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FIRE SIMULATIONS OF A FISHING RESEARCH VESSEL WITH FRP STRUCTURES

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SUMMARY

The fire safety effect of using fibre-reinforced polymer (FRP) as the primary construction material in a fishing research vessel was studied by fire simulations. The effect of FRP structures on fire development was assessed by comparing the simulated gas temperatures and potential heat releases with FRP and steel structures. The structural integrity of FRP structures was assessed using simulated temperatures of the structures as indicators of integrity. The effect of protective mineral wool and intumescent coating layers was also quantified. The results showed that despite the protection, the structural integrity of FRP bulkheads could be compromised in fire conditions. Mineral wool was found to be better protection than the intumescent coating: it can either prevent or postpone the pyrolysis of the FRP bulkhead, depending on the fire exposure.

NOMENCLATURE

CFD	Computational Fluid Dynamics
FDS	Fire Dynamics Simulator
FRP	Fibre-Reinforced Polymer
FRV	Fishing Research Vessel
HRR	Heat Release Rate
TGA	Thermogravimetric analysis

1. INTRODUCTION

The FIBRESHIP project is an ambitious innovation project to develop a new market focused on the construction of commercial vessels in composite materials (Fibre-Reinforced Polymers, FRP) greater than 50 m in length. The main objective of the FIBRESHIP project is to generate the regulatory framework that allows the designing and building of large-length ships in FRP material overcoming the technical challenges identified. In order to achieve this objective, the project is qualifying and auditing innovative FRP materials for marine applications, elaborating new designs and production guidelines, generating production and inspection methodologies, and developing numerical software tools capable of assessing the structural performance validated through experimental testing.

As a part of the work package devoted to design, engineering and development of guidelines, on-board fire events have been simulated to assess the fire safety effect of using FRP as the primary construction material of the vessel, compared to conventional steel structures. This paper describes the fire simulations of a fishing research vessel (FRV) with FRP structures. Several fire scenarios in an accommodation space of a FRV were simulated with a computational fluid dynamics (CFD) software Fire Dynamics Simulator (FDS) [1], version 6.7.1. To create different fire scenarios, the utilized design fires, bulkhead structures and ventilation conditions were varied in the study.

From fire safety aspect, the following matters were of primary interest:

- the effect of FRP structures on fire development in comparison to more conventional steel structures,
- the integrity of the FRP structures in fire conditions,
- the effect of protective material layers on the fire behaviour of the FRP structures.

The effect of FRP structures on fire development was assessed by comparing the gas temperatures and the potential heat releases obtained from simulations with FRP structures to reference simulations where all structures were conventional steel structures. The potential heat release was defined as the heat release due to the complete combustion of all produced gaseous fuel. Due to ventilation-controlled conditions in the studied enclosure, not all produced fuel gas burned. As the studied enclosure was located within a ship superstructure, the unburnt fuel could combust in an adjacent compartment and thus cause rapid fire spread.

As the structural responses of the FRP structures were not explicitly studied in this work, the simulated temperatures of the structures were used as indicators of integrity. It is known that after reaching the glass transition temperature the material will lose a significant portion of its load carrying capacity. The glass transition temperature of FRP materials is typically about 100 °C. Due to the uncoupled nature of the simulations (the structural deformation is not taken into account), there is significant uncertainty in the results after the FRP structures reach high temperatures.

To be able to quantify the effect of protective material layers, two different protective layers on top of the FRP structures were used in the simulations. The increase in the potential heat release, the duration of fuel generation of FRP structures and the extent of pyrolysing areas were compared between the simulations

In addition, one objective of this study was to gain better understanding of simulating enclosure fires with FRP structures. It is to be noted that pyrolysis modelling of complex materials, simulating fires including structural responses or simulating ventilation-controlled enclosure fires are not by any means mature. The results of this study are thus limited in application.

2. SIMULATION INPUT

2.1 GEOMETRY

The simulated space was an accommodation space designated as a multifunctional space in the ship's general arrangement. The longitudinal bulkhead on the starboard side is exterior. Visualization of the room geometry with dimensions is shown in Figure 1.

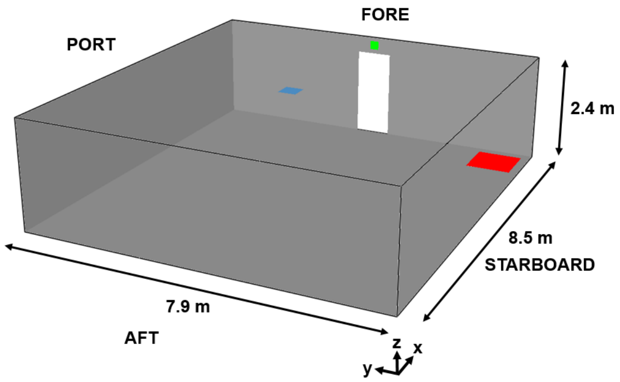

Figure 1: Room geometry with dimensions.

A door was located on the forward transverse bulkhead. The width and height of the door were 0.8 m and 2.0 m, respectively. The status of the door being open was varied in the simulations. An air exhaust was located above the door and a second air exhaust was on the same location on the opposite bulkhead. One of the air exhausts is shown in green in Figure 1, while the second one is not shown. An air supply was located in the middle of the room slightly below the ceiling level, shown in blue in Figure 1. The red square in Figure 1 shows the position of parametric t^2 design fires.

2.2 SURFACES

Three different bulkheads were studied in the simulations: A-60 class steel bulkheads, FRP bulkheads protected with mineral wool, and FRP bulkheads protected with an intumescent coating. The decks below and above the space, i.e., the floor and the ceiling, were defined as A-60 class steel sandwiches in all simulations.

All A-60 class steel structures were defined as sandwich structures consisting of three layers. The external layers were steel and the core was mineral wool. The FRP bulkheads were similarly defined to be sandwich structures with three layers. The external layers were made of FRP material under the trade name SAERTEX LEO®. The core of the sandwich was mineral wool. The protective layer was either an additional external layer of mineral wool or an external layer of intumescent coating. The protective layers were located on the bulkhead side that is inside the studied enclosure.

Three different combinations of bulkhead structures were studied in the simulations. The combination of the bulkheads was one of the following:

- all A-60 class steel, "steel" bulkhead combination.
- all FRP with intumescent coating, "coated FRP" bulkhead combination.
- three of the bulkheads FRP insulated with mineral wool and the fourth bulkhead FRP with intumescent coating, "partially insulated FRP" bulkhead combination.

The bulkhead structures of the different bulkhead combinations and their positions are summarized in Table 1. See Figure 1 for x and y coordinates.

Table 1: Bulkhead structures in the different bulkhead combinations. The structural layers are listed starting from the inside of the studied enclosure.

Bulkhead combination	**Structure**	**Bulkhead**
Steel	2 mm steel + 6 cm mineral wool + 2 mm steel	All
Coated FRP	2 mm coating + 2.9 mm FRP + 4.4 cm mineral wool + 2.9 mm FRP	All
Partially insulated FRP	2 mm coating + 2.9 mm FRP + 4.4 cm mineral wool + 2.9 mm FRP	y = 0.0 m
	6 cm mineral wool + 2.9 mm FRP + 4.4 cm mineral wool + 2.9 mm FRP	y = 7.9 m x = 0.0 m x = 8.5 m

2.3 MATERIAL MODELS

The required material properties for the simulations include density, conductivity, specific heat and emissivity. As the fibre-reinforced polymer was assumed to thermally decompose in the simulations due to the elevated temperatures, a pyrolysis model was needed in addition to the material properties.

2.3 (a) Steel

The material properties of steel corresponded to the properties given for stainless steel in the Eurocode 3, which is the harmonised European standard for design of steel structures [2].

2.3 (b) Mineral wool

The material properties of mineral wool corresponded to general-type stone wool. Material properties of such materials are presented for example in [3].

2.3 (c) Fibre-reinforced polymer

The FRP material properties and the pyrolysis model were based on the experimental results acquired during the FIBRESHIP project. The development of the material model followed the modelling principles presented in [4].

The fibre-reinforced polymer was modelled as consisting of vinyl ester resin, glass fibre and moisture. The mass of FRP material was assumed to consist of 23.75 % of vinyl ester resin, 1.25 % of moisture and 75 % of glass fibre.

The vinyl ester resin was assumed to consist of two components based on the small-scale thermogravimetric analysis (TGA). The mass of the vinyl ester resin was assumed to consist of 42 % of the first resin component and 58 % of the second resin component.

The material properties of the vinyl ester resin components were assumed to be the same. The material properties of the FRP components are presented in Table 2.

Table 2: Material properties of the components of fibre-reinforced polymer.

Resin components 1 and 2	
Emissivity	0.9
Density	1000 kg/m^3
Specific heat	2.152 kJ/kgK
Conductivity	0.25 W/mK
Glass fibre	
Emissivity	0.9
Density	2400 kg/m^3
Specific heat	1.2 kJ/kgK
Conductivity	0.65 W/mK
Moisture	
Emissivity	0.9
Density	1000 kg/m^3
Specific heat	4.0 kJ/kgK
Conductivity	1.2 W/mK

The resin components were assumed to pyrolyse in elevated temperatures. The complex pyrolysis model of FDS was utilized to model the thermal degradation of the material [1]. A simplified presentation of the assumed pyrolysis reaction mechanisms is shown in Table 3. The reaction rates are dependent on the temperature, and some of the reactions are oxidative, i.e., the reaction rates are dependent on the local oxygen concentration. The produced fuel gas was assumed to be propane, which has heat of combustion of approximately 44.6 MJ/kg. The produced inert gas was assumed to be water vapour.

The cone calorimeter results, for both a vinyl ester resin specimen (cured resin) and a specimen consisting of vinyl ester resin and glass fibre (laminate) were utilized to manually estimate the material properties for the glass fibre, the assumed resin components and their solid pyrolysis products. The experimentally measured density was used as a boundary value for the estimated component densities. The material properties were evaluated using expert judgement and similar reference materials to ensure that realistic values were used in the simulations.

Table 3: Reaction mechanisms of resin components.

Component	**Reaction no.**	**Products (yield %)**
Component 1	1	Solid product 1 (10 %) Fuel gas (90 %)
	2	Solid product 1 (80 %) Fuel gas (20 %)
Component 2	1	Solid product 1 (20 %) Fuel gas (80 %)
Solid product 1	1	Solid product 2 (8 %) Fuel gas (92 %)
Solid product 2	–	–

Regarding the assumptions made about the other components of the FRP material, moisture changes phase into water vapour in elevated temperatures. The glass fibre was not considered reactive.

2.3 (d) Intumescent coating

The material properties and the pyrolysis model for the intumescent coating were based on the experimental results acquired during the FIBRESHIP project [5]. The development of the material model follows the modelling principles presented in [4].

Based on the TGA results, the intumescent coating was assumed to consist of two components. The TGA results have been reported in [5]. The material properties of the intumescent coating components were assumed to be the same and are presented in Table 4.

Table 4: Material properties of intumescent coating components.

Intumescent coating components	
Emissivity	1.0
Density	1500 kg/m^3
Specific heat	1.0 kJ/kgK
Conductivity	0.6 W/mK

The intumescent coating components were assumed to pyrolyse in elevated temperatures. The complex pyrolysis model of FDS was utilized to model the thermal degradation of the material [1]. A simplified presentation of the assumed pyrolysis reaction mechanisms is shown in Table 5. The produced fuel gas was assumed to be propane, which has heat of combustion of approximately 44.6 MJ/kg. The produced inert gas was assumed to be water vapour.

Table 5: Reaction mechanisms of intumescent coating components.

Component	**Reaction no.**	**Products (yield %)**
Component 1	1	Inert gas (100 %)
Component 2	1	Solid product 1 (94.6 %) Inert gas (5.4 %)
Solid product 1	1	Solid product 2 (40 %) Fuel gas (60 %)
	2	Solid product 3 (90 %) Fuel gas (10 %)
Solid product 2	1	Solid product 4 (50 %) Fuel gas (50 %)
	2	Solid product 5 (85 %) Fuel gas (15 %)
Solid product 3	1	Solid product 5 (10 %) Fuel gas (90 %)
	2	Solid product 4 (50 %) Fuel gas (50 %)
Solid product 4	–	–
Solid product 5	1	Inert gas (50 %) Solid product 4 (50 %)

2.4 FIRE SCENARIOS AND DESIGN FIRES

Twenty-four (24) different fire scenarios were simulated. The design fire, the bulkhead combination and the ventilation were varied to produce different fire scenarios as follows:

- four (4) design fires: parametric t^2 fire with slow growth rate, parametric t^2 fire with fast growth rate, a refrigerator fire, and an office furniture fire
- three (3) bulkhead combinations: steel, coated FRP, and partially insulated FRP (see Table 1)
- two (2) natural ventilation conditions: leakage and door open (see Section 2.5).

The design fires in the simulations were defined as prescribed heat release rates as a function of time. The simulated physical time is 60 minutes for all fire scenarios.

In the simulations with FRP bulkheads, the FRP material pyrolysed, i.e., generated fuel gas, after reaching sufficiently high temperature. The produced fuel gas ignited if there was enough oxygen available.

In the simulations, the fire began with the ignition of "a burner" with a defined area, describing a parametric t^2 fire, a refrigerator fire, or an office furniture fire. The heat release rate of the burner developed according to a defined curve of heat release rate as a function of time. In the beginning, the surfaces of the fire compartment did not contribute to fire. The combustible surfaces, i.e. FRP with intumescent coating, were assumed to pyrolyse and generate fuel in elevated temperatures. Their thermal degradation was modelled utilizing the pyrolysis model of FDS, with material properties presented above.

In this paper, the performance of FRP structures and protective material layers are discussed on the basis of the results obtained in the office furniture fire simulations. Therefore, the parametric t^2 fires and the refrigerator fire are described below only briefly and the office furniture fire in more detail.

2.4 (a) Slow and fast growth rate t^2 fires

The heat release rate (HRR) of t-squared (t^2) fires was described as $HRR = \dot{Q}_0(t/t_0)^2$, where $\dot{Q}_0$=1000 kW, t is time in seconds and t_0 is 600 s and 150 s for the slow and fast t^2 fire, respectively. As the fire shortly became under-ventilated, it was decided to limit the HRR of the design fire by setting a maximum threshold. The maximum HRRs for the simulations of the rooms with closed door and open door were 5000 kW and 2000 kW, respectively.

2.4 (b) Refrigerator fire

The burning refrigerator was assumed to be 1.6 m high, 0.7 m wide and 0.6 m deep. The room was otherwise empty.
According to Hietaniemi et al. [6], the maximum heat release rate of a refrigerator fire is roughly 2100 kW. In the simulation, the worst-case scenario was considered and thus the refrigerator fire was defined to have a maximum heat release rate of 4200 kW. The fire grew according to a slow t^2 fire growth rate until it reached its maximum heat release rate. After this, the heat release rate started to descend.

2.4 (c) Office furniture fire

The office furniture fire consisted of an explicitly defined workstation fire and modelled office furniture, which took part in the fire. The explicitly defined workstation fire followed closely the experimental heat release rate reported by Kakegawa et al. in [7]. The modelled office furniture was assumed to have similar heat release rate per unit area as a 20 mm thick pine board in cone calorimeter tests of [8] under 50 kW/m^2 irradiance.

The furniture arrangement in the room and the location of the burning piece of table with explicitly defined HRR are presented in Figure 2. Figure 2 shows the fire development 320 seconds after the ignition. The heat release rate of the workstation is shown in Figure 3.

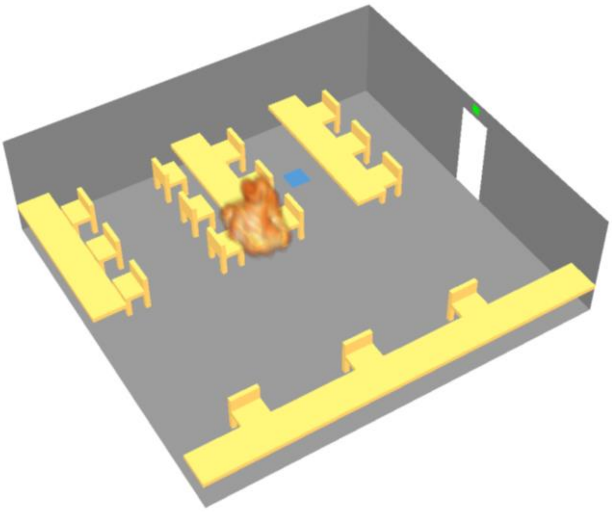

Figure 2: Office furniture fire scenario at t = 320 s.

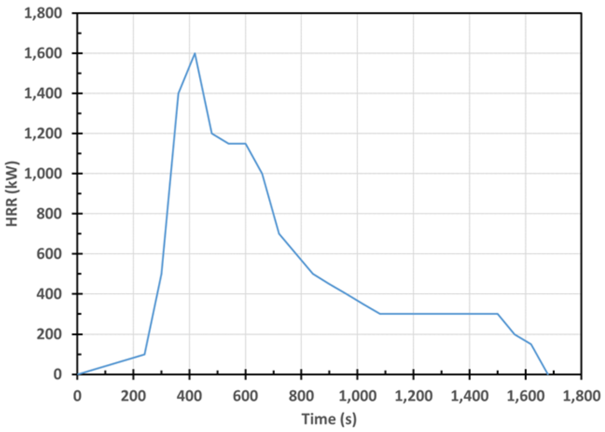

Figure 3: Heat release rate of a workstation.

2.5 VENTILATION

The accommodation space was assumed to be constantly mechanically ventilated in the simulations. The utilized ventilation system model did not take into account the pressure changes in the room caused by the fire. A ventilation rate of 1000 m^3/h was used in the simulations. The ventilation rate was estimated based on the design occupancy of the space and the minimum airflow rate per person as given by ISO 7547 [9]. As per the ISO 7547 design values for a saloon, the used design occupancy is 35 persons [9].

The natural ventilation of the space was modified in the simulations by opening the door in the forward transverse bulkhead. Each design fire was simulated with the door being either open or closed during the whole simulation. The open door was assumed to be connected to a space with constant ambient conditions. This is a conservative assumption, while fresh air was drawn to the space during the fire as the hot gases in the fire room expanded and exited through the door. This increased the heat release rate, because lack of oxygen did not limit the fire.

The enclosure boundaries were assumed to have some leakage, e.g., due to the penetrations through the boundaries. The total leakage area in the simulations with closed door was 0.05 m^2. In the simulations with open door, this leakage boundary condition was not included in the model. When the pressure in the space was below the ambient pressure, 101 325 Pa, fresh air was drawn to the space through the leaking area.

2.6 INSTRUMENTATION

The following quantities were monitored in the simulations:

- gas temperatures and oxygen volume fractions at discrete locations around the room,
- solid temperatures at discrete locations around the room on the bulkheads and the decks,
- mass and volume flows at all air supply and exhaust vents, and mass and volume flows through the door, if it was present in the simulation,
- temperature, visibility, oxygen volume fraction and velocity fields at both transverse and longitudinal planes going through the centre of the room,
- adiabatic surface temperature, burning rate, solid temperatures, and surface density fields at the boundaries of the domain.

3. SIMULATION RESULTS AND ANALYSIS

The results of the simulations with office furniture design fire are presented below as simulated average gas temperatures, simulated temperatures on the front of the first composite layer, potential heat release values, and fuel generation times of bulkheads. Potential heat release is the amount of energy (kWh) released if enough oxygen would be available for complete combustion of produced fuel gas. In the calculation, the produced fuel gas (kg) was scaled by the heat of combustion of the fuel (kJ/kg). The fuel generation times of various bulkheads, i.e. the start and end times of fuel generation, were determined on the basis of the mass loss rate visualisations of the simulations (see Figures 6 and 7).

This section aims to compare the simulations with the same design fire, and highlights the differences caused by the different bulkhead materials and structures.

3.1 SIMULATIONS WITH A CLOSED DOOR

The simulated average gas temperatures during an office furniture fire with a closed door are presented in Figure 4. The coated FRP bulkhead combination gives the lowest average gas temperature, indicating that the insulation capability of the FRP bulkheads with intumescent coating is inferior to both steel bulkheads and the FRP bulkheads with additional mineral wool layer. In the simulation with the coated FRP bulkhead combination, the furniture re-ignition that was present in the other two simulations did not occur. This is assumed to be due to the reduced gas temperature, caused by the greater heat loss through the bulkheads.

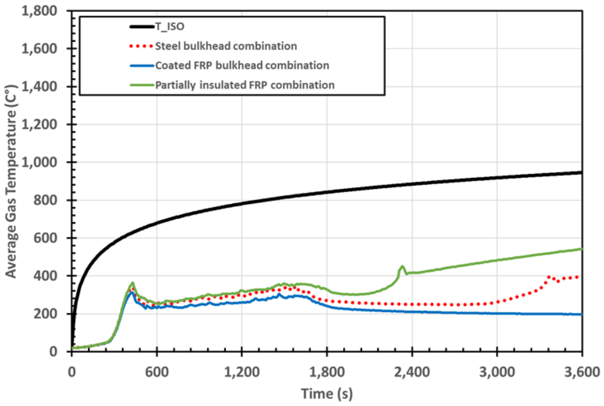

Figure 4: Average gas temperatures with office furniture design fire, door closed.

In the simulations of the office furniture fire with a closed door, the potential heat releases were approximately 530 kWh with the steel bulkhead combination, 380 kWh with the coated FRP bulkhead combination and 2600 kWh with the partially insulated FRP bulkhead combination. The potential heat release in the simulation with the steel bulkhead combination was almost 80 % smaller than in the simulation with the partially insulated FRP bulkhead combination but approximately 40 % greater than in the simulation with the coated FRP bulkhead combination. There are two causes for these differences: the different insulation properties of the bulkheads and the additional fire load due to the combustible FRP bulkheads.

The simulated temperatures on the front of the first composite layer are presented in Figure 5. The presented monitoring points were located on two different bulkheads. In the simulation with the partially insulated FRP bulkhead combination, the monitoring point referred to as "fy0" was located on a bulkhead with protective layer of intumescent coating and the monitoring point referred to as "fxm" was located on a bulkhead with additional mineral wool layer. The effect of the improved thermal protection can be clearly observed in Figure 5, as the temperature on the bulkhead with intumescent coating is over 500 % higher than in the bulkhead with additional mineral wool. On the simulation with the coated FRP bulkhead combination, the temperatures on both bulkheads were very similar during the whole simulation.

The fuel generation of the composite bulkheads was evaluated on the basis of the burning rate of the boundaries of the simulation domain, as illustrated in Figures 6 and 7. The fuel generation times of each composite bulkhead are presented in Table 6. The extent of pyrolysing area at the time of the first bulkhead starting to generate fuel is shown in Figure 6 and at the time of the last remaining bulkhead starting to generate fuel is shown in Figure 7. The bulkheads generated fuel until the end of the simulation. The bulkhead nearest to the workstation fire began to pyrolyse first.

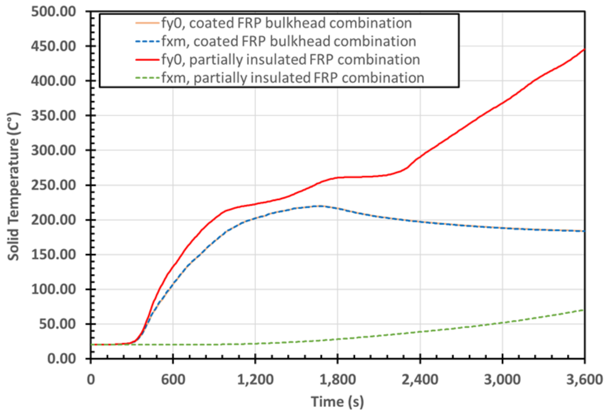

Figure 5: Simulated temperatures on the front of the first composite layer in the office furniture fire, with a closed door.

Table 6: Fuel generation times of the FRP room bulkheads, with a closed door, in the office furniture fire.

Bulkhead	Coated FRP room		Partially insulated FRP room	
	Start (s)	End (s)	Start (s)	End (s)
x = 0.0 m	780	–	–	–
x = 8.5 m	840	–	–	–
y = 0.0 m	900	–	780	–
y = 7.9 m	600	–	–	–

Despite the limited accuracy of the simulations in regards to the structural response, the simulated temperatures on the front of the first composite layers can be used as indicators for the integrity of the bulkhead. As can be observed in Figure 5, the temperature has increased above 100 °C in both monitored bulkheads in the simulation with the coated FRP bulkhead combination and in the bulkhead with intumescent coating in the simulation with the partially insulated FRP bulkhead combination. Only the bulkhead with an additional mineral wool layer in the simulation with the partially insulated FRP bulkheads has not reached the approximate glass transition temperature by the end of the simulation.

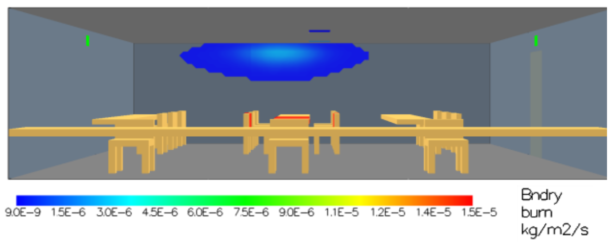

Figure 6: Fuel generation of composite bulkheads of coated FRP room, door closed, with office furniture fire, at t = 600 s.

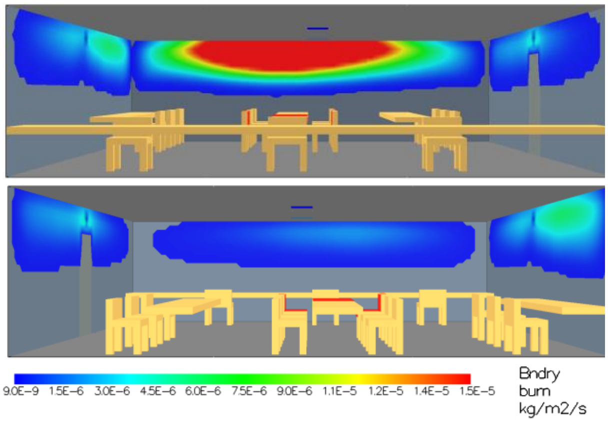

Figure 7: Fuel generation of the composite bulkheads of the coated FRP room, with a closed door, in the office furniture fire, at t = 900 s.

At the end of the simulation, the bulkhead temperatures exceed the approximate glass transition temperature by 80 to 350 %, which suggests that the integrity of the bulkheads could be compromised. Further studies would be required to estimate the structural deformation and its effect to the fire development.

3.2 SIMULATIONS WITH AN OPEN DOOR

The simulated average gas temperatures are presented in Figure 8. In the simulations with an open door, the gas temperature increased fastest in the simulation with the partially insulated FRP bulkhead combination due to the good insulation properties of the FRP bulkheads with additional mineral wool. The steel bulkheads also had better insulation properties than the coated FRP bulkheads, causing the gas temperature to be higher. Similar behaviour was observed in the simulations with a closed door.

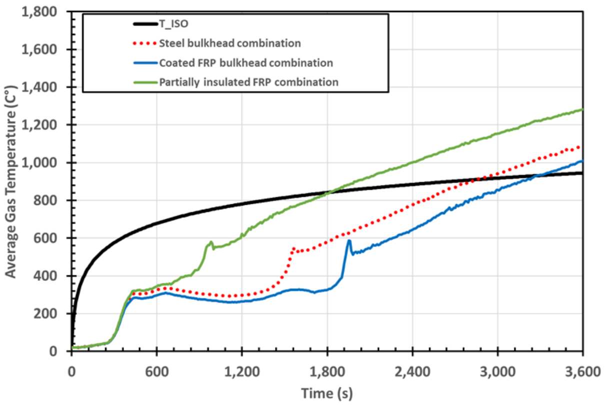

Figure 8: Average gas temperatures with office furniture design fire, door open.

In the simulations of the office furniture fire with an open door, the potential heat release rates were approximately 3200 kWh with the steel bulkhead combination, 5500 kWh with the coated FRP bulkhead combination and 4700 kWh with the partially insulated FRP bulkhead combination. The difference between the steel and the coated FRP bulkhead combinations was approximately 70 % and the difference between the steel and the partially insulated FRP combinations was approximately 50 %.

The difference of 15 % between the potential heat releases in the simulations with the coated and the partially insulated FRP bulkhead combinations can be explained with the fuel generation times of the bulkheads. The fuel generation times are presented in Table 7. In the simulation with the coated FRP bulkhead combination, all bulkheads began to pyrolyse within the first 720 seconds (12 minutes), as the intumescent coating did not provide sufficient protection from the elevated temperatures in the space. In the simulation where the bulkheads had a protective layer of mineral wool, the last bulkhead to pyrolyse did not begin to generate fuel until at 3360 seconds (56 minutes). In the simulation with the steel bulkhead combination, there was no additional fire load provided by combustible bulkhead material, which caused the potential heat release to be smaller.

Table 7: Fuel generation times of FRP room bulkheads, door open, with office furniture fire.

Bulkhead	Coated FRP room		Partially insulated FRP room	
	Start (s)	End (s)	Start (s)	End (s)
x = 0.0 m	600	–	3360	–
x = 8.5 m	720	–	2880	–
y = 0.0 m	660	–	600	–
y = 7.9 m	480	–	2880	–

The simulated temperatures on the front of the first composite layer are presented in Figure 9. The presented monitoring points were located on two different bulkheads. In the simulation with partially insulated FRP bulkhead combination, the monitoring point referred to as "fy0" was located on a bulkhead with a protective layer of intumescent coating and the monitoring point referred to as "fxm" was located on a bulkhead with an additional mineral wool layer. The effect of the improved thermal protection can be clearly observed in Figure 9, as the temperature on the bulkhead with an intumescent coating is over 200 % higher than on the bulkhead with additional mineral wool. In the simulation with the coated FRP bulkhead combination, the temperatures on both bulkheads were very similar during the whole simulation.

As in the simulations with a closed door, the simulated temperatures on the front of the first composite layers can be used as indicators for the integrity of the bulkhead. As can be observed in Figure 9, by the end of the simulation the temperature has increased above 100 °C in all the monitored bulkheads.

At the end of the simulation, the bulkhead temperatures exceed the glass transition temperature by approximately 200 to 800 %, which suggests that the integrity of the bulkheads could be compromised. Further studies would be required to estimate the structural deformation and its effects to the fire development.

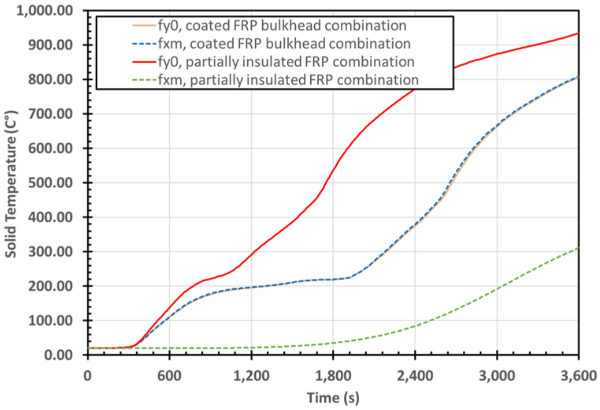

Figure 9: Simulated temperatures on the front of the first composite layer in the office furniture fire, with an open door.

3.3 SUMMARY

On the basis of the simulation results, it is concluded that the additional layer of mineral wool is more effective in thermally protecting the bulkheads than the intumescent coating. Improved insulation protects adjacent spaces from the heat and thus increases the gas temperature in the space in question.

In addition, the additional layer of mineral wool will either prevent or postpone the pyrolysis of the bulkhead, depending on the fire exposure. In the simulations with an open door, the potential heat release rate in the simulations with the FRP bulkheads were 50 and 70 % greater than in the simulation with the steel bulkheads. The potential heat release rate was the largest for the simulation with the protective layer of intumescent coating.

In the simulations with a closed door, the potential heat release rate with the partially insulated FRP bulkheads was approximately 400 % greater than in the simulations with the steel bulkheads. This is due to the fuel gas which was produced by the bulkheads. However, in the simulations with a closed door and the coated FRP bulkhead combination, the potential heat release was reduced by approximately 30 % in comparison to the simulation with the steel bulkheads. This is due to the increased heat loss through the bulkheads, which alters the fire behaviour.

The temperature increase above the glass transition temperature was used as an indicator for significant loss of load carrying capacity. Significant loss of load carrying capacity could mean that the integrity of the bulkheads is compromised. When the door was closed in the simulations, the load carrying capacity of all bulkheads without mineral wool protection could be compromised. When the door was open in the simulations, the load carrying capacity could be compromised also for the bulkhead with mineral wool protection.

4. CONCLUSIONS

Based on the simulation results, FRP materials need to be well insulated to restrain the temperature increase in fire conditions, and the amount of insulation required for compliance with IMO FTP Code Part 11 test should be further assessed. If the material temperature is allowed to increase, the material will begin to contribute to fire and the structure can potentially lose its integrity. In the simulations, the bulkheads that were protected only with the studied 2 mm intumescent coating exceeded the material's glass transition temperature after heat exposure equivalent to only 11 minutes of the standard ISO 834 time-temperature exposure. When the bulkhead was protected by a 60 mm layer of mineral wool instead, the glass transition temperature was exceeded after heat exposure equivalent to 16 minutes of the standard ISO 834 time-temperature exposure.

The results presented in this paper are valid only for the specific protective solutions studied with the layer thicknesses used in the simulations. Further studies are needed for exploring the effect of layer thickness variations on the protective capability.

5. ACKNOWLEDGEMENTS

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