

Simulation Analysis of Thermal Load and Ultimate Bearing Capacity of Hull Girder Under Cabin Fire

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Abstract

The hull structure may collapse or deform severely under fire conditions. In this study, the safety of a ship's cabin structure under fire is evaluated using a dual-zone large eddy fire scenario simulation method and a sequential thermo-mechanical coupling analysis method. Taking a three-compartment section of a naval surface ship as a case study, a machinery room fire scenario was simulated and the fire temperature field was analyzed. Through a dedicated data interface, the full-field time-varying temperature loads were mapped to the finite element model of the compartment section, thereby achieving thermo-mechanical coupled analysis of the cabin structure. The effects of thermal expansion on the hull structure under rising fire temperatures were considered in the evaluation of the residual load-bearing capacity of the cabin. The results indicate that the residual load-bearing capacity of the compartment is closely linked to the fire development stage. Temperature not only significantly affects the mechanical properties of steel but also influences the structural load-bearing capacity through thermally stresses.

Keywords Ship and ocean engineering; Cabin fire; Fire simulation; Thermal load; Thermo-mechanical coupling analysis; Residual bearing capacity

1 Introduction

Fire accidents are a major threat to hull safety, accounting for over 10% of maritime accidents (Baalisampang et al., 2018). The confined cabin layout and limited space

significantly increase fire risks. Once ignited, fires spread rapidly and are challenging to extinguish. Furthermore, high temperatures degrade the mechanical properties of steel, reducing its load-bearing capacity (CECS, 2006; BS, 2003; Eurocode 3, 2005; AISC, 2022), thereby severely compromising ship structural integrity. To enhance ship fire resistance design, ensure personnel safety, and minimize property losses, in-depth research on structural safety under fire conditions is essential.

Ship cabin fire research differs from construction industry studies due to challenges such as limited material diversity, insufficient protective measures, complex structural configurations, and ambiguous load and boundary conditions. Research on multi-cabin fires remains theoretical, lacking coupled simulation models (Paajanen et al., 2013). As a typical large-scale steel structure, there remains a significant gap in current fire safety research for hulls compared to the field of building steel structures. Zhang et al. (2016) experimentally investigated temperature, stress, and displacement in steel structures under fire, with an in-depth analysis of heat transfer processes. Their work systematically summarizes the methods for analyzing structural stability under fire conditions, offering a robust theoretical foundation for the field. Suwondo et al. (2019) investigated the progressive collapse behavior of composite steel frames following exposure to fire after extreme natural disasters. Through a comparison between undamaged

Article Highlights

- The large eddy simulation-based numerical fire modeling method is suitable for simulating ship compartment fire scenarios. This provides a feasible analytical approach for revealing the thermal-dynamic response mechanisms and smoke propagation patterns in compartments during different fire stages.
- The proposed temperature load mapping method effectively transfers the time-varying thermal loads of large-scale hull structures during fire from the fluid dynamics model to the finite element model, enabling thermo-mechanical coupling analysis.
- This study proposes a method for calculating the residual strength of hull structures under fire conditions by integrating computational fluid dynamics and finite element simulation. This approach provides a systematic and effective analytical framework for evaluating the structural safety of ships in fire scenarios.

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frames and those pre-damaged by disaster scenarios, their study demonstrated that pre-existing structural damage significantly exacerbates the risk of fire-induced collapse. Furthermore, the research highlighted the critical influence of both fire propagation dynamics and preceding natural disaster effects on the resulting collapse mechanisms. Roy et al. (2019) investigated the collapse behavior of cold-formed thin-walled steel (CFS) structures through large-scale fire experiments, clarifying the response mechanisms of steel frame walls under fire exposure. Their numerical simulations demonstrated close agreement with experimental outcomes, providing a reliable predictive tool for assessing performance in fire scenarios. Research on ship fires is relatively fragmented and has not formed a complete system spanning from scenario simulation to structural strength prediction.

Regarding the construction of fire scenarios for large-scale ship structures, existing research primarily focuses on smoke spread patterns in compartments, firefighting measures, and personnel protection. Paik et al. (2009) developed a computational fluid dynamics (CFD)-based technique for hydrocarbon fire and explosion modeling, validated experimentally, to enhance hull structure consequence analysis and offshore risk quantification. Hugues et al. (2017) studied smoke flow behavior at openings in ventilated compartments, clarifying its impact on the development and stability of thermal stratification. Their findings contribute to more accurate prediction of smoke propagation and inform the layout of fire safety measures. Frey Gerner et al. (2019) analyzed 20 years of container ship fires, identifying risk patterns, causal factors, and consequences, while proposing a probabilistic fire model. The current fire scenario analyses rarely address how to convert temperature fields into thermal loads for participation in structural strength calculations.

Research on the residual strength of ship structures in fire environments has primarily focused on small-scale components such as hull plates under high-temperature loads. Geudes Soares and Teixeira (2000) simulated the temperature field by directly applying an increasing temperature to the plate and performed strength calculations, finding that local temperature loads significantly affect the ultimate strength of the plate, with structural strength dropping sharply when half of the plate is heated. Stamatios and Manolis (2021) also investigated the ultimate strength of stiffened hull plates under fire conditions by directly applying temperature values. Their study emphasized that modeling the transverse frames of stiffened plates is critical and cannot be simplified. The research also examined the role of steel thermal expansion in the structural response, revealing that under specific boundary conditions, even a moderate temperature increase (below 200 °C) can cause the stiffened plates to reach their ultimate load-bearing state. Ryu et al. (2020) conducted collapse tests on stiff-

ened plate structures under localized thermal loads, using a 1900 TEU container ship's plate frame as a reference. Their work preliminarily explored fire-induced failure mechanisms and evaluated passive fire protection measures. However, it did not propose a structural strength calculation method under high-temperature fire conditions. In fire environments, the analysis of isolated hull members often leads to inaccuracies because the assumed boundary conditions do not align with real-world situations (Lu et al., 2017).

For large hull compartment sections, it is necessary not only to accurately define the boundary conditions but also to precisely simulate the evolution of the structural temperature field, map it to the finite element model for participation in strength calculations, in order to reliably assess the residual load-bearing capacity of the compartment under fire conditions. Silva et al. (2016) developed an interface model using Fire Dynamics Simulator (FDS) to extract thermal parameters via automated code, generating ANSYS-compatible boundary conditions for I-beam thermal-structural analysis. This approach enables coupled thermal-mechanical assessments of ship structures, improving fire safety predictions. Li et al. (2021) used FDS to simulate cabin fires, derived structural heat flux, and combined it with a finite element model to analyze the residual load-bearing capacity of cabin structures in fire environments, aiming to develop a thermo-mechanical coupled calculation method for ship hull structures. Liu et al. (2022) proposed a novel temperature load mapping method based on 3D temperature field mapping. Using a two-deck cabin as an example, they integrated FDS with finite element software to analyze the failure modes, stress distributions, and deformations of the two-deck cabin under different fire heat release rates (0–4 MW). The aforementioned studies on mapping ship fire scenario temperature fields to finite element models all employ FDS-derived methods. Differences in the adopted load extraction methods lead to variations in computational difficulty and accuracy.

To evaluate the temperature response and residual strength of a ship's hull compartment under realistic fire conditions, this study adopts a large-eddy simulation (LES) fire dynamics algorithm coupled with thermo-mechanical structural analysis. An appropriate temperature load mapping method suitable for large-scale ship structures was selected, and a custom FDS-ABAQUS data coupling interface was developed to calculate the residual load-bearing capacity of the compartment structure under various fire scenarios. Section 2 introduces the fundamental conservation laws and heat transfer principles of FDS. Section 3 elaborates on the structural temperature field mapping method. Section 4 describes the setup of cabin fire scenarios and the corresponding temperature field analysis. Section 5 discusses the residual load-bearing capacity of cabin structures under fire conditions. Section 6 outlines the main

conclusions derived from the study.

2 Basic theory of fire dynamics simulator

The Fire Dynamics Simulator, developed by the National Institute of Standards and Technology (NIST), is a CFD-based fire modeling tool. Utilizing the LES framework coupled with combustion modeling, FDS simulates turbulent flame dynamics through numerical solution of the Navier-Stokes equations for low-speed, thermally-driven flows using finite difference methods on rectilinear grids.

2.1 Conservation equation

The governing equations of FDS consist of the following coupled partial differential equations:

The mass conservation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \quad (1)$$

where ρ is the density, kg/m^3 ; t is the time, s; $\mathbf{u}$ is the velocity vector, m/s.

The species conservation is:

$$\frac{\partial(\rho Y_l)}{\partial t} + \nabla \cdot \rho Y_l \mathbf{u} = \nabla \cdot \rho D_l \nabla Y_l + m_l''' \quad (2)$$

where l is the combustible material component; Y_l is the mass fraction of component l ; D_l is the diffusion coefficient of component l ; m_l''' is the formation rate or dissipation rate of component l in unit volume, $\text{kg}/(\text{m}^3 \cdot \text{K})$.

The momentum conservation is:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) + \nabla p = \rho \mathbf{g} + \nabla \cdot \boldsymbol{\tau} \quad (3)$$

where $\mathbf{g}$ is the acceleration of gravity, m/s^2 ; p is pressure, Pa; $\boldsymbol{\tau}$ is the viscous stress tensor.

The energy conservation is:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot \rho h \mathbf{u} - \frac{dp}{dt} = q''' - \nabla \cdot \mathbf{q}_r + \nabla \cdot k \nabla T + \sum_l \nabla \cdot h_l \rho D_l \nabla Y_l \quad (4)$$

where h is the specific enthalpy (J/kg); q''' is the heat generated per unit volume (W/m^3); $\mathbf{q}_r$ is the radiation heat flux vector; k is the thermal conductivity; T is temperature (K); h_l is the specific enthalpy of component l .

The equation of state is:

$$p = \rho R T \sum_i \left(Y_i / M_i \right) \quad (5)$$

where p is the pressure (Pa); R is a gas constant; Y_i is the mass fraction of component; M_i is the relative molecular mass of the mixed gas.

2.2 Solid heat transfer principle of fire dynamics simulator

FDS assumes that the solid surface is composed of multiple layers, each layer consists of multiple material components, which can undergo various thermal degradation reactions. At the same time, heat conduction is assumed to occur solely in the direction normal to the surface, and each reaction can generate various gaseous and solid products.

2.2.1 Heat conduction equation of solids

The one-dimensional heat conduction equation for the solid phase temperature $T_s(x, t)$ is applied in the direction pointing into the solid (the point $x = 0$ represents the surface). The heat conduction in the solid is governed by the following assumptions: (1) No in-plane heat conduction occurs; (2) Each surface unit is treated independently, with no lateral heat transfer between adjacent units.

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} \left(k_s \frac{\partial T_s}{\partial x} \right) + \dot{q}_s''' \quad (6)$$

$$\dot{q}_s''' = \dot{q}_{s,c}''' + \dot{q}_{s,r}''' \quad (7)$$

where k_s is the conductivity pressure; $\rho_s c_s$ is the volumetric heat capacity of the solid; $\dot{q}_{s,c}'''$ is the heat production (loss) rate given by the pyrolysis models for different types of solid and liquid fuels; $\dot{q}_{s,r}'''$ is the radiative absorption and emission in depth.

2.2.2 Radiation heat transfer in solids

If it is assumed that the thermal radiation from the surrounding gases is absorbed within an infinitely thin layer at the surface of the solid obstruction, then the net radiative heat flux is the sum of incoming and outgoing components.

$$\dot{q}_r'' = \dot{q}_{r,m}'' + \dot{q}_{r,out}'' \quad (8)$$

$$\dot{q}_{r,in}'' = \varepsilon \int_{s' \cdot \mathbf{n}_w < 0} I_w(s') |s' \cdot \mathbf{n}_w| d\Omega \quad (9)$$

$$\dot{q}_{r,out}'' = \varepsilon \sigma T_w^4 \quad (10)$$

2.2.3 Convective heat transfer in solids

The calculation of the convective heat flux depends on whether one is performing a direct numerical simulation (DNS) or a large eddy simulation (LES).

In the DNS calculation, the convective heat flux to a solid surface $\dot{q}_c''$ is obtained directly from the gas temperature gradient at the boundary.

$$\dot{q}_c'' = -k \frac{\partial T}{\partial n} = -k \frac{T_{wd} - T_{gd}}{\delta n/2} \quad (11)$$

where k is the thermal conductivity of the gas; n is the spatial coordinate pointing into the solid; δn is the normal grid spacing; T_{gd} is the gas temperature in the center of the first gas phase cell; T_{wd} is the wall surface temperature.

In the LES calculation, the convective heat transfer coefficient, h , is taken as the maximum of its free (natural) and forced forms:

$$\dot{q}_c'' = h(T_{gl} - T_{wl}) \quad (12)$$

$$h = \frac{k}{L} \max \left(Nu_{free}, Nu_{forced}, \frac{2L}{\delta n} \right) \quad (13)$$

where T_{gl} is the gas temperature in the gas phase cell adjacent to the surface; T_{wl} is the wall (surface) temperature; L is a characteristic length; k is the thermal conductivity of the gas. For planar surfaces, L is taken as 1 m and for spheres and cylinders, L is taken as the diameter D .

3 Thermal-mechanical coupling method of cabin structure

Ship fires mostly occur in engine rooms, cargo holds, and deck areas. Compared to deck areas, engine rooms and cargo holds have complex structures, confined spaces, and denser accumulations of flammable hazardous materials. Consequently, fires in these compartments are often more concealed, spread more rapidly, are more difficult to extinguish, and cause more severe damage to the hull structure. Therefore, conducting simulation studies on compartment fire scenarios is of significant practical importance for deepening the understanding of ship fire behavior and enhancing capabilities in structural fire-resistant design and safety assessment.

3.1 FDS space temperature field verification

Based on the large-scale fire experiment investigating smoke spread through a horizontal opening in a mechanically ventilated compartment, as conducted by Hugues et al. (2017), the FDS was used to reconstruct the experimental scenario. The accuracy of the FDS model for this fire scenario was validated by comparing the measured data from spatial temperature sensors with the corresponding numerical simulation results.

The experimental facility comprised two superimposed

compartments separated by a horizontal opening (vent). The lower compartment (L3) measured 6 m × 5 m × 4 m (volume: 120 m³), while the upper compartment (L4) measured 8.5 m × 5 m × 4 m (volume: 170 m³). Each compartment was equipped with a ceiling vent, positioned so as not to interfere with the airflow at the horizontal opening. The rectangular horizontal opening, with dimensions of 1 030 mm × 1 030 mm (area: 1.060 9 m²), was located at the center of the L3 ceiling and was offset relative to the center of the L4 floor.

The fire source was a propane gas burner located in the northwest corner of the L3 compartment, maintaining a steady heat release rate (HRR) of 340 kW throughout the tests. Four thermocouple trees were installed in each compartment, designated as SW, CC, NE, and SE in L4, and SW, CC, NW, and NE in L3. Each tree was equipped with nine K-type thermocouples vertically distributed at heights of 0.05, 0.55, 1.05, 1.55, 2.05, 2.55, 3.05, 3.55, and 3.90 meters above the floor. The overall configuration of the experimental facility is illustrated in Figure 1.

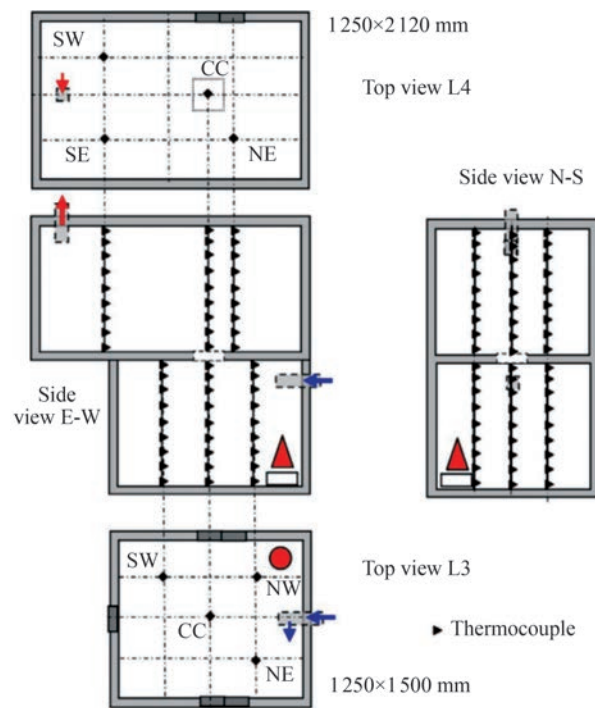


Figure 1 Test scene layout by Hugues et al. (2017)

A corresponding fire scenario was developed in FDS based on the actual experimental setup. The model included the heat source, the horizontal opening, and the ventilation vents. Temperature measurement points were replicated at locations identical to the experiment, as shown in Figure 2. The total simulation time was set to 1 500 s to match the experimental duration. A comparison between the experimental results and the simulation results at various measurement points is presented in Figure 3.

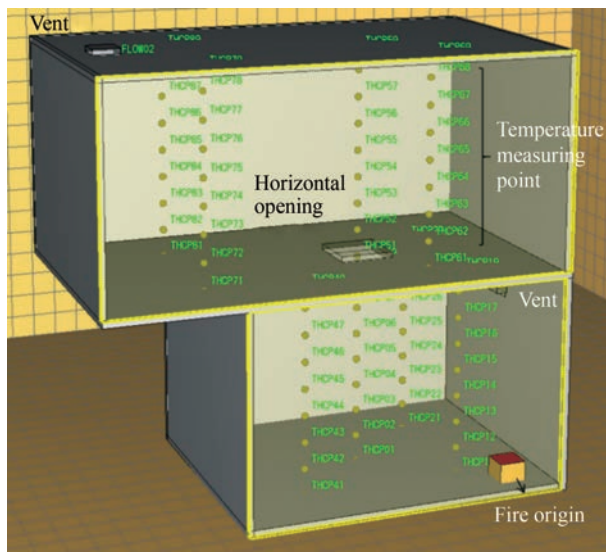
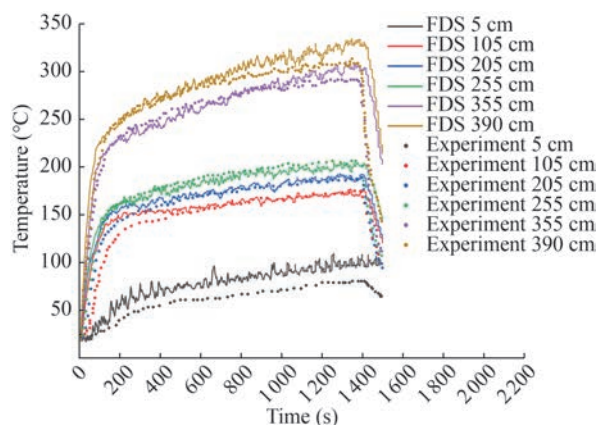
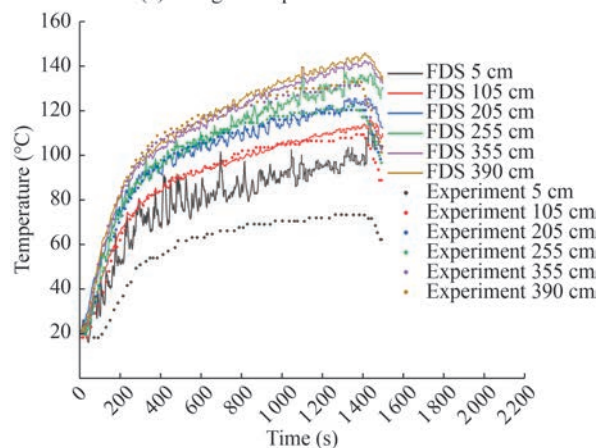


Figure 2 FDS fire model



(a) The gas temperature in L3 room



(b) The gas temperature in L4 room

Figure 3 Comparison of gas temperature between test and simulation model

The temporal evolution of temperature, as captured by both experiment and simulation, delineates a clear three-stage fire development process. The L3 compartment exper-

imented rapid fire growth with swift temperature rise (0–200 s), transitioned to a stable phase with gradual heating (200–1400 s), and finally entered a decay phase marked by a rapid temperature drop (post-1400 s).

An analogous yet delayed trend was observed in L4, where temperatures surged rapidly (0–300 s), climbed slowly (300–1400 s), and then declined (post-1400 s). This hysteresis and the dampened thermal response in L4 are physically explained by its configuration: being adjacent to the fire compartment (L3), the thermal conditions in L4 are principally controlled by the migration of buoyant hot gases from L3 through the interconnecting horizontal opening.

A comparison of experimental and simulated temperature data from the two compartments reveals the following observations. In the L3 compartment, simulation results agree well with experimental measurements. However, in the L4 compartment, while most measurement points show consistent trends between simulation and experiment, the simulated temperatures for points located near the bottom region are significantly higher than the experimental values. The discrepancy may be attributed to the inferior airtightness of the experimental apparatus compared to the simulation model. During actual heat transfer, partial heat dissipates to the external environment through connecting structures, resulting in lower measured temperatures in the bottom region relative to the simulated values.

In summary, the comprehensive simulation of the entire fire process effectively validates the satisfactory accuracy and reliability of FDS in modeling cabin fire scenarios. The model demonstrates strong predictive capability for both the magnitude and evolution of gas temperatures, providing credible data support and a reliable methodological reference for subsequent research and engineering applications.

3.2 Structure temperature field mapping method

The time-varying temperature field of a structure serves as a critical prerequisite for determining the ultimate bearing capacity of a ship's hull under fire conditions. Consequently, developing a robust methodology to accurately and efficiently extract structural temperature data from FDS and seamlessly integrate it into Finite Element Analysis (FEA) software is of paramount importance.

Several researchers have successfully extracted temperature field data from FDS and transferred it to finite element analysis software using the heat flux density method (HFM) (Li et al., 2021). These studies have demonstrated the feasibility of obtaining structural temperature fields from FDS fire simulations. The present study introduces an alternative approach—the temperature field method (TFM)—which directly outputs structural temperature data. A comprehensive comparative analysis is conducted between TFM and HFM, evaluating their computational

efficiency and temperature data accuracy.

Given that HFM computes heat flux using time-averaged data, providing an average value over a specified period, this study implements two distinct HFM averaging approaches to allow for a more thorough comparative analysis with TFM.

Assuming a total fire duration of 1 500 s, divided into 15 intervals of each 100 s, the HFM procedure is implemented as follows: Nodal coordinates and heat flux data are extracted from FDS. For plate elements, data from both faces and all directions are integrated and mapped as thermal boundary conditions onto the corresponding FE model. A subsequent heat transfer analysis then yields the structural temperature field.

HFM1: This method extracts the interval-average heat flux for each sequential 100-second period (denoted R_1 for 0–100 s, R_2 for 100–200 s, ..., R_{15} for 1 400–1 500 s). These values are applied as boundary conditions in the FE software. The structural surface temperatures at 100, 200, ..., 1 500 s (denoted $T_1, T_2, \dots, T_{15}$) are obtained through a progressive, sequential thermal analysis.

HFM2: This method calculates the cumulative-average heat flux up to each time point (denoted r_1 for 0–100 s, r_2 for 0–200 s, ..., r_{15} for 0–1 500 s). These cumulative averages are then used in the FE analysis to determine the structural surface temperatures at the corresponding time points ($T_1, T_2, \dots, T_{15}$).

The conceptual frameworks for heat flux extraction in the two HFM approaches are depicted in Figure 4, where:

s = structural surface area (m^2)

C = specific heat capacity ($\text{J/kg}\cdot\text{K}$)

m = mass (kg)

In contrast, TFM features a more straightforward procedure. It extracts nodal coordinates and temperature data from FDS simulation results. For plate structures, it only requires retrieving temperature data from one side of the elements and integrating this information into the load field of the finite element model. This integrated temperature load is then directly applied as structural thermal loading in subsequent strength calculations.

The structural surface temperatures at 100, 200, ..., up to 1 500 s (denoted $T_1, T_2, \dots, T_{15}$) are directly extracted from FDS and mapped as the temperature load boundary condition for the corresponding time points in the finite element model.

Both HFM and TFM require that the grid resolution in the FDS simulation closely matches the mesh size in the finite element model when mapping heat flux or temperature data. This consistency is essential to accurately capture nodal information within the finite element model during the data transfer process.

Utilizing the aforementioned FDS compartment fire model detailed in Section 3.1, a systematic comparative analysis is undertaken to assess the efficacy of prevailing

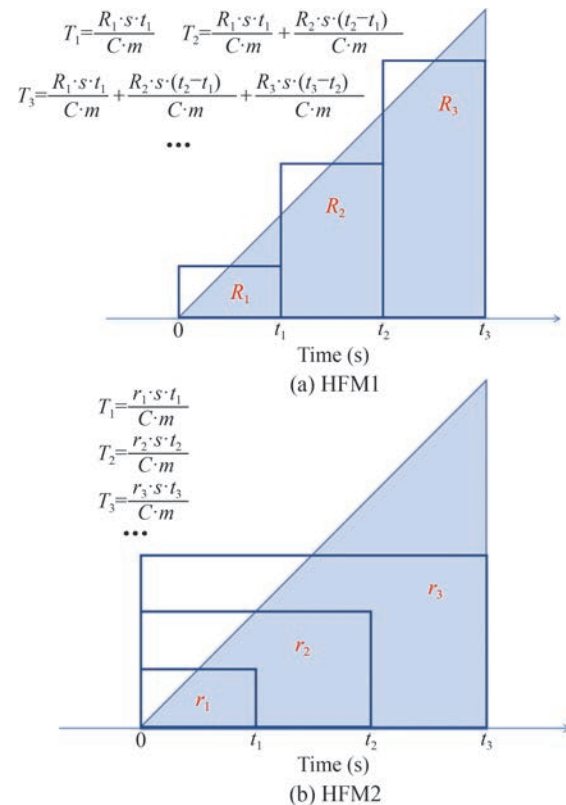


Figure 4 Introduction of HFM method in FDS

methodologies for inferring structural temperature fields, following the assignment of relevant material properties to the structural elements.

The structural material specified for the bulkhead was Q235 steel with a thickness of 10 mm. Its room temperature elastic modulus, yield strength, and tensile strength are 206 GPa, 235 MPa, and 375–460 MPa, respectively. The degradation of mechanical properties under elevated temperatures was modeled in accordance with the European Code (Eurocode 3, 2005), and the corresponding stress-strain relationships are depicted in Figure 5. The primary thermophysical parameters used in the analysis are provided in Table 1.

The finite element model of the bulkhead was faithfully

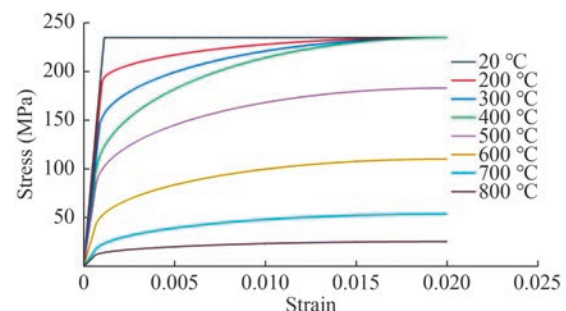


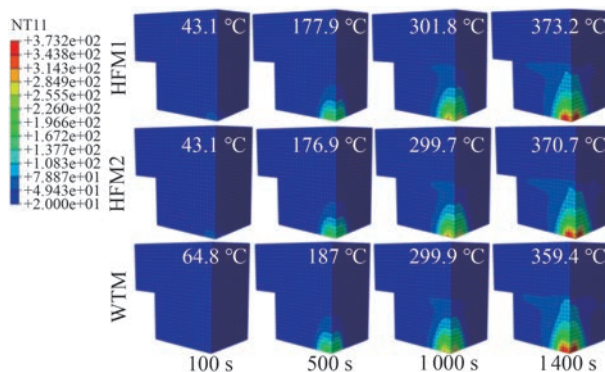
Figure 5 The stress-strain relationship of marine steel Q235 at elevated temperatures

Table 1 Main thermophysical parameters of steel Q235

T (°C)	Thermal expansion coefficient ($10^{-5}/^{\circ}\text{C}$)	Specific heat ($\text{J}/\text{kg}\cdot^{\circ}\text{C}$)	Thermal conductivity ($\text{W}/\text{m}\cdot^{\circ}\text{C}$)
20	1.22	439.80	53.34
200	1.36	529.76	47.34
300	1.44	564.74	44.01
400	1.52	605.88	40.68
500	1.60	666.50	37.35
600	1.68	759.92	34.02

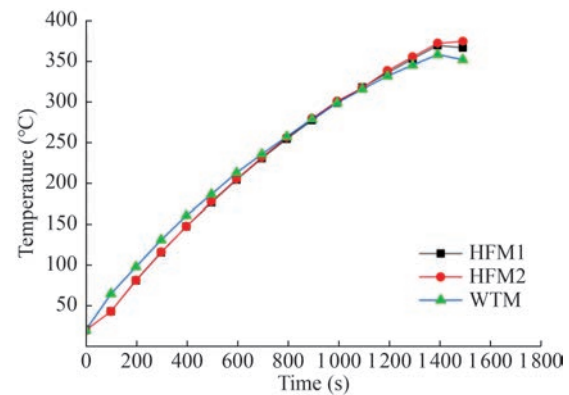
reconstructed in ABAQUS based on the geometrical dimensions and coordinate system of the FDS model. The load data were then introduced into the ABAQUS environment via the three previously outlined methodologies (HFM1, HFM2, and TFM) to implement the structural temperature analysis.

Referring to the fire development process illustrated in Figure 3, the structural temperature mapping results at four characteristic time points (100 s, 500 s, 1 000 s, and 1 400 s) are compared in Figure 6. The analysis indicates that the temperature contours obtained by the different methods exhibit strong consistency in their overall distribution. A clear thermal gradient is observed, with regions closer to the fire source exhibiting higher temperatures and greater fluctuations. As the fire progresses, the high-temperature zone expands, and the contours effectively capture the dynamic heating process of the structure.

**Figure 6** Comparison of temperature cloud maps of each method

To enable a quantitative assessment, the temporal evolution of the maximum temperature within the bulkhead structure is plotted in Figure 7. The data show that the maximum temperature rises approximately linearly prior to 1 400 seconds, after which it begins to decrease. This trend closely aligns with the overall variation pattern of the cabin's gas temperature. It is noteworthy that while the peak structural temperature is comparable to the gas temperature, the thermal field within the structure is spatially heterogeneous, characterized by a highly concentrated high-temperature

zone near the fire source with negligible temperature elevation elsewhere. Consequently, substituting bulk gas temperature for the actual structural temperature field in a strength evaluation would yield a non-conservative and potentially unsafe estimation of the residual capacity.

**Figure 7** Comparison of the highest temperature of each method

A comparison of the two HFM methods reveals their distinct characteristics. HFM1 calculates the average heat flux over segmented intervals and accumulates the temperature change incrementally, which effectively mitigates errors induced by abrupt fluctuations in heat flux. In contrast, HFM2 employs a global average over the entire duration. For the present case, characterized by a stable heat release rate and simple structure, both methods are acceptable. However, HFM1 is expected to achieve superior accuracy in scenarios with highly transient heat release rates or complex structures, albeit at the cost of increased computational expense.

The TFM is based on the FDS solid conduction model, which simplifies heat transfer to a one-dimensional process normal to the surface, neglecting lateral conduction between adjacent elements. This simplification effectively models the temperature rise driven by surface heat flux. While TFM and HFM share the same underlying physical principles, the HFM relies on time-averaged heat flux as an input, a step that can introduce errors when dealing with complex structures or highly transient fire scenarios. In contrast, the TFM directly outputs the transient temperature field, making it inherently more suitable for simulating rapidly changing fire conditions.

Both HFM and TFM offer considerable value for investigating the ultimate bearing capacity of large-scale ship thin-walled structures under fire conditions. A systematic comparison and analysis of these two methods are presented in Table 2, evaluating them across key aspects such as operational complexity, resulting accuracy, and applicability scope.

Based on the comparative findings, this study selects a full-scale ship cabin segment as the analysis object. The TFM is employed to map the structural temperature field

Table 2 Applicability of HFM and TFM methods

	HFM	TFM
Difficulty in operation	The method is operationally complex, as it requires extracting bi-directional heat flux data for shell elements and performing a separate heat transfer analysis in the FE software to obtain the temperature load	The operation is simple, requiring only the direct extraction of time-varying surface temperature data for shell elements, which is then directly applicable as the thermal boundary condition in the FE analysis
The accuracy of results	This method uses time-averaged heat flux, which can lead to inaccuracies when simulating fires with rapidly fluctuating heat release rates or when analyzing structures with complex geometries	This method provides instantaneous temperature data, avoiding spatiotemporal averaging errors. Its accuracy is directly tied to the precision of the FDS-calculated surface heat flux and the underlying mesh density
Method extension	Its extensibility is constrained by the difficulty in precisely specifying convection and radiation parameters in the FE software, which often requires empirical estimation and may not accurately represent actual fire conditions	It exhibits strong extensibility, as it directly supplies the time-varying temperature field, bypassing complex parameter definitions and supplementary heat transfer analysis, thus facilitating easy implementation
Sphere of application	This method is applicable to simple structural arrangements like plane grillages and can be used to analyze single thin-shell components within an FE model	The method is applicable to thin-walled and solid structures across a wide range of sizes

from the fire simulation onto the finite element model, thereby enabling a subsequent evaluation of the residual bearing capacity of the hull structure under high-temperature fire conditions.

3.3 Thermal-mechanical coupling analysis

This study implements TFM to transfer thermal load data from FDS to finite element analysis. The workflow comprises three key phases: (1) establishing an ABAQUS model with identical geometric configuration to the FDS cabin while defining temperature-dependent material properties; (2) mapping TFM-derived temperature fields as nodal boundary conditions through coordinate indexing; (3) executing sequentially coupled thermo-mechanical analyses incorporating steel thermal expansion effects. The simulation framework yields both the structural stress distribution under thermal loading and the ultimate bending moment capacity under combined thermo-mechanical conditions, with the complete workflow illustrated in Figure 8.

A Cartesian coordinate system is established, originating at the lowest central point on the terminal bottom plate of the three-cabin segment. The reference frame is oriented as follows: the positive *y*-direction extends along the ship's length toward the aft bulkhead, the positive *x*-direction across the ship's beam toward starboard, and the positive *z*-direction vertically upward.

The fire scenario was simulated using a three-cabin model centered on the engine room. This approach serves a dual purpose: it reduces modeling workload and computational cost, while the inclusion of adjacent fore and aft cabins ensures relative continuity in heat transfer, thereby preserving accuracy. FDS primarily simulates fire scenarios through computational fluid dynamics modeling. It cal-

4 Cabin fire scene simulation and temperature field analysis

4.1 Selection of cabin model

For surface vessels, the engine room is typically located amidships, where the hull girder bending moment is greatest. Engine rooms are densely packed with fuel and electrical equipment, making them highly prone to fires. If an engine room fire occurs, it will severely threaten the safety of the hull structure. To investigate this scenario, the present study examines a representative surface ship with a 14.4 m beam and 3.87 m standard draft (Figure 9). The engine room, spanning 24.15 m longitudinally with cross-sectional dimensions of 14.4 m (breadth) × 10.8 m (height), occupies three deck levels within the midship region. Figure 10 details the corresponding structural configuration.

culates convective heat transfer, conductive heat transfer, and thermal radiation to obtain the time-varying temperature field of structures exposed to fire. To balance computational efficiency, modeling extremely small components would require a significantly higher mesh density to resolve their thermal response accurately, despite their negligible influence on the overall flow field. Therefore, a reasonable simplification strategy is often adopted in practice to maintain computational feasibility. Following the cabin fire modeling methodology of Liu et al. (2021), secondary structures such as stiffeners and brackets were omitted; only primary partitioning structures like longitudinal/transverse bulkheads and decks were modeled and assigned material properties. The omission of these minor structural

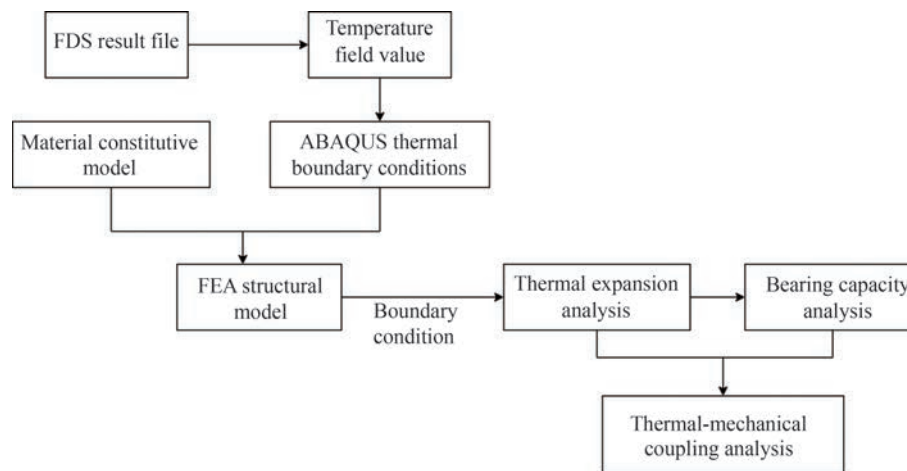


Figure 8 Cabin fire thermal-mechanical coupling calculation process

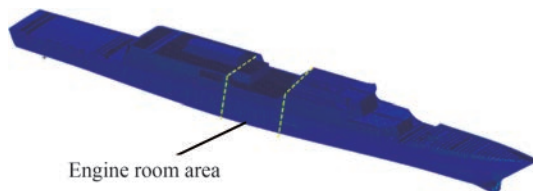


Figure 9 Finite element model of target ship

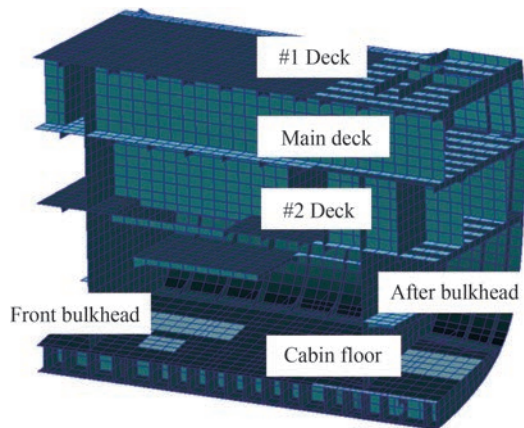


Figure 10 Profile view of engine room region

details has negligible impact on the overall temperature distribution within the compartments.

Since ventilation conditions significantly influence fire development, the FDS model incorporates corresponding internal ventilation boundaries based on the target ship's cabin layout, including the configuration of doors and vents. To account for heat exchange between the hull and the surrounding environment, the exterior of the cabin is defined as an open boundary. Figure 11 illustrates the FDS cabin fire scene model.

4.2 Material properties

Elevated temperatures alter the mechanical and thermal

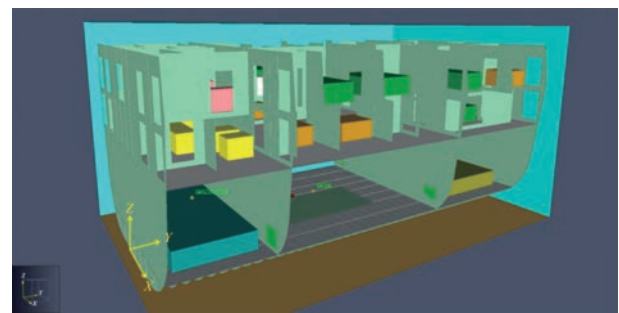


Figure 11 Three-cabin FDS model

properties of steel, leading to a reduction in its load-bearing capacity. At high temperatures, material property degradation influences the stress field distribution within the engine room, potentially causing premature structural damage. In this study, Q235 steel—a common material for hull structures—is selected, with its key thermophysical properties derived from the data in Table 1 and Figure 5. The effects of high-temperature creep and strain rate are not considered in this study.

4.3 FDS parameter setting

The fire source configuration is a critical aspect of fire scene modeling, primarily involving the selection of fire type and determination of heat release rate. As engine room fires typically involve diesel combustion (classified as Type B fires), heptane was selected as the fuel surrogate due to its similar combustion characteristics to diesel (Table 3 for physicochemical properties), the soot yield was set to 0.015. The fire source was positioned on the engine room's bottom plate adjacent to the front bulkhead, with a designated area of 6 m².

The heat release rate (HRR) represents the thermal energy released per unit time during material combustion. Common HRR modeling approaches include: (1) the t^2 steady fire model, (2) piecewise averaging method, (3) piece-

Table 3 Physicochemical properties of heptane

Parameters	Values
Density (kg/m ³)	684
Specific Heat (kJ/(kg·K))	2.246
Combustion heat (kJ/g)	44.6
Conductivity (W/(m·K))	0.44
Boiling point (°C)	98.5

wise linear method, and (4) mass loss rate-based determination. The t^2 steady fire model employs a piecewise function to simulate complete fire dynamics, where HRR initially grows with the square of time, sustains at peak value, then gradually decays until extinction. This model demonstrates superior alignment with actual fire behavior (Hostikka and Keski-Rahkonen, 2003), and is consequently adopted in this study to simulate the continuous fire progression in engine rooms. The governing equation is as follows:

$$\bar{Q}(t) = \begin{cases} \alpha t^2 & 0 < t < t_1 \\ \bar{Q}_{\max} & t_1 < t \leq t_2 \\ \bar{Q}_{\max} \times \left[\frac{(t - t_3)}{(t_2 - t_3)} \right]^2 & t_2 < t \leq t_3 \end{cases} \quad (14)$$

where $\bar{Q}_{\max}$ represents the maximum heat release rate, kW, for flammable liquids such as gasoline and diesel, HRR typically ranges from 1000 to 3000 kW; t denotes the combustion time, s, t_1 is the time required for the heat release rate to reach its maximum value, t_2 is the time when the heat release rate begins to decay, t_3 is the time required for complete decay to zero; α is the fire growth coefficient, kW/s², for engine room oil fires, which are classified as ultra-fast growth pool fires, the recommended value for α is 0.178 kW/s².

Radiation heat transfer was simulated using the Finite Volume Method (FVM), with 100 discrete solid angles applied in both the polar and azimuthal directions (NRA = 100, NRB = 100). The subgrid-scale turbulence model utilized default values of 0.5 for both the turbulent Schmidt and Prandtl numbers.

Mesh sensitivity analysis is an essential component of CFD studies. Since the smoke temperature beneath the second deck—directly above the fire source—proves highly sensitive to grid resolution, a sensitivity analysis was conducted by varying the characteristic cell sizes in the FDS model. Taking the 12 MW heat release rate as an example, the specific parameters used for this analysis are provided in Table 4.

The mesh sensitivity analysis demonstrated that for the key parameter of peak smoke temperature beneath the second deck, the results obtained with a cell size of 0.25 m

Table 4 FDS grid sensitivity analysis (12 MW peak HRR)

Type	Size (m)	Element number	$D^*/\Delta x$	Time (h)	Peak temperature (°C)
Coarse mesh	0.5	40 000	5.144	4	499
Basic mesh	0.25	325 000	10.288	32	510
Fine mesh	0.12	258 0000	20.575	256	513

differed by less than 1% from those obtained with the finer 0.12 m grid. $D^*/\Delta x$ denotes the mesh resolution exponent, with $4 < D^*/\Delta x < 16$, the 0.25 m grid provides adequate resolution of flame structure and plume dynamics. In addition, it significantly reduces computational time. Considering the requirements for subsequent load mapping to the finite element mesh and overall computational efficiency, the 0.25 m grid level was selected for all further analyses.

4.4 Setting of temperature measuring points and slices

FDS software offers two primary methods for temperature monitoring: discrete measuring points and environmental slices. The temperature measuring points simulate thermocouple functionality, recording temperature variations at fixed locations throughout the fire event. Environmental slices provide comprehensive monitoring of fire dynamics parameters, including temperature distribution, pressure fields, and flow velocity profiles across the designated cross-section.

To monitor fire source dynamics and cabin ambient temperature variations during compartment fires, seven temperature measurement points were strategically positioned around the fire source. Additional ambient temperature slices were established at both the mid-longitudinal section and beneath the second deck (Figure 12). The configuration includes:

Measurement points 1–4: Vertically aligned along the Z-axis on the fire source cabin's longitudinal section.

Measurement point 5: Positioned adjacent to the second deck's ventilation opening.

Measurement points 6 and 7: Located in the central fire source region near the cabin.

Environmental slices are located at the mid-longitudinal section of the cabin and below #2 deck.

The precise coordinates of all measurement points and environmental slices are provided in Table 5.

4.5 Fire scenario and ventilation sensitivity analysis

The complex environment of a ship's engine room leads to significant variability in both HRR of potential fires and the resulting smoke flow dynamics, which are strongly

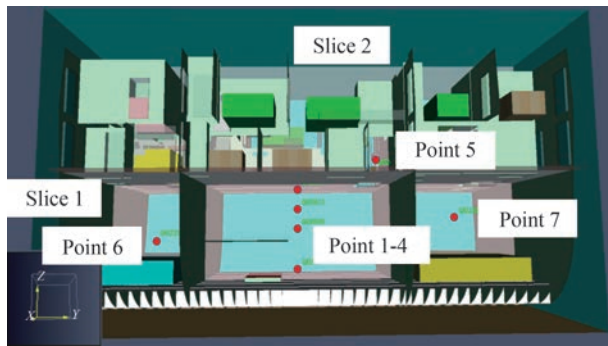


Figure 12 Slice and measuring points layout

Table 5 Coordinate position of measuring points and temperature slices

Parameters	Coordinate	Area
Point 1	(0, 11, 1.5)	Longitudinal profile in the engine room
Point 2	(0, 11, 3.5)	Longitudinal profile in the engine room
Point 3	(0, 11, 4.5)	Longitudinal profile in the engine room
Point 4	(0, 11, 5.5)	Longitudinal profile in the engine room
Point 5	(0.5, 15.5, 6.5)	Near the vent on #2 Deck
Point 6	(0.9, 2.85, 3)	Cabins near the fire source
Point 7	(0.9, 20.2, 4)	Cabins near the fire source
Slice 1	Z = 5.8	Below #2 Deck
Slice 2	X = 0	Middle longitudinal section

influenced by ventilation conditions. These factors substantially affect the spatial distribution of gas temperatures within the compartment, thereby determining the thermal load imposed on the structure.

Two additional fire scenarios with heat release rates of 6 MW and 18 MW were incorporated, combined with three ventilation conditions:

Three fire source heat release rates (6 MW, 12 MW, 18 MW) were selected and combined with below three ventilation conditions to form the analytical matrix.

(1) Normal ventilation: All ventilation openings in the engine room were fully open, including four bottom vents and one vent on the upper second deck. The bottom vents were assigned a specified ventilation rate of 8 m/s.

(2) Restricted ventilation: The four bottom vents in the engine room were closed, leaving only the vent on the second deck operational.

(3) Unrestricted ventilation: Ventilation openings were modeled as slots without imposed velocity constraints, allowing free flow.

Table 6 Fire scene setting conditions

Condition	Normal ventilation	Restricted ventilation	Unrestricted ventilation
6 MW	Case 1	Case 2	Case 3
12 MW	Case 4	Case 5	Case 6
18 MW	Case 7	Case 8	Case 9

Figure 13 illustrates the temperature variation at Measuring Point 2 under different working conditions as the cabin fire develops. Analysis indicates that both the heat release rate of the fire source and the ventilation conditions significantly influence the spatial distribution of gas

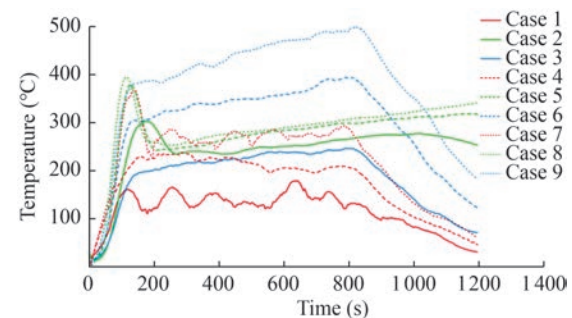


Figure 13 Temperature evolution at measuring point 2 under all working conditions

temperature within the compartment. Under well-ventilated conditions, a higher heat release rate corresponds to an elevated smoke temperature in the space. For the same heat release rate, different ventilation configurations lead to distinctly different temperature trends at the engine room's central measuring point: temperatures are significantly higher under unrestricted ventilation than under normal ventilation. When ventilation openings are restricted and the fire relies solely on the second-deck opening for oxygen supply, the fire intensity initially increases rapidly but subsequently decays. However, due to inadequate ventilation and consequent heat accumulation, the temperature decline is markedly delayed.

The temperature variations at the measuring point across all working conditions fall within a reasonable range, and the cabin FDS model demonstrates significant sensitivity to changes in both the fire's heat release rate and ventilation conditions. Case 4 most closely represents the actual operational state of the engine room and accurately captures the complete development process of a compartment fire. Therefore, this scenario has been selected as the representative condition for subsequent in-depth analysis of the cabin structure and smoke temperature field.

4.6 Temperature field analysis of cabin structure

Upon ignition, diesel fires exhibit rapid development

followed by stable combustion. The t^2 steady fire model characterizes the process with three distinct phases: growth, steady-state, and decay phases. A simulation duration of 1 200 s was selected to adequately capture the complete fire evolution.

Figure 14 displays the temporal temperature profiles at each measurement point under a 12 MW heat release rate (Figure 15), the temperature change trend of 7 measuring points is as follows:

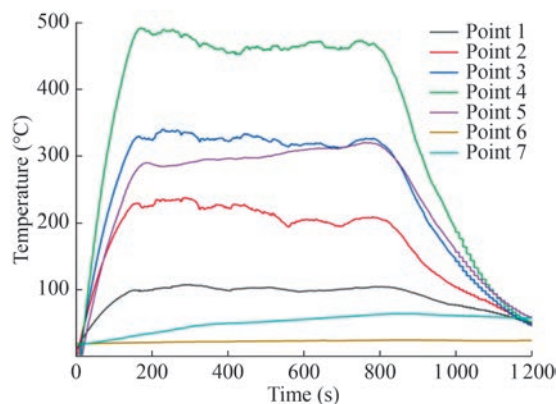


Figure 14 Measuring points temperature in cabin

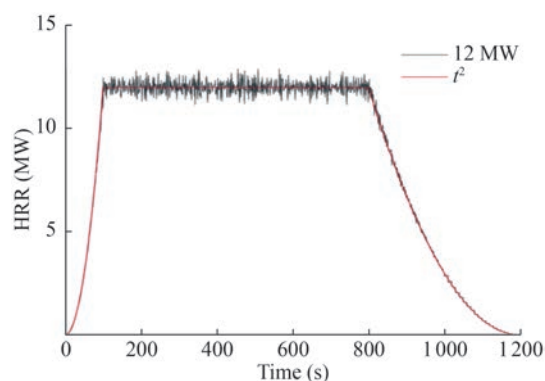


Figure 15 The curve of heat release rate under 2 000 kW/m² fire source

Points 1–4 (vertical alignment above fire source): The temperature trends at these measurement points are synchronized with changes in the heat release rate of the fire source. Within the first 200 s, temperatures rise rapidly; between 200 s and 800 s, they remain stable; after 800 s, temperatures gradually decrease.

Point 5 (near the vent on #2 Deck): Although located in the compartment above the fire source, the flow of smoke carries substantial heat, resulting in the detection of relatively high temperatures. The monitored temperature variations also reflect the changing trend of the HRR of the fire.

Points 6 and 7 (adjacent compartment): Small fluctuations in temperature were observed. Although heat transfer still occurs, the isolating effect of the bulkhead limits its efficiency, resulting in a noticeable difference compared to

the temperatures measured at point 5.

Figures 16 and 17 present the temperature distributions on different cross-sections during various fire development stages. Specifically: Figure 16 displays the ambient temperature distribution at the compartment's top (near #2 Deck), Figure 17 shows the ambient temperature distribution along the cabin's longitudinal section.

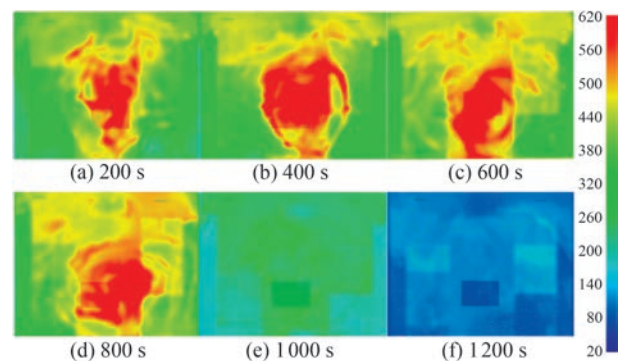


Figure 16 Environmental temperature distribution under the second deck at different instants

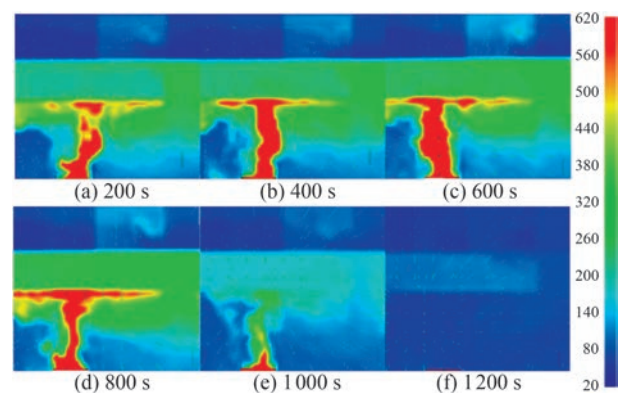


Figure 17 Environmental temperature distribution at longitudinal section at different instants

Cross-referencing with Figure 14 reveals three key findings:

(1) Thermal stratification: During the fire growth phase, buoyant smoke flow transports significant thermal energy upward, causing rapid temperature elevation above the fire source, whereas the cabin floor exhibits gradual heating.

(2) Ventilation impact: The temperature distribution exhibits strong dependence on ventilation conditions. Heat transfer through openings facilitates smoke propagation to adjacent areas, where ventilation configuration may either intensify or mitigate fire severity.

(3) Fire dynamics: The fire's evolution is primarily governed by the source's heat release rate, while smoke movement dictates the spatial temperature distribution patterns.

The temperature distribution across the top deck structure of the engine room is illustrated in Figure 18. Compared with the air temperature distribution at the same

location (Figure 16), the structural temperature exhibits a pronounced thermal lag. Heat from the air is transferred to the structural steel via conduction, convection, and radiation, resulting in a gradual temperature rise in the steel. When the ambient temperature decreases, thermal inertia causes heat to continue transferring to the structural steel, leading to a sustained temperature increase even after the ambient temperature declines. Furthermore, since heat propagates through the steel, the heating area of the cabin expands overall during the later stages of fire development, even as the peak cabin temperature declines.

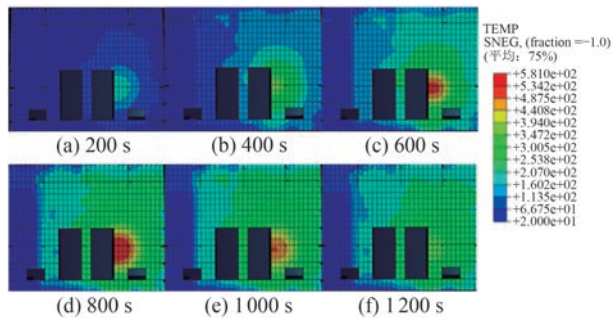


Figure 18 Structural temperature distribution under the second deck at different instants

Due to temperature variations, the mechanical properties of steel degrade significantly, adversely affecting its strength, toughness, and other key performance metrics. Consequently, the structural temperature field is crucial for accurately assessing the residual load-bearing capacity of a ship's hull under fire conditions.

5 Residual strength analysis of ship structure under cabin fire

5.1 Finite element model of cabin section

During ship navigation in waves, the combined effects of gravity and buoyancy induce hogging and sagging phenomena. Severe hogging and sagging can cause significant hull damage or even rupture, placing the structure in a critical condition. Multi-point constraints (MPC) were implemented in the model, with the reference constraint point coupled to the stress surface (both ends of the model) to simulate simply supported boundary conditions. During the heating stage, displacements in the x -direction and rotations about the y -axis and z -axis were constrained. During the loading stage, a bending moment is applied by imposing an angular displacement, specifically a rotation of 0.01 radians about the y -axis. The corresponding loading curve is presented in Figure 19.

The ultimate bearing capacity of the cabin section under each working condition is defined as the peak moment

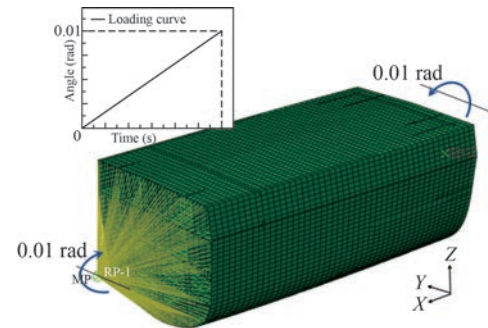


Figure 19 Loading curve and ABAQUS model of cabin

value in the moment-rotation curve at the MPC point, based on which a comparative analysis of the structural capacity across different scenarios is conducted.

To account for the effects of the temperature field, the S4RT element was selected for modeling. This element is a four-node, thermally coupled curved shell unit with six degrees of freedom per node, making it suitable for large-deformation analysis of thin-shell structures.

A mesh convergence study was conducted to minimize discretization error. As summarized in Table 7, the ultimate bending moment obtained with mesh configuration C is in close agreement with that of the finer mesh configuration D, meeting the required accuracy while offering better computational efficiency. Consequently, mesh configuration C was adopted for the finite element analysis of the cabin section. Furthermore, its mesh size aligns well with the FDS grid, ensuring high fidelity in the mapping of thermal loads.

Table 7 Mesh sizes and ultimate bending moment.

Model	Mesh size/m	Mesh numbers	Ultimate bending moment/ 10^5 kN·m
A	0.50	13427	6.96
B	0.40	20980	7.00
C	0.25	53709	7.02
D	0.10	335681	7.02

This study focuses on the methodology for mapping thermal loads and assessing structural strength under fire conditions. Compared to the substantial thermal deformation, initial imperfections represent a relatively minor factor, and therefore were not considered in the present numerical simulations.

5.2 Residual bearing capacity of cabin at different fire moments

Figure 20 presents the temperature load mapping results on the cabin's finite element model at $t = 800$ s. The temperature distributions obtained from both FDS and ABAQUS simulations demonstrate excellent agreement,

validating the effectiveness of the TFM method for transferring structural temperature loads from FDS to finite element models as thermal boundary conditions.

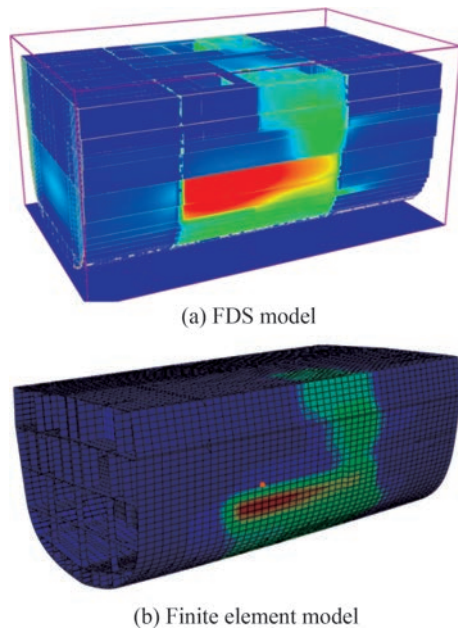


Figure 20 Cabin temperature field mapping

Figure 21 demonstrates that ship cabins exposed to fire exhibit significantly reduced ultimate bearing capacity compared to those under normal conditions. The residual bearing capacity varies with fire development stages due to differing thermal loads on the cabin structure. During the growth and fully-developed stages (0–800 s), continuous

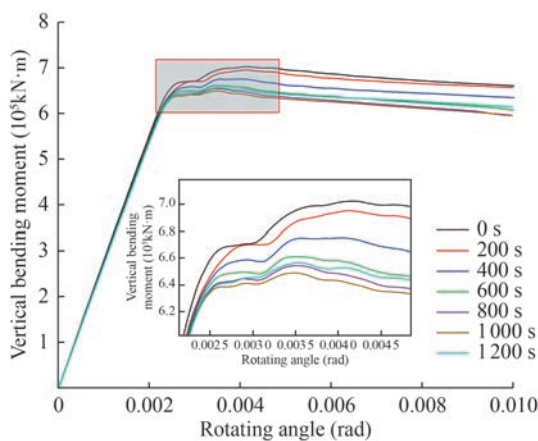


Figure 21 Hull bending moment-rotation curve at each fire moment

expansion of the heated area and rising temperatures lead to progressive deterioration of structural capacity. During the initial decay phase (800–1 000 s), the cabin temperature began to decrease. However, thermal diffusion expanded the heated area, leading to a further reduction in load-bearing capacity. In the later decay phase (1 000–1 200 s), as the

temperature continued to decrease and the thermal diffusion zone stabilized, the structural load-bearing capacity exhibited a partial recovery.

In summary, the structural temperature represents the critical parameter governing the residual bearing capacity of ship cabins during fire scenarios. The temperature evolution directly governs the degradation of structural material properties, consequently determining the cabin's residual load-bearing performance.

5.3 Residual bearing capacity of cabin considering thermal expansion

Fire represents a dynamically evolving process with sustained thermal development. During this progression, structural components undergo thermal expansion as temperatures rise, generating significant thermal stresses. These thermally-induced stresses exert considerable influence on the cabin's residual load-bearing capacity during fire incidents, an effect that cannot be overlooked in structural integrity assessments.

To accurately assess the residual load-bearing capacity of ship cabins under combined thermal and mechanical loading during fire incidents, a sequential thermal-mechanical coupling analysis was implemented. The methodology consists of two key phases: (1) thermal loading analysis to account for thermally-induced stresses from fire exposure, followed by (2) mechanical loading through imposed rotational displacements at both cabin ends to evaluate the residual structural capacity.

As shown in Figure 22, the moment-rotation curves at different fire stages exhibit a non-zero initial moment at the onset of loading. This is attributed to the thermal stress developed within the structure during the heating phase, the underlying mechanism of which is illustrated in Figure 23.

The observed initial jump is attributed to thermal stress, resulting from the classic “thermal bending” mechanism due to restrained thermal expansion. In the fire growth phase, the lower hull is heated more rapidly than the upper

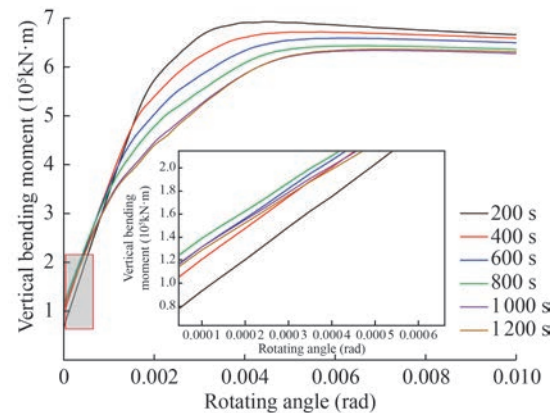


Figure 22 Hull bending moment-rotation curve considering expansion thermal stress

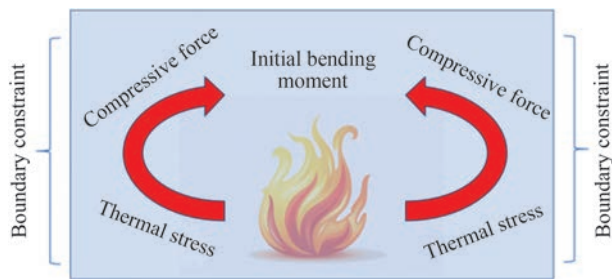


Figure 23 Mechanism of “thermal bending”

part by flames and hot gases. The resulting tendency of the bottom plate to expand longitudinally is restrained by the much cooler deck, as the hull girder is a continuous structure. This restraint generates a self-equilibrating internal stress system, producing a net internal ‘thermal moment’ across the section. For a bottom-heated scenario, this moment causes a global bending deformation equivalent to bottom tension and top compression.

The initial bending moment exhibits a correlation with the fire timeline. It undergoes a steady increase throughout the development stage. Notably, during the decay stage (after 1 000 s), the moment sustains a magnitude comparable to that at 600 s. This occurs because heat transfer enlarges the heated area, generating increased thermal stress that compensates for the reduction in peak temperature.

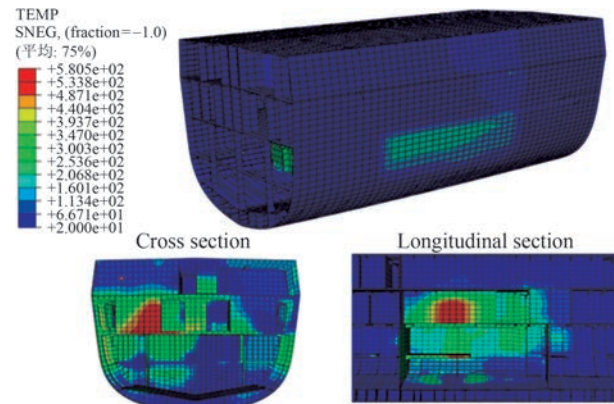
Figure 24 demonstrates significant thermal-structural deformation in the cabin’s high-temperature regions at $t = 800$ s under thermal stress conditions. The deformation manifests as: (1) characteristic buckling patterns (wavelike folds) along the cabin side panels, and (2) pronounced lateral deflection of both transverse and longitudinal bulkheads. These deformation modes originate from temperature-dependent stress redistribution within the structure, ultimately causing measurable geometric distortions in both the external cladding and internal structural components.

In sequentially coupled thermo-mechanical analysis, the presence of thermal stress effectively establishes a new initial mechanical state for the hull structure, which serves as the basis for evaluating the residual load-bearing capacity of the cabin section under end rotation. Referring to Figure 22, systematic analysis of the moment-rotation relationship leads to the following key conclusions:

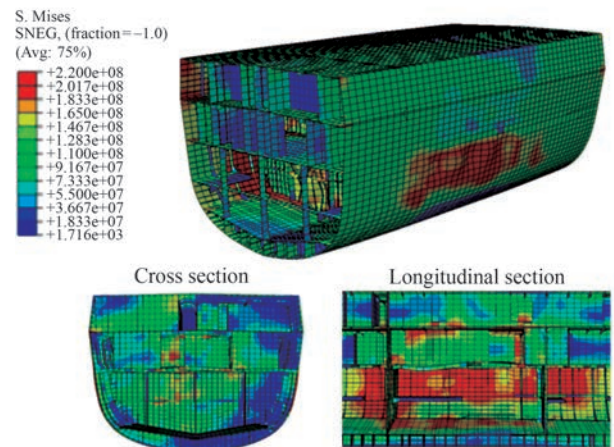
(1) During the fire growth and fully developed stages (0–800 s), the load-bearing capacity of the hull structure exhibits a progressive degradation trend with increasing thermal load.

(2) In the early decay stage (800–1 000 s), although the ambient temperature begins to decline, the continuous expansion of the heat-affected zone leads to a further reduction in structural load-bearing capacity.

(3) In the late decay stage (1 000–1 200 s), the heated area continues to expand while the overall temperature decreases further. Unlike the scenario without thermal expansion considered in Section 5.2, no recovery of resid-



(a) Temperature cloud diagram



(b) Stress cloud diagram

Figure 24 The state diagram of cabin section under thermal stress

ual load-bearing capacity is observed, which is attributed to the combined effects of spatial temperature distribution evolution and thermal stress.

These findings indicate that under fire conditions, thermal effects not only lead to the degradation of material properties but also influence the global structural stability through thermally induced stress mechanisms.

5.4 Analysis and discussion

Analysis of Figure 25 indicates that during the early stage of fire development (0–600 s), the residual load-bearing capacity of the cabin section is consistently lower when thermal stress is considered compared to the scenario where thermal effects are neglected. However, this reduction remains relatively modest, primarily because the limited heated area does not generate significant thermal expansion forces, and the degradation in load-bearing capacity is still predominantly governed by the temperature-dependent reduction in material properties.

However, during the later stage of fire development (600–1 200 s), after the temperature peaks and begins to decline, the heat-affected zone within the cabin continues to

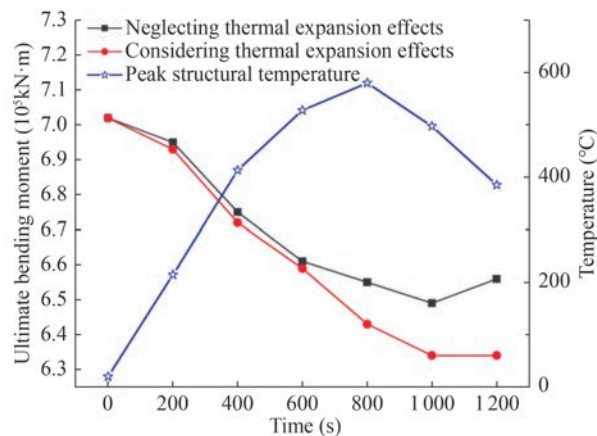


Figure 25 The state diagram of cabin section under thermal stress

expand. This enlarged thermally influenced region induces greater thermal expansion forces. As a result, the ultimate bearing capacity of the cabin section considering thermal expansion is significantly lower than that of the scenario ignoring thermal expansion. This demonstrates that thermal expansion effects must be considered in the strength assessment of ship hull structures under fire conditions, particularly during the later stages of fire development. When a large portion of the structure becomes heated, the resulting thermal expansion forces can substantially degrade the load-bearing capacity.

In the fire-resistant design of hull structures, it is necessary to consider not only the degradation of steel mechanical properties caused by high temperatures and the consequent reduction in load-bearing capacity but also the additional influence of thermally-induced stresses generated by temperature fluctuations in the fire environment on structural strength. Particularly in large-scale fire scenarios involving severe temperature fluctuations, the hull structure will be subjected to the coupled effects of thermal stresses and wave loads, resulting in an actual load-bearing capacity that is generally lower than the evaluation obtained by considering only material softening at high temperatures.

Furthermore, the thermal stresses induced by fire can cause irreversible plastic deformation in the hull structure. Such deformation aggravates pre-existing damage in the hull and adversely affects the fatigue strength of the fire-exposed vessel. Therefore, this unfavorable effect should be fully taken into account in the fire-resistant design and safety assessment of hull structures.

6 Conclusions

This study employs a large-eddy simulation program to establish a fire model for large-scale ship cabins, analyzing the variation trends of smoke temperature inside the

cabin. An efficient temperature load mapping procedure for the cabin structure was developed to transfer the structural temperature field from the fire model to the finite element model. The residual load-bearing capacity of the cabin structure under high-temperature fire conditions was then evaluated, leading to the following conclusions:

(1) This study presents a comparative analysis of two FDS-based temperature load derivation methods: the Heat Flux Method (HFM) and the Temperature Field Method (TFM). The TFM demonstrates superior performance, it enables precise temperature load mapping onto finite element models, facilitating accurate thermal-mechanical coupling simulations; the method provides intuitive visualization of structural temperature gradients; and it serves as direct thermal boundary conditions without requiring additional transformations.

(2) The fire simulation was conducted in FDS with appropriately configured thermodynamic parameters for structural materials. Using the Temperature Field Method, successfully mapped the simulated structural temperatures to thermal boundary conditions for finite element analysis. Validation studies demonstrate the method's effectiveness in evaluating residual load-bearing capacity under fire conditions. It has successfully solved the long-standing problems that it is difficult to accurately simulate the fire temperature field of large-sized hull structure and that it is impossible to simply and accurately input the simulation results into finite element software for analysis. This provides powerful technical support for relevant research and engineering practices.

(3) The elevated temperatures during fire incidents cause substantial degradation in the mechanical properties of ship structural steel, resulting in a marked reduction of the hull's load-bearing capacity. This thermal degradation represents the primary determinant of structural residual strength under fire conditions. Furthermore, fire progression constitutes a dynamic thermal-structural coupling process wherein continuously increasing temperatures generate significant thermal stresses that further compromise structural integrity. Consequently, a rigorous assessment of hull structural safety under fire conditions must explicitly account for thermally-induced expansion effects through coupled thermal-mechanical analysis to ensure comprehensive evaluation of structural integrity.

(4) The thermal impact on hull structures is characterized by two critical phenomena: temperature-dependent material degradation and thermally-induced stress redistribution, both of which significantly compromise structural integrity through property deterioration and deformation-induced capacity reduction. This dual mechanism underscores the necessity for comprehensive research into characteristic fire scenarios to establish scientifically robust frameworks for fire-resistant design and safety assessment. Such systematic investigation will yield fundamen-

tal principles essential for optimizing structural performance and ensuring vessel survivability under extreme fire conditions.

The present study on the load-bearing capacity of ship structures under fire conditions has certain limitations. The adopted material constitutive model does not consider creep and strain rate effects, which may lead to non-conservative predictions of structural deformation. In addition, the finite element modeling approach does not incorporate initial geometric imperfections, potentially resulting in overestimated global stability and ultimate strength. Future work will focus on integrating more refined material constitutive relations and properly accounting for initial imperfections in numerical models, so as to more accurately characterize the influence of high-temperature environments on the ultimate load-bearing capacity of ship structures.

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