Fire Spread Simulation Tool for Cruise Vessels

Erik Hedin, Lars Strandén and Johannes Lundsten

***Abstract*—**In 2002 an amendment to SOLAS opened for lightweight material constructions in vessels if the same fire safety as in steel constructions could be obtained. FISPAT (FIreSPread Analysis Tool) is a computer application that simulates fire spread and fault injection in cruise vessels and identifies fire sensitive areas. It was developed to analyze cruise vessel designs and provides a method to evaluate network layout and safety of cruise vessels. It allows fast, reliable and deterministic exhaustive simulations and presents the result in a graphical vessel model. By performing the analysis iteratively while altering the cruise vessel design it can be used along with fire chamber experiments to show that the lightweight design can be as safe as a steel construction and that SOLAS regulations are fulfilled.

***Keywords*—**Fire spread, network, safety, simulation.

I. INTRODUCTION

THE superstructure of passenger vessels was until 2002 regulated to steel structures. These structures were good from a fire safety point of view but their weights limited cargo load and number of cabins. Most cruise vessels have to be able to go through the Panama Canal which restricts size and draft to be within Panamax. The draft is proportional to the vessel weight and therefore the number of cabins has been hard to increase without violating panamax since more cabins equals more weight. The regulation 17 amendment to the *International Convention for the Safety of Life at Sea* (SOLAS) [1]in 2002 deregulated the use of steel in cruise vessel constructions. This made the use oflightweight materials possible if the same level of fire resistance as a steel construction could be proven. The fire safety analysis should be performance based which permits an increase in firefighting systems to compensate for the poorer fire properties of lightweight materials. The fact is that the lightweight materials can start burn at lower temperatures, has less mechanical strength and contains glue that becomes week at temperatures above 100°C.The*Lightweight Construction Applications at Sea* (LASS) project [2] was started in 2005 and analyzed these new construction types in five vessels and one offshore living quarter. The project was partly financed by the Swedish Governmental Agency for Innovation Systems(Vinnova) [3] and aimed at improving the efficiency of marine transport and increasing the competitiveness of the Swedish shipping industry.

E. Hedin is with the Technical Research Institute of Sweden, Borås, Box 857, SE-50115 Borås, Sweden (phone: +46(0)10-516-5836; fax: +46(0)10-516-5635; e-mail: erik.hedin@sp.se).

L. Strandén is with the Technical Research Institute of Sweden, Borås, Box 857, SE-50115 Borås, Sweden (phone: +46(0)10-516-5552; fax: +46(0)10-516-5635; e-mail: lars.stranden@sp.se).

J. Lundstenworks atmBlox, Sveavägen 52, SE-11134Stockholm, Sweden (phone: +46(0)8-791-2705; e-mail: johannes.lundsten@mblox.com).

The LASS project was finished in 2009 and then continued with the LASS-c project where cruise vessels were analyzed from the same perspective.FISPAT was developed within the LASS-c project.

There are several different ways to show that cruise vessels with composite superstructures can have the same fire safety as steel superstructures and thereby meeting the SOLAS requirements. Often several tests and simulations need to be combined. One way is to perform simulations on a model of the vessel to find fire sensitive parts and then introduce redundant systems into the simulation model to see the effects on fire safety. In combination with real fire tests, this analysis demonstrates that the fire safety of the lightweight construction is as safe as the steel construction.

There are many requirements that are to be met during construction designs. Each requirement typically maps to a certain sub-system and interdependencies between subsystems can be hard to grasp.As a consequence the whole system functionality may suffer. A concrete example is the largest ferries wheel in the world, the Singapore Flyer. Even though it had a backup system that would take over if the primary system failed, a control room fire in 2008 shut down the whole wheel. The post-fire analysis showed that the backup system cabling was drawn in the same control room as the primary system cabling. The control room fire took both systems out trapping over 100 people for over 6 hours. The Singapore Flyer was forced to an expensiveand reputation breaking one month stand-still. FISPAT (FIreSPread Analysis Tool) is a computer application presented in this paper that detects this kind of network routing flaws before constructions are built**.**

FISPAT is a computer application where a cruise vessel model is used for fire spread and fault injectionsimulations. The vessel model in FISPAT consists of rooms, networks and devices where the latter map dependencies between networks. Fire spread simulations are performed on the vessel model which can be extended within FISPAT to include additional networks and/or devices. The simulation results are presented graphically in the vessel model and can be sorted category wise by the user. Thereby the most fire sensitive areas of the cruise vessel and which networks and/or devices are essential for the firefighting capabilities of the vessel can be identified. The simulations made in FISPAT can be used to prove that lightweight materials can have the same fire resistance as steel structures and that safety regulations are met.

This article has the following chapters: II presents related work, III explains the Vessel Model used in simulations, IV how simulations are carried out, V presents a test run evaluation, VI discusses the simulation performances and VII draws conclusion and presents future work.

II. RELATED WORK

Many fire spread analysisapplications are focused on the spread of toxic gases in buildings and how long a scenario takes to complete [4],[5]. There are also applications for modeling of passenger evacuation from cruise vessels [6]. When it comes to network analysis there are programs like KYPipe [7] which is not optimized for cruise vessels and focuses on network pressure and not network and device dependencies. Other applications like AVAL [8] focus on vessel vulnerability assessments but that is to evaluate combat artillery damage. Little research has focused on finding the optimal network and devices layout within cruise vessels.

We believe FISPAT is a unique application that focuses on finding the optimal network layout for cruise vessels and that it can be part of a thorough cruise vessel design. The implementation of exhaustive simulations can save much time and effort compared to manual analysis and result infaster, cheaper and safer cruise vessel designs.

III. VESSEL MODEL

The FISPAT vessel model is three dimensional and consists of rooms, networks and devices. The vessel model is built by the user and used by the application to simulate fire and fault spread. Part of a vessel model in one floor is presented in Fig. 1. There are no limits to how large the vessel model can be. To be useful it must contain at least one room, two networks and one device which would allow for fault injection to be simulated in two networks in a room.

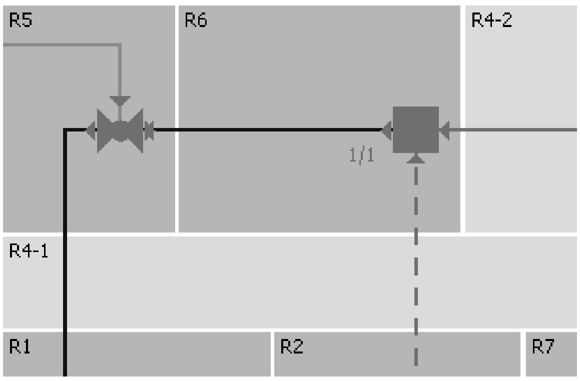

Fig. 1Vessel model with pump (square), sectioning device (bowtie), functioning networks (solid lines) and a non-functioning network (dashed line). The network color indicates network type in FISPAT.

Vessel models can also contain fire walls which are graphical red lines that delineate fire sections. These have no functionality in simulations; they are merely present to simplify post-simulation user analysis.Vessel models that stretch over multiple decks can be navigated in the user interface to choose deck to display.

The room file is constructed manually while networks and devices are built and easily altered through the graphical user interface. Once the networks and devices are constructed they can easily be saved for later use. The saved files can be altered further once reloaded. Rooms are three dimensional cuboids but other shapes can be constructed by linking several cuboids together. Each of these linked cuboids has its individual room number; they are sub-rooms implying fire is spread between them. A room is either burning, containing smoke or neither. A burning room will spread fire to neighboring rooms that are set to be “fire spreading neighbors”, sub-rooms or if both lack functioning water networks. Once the room file is loaded FISPAT maps neighbors depending on their three dimensional location in the cruise vessel. Rooms need to have overlapping walls or the floor of one room needs to be part of the ceiling of another for them to be neighbors. Only a common corner is not enough.

Networks have three dimensional paths while devices are located in a single three dimensional point. The positioning of networks and devices with respect to rooms need to be the set; however the positioning within a room is not important for simulation results. Both networks and devices are either functioning or non-functioning. Devices are split between Apparatus and Sectioning devices where the former map dependencies between networks and the latter prevent network faults to spread to other networks. A sectioning device separates two or more networks of the same kind.If a functioning sectioning device is connected between two networks a fault in one network will not spread to the other. If the sectioning device is non-functioning the fault will spread also to the other network; the sectioning device has become transparent. Apparatuses are further divided into pumps, control units etc which is merely for user facilitation; their functionality is the same i.e. to map network dependencies. Both apparatuses and sectioning devices need to have at least one input network that they depend on.An apparatus or a sectioning device without at least one input network is not meaningful. As long as at least one input network is functioning, so is the device, but if all input networks of one kind are non-functioning the device will also become non-functioning.Networks can in turn depend on one or several devices which can be redundant or not. A network that depends on two redundant devices will become non-functioning once less than two of the devices are functioning.Redundancy and dependencies between two input networks, one apparatus and one output network is illustrated in Fig. 2.

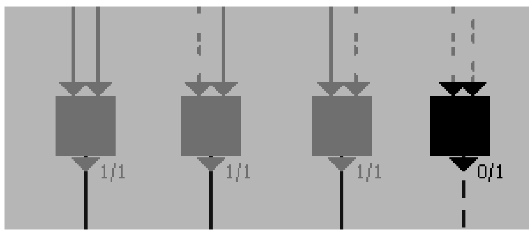

Fig. 2A pump with two electrical networks as input and one water network as output. The input networks are redundant and the pump is functioning(grey box) as long as one of the input networks is functioning (solid line). The pump becomes non-functioning (black) once both input networks are non-functioning (dashed)

Cruise vessels contain different kinds of networks of which six can be modeled in FISPAT; electric power, water, ventilation, hydraulic, pneumatic and control. The difference between themis partly graphical to enhance user experience and partly because different networks have different properties. All networks are damaged (become non-functioning) by fire except water networks that have a control option whether it should be damaged by fire or not. This is to allow for simulating different types of pipes; some of which may become non-functioning by fire and some that don´t. A pessimistic approach is taken in the simulations; if a network is present in a burning room, the whole network will become non-functioning (except water networks where the control option needs to be set). Devices also become non-functioning when in a burning room.

IV. Simulations

FISPAT supports two different kinds of simulations; single and exhaustive. A simulation starts with an initial state and ends at the result state. The states in between are not visible for the user since they are not relevant for the vessel design evaluation. Notion of time is not relevant in simulations meaning there is no evaluation on how long a simulation takes or how long a real scenario would take. Furthermore, human interaction such as firefighting or manual valve operations is not simulated. Neither are human casualties. The simulations are deterministic meaning one initial state always produces the same result state. In a single simulation the user sets up an initial statespecifying which roomsare initially on fire and which networks and devices are initiallynon-functioning.FISPAT thensimulates the fire and fault spread and presents the result state to the user along with information on thenumber of burning rooms and number of non-functioning networks and devices at the result state. In an exhaustive simulation the user can set up an initial state if wanted but it is not necessary. However the user needs to specify how many rooms are to be initially burning and how many networks and devices are to be initially non-functioning.

The simulation engine then simulates all possible combinations of the initial parameters chosen. Since there are potentially very many result states produced, the user can also define what is required from the result state to be saved. For example, only simulations that result in ten rooms burning and seven networks non-functioning should be saved.Simulation results that do not meet these criteria are not saved. This simplifies the post-simulation user analysis since the number of result states is limited.

FISPAT uses multi-threading and takes advantage of all computer processors. A distribution method is implemented that suppliesthe processor with a new initial state once a simulation is done. To minimize the amount of saved data only the initial states are saved if the result state meets saving criteria. If the user wants to display the result state vessel model, a single simulation with the saved parameters is performed and presented. Initial states that would produce the same result states are identified before simulations are even started to reduce the number of simulations and hence the time it takes to perform exhaustive simulations. If two or more rooms are to spread fire between each other during the first simulation cycle only one of these simulations isactually performed.

Each simulation, single or exhaustive, has three control options that need to be set and which affect simulation outcome. If a burning room lacks functioning water network the control option “spread fire if no sprinkler” spreads the fire to all neighboring rooms that also lack functioning water network. Water networks become non-functioning by fire with the control option “water network non-functioning by fire”. If ventilation networks are present they will spread fire between rooms they are located in if the control option “ventilation spreads fire” is chosen. The control options cater for more or less pessimistic simulation approaches and allow different fire spreading scenarios to be evaluated.Once fire is present in a room during a simulation it cannot be put out and once fire is present so is smoke. Neighboring rooms spread fire between each other if they are set to be ”fire spreading neighbors” or, if the control option “spread fire if no sprinkler” is chosen, both lack functioning water network. Once fire is present in a room, all devices and all networks except water are turned non-functioning. When a network or device has become non-functioning it cannot become functioning again in the same simulation. The non-functionality is spread throughout the vessel model until no more networks or devices become non-functioning. The fire spreading between rooms continues until the vessel model state is unchanged. The results can be sorted on fields such as number of rooms burning and number of non-functioning devices. This allows for post-simulation analysis where the worst case scenario is easily identified and the corresponding initial vessel state can be displayed. When simulations are finished and the result analyzed it is easy to alter cruise vessel layout to evaluate different network paths and device placements. The optimal cruise vessel layout is found by performing iterative exhaustive simulations while altering the layout. Note that what is considered optimal can differ between users; it might be number of rooms burning, number of rooms containing functioning water network or something else. It is important to state what is to be analyzed before simulations are performed.

V.Evaluation

For large cruise vessels the manual analysis of fire spread becomes overwhelming quite fast. This is especially true if networks and devices are to be added or altered during the analysis to allow for different layouts. The complexity of cruise vessel design is illustrated in twoexhaustive simulation examples.

Fig. 3 represents a cruise vessel with eight rooms, eight networks and five devices in one deck. Rooms R4-1 and R4-2 are sub-rooms meaning they spread fire between each other. A fire in one of these rooms will immediately spread to the other. In this evaluation fire is spread between rooms that lack functioning water network and water networks are unaffected by fire, i.e. they do not become non-functioning if they are present in a burning room.

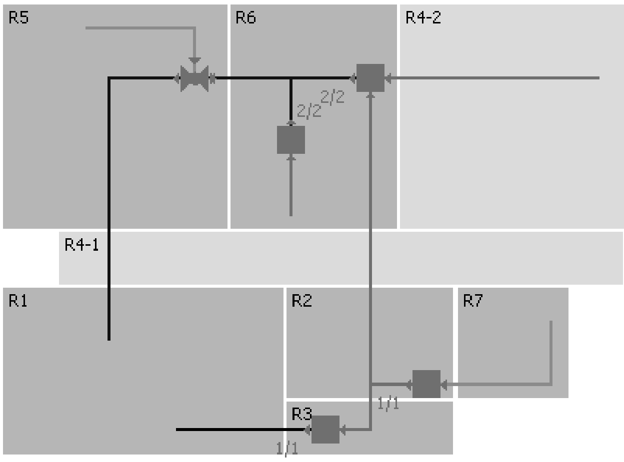

Fig. 3Graphical representation of the cruise vessel model used in the exhaustive simulation examples

The networks and devices are interdependent as illustrated by the arrows. An arrow pointing towards the device indicates the device depends on the network while an arrow pointing away from a device indicates that the network depends on the device. The sectioning device in R5 has a double pointing arrow on its right indicating that it depends on the water network on its right and that the water network depends on the sectioning device. If one of them becomes non-functioning, so will the other.

The first example is an exhaustive simulation with one room initially on fire in the vessel model shown in Fig. 3. Result from the exhaustive simulation with one room initially burning is presented in Table I.

The exhaustive simulation of a fire starting in one room gives five result states even though there are eight rooms. This is because FISPAT reduces initial states that would have the same result state as explained in Section IV. Rooms R4-1 and R4-2 are sub-rooms; hence it is enough to simulate an initial fire in one of them. The same holds for rooms R2, R3 and R7 since these lack functioning water networks and will always spread fire between each other. As a consequence only one simulation with R4-1 or R4-2 and only one with R2, R3 or R7 as initially burning will be performed.

TABLE I
EXHAUSTIVE SIMULATION RESULTS WITH ONE ROOM INITIALLY BURNING

Simulation	Rooms burning	Rooms with smoke	Non-functioning networks	Non-functioning devices
Simulation 1	1	0	1	0
Simulation 2	3	0	3	2
Simulation 3	8	0	8	5
Simulation 4	1	0	1	1
Simulation 5	8	0	8	5

The worst outcomes are simulations 3 and 5 where all rooms are on fire and all networks and devices are non-functioning. Displaying these initial vessel model states reveals that R4-1 and R6 are initially burningin one simulation each.The initial state of simulation 3 with R4-1 initially burning is shown in Fig. 4.

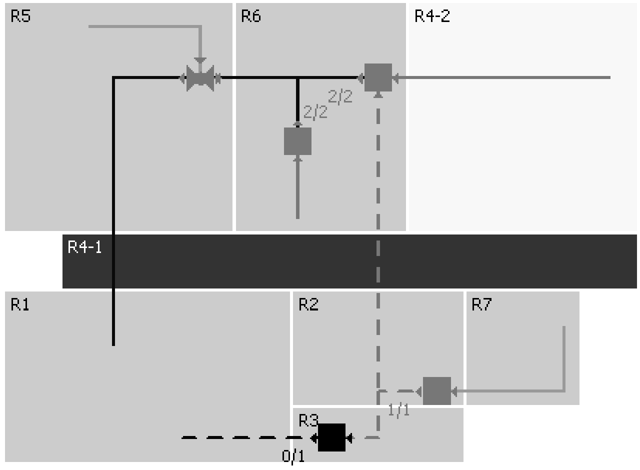

Fig. 4 Graphical representation of the initial state of the cruise vessel model used in the example with room R4-1 initially burning

The fire makes the electrical network non-functioning and also spread to R4-2 since they are fire spreading neighbors (sub-rooms). In R4-2 the electrical network will become non-functioning by the fire. With both electrical network inputs non-functioning, the rightmost pump in R6 will become non-functioning causing the water network in R6 to become non-functioning (this network is set to need two redundant pumps). The sectioning device in R5 will lose its functionality since there is a double dependency between this and the water network coming from R6. Now the fire will spread from R4-2 to R6 and on to R5 since all lack functioning water networks. With no functioning water network in the vessel model, all rooms will become burning and all networks and devices will become non-functioning.

The same derivation can be done for the initial fire in R6 (not shown) that first will make the electric networks and the devices non-functioning, causing the water networks to become non-functioning and the whole vessel model to burn.

The second example shows fault injection in the same vessel model as previous example, see Fig. 3. One network and one device are set to be initially non-functioning. This simulation produces 40 result states since there are eight networks and five devices that are initially set non-functioning in each simulation. The five worst outcomes with respect to non-functioning networks and devices are presented in Table II.

The result state from simulation 14 presented in Table II is shown graphically in Fig. 5. The initially non-functioning network is double-dashed and located in room R4-2 while the initially non-functioning device is located in room R2. The networks that are non-functioning as a consequence of other non-functioning networks and devices are single-dashed while the devices that are non-functioning as a consequence of other networks and devices that are non-functioning are black.

TABLE II
EXHAUSTIVE SIMULATION RESULTS WITH ONE NETWORK AND ONE DEVICE INITIALLY NON-FUNCTIONING

Simulation	Rooms burning	Rooms with smoke	Non-functioning	Non-functioning

			networks	devices
Simulation 14	0	0	5	4
Simulation 15	0	0	5	4
Simulation 19	0	0	5	4
Simulation 40	0	0	5	4
Simulation 7	0	0	4	3
Simulation 16	0	0	4	3
Simulation 17	0	0	4	3
Simulation 33	0	0	4	3

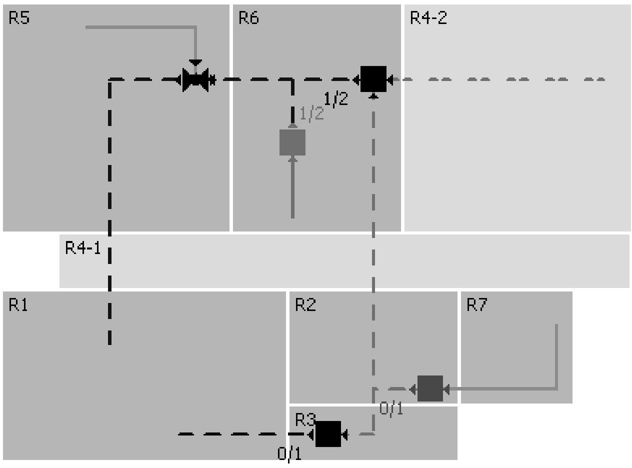

Fig. 5 Graphical representation of the cruise vessel model used in the example with network in R4-2 and device in R2 initially non-functioning

These two examples are quite easy to evaluate by manual analysis but for cruise vessels with up to 1000 different compartments on each floor together with several water networks, redundant electrical networks, pumps, control units etc. the amount of data to analyze becomes overwhelming. FISPAT finds the most fire sensitive areas and presents them to the user in an easily interpretable manner.

VI. Performance

The fire spread analysis needs to be correct, reliable and fast. The cruise vessel model shown in Fig. 3 can be used for analyzing other initial states that produces more result states. To provide a glimpse of the performance of FISPAT simulations, exhaustive simulations are made with three rooms initially burning and four networks and two devices initially non-functioning. The same control options are used as in section V.

The number of simulations made, if no optimization would have been built in to the program, would be

$$\binom{3}{8}\binom{4}{8}\binom{2}{5} = 39200 \cdot \qquad (1)$$

However FISPAT reduces the simulations that would have the same result state and hence only needs to set one of R4-1 and R4-2 (sub-rooms) initially burning and one of R2, R3 and R7 (no functioning water network) initially burning. Instead of setting 3 of 8 rooms as initially burning only 3 of 5 rooms need to be set. This result in

$$\binom{3}{5}\binom{4}{8}\binom{2}{5} = 7000 \qquad (2)$$

simulations which is an 82.1% reduction of simulations that needs to be performed.

The 7000 simulations takes about 100-200 milliseconds to perform on a PC with Intel Core 2 Duo processors at 2.4 GHz and 2 GB of RAM. The time for each simulation depends on how much “fire spread“ that is taken place in the simulation i.e. how many rooms that have fire spreading neighbors and how many networks and devices that are set non-functioning. The more fire spread and fault propagation that occurs the longer time a simulation requires. By reducing initial states that would produce the same resulting state and using all available processors FISPAT allows efficient simulation of the fire spread.

VII. Conclusion and Future Work

This paper presents FISPAT that has proven to perform fast and deterministic simulations of fire and fault propagation in cruise vessels. These simulations can be used to find fire and fault sensitive areas in cruise vessels and enhance the vessel design by iterative exhaustive simulations. The simulations can be used to prove that vessels built out of lightweight materials can maintain the same fire safety as steel structure vessels, thereby complying with SOLAS regulation 17 [1].

Initial vessel states that would have the same result state are efficiently removed before simulations are even started, simplifying post-simulation user analysis. Performing exhaustive simulations facilitates finding worst case scenarios out of possibly thousands of initial states by simulating all possible combinations of rooms burning and networks and devices initially non-functioning. When a vessel model is analyzed it is easy to alter its layout to find one with superior fire resistance properties. By performing this process iteratively, the best cruise vessel design can be found.

FISPAT can be used within different areas apart from cruise vessels; for example virus spread within computer networks. Viruses would be modeled as fires and routers and firewalls would be modeled as devices and sectioning devices which would prevent the viruses from spreading between computers and networks. The software code could also easily be modified or extended to provide graphics to better accommodate this and other simulation areas.

FISPAT could also be used on oil platforms and other large buildings such as skyscrapers with few alterations since their layout it very similar to cruise vessels with rooms, networks and devices in multiple floors. Large warehouses could also be analyzed. In that case, one large area could be divided into several smaller ones in which fire origins could be simulated and the spreading analyzed. Possibly unfavorable dependencies could be found along with poor network paths.

By doing this analysis simultaneously as the drawings the optimal layout can be found before the construction is built.

A future improvement of FISPAT could be to enable the loading of CAD files to set up the vessel model rooms. The FISPAT vessel model is currently manually created from the CAD drawings of the vessel which is time consuming. This would save a lot of time and possibly extinguish the human error factor when translating CAD drawings to the FISPAT vessel model format. The vessel model could also need to be extended to allow rooms with different shapes than cuboids.

Probabilistic calculations on damage stability, i.e. how the cruise vessel behaves when partly filled with water, are required from 2010 on cruise vessels. FISPAT could be extended with this ability once the CAD file loading is in place. The modularity of FISPAT with the vessel model and simulation engine separated allows for smooth extension withadditional features.

FISPAT should be seen as one way to prove that a cruise vessel built out of lightweight material is as safe as a cruise vessel built out of steel. However, complementary experiments in fire chambers are also important to find the fire resistance in the materials themselves.

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