4/

&HOLE XB = 51.8, 52.3, 19.2,20.1 ,0.3 ,2.4 /

&HOLE XB =52.1,53,15.9,16.4,0.3,2.4 /

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EVACUATION GEOMETRY

```
&OBST XB = 21.3, 33.5, 29.4, 37.9, 0.3, 3, EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB = 33.5, 59.4, 33.7, 37.9, 0.3, 3, EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB = 21.3, 33.5, 2.2, 10.6, 0.3, 3, EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB = 33.5, 59.4, 2.2, 6.3, 0.3, 3, EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB = 33.5, 43.1, 14.8, 24.4, 0.3, 3, EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB = 33.5, 36, 12.1, 14.8 0.3, 3, EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB = 36, 36.3, 6.6, 10.3, 0.3, 3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 1

&OBST XB = 38.8, 39.1, 6.6, 10.3, 0.3, 3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 2-3

&OBST XB = 41.6, 41.9, 6.6, 10.3, 0.3, 3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 3-4

&OBST XB = 44.4, 44.7, 6.6, 10.3, 0.3, 3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 4-5

&OBST XB = 36.1, 47.1, 14.5,14.8,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB = 36,36.3,12.5,14.5,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 33.2,33.5,12.5,27.7,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 29.6,33.5, 25.1, 25.4 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 6

&OBST XB= 29.6,33.5, 22.5, 22.8 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 7-8

&OBST XB= 29.6,33.5, 19.9, 20.2 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/  cabin 8-9

&OBST XB= 29.6,33.5, 17.3, 17.6 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/  cabin 9-10

&OBST XB= 29.6,33.5, 14.7, 15 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/  cabin 10-11

&OBST XB= 33.5,39.4,24.1,24.4,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 39.4,39.7,24.1,27.7,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 12-13

&OBST XB= 39.7,47.1,24.7,25 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 36.3, 36.6,24.4 ,27.7 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/  cabin f2-12

&OBST XB= 42.1, 42.4, 25, 28.3 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 13-14

&OBST XB= 44.8, 45.1, 25, 28.3,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 14-15

&OBST XB= 43.1,43.4,14.9,24.7,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 43.4,47.1,21.4,21.7 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 16-17

&OBST XB= 43.4,47.1,17.8,18.1 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 17-18

&OBST XB = 38.7,39,12.1,14.5,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 19-20

&OBST XB = 41.4,41.7,12.1,14.5,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 20-21

&OBST XB = 44.1,44.4,12.1,14.5,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 21-22

&OBST XB = 46.8,47.1,12.1,14.5,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 22-23
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```
&OBST XB = 49.5,49.8,12.1,14.5,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 23-24

&OBST XB= 52.6,52.9,25.1,28,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 25-26

&OBST XB= 55.6,55.9,25.1,28,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/ cabin 26-27

&OBST XB= 55.2,55.5,30.5, 33.4,0.3,3,  EVACUATION=.TRUE., COLOR='BLUE'/  cabin 28

&OBST XB= 49.1,49.4,30.5, 33.4,0.3,3,  EVACUATION=.TRUE., COLOR='BLUE'/  cabin 29

&OBST XB= 45.4,45.7,30.5, 33.4,0.3,3,  EVACUATION=.TRUE., COLOR='BLUE'/  cabin 29-30

&OBST XB= 42.4,42.7,30.5, 33.4,0.3,3,  EVACUATION=.TRUE., COLOR='BLUE'/  cabin 30-31

&OBST XB= 39.4,39.7,30.5, 33.4,0.3,3,  EVACUATION=.TRUE., COLOR='BLUE'/  cabin 31

&OBST XB= 49.4,55.2,30.5, 33.4,0.3,3,  EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB= 21.3, 27.8, 10.6, 24.4,0.3,3,  EVACUATION=.TRUE., COLOR='INVISIBLE'/

&OBST XB= 55.1,59.4,11.6,11.9,0.3,3,  EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 24, 25.8, 27.7, 28 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 23.7, 24, 24.7, 28 ,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/

&OBST XB= 59.4,59.7, 16.3, 25.1 ,0.3,3, SURF_IDS='INERT2','COMPOSITE_WALL','INERT2'/

&OBST XB= 47,47.3,6.5,10.3,0.3,3, EVACUATION=.TRUE., COLOR='BLUE'/
```

Cabin Doors

```
&HOLE XB = 59, 60, 20.2,21.2 ,0.3 ,2.4 /

&HOLE XB =48.5,49.4,9,11,0.3,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 51.8, 52.3, 19.2,20.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 34.9, 35.8, 10.2, 10.7 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 37.1, 38, 10.2, 10.7 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 39.9, 40.8, 10.2, 10.7 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 42.8, 43.7, 10.2, 10.7 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 45.6, 46.5, 10.2, 10.7 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 37.1, 38, 11.7, 12.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 39.9, 40.8, 11.7, 12.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 42.5, 43.4, 11.7, 12.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 45.4, 46.3, 11.7, 12.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 47.8, 48.7, 11.7, 12.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 50, 50.9, 11.7, 12.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /

&HOLE XB = 29.4,29.7, 13.2, 14.1 ,0.3 ,2.4 , EVACUATION=.TRUE. /
```

```
&HOLE XB = 29.4,29.7, 15.7, 16.6 ,0.3 ,2.4 , EVACUATION=.TRUE. /
&HOLE XB = 29.4,29.7, 18.3, 19.2 ,0.3 ,2.4 , EVACUATION=.TRUE. /
&HOLE XB = 29.4,29.7, 20.9, 21.8 ,0.3 ,2.4 , EVACUATION=.TRUE. /
&HOLE XB = 29.4,29.7, 23.5, 24.4 ,0.3 , 2.4 , EVACUATION=.TRUE. /
&HOLE XB = 29.4, 29.7, 26.1, 27 ,0.3 , 2.4 , EVACUATION=.TRUE. /
&HOLE XB = 34.9, 35.8, 27.6, 28.1,0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 37.4, 38.3, 27.6, 31, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 40.5, 41.4, 27.8, 31, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 43.3, 44.2, 27.8, 31, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 45.8, 46.7, 27.8, 29, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 46.8, 47.7, 30, 31, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 56.6, 57.5, 25, 31, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 50.6, 51.5, 27.5, 28.6, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 53.6, 54.5, 27.5, 28.6, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 56.8, 57.7, 11.5, 12, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 54.7,55.2,10.1,11, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 46,48, 22.6,23.5, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 46,48, 19.3, 20.2 , 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 46,48, 15.7, 16.6, 0.3, 2.4 , EVACUATION=.TRUE./
&HOLE XB = 59, 60, 29, 29.9, 0.3, 2.4 , EVACUATION=.TRUE./
```

Exits

```
/1
&HOLE XB =  52.5,53.4,9.4,9.8,0.3,2.3 , EVACUATION=.TRUE. /
&EXIT ID='Ex1', IOR = -2,
    COLOR='YELLOW', HEIGHT=2, SHOW=.TRUE.,
     XYZ= 52.8, 9.5, 1.3,
     XB= 52.5,53.4,9.4,9.4,0.31,2.2/
/2
&HOLE XB =  33.9,34.8,29.2,29.6,0.3,2.4 , EVACUATION=.TRUE. /
&EXIT ID='Ex2', IOR = +2,
     COLOR='YELLOW', HEIGHT=2, SHOW=.TRUE.,
     XYZ= 34.3, 29.3, 1.3,
```

```
    XB= 33.9,34.8,29.5,29.5,0.31,2.2/
/3
&HOLE XB= 21.3,22,28,28.9,0.3,2.4,  EVACUATION=.TRUE./
&EXIT ID='Ex3', IOR = -1,
        COLOR='YELLOW', HEIGHT=2, SHOW=.TRUE.,
    XYZ= 21.8, 28.3, 1.3,
    XB= 21.6, 21.6, 28,28.9, 0.31, 2.2/
/4
&HOLE XB= 23.6,24.1,26.5,27.7,0.3,2.4,  EVACUATION=.TRUE./
&EXIT ID='Ex4', IOR = +1,
    COLOR='YELLOW', HEIGHT=2, SHOW=.TRUE.,
    XYZ= 23.9, 27.2, 1.3,
    XB= 24, 24, 26.5,27.7, 0.31, 2.2/
==============================================================================
PERSONS
&PERS   ID='Child',
          FYI='IMO properties being used ',
          DEFAULT_PROPERTIES='Child',
          HUMAN_SMOKE_HEIGHT=1.6,
          PRE_EVAC_DIST=5,
          PRE_MEAN=3.44,
          PRE_PARA=0.94,
          PRE_HIGH=400,
          PRE_PARA2=0,
          OUTPUT_FED=.TRUE.,
          TDET_SMOKE_DENS= 650,
          COLOR_METHOD=0/
&PERS   ID='Male',
          FYI='IMO properties being used ',
          DEFAULT_PROPERTIES='Male',
          HUMAN_SMOKE_HEIGHT=1.7,
          PRE_EVAC_DIST=5,
```

```
          PRE_MEAN=3.44,
          PRE_PARA=0.94,
          PRE_HIGH=400,
          PRE_PARA2=0,
          OUTPUT_FED=.TRUE.,
          TDET_SMOKE_DENS= 650,
          COLOR_METHOD=0/
&PERS   ID='Female',
          FYI='IMO properties being used ',
          DEFAULT_PROPERTIES='Female',
          HUMAN_SMOKE_HEIGHT=1.7,
          PRE_EVAC_DIST=5,
          PRE_MEAN=3.44,
          PRE_PARA=0.94,
          PRE_HIGH=400,
          PRE_PARA2=0,
          OUTPUT_FED=.TRUE.,
          TDET_SMOKE_DENS= 650,
          COLOR_METHOD=0/
&PERS   ID='Elderly',
          FYI='IMO properties being used ',
          DEFAULT_PROPERTIES='Elderly',
          HUMAN_SMOKE_HEIGHT=1.7,
          PRE_EVAC_DIST=5,
          PRE_MEAN=3.44,
          PRE_PARA=0.94,
          PRE_HIGH=400,
          PRE_PARA2=0,
          OUTPUT_FED=.TRUE.,
          TDET_SMOKE_DENS= 650,
          COLOR_METHOD=0/
&PERS   ID='Female_crew',
```

```
        FYI='IMO properties being used ',
        DEFAULT_PROPERTIES='Female',
        VELOCITY_DIST= 1,
        VEL_LOW=0.93,
        VEL_HIGH=1.55,
        PRE_EVAC_DIST=5,
        PRE_MEAN=3.44,
        PRE_PARA=0.94,
        PRE_HIGH=400,
        PRE_PARA2=0,
        HUMAN_SMOKE_HEIGHT=1.7,
        OUTPUT_FED=.TRUE.,
        TDET_SMOKE_DENS= 650,
        COLOR_METHOD=0/
&PERS   ID='Male_crew',
        FYI='IMO properties being used ',
        DEFAULT_PROPERTIES='Male'
        VELOCITY_DIST= 1,
        VEL_LOW=1.11,
        VEL_HIGH=1.85,
        PRE_EVAC_DIST=5,
        PRE_MEAN=3.44,
        PRE_PARA=0.94,
        PRE_HIGH=400,
        PRE_PARA2=0,
        HUMAN_SMOKE_HEIGHT=1.7,
        OUTPUT_FED=.TRUE.,
        TDET_SMOKE_DENS= 650,
        COLOR_METHOD=0/
==========================================================================
Initial position of evacuees
&EVAC   ID='Male_crew',
```

```
       NUMBER_INITIAL_PERSONS=12,
       XB= 28.2 ,66 ,2.2,  20.05, 0.31, 2.2
       AVATAR_COLOR='SEPIA',
       MESH_ID = 'EVAC_MESH_1',
       KNOWN_DOOR_NAMES='Ex1' ,'Ex2', 'Ex3', 'Ex4',
       KNOWN_DOOR_PROBS = 1,0.5,1,1,
       FLOW_FIELD_ID='EVAC_MESH_1',
       PERS_ID='Male_crew'/
&EVAC  ID='Male_crew_2',
       NUMBER_INITIAL_PERSONS=13,
       XB= 28.2 ,66 ,20.05,  37.9, 0.31, 2.2
       AVATAR_COLOR='SEPIA',
       MESH_ID = 'EVAC_MESH_2',
       KNOWN_DOOR_NAMES='Ex1' ,'Ex2', 'Ex3', 'Ex4',
       KNOWN_DOOR_PROBS = 1,0.5,1,1,
       FLOW_FIELD_ID='EVAC_MESH_1',
       PERS_ID='Male_crew'/
&EVAC  ID='Female_crew',
       NUMBER_INITIAL_PERSONS=13,
       XB= 28.2 ,66 ,2.2,  20.05, 0.31, 2.2
       AVATAR_COLOR='SEPIA',
       MESH_ID = 'EVAC_MESH_1',
       KNOWN_DOOR_NAMES='Ex1' ,'Ex2', 'Ex3', 'Ex4',
       KNOWN_DOOR_PROBS = 1,0.5,1,1,
       FLOW_FIELD_ID='EVAC_MESH_1',
       PERS_ID='Female_crew'/
&EVAC  ID='Female_crew_2',
       NUMBER_INITIAL_PERSONS=13,
       XB= 28.2 ,66 ,20.05,  37.9, 0.31, 2.2
       AVATAR_COLOR='SEPIA',
       MESH_ID = 'EVAC_MESH_2',
       KNOWN_DOOR_NAMES='Ex1' ,'Ex2', 'Ex3', 'Ex4',
```

```
      KNOWN_DOOR_PROBS = 1,0.5,1,1,
      FLOW_FIELD_ID='EVAC_MESH_1',
      PERS_ID='Female_crew'/
&EVAC ID='Children',
      NUMBER_INITIAL_PERSONS=2,
      XB= 28.2 ,59.4 ,2.2 ,20.05 , 0.31, 2.2
      AVATAR_COLOR='BLUE',
      MESH_ID = 'EVAC_MESH_1',
      PERS_ID='Child'/
&EVAC ID='Children_2',
      NUMBER_INITIAL_PERSONS=2,
      XB= 28.2 ,59.4 ,20.05,37.9 , 0.31, 2.2
      AVATAR_COLOR='BLUE',
      MESH_ID = 'EVAC_MESH_2',
      PERS_ID='Child'/
&EVAC ID='Females',
      NUMBER_INITIAL_PERSONS=3,
      XB= 28.2 ,59.4 ,2.2,  20.05, 0.31, 2.2
      AVATAR_COLOR='BLACK',
      MESH_ID = 'EVAC_MESH_1',
      KNOWN_DOOR_NAMES='Ex1','Ex2', 'Ex3', 'Ex4',
      KNOWN_DOOR_PROBS = 1,0.5,0,0.5,
      PERS_ID='Female'/
&EVAC ID='Females_2',
      NUMBER_INITIAL_PERSONS=2,
      XB= 28.2 ,59.4 ,20.05,  37.9, 0.31, 2.2
      AVATAR_COLOR='BLACK',
      MESH_ID = 'EVAC_MESH_2',
      KNOWN_DOOR_NAMES='Ex1','Ex2', 'Ex3', 'Ex4',
      KNOWN_DOOR_PROBS = 0.5,1,0,0.5,
      PERS_ID='Female'/
&EVAC ID='Males',
```

```
          NUMBER_INITIAL_PERSONS=2,
          XB= 28.2 ,59.4 ,2.2 ,20.05 , 0.31, 2.2
          AVATAR_COLOR='GREEN',
          MESH_ID = 'EVAC_MESH_1',
          KNOWN_DOOR_NAMES='Ex1','Ex2', 'Ex3', 'Ex4',
          KNOWN_DOOR_PROBS = 1,0.5,0,0.5,
          PERS_ID='Male'/
&EVAC     ID='Males_2',
          NUMBER_INITIAL_PERSONS=3,
          XB= 28.2 ,59.4 ,20.05 ,37.9 , 0.31, 2.2
          AVATAR_COLOR='GREEN',
          MESH_ID = 'EVAC_MESH_2',
          KNOWN_DOOR_NAMES='Ex1','Ex2', 'Ex3', 'Ex4',
          KNOWN_DOOR_PROBS = 0.5,1,0,0.5,
          PERS_ID='Male'/
&EVAC     ID='Elderly',
          NUMBER_INITIAL_PERSONS=4,
          XB= 28.2 ,59.4 ,2.2 ,20.05 , 0.31, 2.2
          AVATAR_COLOR='YELLOW',
          MESH_ID = 'EVAC_MESH_1',
          KNOWN_DOOR_NAMES='Ex1','Ex2', 'Ex3', 'Ex4',
          KNOWN_DOOR_PROBS = 1,0.5,0,0.5,
          PERS_ID='Elderly'/
&EVAC     ID='Elderly_2',
          NUMBER_INITIAL_PERSONS=4,
          XB= 28.2 ,59.4 ,20.05 ,37.9 , 0.31, 2.2
          AVATAR_COLOR='YELLOW',
          MESH_ID = 'EVAC_MESH_2',
          KNOWN_DOOR_NAMES='Ex1','Ex2', 'Ex3', 'Ex4',
          KNOWN_DOOR_PROBS = 0.5,1,0,0.5,
          PERS_ID='Elderly'/
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Places where no agents will be generated

```
&EVHO  ID='fire area',
       XB= 49, 52, 18.5, 25,0.31,2.2
       MESH_ID = 'EVAC_MESH_1'/
&EVHO  ID='fire area_2',
       XB= 49, 52, 18.5, 25,0.31,2.2
       MESH_ID = 'EVAC_MESH_2'/
&EVHO  ID = 'Exit1',
       XB= 50.5, 55.1 , 6.3, 11 , 0.31, 2.2 /
&EVHO  ID = 'Exit2',
       XB = 33.5, 36.5, 29.2, 33.7, 0.31,  2.2/
&EVHO  ID = 'Exit3',
       XB = 21.3, 22.5, 24, 30 ,0.31 ,2.2/
&EVHO  ID = 'Exit3_1',
       XB = 22.2, 28, 24, 30 ,0.31 ,2.2/
&EVHO  ID='Wheel_house1',
       XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
       EVAC_ID='Females',
       MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house1_1',
       XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
       EVAC_ID='Females_2',
       MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house1_1_1',
       XB= 58.7, 65.7, 28.9, 37.7, 0.31, 2.2
       EVAC_ID='Females',
       MESH_ID='EVAC_MESH_2'/
&EVHO  ID='Wheel_house1_1_1_1',
       XB= 58.7, 65.7, 28.9, 37.7, 0.31, 2.2
       EVAC_ID='Females_2',
       MESH_ID='EVAC_MESH_2'/
&EVHO  ID='Wheel_house2',
```

```
      XB= 49, 58.7, 16,25 ,0.31, 2.2
      EVAC_ID='Females',
      MESH_ID='EVAC_MESH_1'/
&EVHO ID='Wheel_house2_1',
      XB= 49, 58.7, 16,25 ,0.31, 2.2
      EVAC_ID='Females_2',
      MESH_ID='EVAC_MESH_2'/
&EVHO ID='Wheel_house3',
      XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
      EVAC_ID='Males',
      MESH_ID='EVAC_MESH_1'/
&EVHO ID='Wheel_house3_1',
      XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
      EVAC_ID='Males_2',
      MESH_ID='EVAC_MESH_1'/
&EVHO ID='Wheel_house3_1_1',
      XB= 58.7, 65.7, 28.9, 37.7, 0.31, 2.2
      EVAC_ID='Males',
      MESH_ID='EVAC_MESH_2'/
&EVHO ID='Wheel_house3_1_1_1',
      XB= 58.7, 65.7, 28.9, 37.7, 0.31, 2.2
      EVAC_ID='Males_2',
      MESH_ID='EVAC_MESH_2'/
&EVHO ID='Wheel_house4',
      XB= 49, 58.7, 16,25 ,0.31, 2.2
      EVAC_ID='Males',
      MESH_ID='EVAC_MESH_1'/
&EVHO ID='Wheel_house4_1',
      XB= 49, 58.7, 16,25 ,0.31, 2.2
      EVAC_ID='Males_2',
      MESH_ID='EVAC_MESH_2'/
&EVHO ID='Wheel_house5',
```

```
       XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
       EVAC_ID='Children',
       MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house5_1',
       XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
       EVAC_ID='Children_2',
       MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house5_1_1',
       XB= 58.7, 65.7, 28.9, 37.7, 0.31, 2.2
       EVAC_ID='Children',
       MESH_ID='EVAC_MESH_2'/
&EVHO  ID='Wheel_house5_1_1_1',
       XB= 58.7, 65.7, 28.9, 37.7, 0.31, 2.2
       EVAC_ID='Children_2',
       MESH_ID='EVAC_MESH_2'/
&EVHO  ID='Wheel_house6',
       XB= 49, 58.7, 16,25 ,0.31, 2.2
       EVAC_ID='Children',
       MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house6_1',
       XB= 49, 58.7, 16,25 ,0.31, 2.2
       EVAC_ID='Children_2',
       MESH_ID='EVAC_MESH_2'/
&EVHO  ID='Wheel_house7',
       XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
       EVAC_ID='Elderly',
       MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house7_1',
       XB= 58.7, 65.7, 2.5, 28.9, 0.31, 2.2
       EVAC_ID='Elderly_2',
       MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house8',
```

```
        XB= 49, 58.7, 16,25 ,0.31, 2.2
        EVAC_ID='Elderly',
        MESH_ID='EVAC_MESH_1'/
&EVHO  ID='Wheel_house8_1',
        XB= 49, 58.7, 16,25 ,0.31, 2.2
        EVAC_ID='Elderly_2',
        MESH_ID='EVAC_MESH_2'/
================================================================================
&SLCF PBZ= 1, QUANTITY='VELOCITY', VECTOR=.TRUE., EVACUATION = .TRUE./
================================================================================
DEVICES
&BNDF QUANTITY= 'WALL TEMPERATURE'/
================================================================
Gas' temperatures and velicity
&DEVC XYZ= 40.5, 11.4 , 2.3, ID= 'Tco 1' , QUANTITY = 'TEMPERATURE'/
&DEVC XYZ=  50.5 , 15.4 , 2.3, ID= 'Tco 2'  , QUANTITY = 'TEMPERATURE'/
&DEVC XYZ= 48.2,21.5, 2.3 ,  ID= 'Tco 3'  , QUANTITY = 'TEMPERATURE'/
&DEVC XYZ= 38.4 , 29.4 , 2.3, ID= 'Tco 4'  , QUANTITY = 'TEMPERATURE'/
&DEVC XYZ=  28.7, 20.1 ,  2.3 , ID= 'Tco 5'  , QUANTITY = 'TEMPERATURE'/
&SLCF PBZ = 2.3, QUANTITY = 'TEMPERATURE'/
&SLCF PBZ = 2.3, QUANTITY = 'VELOCITY', VECTOR =.TRUE./
==============================================================
Radiation to the floor
&DEVC XYZ= 40.5, 11.4 , 0.3, ID= 'Rco 1' , QUANTITY = 'INCIDENT HEAT FLUX', IOR = 3/
&DEVC XYZ=  50.5 , 15.4 , 0.3, ID= 'Rco 2' , QUANTITY = 'INCIDENT HEAT FLUX', IOR = 3/
&DEVC XYZ= 48.2,21.5, 0.3 ,  ID= 'Rco 3' , QUANTITY = 'INCIDENT HEAT FLUX', IOR = 3/
&DEVC XYZ= 38.4 , 29.4 , 0.3,  ID= 'Rco 4' , QUANTITY = 'INCIDENT HEAT FLUX' , IOR = 3/
&DEVC XYZ=  28.7, 20.1 ,  0.3 , ID= 'Rco 5' , QUANTITY = 'INCIDENT HEAT FLUX' , IOR = 3/
==============================================================
Visibility
&SLCF PBZ = 2.3, QUANTITY = 'VISIBILITY'/
============================================
```

O2 mass fraction

```
&SLCF XB= 19.5, 66, 2, 38, 0.3 ,2.3 , QUANTITY='MASS FRACTION', SPEC_ID='OXYGEN'/
```

```
============================================================
```

Smoke layer height and temperature

```
&DEVC XB= 40.5, 40.5, 11.4 , 11.4 , 0.3 , 3, ID= 'SHco 1' , QUANTITY = 'LAYER HEIGHT'/

&DEVC XB=  50.5 ,50.5 , 15.4 , 15.4 , 0.3 , 3, ID= 'SHco 2'  , QUANTITY = 'LAYER HEIGHT'/

&DEVC XB= 48.2 , 48.2 ,21.5, 21.5, 0.3 , 3 ,  ID= 'SHco 3'  , QUANTITY = 'LAYER HEIGHT'/

&DEVC XB= 38.4 , 38.4 , 29.4 , 29.4 , 0.3 , 3, ID= 'SHco 4'  , QUANTITY = 'LAYER HEIGHT'/

&DEVC XB=  28.7,  28.7 , 20.1 , 20.1 , 0 , 3 , ID= 'SHco 5'  , QUANTITY = 'LAYER HEIGHT'/

&DEVC XB= 40.5, 40.5, 11.4 , 11.4 , 0.3 , 3, ID= 'SUTco 1' , QUANTITY = 'UPPER TEMPERATURE'/

&DEVC XB=  50.5 ,50.5 , 15.4 , 15.4 , 0.3 , 3, ID= 'SUTco 2'  , QUANTITY = 'UPPER TEMPERATURE'/

&DEVC XB= 48.2 , 48.2 ,21.5,  21.5, 0.3 , 3 ,  ID= 'SUTco 3'  , QUANTITY = 'UPPER TEMPERATURE'/

&DEVC XB= 38.4 , 38.4 , 29.4 , 29.4 , 0.3 , 3, ID= 'SUTco 4'  , QUANTITY = 'UPPER TEMPERATURE'/

&DEVC XB=  28.7, 28.7 , 20.1 , 20.1 , 0 , 3 , ID= 'SUTco 5'  , QUANTITY = 'UPPER TEMPERATURE'/

&TAIL /
```

APPENDIX B: MESH SENSITIVITY GRAPHS

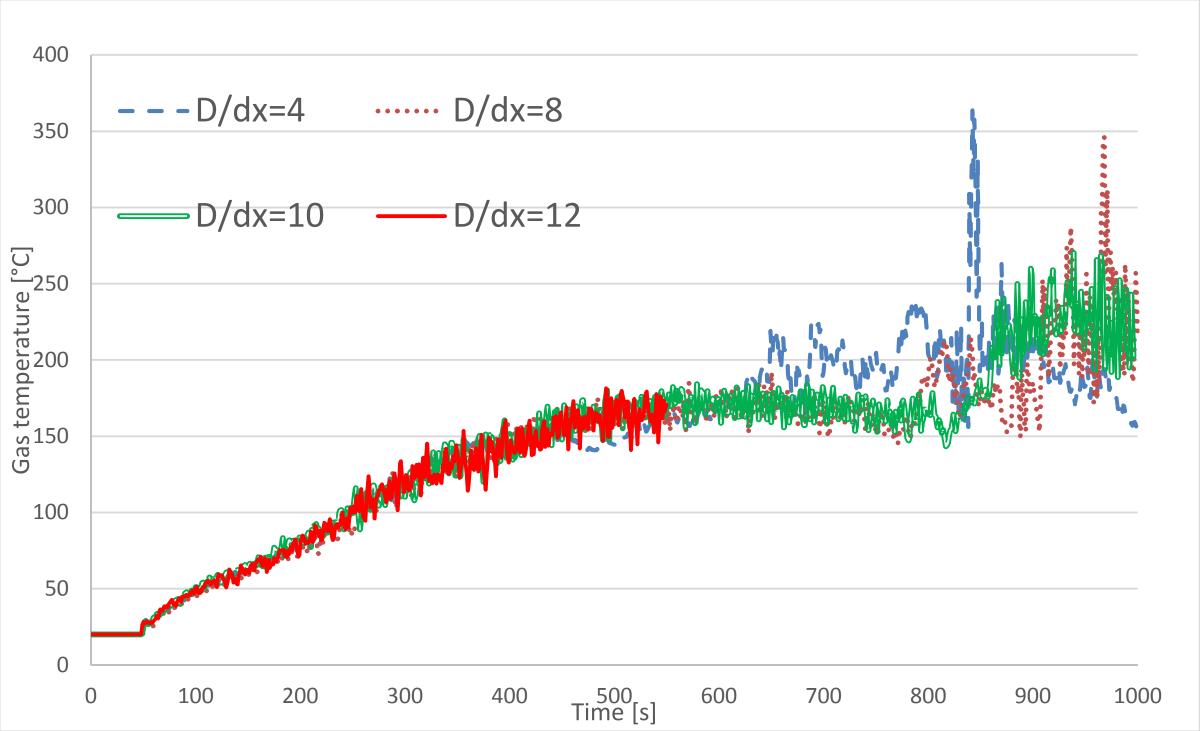

Figure 33 Gas temperature at point 1 for all meshes

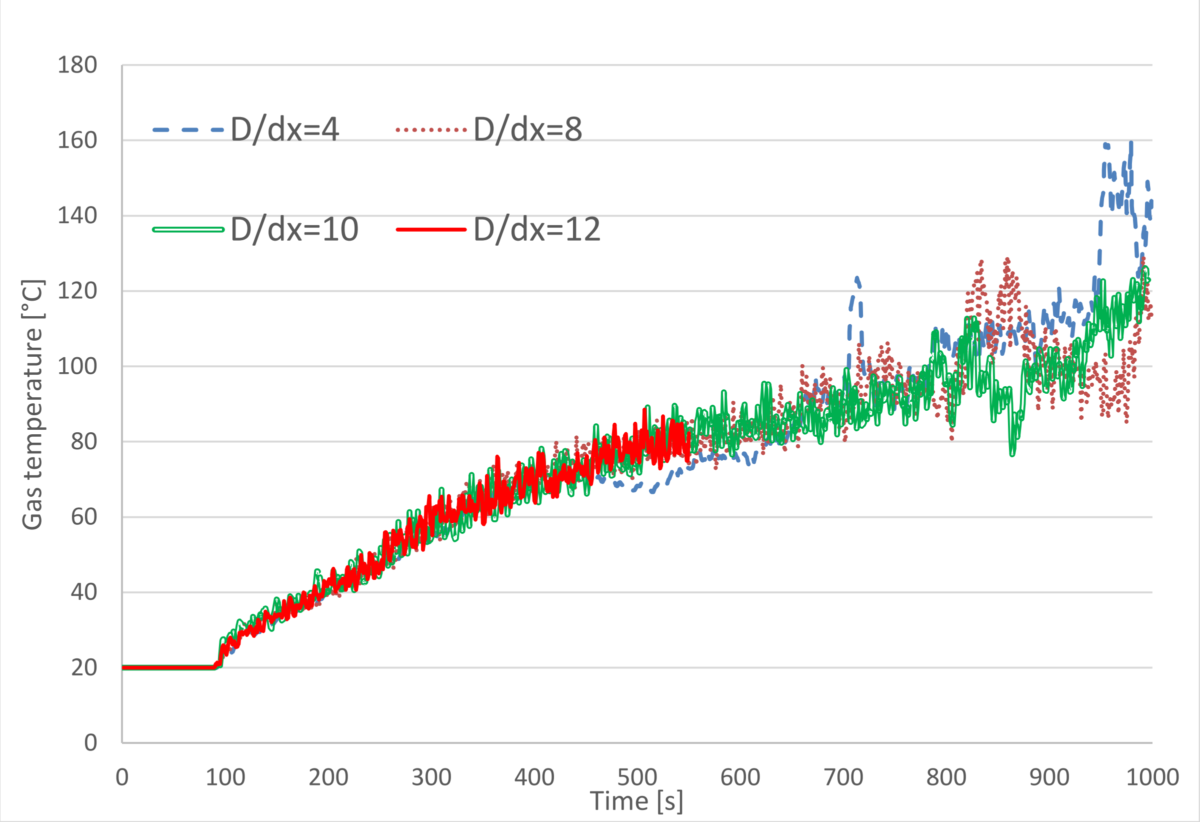

Figure 34 Gas temperature at point 2 for all meshes

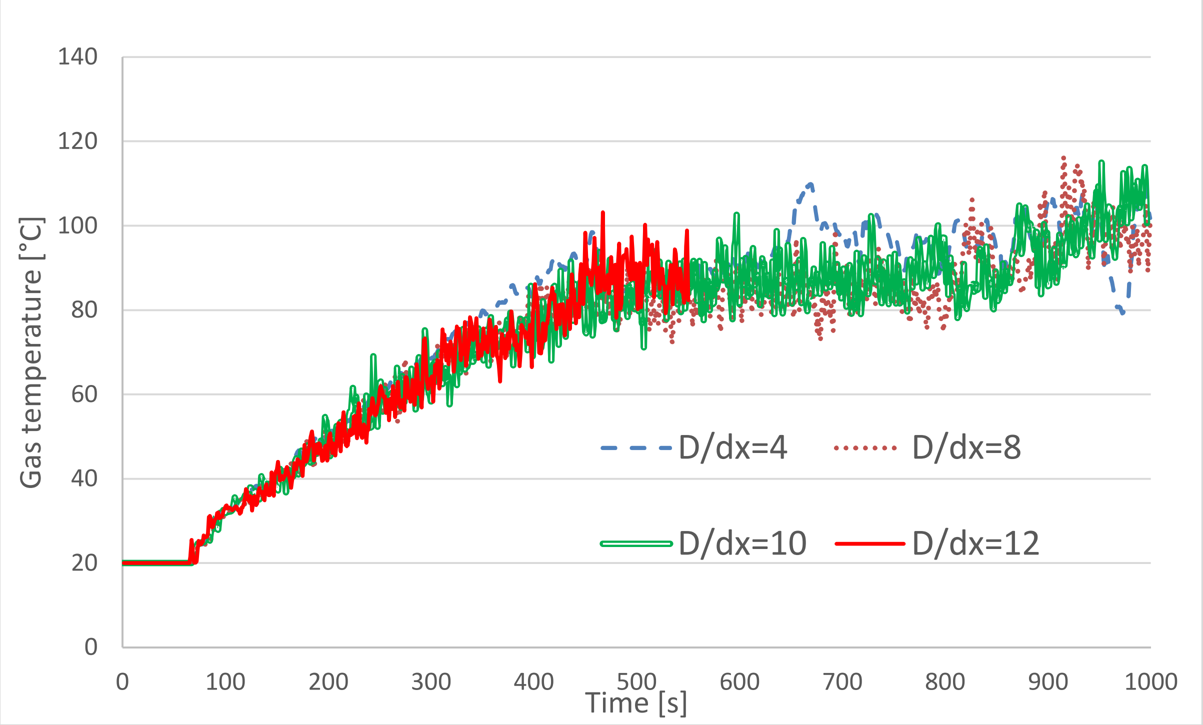

Figure 35 Gas temperature at point 4 for all meshes

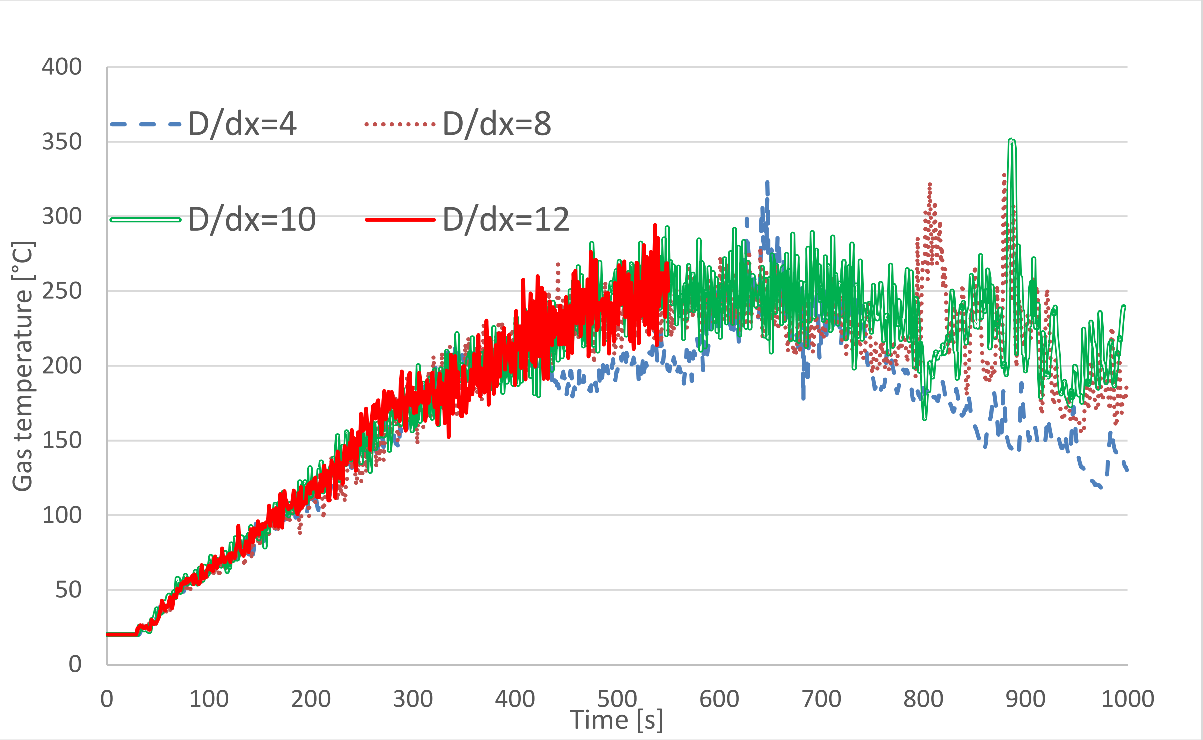

Figure 36 Gas temperature at point 5 for all meshes

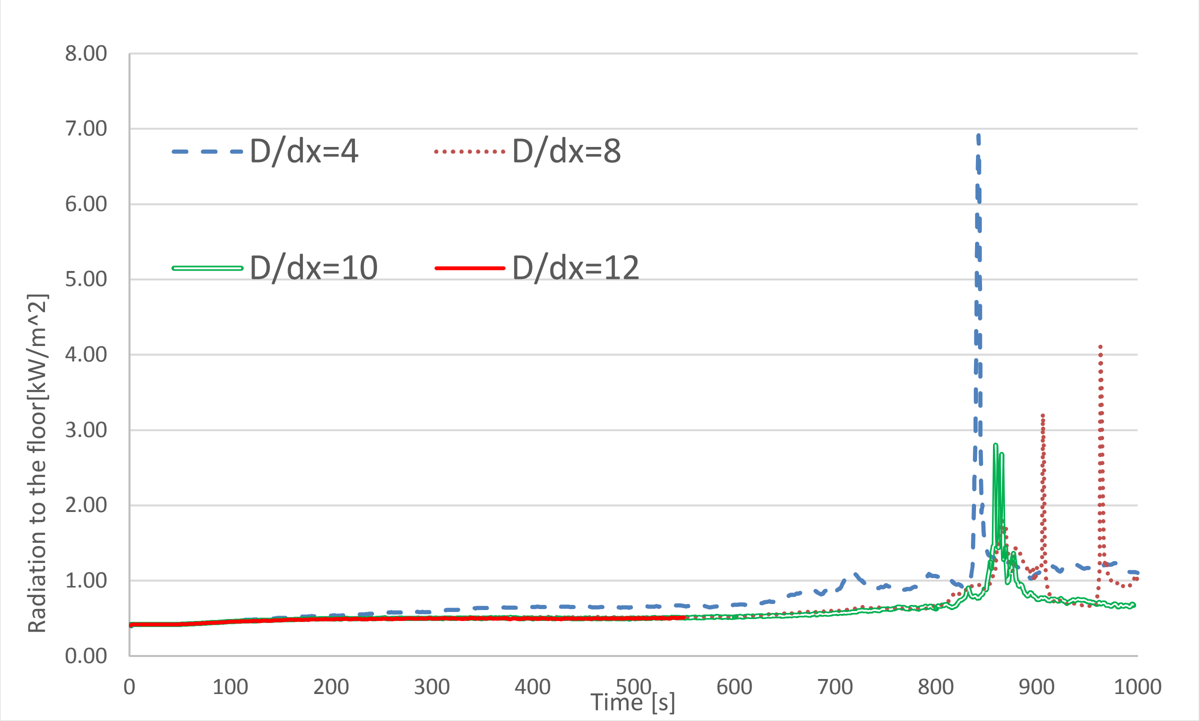

Figure 37 Radiation to the floor at point 1 for all the meshes

Figure 38 Radiation to the floor at point 2 for all the meshes

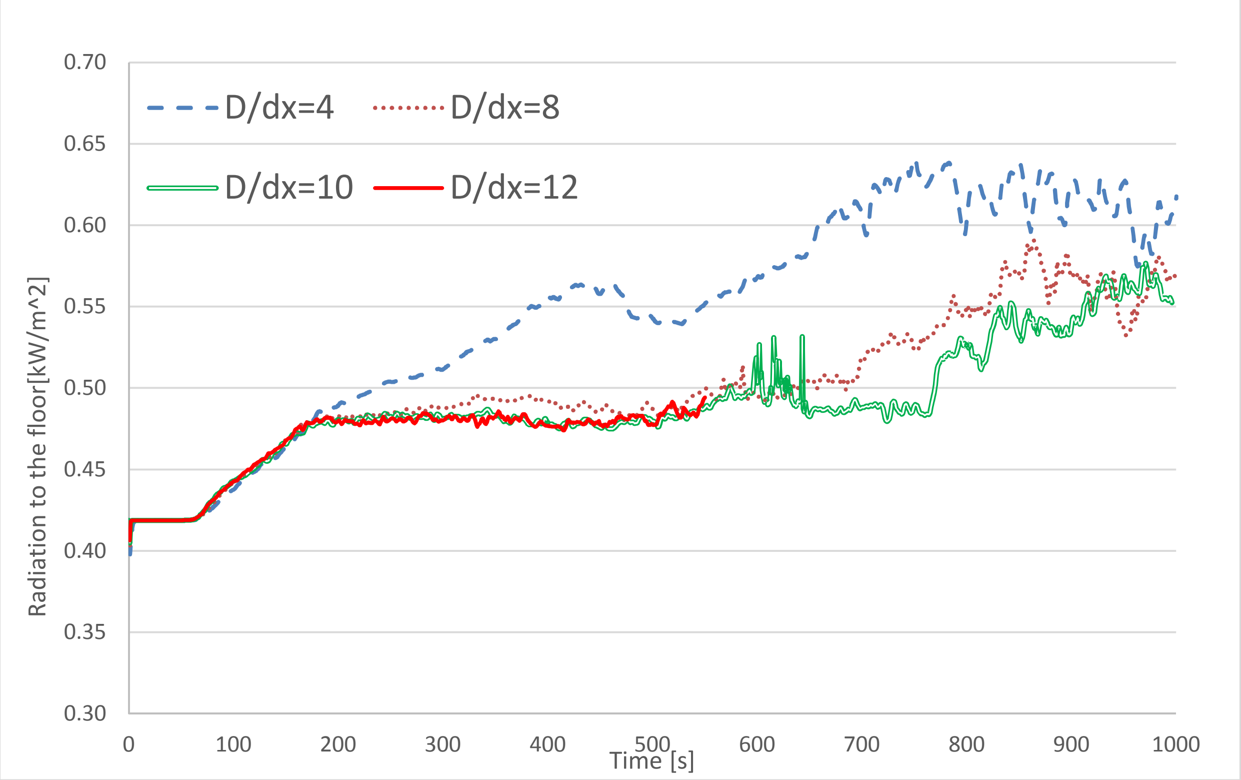

Figure 39 *Radiation to the floor at point 4 for all the meshes*

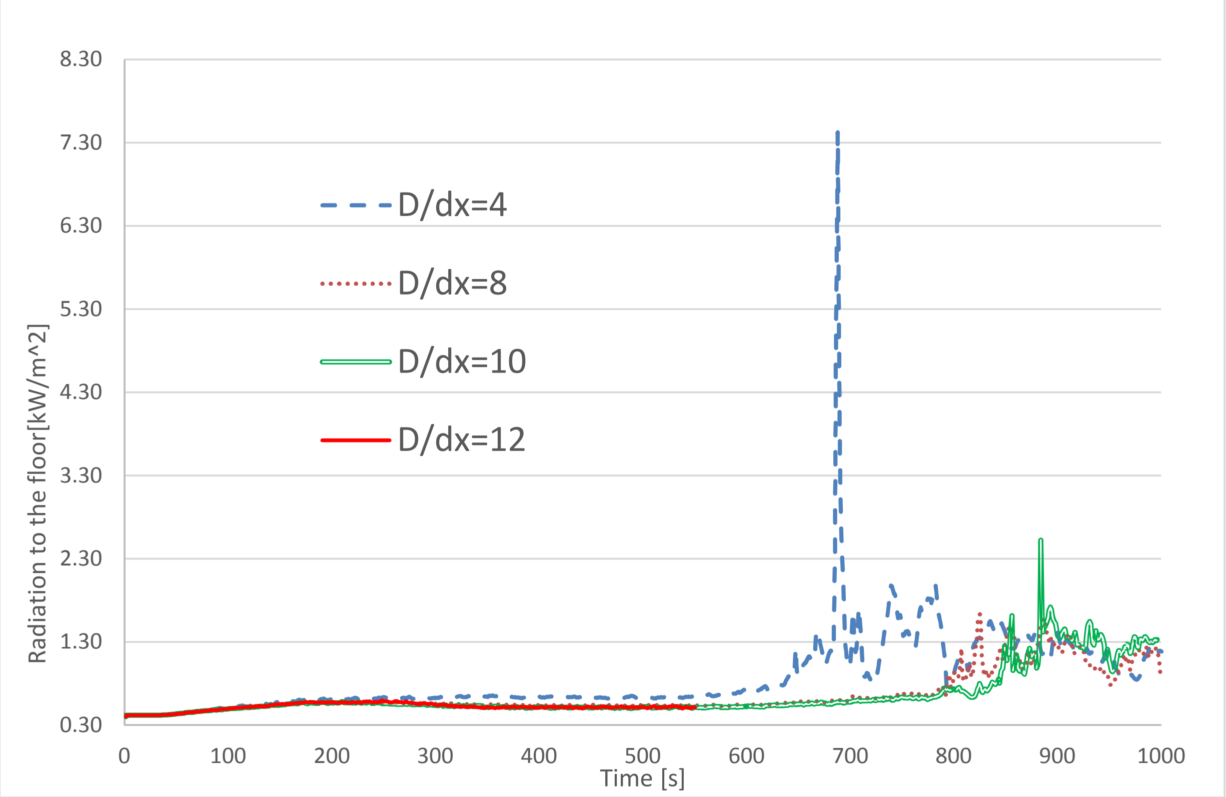

Figure 40 *Radiation to the floor at point 5 for all the meshes*

APPENDIX C: COMPLETE EVACUATION RESULTS

Table 12 Evacuation results for the steel set-up

Fire 1		Fire 2		Fire 3		Fire 4	
Travel time [s]	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**
261	0,03	249	0,04	299	0,17	204	2
262	0,03	273	0,08	314	0,17	211	3
287	0,09	300	0,08	328	0,31	223	1
292	0,06	316	0,12	339	1	227	4
310	0,09	340	0,13	359	0,30	237	0,16
316	0,04	344	0,12	360	0,29	238	1
317	0,07	361	0,20	361	0,32	256	2
323	0,07	365	0,15	364	0,34	283	0,18
323	0,09	368	1	373	0,17	291	0,33
328	0,04	370	0,15	377	0,36	297	1
349	0,05	384	0,17	378	0,17	300	1
362	0,14	391	0,24	380	0,30	305	0,99
373	0,14	393	0,27	384	0,40	317	2
373	0,07	395	0,19	386	0,28	321	2
381	0,17	396	0,23	390	0,21	337	2
391	0,09	401	0,17	394	0,22	347	1
395	0,10	414	0,37	395	0,37	361	0,73
398	0,07	414	0,24	396	0,37	363	6
402	0,18	417	0,25	396	1	370	0,98
408	0,12	418	0,25	398	0,37	377	2
410	0,11	428	0,27	403	0,27	384	0,60
410	0,18	431	1	409	0,37	389	3
412	0,11	440	0,41	413	0,41	392	0,97
414	0,10	440	0,31	413	0,32	396	2
418	0,12	440	0,29	416	0,45	400	1
424	0,10	442	0,26	418	0,43	404	0,35
430	0,20	445	0,26	422	0,47	405	1
432	0,10	454	0,33	426	0,51	406	1
445	0,24	458	0,27	443	0,27	407	0,81
448	0,21	459	0,32	452	0,40	411	0,62
460	0,28	461	0,35	455	0,36	414	2
467	0,20	467	0,35	456	0,37	416	2
471	0,19	468	0,20	464	0,32	417	1
474	0,16	475	0,38	468	1	418	4
478	0,17	481	0,40	468	1	422	4
484	0,18	489	0,41	477	0,64	423	0,88
484	0,16	495	0,43	484	0,71	424	1
491	0,35	496	0,38	487	0,64	428	0,74
492	0,19	503	0,47	488	0,56	435	2
496	0,17	519	0,69	489	0,59	438	0,93
502	0,21	530	0,57	494	0,74	438	1
506	0,21	537	0,43	494	0,41	440	0,97

506	0,21	540	0,77	498	0,43	440	0,93
548	0,34	550	0,66	505	0,52	440	0,84
571	0,43	561	1	509	0,88	443	2
583	0,34	561	0,59	540	0,49	446	1
587	0,36	571	0,67	565	0,91	469	1
588	0,34	600	0,79	607	0,78	491	3
594	0,27	615	0,88	613	0,82	503	2
614	0,57	644	0,99	662	0,97	530	1

Table 13 Evacuation results for unprotected composite set-up

Fire 1		**Fire 2**		**Fire 3**		**Fire 4**	
Travel time [s]	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**
174	0,00	219	0,02	157	3	130	2
174	1	220	1	180	2	133	3
188	1	220	1	209	1	136	5
194	0,02	229	0,03	226	0,19	138	5
204	1	243	0,04	240	2	148	2
205	0,00	247	3	247	0,13	149	4
206	0,01	255	1	284	1	150	6
207	0,01	257	0,10	289	1	151	6
207	0,02	260	0,11	295	1	151	6
208	0,01	273	0,08	301	2	155	3
214	0,01	274	0,14	307	0,52	157	3
218	0,04	280	0,16	309	3	159	3
230	0,02	296	1	310	0,20	160	4
232	0,01	300	1	311	1	162	4
234	0,01	305	0,25	318	2	172	3
256	0,03	313	0,28	320	0,77	178	5
258	1	313	0,28	321	2	185	6
260	0,07	315	1	323	1	191	1
271	1	316	0,29	330	2	192	4
279	1	327	0,50	330	0,91	193	5
281	1	339	0,64	332	3	194	6
285	0,05	342	0,23	333	1	197	9
300	1	344	0,37	335	1	198	4
310	0,14	344	1	335	2	199	2
318	0,05	344	1	344	2	200	4
326	1	346	0,38	345	2	200	3
330	1,00	347	1	349	1	200	3
331	0,07	353	0,11	351	0,34	201	4
335	0,22	358	1	356	0,07	204	1
337	0,17	363	0,77	356	0,94	207	5
338	0,18	364	1	356	0,89	208	6
351	0,11	364	0,19	380	2	208	5
361	0,14	378	0,56	385	3	211	4
372	0,17	378	0,56	395	1	212	3
376	0,29	387	1	396	1	212	7
386	0,49	390	2	400	4	212	7

386	2	393	1	402	1	213	6
393	0,29	394	0,62	403	1	214	7
399	0,73	398	0,65	403	3	216	7
403	0,39	400	1	405	3	216	5
404	1	419	0,73	411	2	217	3
410	3	430	1	420	1	217	4
412	0,41	438	0,84	424	0,92	225	5
419	0,40	440	1	430	0,71	225	4
431	1	442	0,87	430	2	226	7
440	0,83	443	1	445	0,81	243	4
459	1	447	1	447	1	247	10
473	0,77	450	0,87	452	1	249	4
491	2	457	0,68	452	0,99	257	5
491	0,80	459	0,98	461	1	263	0,93

Table 14 Evacuation results for protected composite set-up

Fire 1		**Fire 2**		**Fire 3**		**Fire 4**	
Travel time [s]	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**	**Travel time [s]**	**Max FED/Deads**
266	0,06	298	0,11	251	0,06	175	3
275	0,05	330	0,14	282	1	214	1
284	0,06	340	0,17	293	2	227	2
285	0,03	342	0,13	294	1	254	2
301	1	349	0,15	300	1	256	2
319	0,07	365	0,28	312	0,54	275	0,39
335	0,07	365	0,28	314	0,33	282	0,39
340	0,06	370	0,19	315	1	285	3
342	0,10	387	0,28	334	1	286	1
347	0,09	391	0,22	338	0,13	288	0,43
349	0,11	395	0,24	344	1	314	1
350	0,09	402	1	356	0,55	323	1
358	0,07	405	0,39	356	1	324	3
363	0,11	405	0,36	356	2	335	1
364	0,14	411	0,27	360	1	347	1
365	0,11	416	0,36	363	0,49	351	0,67
370	0,13	417	0,45	363	3	352	0,54
372	0,08	422	0,30	363	0,79	355	4
377	0,05	423	0,38	365	0,80	356	1
380	0,13	440	0,66	368	0,65	363	2
395	0,12	441	0,29	370	1	364	2
405	0,16	441	0,35	376	5	367	3
406	0,11	442	1	378	0,57	376	1
413	0,09	443	0,22	379	1	378	1
421	0,12	449	0,29	395	0,48	382	2
424	0,18	451	0,56	396	1	383	0,82
427	0,14	452	0,44	398	0,71	388	1
430	0,13	454	0,39	403	1	389	3
438	0,23	454	0,32	407	0,90	389	3
440	0,11	461	0,45	408	0,53	393	1

441	0,13	461	0,33	408	0,65	393	3
448	0,09	466	0,54	409	3	399	0,58
449	0,13	472	0,43	414	0,36	409	1
472	0,22	473	0,38	414	0,46	410	0,63
482	0,19	477	0,65	421	0,90	417	1
485	0,24	481	0,68	424	3	417	2
502	0,14	487	0,98	431	2	419	0,93
508	0,16	498	0,69	440	0,39	421	2
508	0,23	505	0,38	443	0,52	422	1
519	0,23	508	0,42	448	0,99	440	0,81
522	0,33	508	0,29	459	1	444	1
526	0,16	510	0,57	463	0,94	454	1
594	0,34	522	1	475	1	461	1
622	0,77	529	0,82	494	0,62	473	1
622	0,58	533	0,93	496	0,54	477	0,93
636	0,38	534	0,68	496	0,54	478	0,93
655	0,49	550	0,94	496	0,54	519	0,97
674	0,46	554	0,34	521	0,78	525	2
680	0,79	589	0,86	531	1	572	1
698	0,48	593	0,95	552	0,94	633	1

APPENDIX D: EVACUATION RESULTS IN BAR GRAPHS

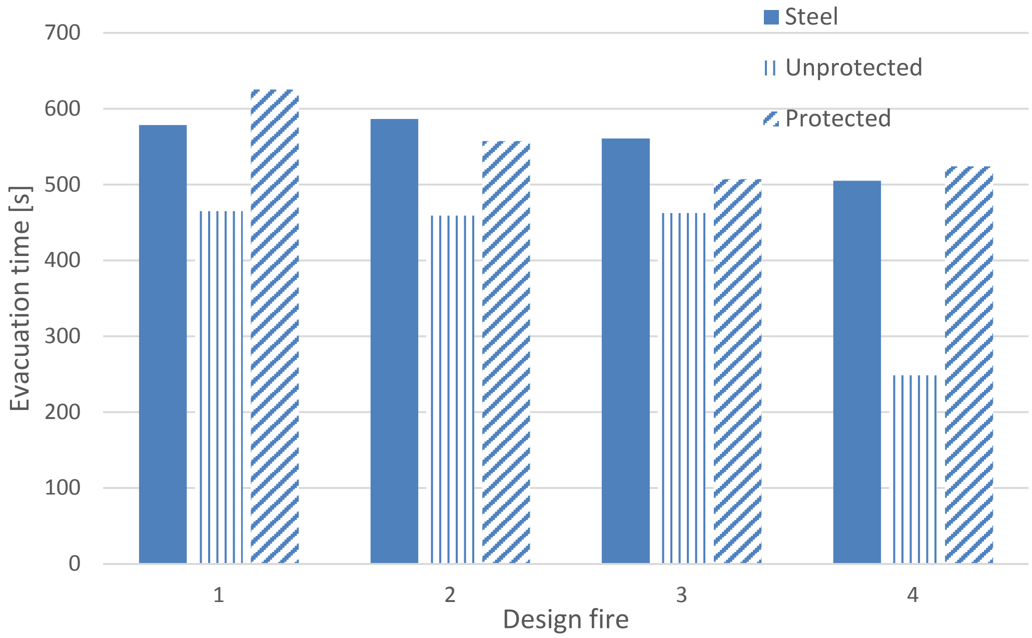

Figure 41 Effect of the design fire on the evacuation time

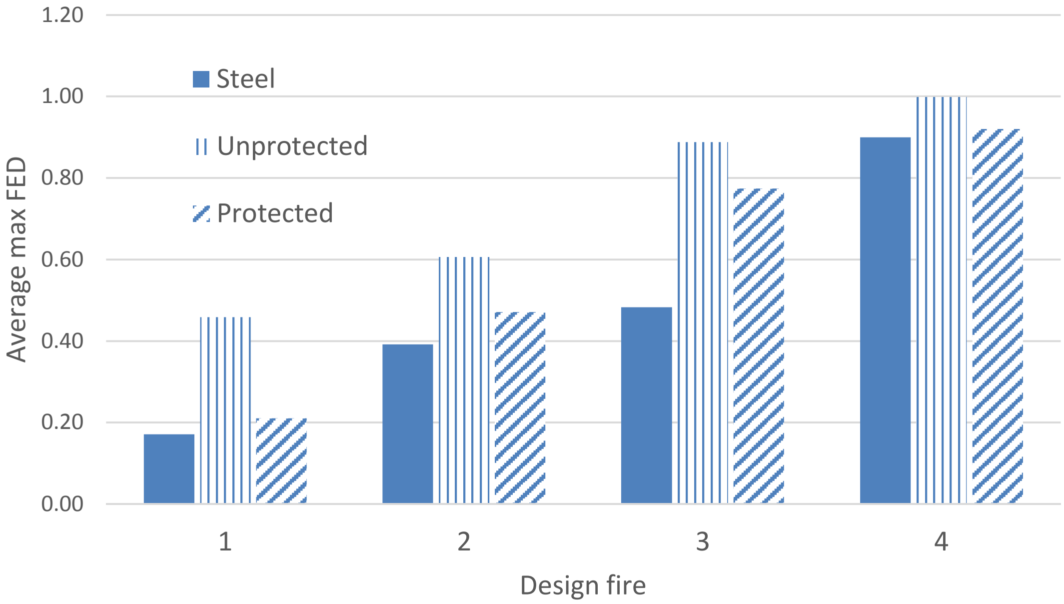

Figure 42 Effect of the design fire on the average maximum FED

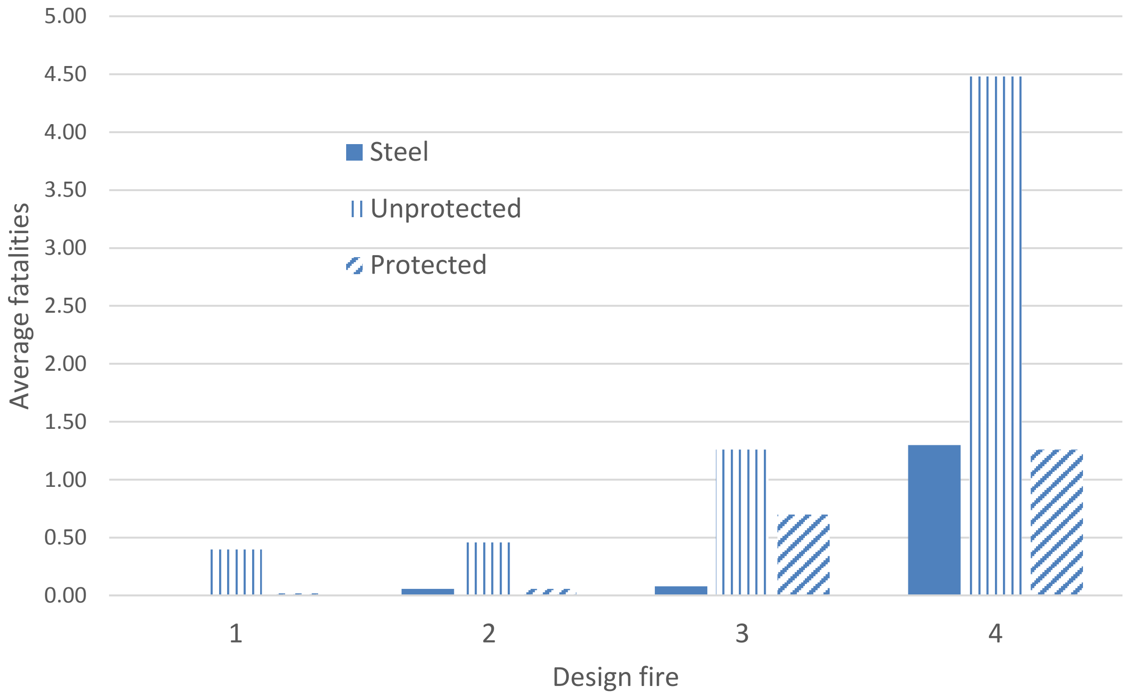

Figure 43 Effect of the design fire on the average fatalities

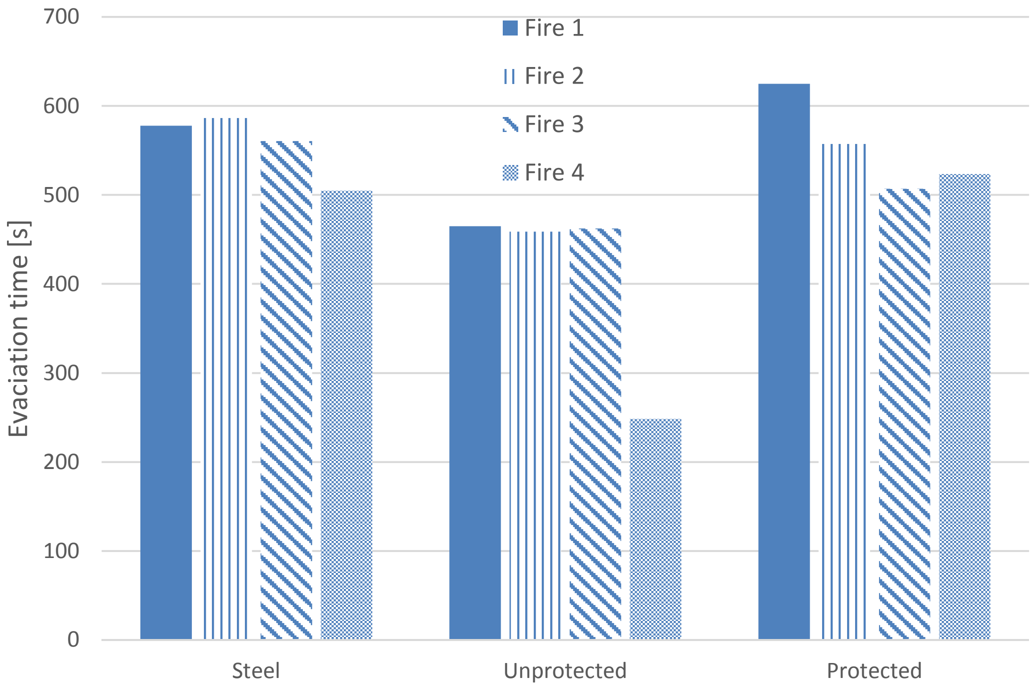

Figure 44 Effect of the material set-up on the evacuation time

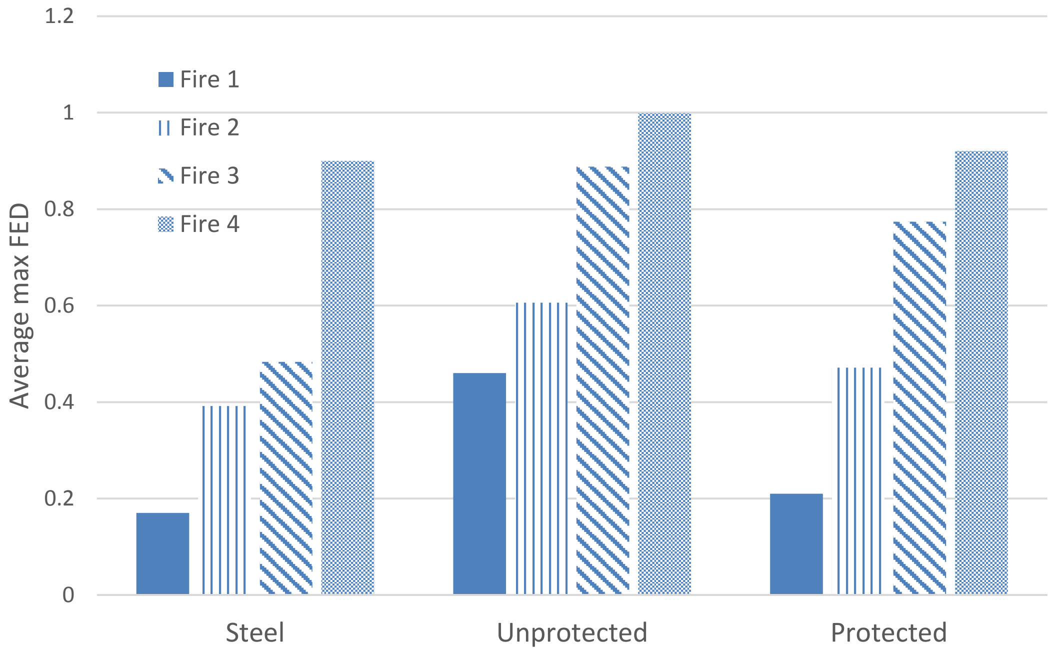

Figure 45 Effect of the material set-up on the average maximum FED

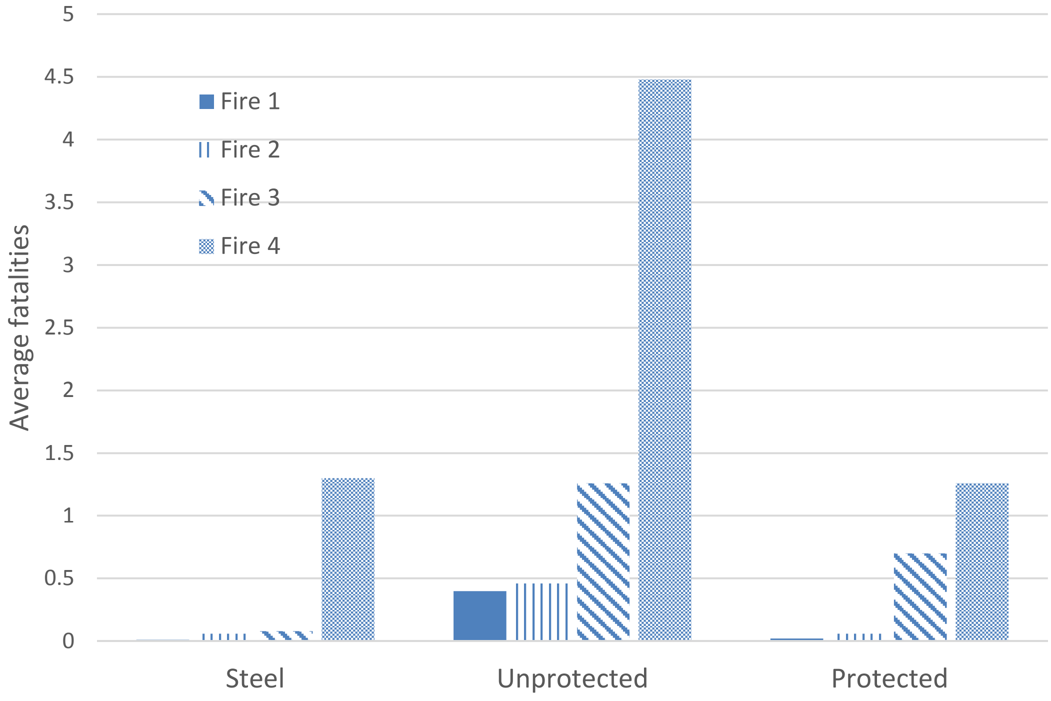

Figure 46 Effect of the material set-up on the average fatalities