Performance-based on-board damage control system for ships

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ABSTRACT

The most severe accidents in the maritime sector involve fire or stability loss due to flooding. Such accidents result in the loss of life and property as well as environmental pollution. The prevention of such severe outcomes of maritime accidents requires fast and effective responses. Hence, accurate accident information must be provided to decision makers to develop an emergency response. Furthermore, information regarding an accident’s development over time must be provided to formulate a targeted response.

This paper describes a performance-based on-board damage control system for ships instituted when a fire or flooding occurs. A sensor network is adapted to detect fires and flooding. The developed sensor network uses a digital inclinometer, CCTV network, and real-time locating system for the crew and wave radar system. Fire spread and ship behavior due to flooding in the time domain are simulated based on fire and flooding accident scenarios. Subsequently, the results are compiled into a system database as an important information source for decision makers. On-board accident conditions and response actions can be communicated to on-shore stations in real time via a long-term-evolution maritime network and satellite system. The system can be used as an evaluative tool for accident response crew training.

1. Introduction

The initial on-board response during a maritime accident is critical for minimizing damage, as rapid support cannot yet be obtained from external sources. The extent and scale of damage and loss of life increase rapidly when an initial response fails. Therefore, good operational conditions must be maintained or the crew on a ship must remain safe through an efficient response in the initial stages of an accident.

To achieve this aim, a rapid accident detection is required. Next, the prediction of effects based on the location and scale of an accident as time passed must be provided to the decision maker, particularly considering sea conditions in cases of flooding. Subsequently, an appropriate response procedure must be established based on the present conditions and predictions. Finally, imprudent decisions and actions by on-board decision makers owing to urgency and fear must be prevented through real-time communication via synchronized on-board and on-shore systems.

An on-board damage control system that can support decision making was developed. The system includes a sensor network, emergency response procedures, communication between on-board and on-shore teams, training support, and a control console. Furthermore, it tracks crew locations and employs a database of fire and flooding accident simulations.

The developed system was installed on a training vessel for testing and verification. A firefighting drill was performed on the vessel using the developed system. From fire alarm initiation to fire suppression, the system and procedures involved were operated well.

2. Current state of related technologies and systems

2.1. Technologies for fire and damage safety

Studies regarding methods to improve fire safety performance in the ship design stage has primarily focused on cruise vessels (Hakkarainen, 2010).
Damage control systems were initially developed for navy vessels, particularly for battleships. Damage control systems ensure ships maintain engagement capabilities after being damaged through an enemy attack or by accident.

With the development of information and communication technologies, this system now uses sensors, networks, databases, remote control technologies and so on. To support the decision-making process for emergency response, methodologies for the flooding extent and breach assessment of damaged passenger ships were investigated using coupling flooding level sensors and time-domain flooding simulation technology (Pennanen et al., 2015; Ruponen et al., 2017; Rupone et al., 2019; Karolius et al., 2020).

The Cruise Line International Association (CLIA, former ICCL) has sought the IMO to develop on-board damage control systems to improve ship safety and prevent the loss of life from maritime accidents (IMO, 2002). Such a system should allow one to monitor and control accessible fire safety systems, damage control equipment, and decision support systems. Furthermore, the CLIA has emphasized the need for shore-based emergency operation centers to provide full accident support to ships (IMO, 2002). To improve the safety of large passenger ships in an emergency, such damage control systems have been developed and implemented on numerous cruise ships on a voluntary basis (Martec, 2020).

The main functions of recently developed and reserved systems include accident detection by sensors, monitoring, control, emergency shutdown functions, crew locating, stability calculation, and decision making support.

2.3. Challenges

Existing systems only provide an ignition compartment in the case of a fire and ensure stability in calm waters in response to hull damage. The spread of fire, smoke, and heat due to fire is critical for monitoring firefighting and evacuation purposes. Additionally, ship behaviors with progressive flooding and wave effects in cases of hull damage are essential for maintaining ship stability. Such information is essential for a decision maker to develop an appropriate response. In performance-based simulations, simulation tools must be applied immediately using the necessary on-board data.

Although time-domain progressive flooding simulation technologies for on-board tools to assess the damage stability and safety of passenger ships have been investigated, most of them focused on static stability only. To improve accuracy, simulations should be updated frequently (Ruponen et al., 2019). After a damage occurs, only a limited amount of time is available to perform counter actions to mitigate the flooding risk of capsizing. The instant estimation of the ‘time-to-capsize’ or ‘time-to-evacuation’ involves several uncertain variables and requires rapid computational methods. If a rapid calculation method will be available in the near future, it can then be installed as part of an on-board damage control system while considering the wave effect.

The Delphi Emergency Decision Support System (EDSS) assumes and claims a database where a significant set of damage scenarios and their evolution in time, obtained by numerical simulations under various loading and environmental conditions, are stored (Trinca et al., 2017). Therefore, in this study, a database that stores performance-based simulation results for on-board emergency response was adapted. To build a database, accident scenarios based on ship characteristics such as ship size and internal arrangement as well as operational routes to determine environmental conditions such as waves can be evaluated. For example, hull damage cases involving grounding and collision can be investigated from casualty analysis data and ship characteristics. Subsequently, performance-based simulations can be performed for each case while considering various wave heights and directions. The simulated wave data can be selected based on ship operational routes and ship sizes and types. In cases of fire, fire simulations can be performed while considering the characteristics of ship features, such as the engine rooms, galleys, and cabins. Finally, fire and flooding simulation results can be stored as part of a database. Subsequently, similar accident cases can be referenced from this database such that a decision maker can establish a response plan when an accident occurs.

Technologies for crew location tracking, data sharing between on-board and on-shore systems, and training support facilities were investigated and developed, and the developed system was implemented and tested on a training vessel. The system was investigated and developed over a 5-year project to improve maritime safety (Lee et al., 2019).

3. System development

3.1. Sensor network

A ship comprises many sensors. Such sensors are designed based on different specifications, signal characteristics, and interface protocols by manufacturers. In the present study, several types of sensors such as smoke, flame, and heat detectors for fires and flooding detectors, as well as level gauges for flooding were analyzed for signal characteristics and interface protocols based on product specifications. A CCTV network was used to collect visual information, a digital inclinometer was employed for ship heeling, and a wave radar system was employed to collect real wave data. Furthermore, the signal and control protocol for CO₂ and water mist systems were analyzed to integrate a sensor network. Hence, all types of damage control activities can be displayed and confirmed on an on-board control screen.

Continually generated and displayed big data from a system under normal conditions via a CCTV, digital inclinometer, and wave radar
Fig. 1. Monitoring block diagram of hybrid ship sensors.

Fig. 2. Experimental facility for location tracking on captain deck (Kim et al., 2020).

Fig. 3. Experimental results for location tracking on captain deck (Kim et al., 2020).
3.2. Crew location tracking

When a decision maker knows the locations of the crew during a fire or flooding accident, he or she can develop an efficient response (Kang et al., 2011). To maintain personal privacy under normal conditions, such tracking technologies only operate in emergency situations.

A four-channel radio frequency identification (RFID) reader was used to identify the crew locations in large spaces, such as decks and corridors. The RFID readers were installed at each deck and corridor entrance. When a crew member carries an RFID tag, information regarding the individual and his/her current position can be identified.

In this study, movements through large spaces were monitored by three-axis acceleration and gyroscope sensors. The rotation components reflected in the three-axis acceleration sensor outputs were disregarded, and the three values for each axis were combined into one value using the signal vector magnitude method. Movement distances were obtained from this unified value, and movement directions were determined from gyroscope sensors. Processed location tracking data were sent to the ship access points via wireless communication. Our experiments show that location errors resulting from this method were within only a few meters, which is excellent for our research purposes.

Fig. 2 shows an example of an experimental facility of a captain deck with the access point (AP) of the training ship. Fig. 3 shows the experimental results, i.e., the analyzed data of the moving steps and moving angle variation from starting point A to other points based on the acceleration and gyroscope sensor signal. For the moving case from point A to point B and from point A to point D, it was confirmed that the moving angle changed by 90°. This means that the implemented system for the location tracking monitored the crew location by the moving angle and steps. The crew’s location was displayed on the console screen with a ship plan view.

The manufactured portable unity device including an RFID tag as well as acceleration and gyroscope sensors was sufficiently small to attach to the back of a two-way radio.

3.3. Database of performance-based simulation results

Several fire risk analyses and simulations for ships have been conducted (Fireproof, 2012; Su and Wang, 2013; Kang et al., 2017) mainly to improve fire safety in the design stage. Spaces or compartments with high fire risks, such as engine rooms, galleys, and cabins, must be modeled for fire simulation. A fire simulation model considers the geometries, combustibles, combustible heat release rates, doors and windows, and ventilation and fire extinguishing equipment. Table 1 provides a typical example of fire simulation conditions employed for the cadet cabins and engine rooms of the training vessel. In this study, 15 fire simulation cases were considered: 10 cases of class-A fire for the living space including the cadet, crew members, and trainee rooms; two cases of class-B fire due to oil mist in the engine room space; two cases of class-C fire due to electric goods in the galley; and one case of class-C fire due to communication equipment in the navigational bridge.

Fire simulations were performed using the Fire Dynamics Simulator three-dimensional (3-D) analysis and computational fluid dynamics model developed by the National Institute of Standards and Technology (McGrattan, 2020). The simulations generated data of temperature changes, spread of smoke, extinguishing effects, effects of adjoining compartments, etc. Risk estimations for adjoining compartments, firefighting strategies, and evacuation routes can be realized based on such results. The results were stored in a database for developing fire responses. When fire sensors detected a fire in a specific compartment, the system extracted the simulated results from the database. Subsequently, fire risks, firefighting strategies, and evacuation routes were simultaneously presented on a console screen.

The use of performance-based simulations in cases of hull damage is essential to prevent the worsening of conditions. The purpose of such simulations is to analyze and evaluate whether flooding will worsen, and if so, the time required for the ship to capsize or sink. The behavior analyses of damaged ships under different wave conditions have been performed (Sodding, 2002; Santos et al., 2002; Lee et al., 2007). A time-domain theoretical model applicable to any type of ship or arrangement to predict damaged ship motion and accidental flooding has been developed considering the effects of compartment flooding (Lee et al., 2007). In this study, a new model for vented compartments

<table>
<thead>
<tr>
<th>Fire source</th>
<th>Ventilation</th>
<th>Fire extinguishing equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadet</td>
<td>open</td>
<td>on</td>
</tr>
<tr>
<td>cabin</td>
<td>open</td>
<td>on</td>
</tr>
<tr>
<td>Engine</td>
<td>closed</td>
<td>off</td>
</tr>
<tr>
<td>room</td>
<td>closed</td>
<td>off</td>
</tr>
</tbody>
</table>

Fig. 4. Damage locations for collision and grounding of training ship.
and an accumulator model that can adjust the inner pressure automatically (even for systems with several compartments and openings, particularly for fully flooded compartments) was used for damaged ship behavior simulations (Lee, 2015).

However, this model cannot be directly applied through an on-board accident response system because of the limited execution time, insufficient domain knowledge of general crew members, and complexities of simulation software. Stability safety and ship behavior under hull damage conditions must be evaluated and predicted considering progressive flooding and real wave effects following an accident.

The total number of damage cases is affected by the ship size and its internal compartment and arrangement. A large cruise ship with many compartments can result in many damage cases, unlike tankers or bulk carriers with simple arrangements. In this study, 54 collision damage cases on the ship side shell (yellow circle) and 19 grounding damage cases at bottom (green circles) were analyzed while considering the internal arrangement of the training ship, as shown Fig. 4. The main specifications of the ship Hanbando are shown in Table 2. It was assumed that the number of compartments damaged due to an accident ranged from one to four. This number depends on the extent of damage to the sides and bottom of the ship. The maximum damage extent and depth by collision and grounding were derived from IMO/MEPC.110 (IMO, 2003). Three different damage sizes (hole) existed for each damage case. The wave considered had eight angles with a 45° interval for the head, beam, following, and quartering sea. The wave height adopted for the simulation was the mean wave height 1.88 m, 3.25 m and 5 m for sea states 4, 5, and 6, where the operational profile was considered for the training ship. The loading condition will be changed by consuming items such as fuel, fresh water, and food during the operation. The loading conditions were applied for 25% of the consumed condition. More than 5000 simulation cases based on different combinations of damage compartments, wave directions, wave heights, and loading conditions were conducted for the training vessel. The maximum simulation time was applied for 1 h.

The simulation results reflect the ship behaviors in the time domain based on the heave, roll angle, and pitch angle values as safety assessment parameters. The system extracted simulated results from a database based on damaged compartments and wave data when the ship experienced hull damage by grounding or collision. Subsequently, accident data from damaged compartments were obtained from flooding sensors or user inputs, and wave data were generated through the processing of wave radar signals or from user inputs.

The system provided heave, roll angle, and pitch angle data under damaged conditions in the time domain. Subsequently, the decision maker can confirm whether the current conditions are dangerous. If the conditions are regarded as dangerous, then ship safety can be improved through ballasting or changing the ship’s direction relative to the waves based on the system recommendations. Fig. 5 shows the simulation results of the roll motion with zero speed, wave angle of 315°, and various sea states. The damage location and compartments are shown in Fig. 6. The maximum roll motion amplitude of the ship was maintained at approximately 4° with initial heel angle 2° up to 1 h at sea-state 4 and 5 conditions, as shown in Fig. 5. However, at sea-state 6, the roll amplitude increased gradually up to 14° after 1 h.

3.4. Data sharing between on-board and on-shore systems

The decision maker and crew may flounder in an emergency situation following an accident. Although sufficient time is available to protect the ship and human life when a minor accident occurs, an

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Main specifications of training ship Hanbando.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Speed(Kts)</td>
<td>15.5</td>
</tr>
<tr>
<td>Length Between Perpendicular (m)</td>
<td>103.0</td>
</tr>
<tr>
<td>Breadth (Moulded, m)</td>
<td>16.0</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>7.8</td>
</tr>
<tr>
<td>Max. no. of crews (person)</td>
<td>39</td>
</tr>
<tr>
<td>Max. no. of trainee</td>
<td>162</td>
</tr>
</tbody>
</table>

Fig. 5. Example of roll motion variation with various sea states.

Fig. 6. Damage case for Fig. 5.
ineffective and unreasonable response can result in serious outcomes. Objective monitoring and technical guidance can reduce the likelihood of an ineffective decision being made. It can be confirmed that irrational decisions by the captain or crew members had resulted in tragic maritime disasters (MCIB, 2013; Kim et al., 2016). A master’s counter-actions can be monitored and on-board decisions can be supported by performing additional simulations using the same input data recorded on-board (Trincas et al., 2017). Hence, a communication system between on-board and on-shore stations in an accidental situation is extremely important in preventing loss of lives and properties as well as marine pollution.

The Vessel TRIAGE method (Nordstrom et al., 2016) has been investigated and introduced. It offers a novel method to assess and communicate the safety level of vessels in a maritime distress situation and addresses the requirement by search and rescue (SAR) operators. The proposed method was developed in close cooperation with various stakeholders and is used to categorize the situation in one of four Vessel TRIAGE safety levels to improve SAR activity.

Response procedures and actions from on-board accident detection to completion were translated to on-shore systems via long term evolution-maritime (LTE-Maritime) for coastal routes and via satellite for ocean routes. The on-board and on-shore systems are basically the same, but the on-shore system does not connect the ship’s sensor network and crew location tracking. In other words, the on-shore system has the same console, database, and user interface as the on-board system. When an accident is detected by a sensor, the sensed data are analyzed and transmitted to the console system in a simple and small-sized format. Subsequently, the console is activated by the received signal and accident information, such as the location and type of accident, display on the console with a user interface. For example, in the case of fire, fire simulation results in the time domain are extracted from the database based on accident information and displayed on the console. Furthermore, a response procedure including evacuation is suggested. The information such as analyzed location and type of accident, and analyzed crew location is transmitted to the on-shore system via LTE-Maritime or satellite simultaneously. The on-shore system is activated in the same manner. If new events such as new sensor signals, decision making, injuries, and actions occur in the ship, then the event information is also transmitted to the on-shore system. Therefore, the console of the on-board and on-shore systems maintain and display the same information except for the CCTV video because the data size is extremely large for transmission. Subsequently, an on-shore engineer or officer can advise when an on-board decision maker has initiated an ineffective response.

### 3.5. Training support

According to the Emergency Training and Drills, Regulation 19-Chapter III of SOLAS, all crew members must participate in at least one abandoned ship drill and one fire drill every month, and details of such on-board training must be recorded in a log book prescribed by the administration (IMO, 2009). The regulations, rules, and guidelines of administration and the documents of shipping companies and institutes for crew training were investigated to incorporate training support facilities into the developed system.

As shown in Table 3, 14 items were measured in the training scenario. Important information such as the dates, times, crew members involved, equipment mobilized, orders, and procedures were recorded in the system during training. Subsequently, an official document was produced to evaluate the training results after training. The system was used to validate the “injury due to fire” scenario during a regular fire drill in the training ship.

### 3.6. User interface and console

We developed a simple, user-friendly interface to limit errors and improve response times based on our consultation with several hundred experts, including crew members, captains, training instructors, researchers, and shipping company specialists. The system requirements, including the console, user interface, redundancy, functional and interlocking requirement, response strategy, and decision support were categorized and evaluated based on consultation. The items related to the user interface and console are shown in Table 4. According to the four principles of user interface design, intuitiveness, efficiency, learnability, and flexibility, the items were designed with a console considering almost all requirements. In the initial research stage, a console with two screens was designed, developed, and tested. Recently, to reduce weight and occupied space and to improve visibility, a new console with a single 55-inch touchscreen was adapted.

A user can use the touchscreen to create a single or partitioned screen. Fig. 7 shows screenshots of the console. The left part in Fig. 7(a) shows the ship plan view; the red vertical line indicates the watertight bulkhead, and the sky-blue vertical line indicates the main vertical zone. The CCTV images in the ship’s major compartments and positions are confirmed in the upper right part. The monitoring system for water mist systems in the ship display are shown as rectangles at the right lower part under the CCTV images, whereas the monitor for CO2 systems are shown as circles, as shown in Fig. 7(a). Fig. 7(b) shows the fire accident response screen and the procedure involved. The left part in the screen shows the response procedure. All activities, such as recognition and confirmation for fire location and type, evacuation, deployment of firefighting team, injuries, and operation of automatic firefighting equipment from beginning to termination are shown. The operator of the system should mark the response events during the response process. To improve visibility and readability, they were represented as a graph, as shown Fig. 7(c). The large red circle indicates major events, the green circle the completion status including the related response, the yellow

### Table 3

<table>
<thead>
<tr>
<th>Training scenarios</th>
<th>Training Scenarios</th>
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<tbody>
<tr>
<td>Fire/Explosion</td>
<td>Fire on deck</td>
</tr>
<tr>
<td></td>
<td>Fire in cargo area</td>
</tr>
<tr>
<td></td>
<td>Fire in auxiliary machinery room</td>
</tr>
<tr>
<td></td>
<td>Fire on galley</td>
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<tr>
<td>Flooding</td>
<td>Flooding by pipeline damage</td>
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<tr>
<td></td>
<td>Flooding by collision</td>
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<tr>
<td></td>
<td>Flooding by grounding</td>
</tr>
<tr>
<td></td>
<td>Evacuation due to flooding by collision</td>
</tr>
<tr>
<td>Injury</td>
<td>Injury due to fire</td>
</tr>
<tr>
<td></td>
<td>Injury due to flooding</td>
</tr>
<tr>
<td>Pollution and Control</td>
<td>Pollution prevention and control</td>
</tr>
<tr>
<td>Failure of Main Engine</td>
<td>Failure of main engine</td>
</tr>
<tr>
<td>Emergency Maneuvering</td>
<td>Manual maneuvering based on system faults</td>
</tr>
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</table>

### Table 4

<table>
<thead>
<tr>
<th>Summarized requirement for user interface and console design.</th>
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<tbody>
<tr>
<td>Zoom-in and zoom out of object in screen</td>
</tr>
<tr>
<td>Saving screen when event occurs</td>
</tr>
<tr>
<td>Input by shortcut key to activate major function</td>
</tr>
<tr>
<td>Input by touch screen for emergency management</td>
</tr>
<tr>
<td>Provision of accident information on screen</td>
</tr>
<tr>
<td>Provision of damage response status</td>
</tr>
<tr>
<td>Two-dimensional, three-dimensional, and isometric views of deck plan</td>
</tr>
<tr>
<td>Automatic system activation by sensor signal when accident occurs</td>
</tr>
<tr>
<td>CCTV interface</td>
</tr>
<tr>
<td>Interface with ship wireless communication system</td>
</tr>
<tr>
<td>Simple and easy to use</td>
</tr>
<tr>
<td>Intuitive and symbolized graphical symbols for accident response</td>
</tr>
<tr>
<td>Database for ship behavior prediction and fire progression by accident</td>
</tr>
<tr>
<td>Provision of accidental location and compartment</td>
</tr>
<tr>
<td>Location of fire doors, watertight doors, hatches, openings, and fire extinguisher</td>
</tr>
<tr>
<td>Audio recording during damage response</td>
</tr>
</tbody>
</table>
Fig. 7. Screenshots of console.
circle the partial completion with related actions, and the white colored circle represents “not responded yet.” It was reproduced by converting a screen shot from Korean to English for the readers.

The zones or compartments affected by fire in the case of a fire accident are displayed at the middle and right upper parts of the ship plan, as shown in Fig. 7(b). The class-A fire at the second deck forepart occurred, and the system extracted simulation results such as the temperature, smoke, and evacuation time from the fire simulation database. The spread of temperature and smoke from the fire origin to the upward and adjacent areas as time progressed occurred through the corridor, vent, and opened connection. The risk of the zone being affected by fire in this was evaluated based on the temperature, smoke height, and available evacuation time, as shown in Table 5 and Fig. 8. ASET and RSET in Table 5 indicate the available safe egress time and required safe egress time, respectively. In Fig. 7(b), the red zone indicates very danger, amber indicates danger, and yellow–green indicates caution. The graphical symbols for accident response are shown in the lower right part of Fig. 7(b), and the symbols are marked at the lowest position of the middle part automatically or by the user. For example, the symbols are marked to denote fire occurrence, black smoke spread, thermal diffusion, insensible injury, etc. in the white rectangular box in Fig. 7(b).

### 3.7 System installation and validation

The system components were tested for functionality from an on-shore virtual signal processor. After validating the system functionality, the system was tested in a ship environment. We can confirm that each component adapted well to the ship systems (i.e., fire sensors, CCTV cameras, communication protocols, etc.). The data sharing between the on-board and on-shore systems operated well via LTE-Maritime and satellite communication. Hence, all components were integrated into the system, which is known as the KRISO damage control system.

We used a training ship to test the system in a real ship environment. A 3-D model of hull form and arrangement was built, and a performance-based simulation for the database was performed for fire and flooding accident cases. Finally, the system was installed into the ship’s system.

A regular fire drill was performed on the ship based on the regulations. Fire sensors were activated by artificial smoke for training purposes, and the system was activated from standby mode. The locations of the activated sensor and compartment were shown on the screen of the system console. Subsequently, the system yielded fire simulation results from the database, CCTV data, and crew locations. The ship commander controlled the entire process until fire suppression, and all information collected during the fire drill was recorded (in Korean) in the system. The total number of crew members involved in the fire drill was 19, i.e., 13 for fire suppression, three for handling one injured person, one system operator, and one decision maker.

The system was effectively installed on an existing ship and operated well through a fire drill.

### 4. Concluding remarks

When a maritime accident occurs, it is imperative to respond quickly and efficiently based on accurate information. Hence, all pertinent information available to a decision maker must be provided in a suitable form. Such information must be intuitive, readable, unambiguous, and straightforward. Useful data include information regarding accident type, fire and flooding locations, expected accident developments, and response procedures.

In this study, a sensor network that immediately detects accidents through sensors, a crew location tracking system, a fire and flooding simulation database, a system for information sharing between ship and on-shore stations, and a training support system was tested, developed, and installed on an existing ship. We confirmed that the system operated well in a real ship environment. Fire detection, crew tracking, on-shore communication, and fire response based on response procedures and fire simulation database results operated normally during a fire drill.

Maritime accidents are inevitable despite efforts to limit their occurrence. Therefore, the developed system will be essential to limit the loss of life, maritime pollution, and property loss from maritime accidents. The system is not an absolute solution that addresses all types of accidents; however, it is applicable as an on-board decision support for maritime accident response.

### CRediT author statement

**Dongkon Lee**: The research project leader, configuring research processes and analyzing system performance, original draft preparation.

**Sokjin Kim**: User interface and crew location recognition system development.

**Sung-Chul Shin**: Concept design of onboard system operation and training.

**Jin Choi**: Development of flooding simulation database.

**Beom Jin Park**: Development of fire simulation database.

**Hee Jin Kang**: Project manager, Concept design of whole system, writing-reviewing and editing.

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**Table 5**

<table>
<thead>
<tr>
<th>Risk level</th>
<th>Temperature (°C)</th>
<th>Smoke height (from floor, m)</th>
<th>Evacuation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very danger</td>
<td>&gt;70</td>
<td>&lt;1.5</td>
<td>RSET &gt; ASET</td>
</tr>
<tr>
<td>Danger</td>
<td>30–70</td>
<td>&gt;1.5</td>
<td>RSET ≤ ASET</td>
</tr>
<tr>
<td>Caution</td>
<td>&lt;30</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

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**Fig. 8**. Evacuation time for human life safety.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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