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Recent Advances in CFD-based Bridge Fire Evaluations: A Brief Review

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Abstract

Bridges, as the main elements of transportation networks, demand significant attention due to their unique structural characteristics and high consequences of fire incidents. So, it is crucial to enhance the fire resilience of these structures. Various studies have focused on the integration of advanced fire modeling techniques, including computational fluid dynamics (CFD), the finite element method (FEM), and artificial intelligence (AI) to improve the fire responses of the bridges. This article provided an overview of recent advancements in bridge fire modeling and addressing methodologies, challenges, and future directions for enhancing the fire resilience of bridge structures. Natural language processing (NLP) was employed for an in-depth exploration of bridge fire engineering topics and integrated CFD, FEM, and AI techniques. It has highlighted the importance of AI in enhancing real-time fire prediction and reducing related computational demands, emphasizing the importance of developing AI integrated approaches for the accelerated and effective post-fire assessment of bridge structures, considering their unique structural challenges and high impact of fires.

Keywords: Bridge; Fire safety; CFD; FEM; AI; NLP, Fire resilience; Fire prediction; Post-fire assessment

Abbreviations: CFD: Computational Fluid Dynamics; FEM: Finite Element Method; AI: Artificial Intelligence; NLP: Natural Language Processing; FDS: Fire Dynamics Simulator; RANS: Reynolds-Averaged Navier-Stokes; LES: Large Eddy Simulation; DNS: Direct Numerical Simulation; HRR: Heat Release Rate; FE: Finite Element; RAI: Rapid, Automated, and Intelligent; IOT: Internet of Things

Introduction

The evolution of mathematical modeling in fire safety and incorporation of field modeling through Computational Fluid Dynamics (CFD) into fire research has marked a major development in this field [1-3]. This approach offers a more detailed and accurate representation of fire behavior within various settings [4,5]. Among various CFD tools, the Fire Dynamics Simulator (FDS) is notably the most used model due to its comprehensive capabilities in simulating fire dynamics [6,7]. Despite the higher computational demands, CFD modeling is a critical response to the limitations of conventional standard time-temperature curve and zone modeling in capturing the complex details of fire-structure interactions [8-14]. CFD models can incorporate complex variables such as building geometry, ventilation, and fuel load as well as detailed analysis of fire growth, spread. In fire CFD modeling, Reynolds-Averaged Navier-Stokes (RANS) models are widely used for their efficiency in averaging complex flows. Large Eddy Simulation (LES) models offer more detailed data but require finer meshes and greater computational resources. Direct Numerical Simulation (DNS) provides comprehensive flow analysis but demands extensive mesh resolution and high computational power, limiting its use primarily to research. The modeling approach of CFD provides detailed insights into fire evolution and its interaction with structural elements. Such detailed modeling is essential for predicting structural responses to fire and designing buildings that are resilient to fire hazards [6,15-17].

The integration of CFD with finite element method (FEM), and artificial intelligence (AI) in structural fire engineering marks a significant stride in fire safety research [18-24]. While CFD comprehensively simulates the behavior of fire and smoke, FEM focuses on assessing the structural responses under fire-induced stress. Building upon the foundation established by CFD and FEM, the integration of AI into structural fire engineering not only reduces the high computational demands but also enables real-time fire identification and prediction [25-27]. The combined use of CFD, FEM, and AI facilitates rapid response during fire events and effective assessment of post-fire conditions. This agile approach allows for more precise and timely decision-making in both the prevention and aftermath of fires, thereby enhancing the fire resilience of the structures. The use of FDS models in bridge fire assessment is a major focus in structural fire research. Bridges, as one of the main structural types and critical components of transportation networks, demand specific attention due to their unique structural characteristics and the severe impact that fires can have on them. The catastrophic nature of bridge fires not only poses a threat to public safety but also leads to considerable economic losses and disruptions in transportation networks [28-32]. The geographical spread of major bridge fire incidents, categorized by the severity of damage is demonstrated in Figure 1. These incidents have highlighted the vulnerability of bridges to fire and underscored the need for advanced fire evaluation techniques. Therefore, applying field modeling in bridge contexts, particularly integrating CFD, FEM, and AI, is of both academic interest and practical urgency. This review provides a summary of CFD modeling in bridge fire studies from the last decade. Utilizing Natural Language Processing (NLP), a broad range of articles were analyzed and narrowed down to 10 studies for a more detailed assessment. This process aimed to explore various methodologies, identify challenges, and outline potential future directions for enhancing the fire resilience of bridges.

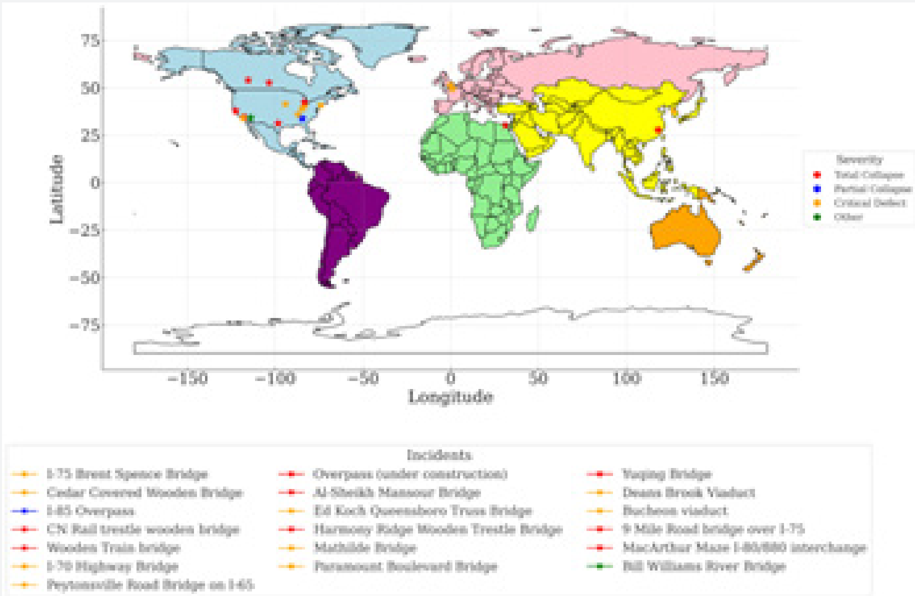

Figure 1: Global spread of bridge fire incidents.c

Use of CFD in Bridge Fire Engineering

The application of FDS models in bridge fire evaluation is a significant area of focus in structural fire research. In FDS simulations, the source of the fire, which is often a vehicle accident, is typically modeled as a rectangular shape with the top surface designated as the burning area. The Heat Release Rate (HRR) for different vehicles varies, with the flammable liquid tankers having the highest HRR. The combustion characteristics for each vehicle fire are defined based on information provided by SFPE Handbook of Fire Protection Engineering [33] As one of the notable CFD-based bridge fire studies, J Alos-Moya et al. [34] employed FDS and ABAQUS to analyze the I-65 overpass bridge in Birmingham, Alabama, which collapsed due to a fire in 2002. Their comprehensive study focused on the effects of factors such as HRR and temperature discretization from CFD to a finite element (FE) model on the fire responses of bridges. The FE model successfully simulated the structural behavior, including web buckling and deformation. This study underscores the limitations of the current design standards and the importance of performance-based approaches in bridge fire safety. Gong X, Agrawal A, [35] investigated the Ed Koch Queensboro Bridge fire in New York City using sequential thermo-mechanical analysis. They employed FDS for fire simulation and ABAQUS for the structural response.

Their analysis results revealed a significant temperature rise and out-of-plane stringer deformations, although the load-bearing capacity of the bridge under normal conditions was maintained. This research highlights the importance of post-fire assessments and the need to retrofit fire-damaged components of bridges. Peris-Sayol G, et al. [36] focused on the fire response of steel bridges, and examined the impact of fire position, bridge configuration,

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and wind speed. Utilizing adiabatic surface temperatures from FDS as input for ABAQUS thermomechanical analysis, their study identified the most damaging scenarios as tanker fires near bridge abutments, particularly in single-span bridges with minimal vertical clearance. The findings showed that the thermal responses and structural integrity were significantly influenced by factors such as vertical clearance and fire load position. This study offers new insights into the modeling of bridge fires and emphasizes the importance of specific parameters in predicting the integrity of steel bridges under fire. Wang and Liu [37] studied the buckling behavior of steel bridges under fire using FDS for fire characteristics and ANSYS for buckling analysis. Their findings revealed that bridge temperatures significantly increased during a tanker fire, with a critical buckling stress reduction in the steel bridge web within 17 min of exposure to a tanker fire, indicating early structural failure. They identified the optimal rescue time for such fires to be within the first 15 minutes.

The validation study by Alos-Moya et al. [38] is considered one of the key CFD-based bridge fire studies. They conducted a simulation study to validate modeling approaches for bridge fire scenarios using Valencia bridge fire tests that were performed earlier. Their methodology included experimental fire tests under a composite bridge and utilized both a simplified approach (Heskestad and Hamada's correlation) and FDS. The findings revealed the limitations of the simplified approach in large-scale scenarios, whereas the FDS model provided accurate simulations of the fire dynamics and thermal impacts. This study significantly enhances the understanding and accuracy of fire simulation tools used in bridge safety engineering. Zou et al. [39] investigated the performance of suspension bridge hangers exposed to fires caused by hazardous material (HazMat) accidents, with a particular focus on the impact of wind effects. They used FDS to simulate various scenarios considering the fuel size, transverse offset distance, and wind. Their analysis of the post-fire conditions based on the material properties of the bridge hangers indicated that wind speed, spill size, and hazardous material type significantly influenced the peak temperatures. Notably, higher wind speeds intensified temperature rises, elevating the risk of structural damage. Their findings demonstrated major reductions in the yield strength of steel hangers during fire events and emphasized the correlation between the yield strength and temperature. This study offers insights into the thermal effects of HazMat fires on suspension bridge hangers, highlighting the critical influence of the wind in such scenarios. Cui et al. [40] employed FDS and ANSYS to investigate the stability performance of a three-pylon suspension bridge considering a nearby tanker fire with varying burning time, fire area, and fire location.

Their analyses demonstrated that conventional fire temperature curves, which ignore height effects, often overestimate fire effects. They observed that the stability coefficient of the bridge was significantly influenced by fire size and location, with notable reductions after 30 min of fire exposure. This research contributes to safety assessment and maintenance strategies for cable-supported bridges with steel pylons. Yu et al. [41] focused on the Wuhan Yangtze River Bridge, a long-span double-deck suspension bridge, and analyzed its responses to tanker fire exposure. They utilized FDS to generate temperature data for a tanker fire scenario on the upper deck of a bridge and conducted thermomechanical analysis with ANSYS to determine the shortest failure time of the main cable and the critical duration for fire rescue. They observed that the tanker location significantly affected the fire response of the bridge, and that the middle lane on the upper deck of the suspension bridge was a relatively safe lane during such fire scenarios. This study highlights the importance of considering fire scenarios in bridge design, especially for the main urban passages with heavy traffic and high fire risk. Xu and Liu [42] combined CFD and FEM to simulate the response of a steel box bridge to a tanker fire beneath it. Their experimental validation on the steel beams added credibility to their approach. The FE model effectively demonstrated the inhomogeneous thermomechanical response of the bridge under actual fire conditions, noting girder failure due to buckling in less than 10 minutes. This study validates the effectiveness of coupled CFD-FEM methods in replicating complex fire scenarios and highlights their importance in accurate bridge fire evaluations.

The study by Lu et al. [43] shifted towards AI integration in bridge fire field modeling. They developed a novel approach combining FDS, FEM, and a Kriging-based AI algorithm for the enhanced post-fire analysis of RC bridges, overcoming the limitations of the conventional FEM to accurately assess the post-fire conditions of bridges. Their model successfully predicted the static behavior of an actual fire-affected bridge, proving its effectiveness in fundamental structural assessments such as load-bearing capacity and crack formation predictions. This approach represents a significant advancement in bridge fire engineering by providing a more accurate and reliable method for evaluating and monitoring bridge structural integrity post-fire, which is crucial for post-disaster assessment and retrofitting. In the performed studies, assumptions about fuel bed sizes varied from specific dimensions to estimates based on observations and spillage percentages. The FE analysis in these studies mainly employed software such as ABAQUS and ANSYS, focusing on specific elements or sections rather than the entire bridge model, and commonly performed thermomechanical analysis using adiabatic surface temperature data obtained from FDS models. These studies identified that the fire position, HRR, structural configuration, and wind play a critical role in determining the impact of fires on bridges. They emphasized the critical need for precise modeling techniques to understand and mitigate the impacts of fires on bridges.

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Knowledge Gap and Future Trend

An essential observation from existing studies is the limited capacity of current bridge design practices to address fire hazards, which highlights the need for more comprehensive guidelines. Despite these advancements, a notable knowledge gap persists in the integration of AI with advanced computational modeling techniques in the context of bridge fires. Integrating AI into these practices can significantly enhance the resilience of bridges to fire hazards, leading to improved safety and design methodologies [44]. Recent studies in the field of bridge fire analysis have made major progress through AI integration. The use of machine learning algorithms such as random forests, support vector machines, and generalized additive models has been pivotal for assessing the risk of fire hazards in bridges [44]. Furthermore, the development of a Rapid, Automated, and Intelligent (RAI) approach has enhanced the identification of bridges vulnerable to fire [45]. Current AI applications in bridge fire analysis rely predominantly on historical or actual fire incident data. This reliance constrains the models to scenarios that have already occurred, thereby limiting their ability to predict or simulate novel or extreme fire conditions that have not been previously recorded [46,47]. Computational models, such as CFD and FE, are crucial for simulating the dynamic behavior of bridges under fire. However, the integration of AI with these models has not been explored extensively. AI has the potential to enhance these simulations by providing predictive insights, optimizing simulation parameters, and offering faster and more accurate interpretations of complex fire dynamics. The bridge fire analysis field would benefit significantly from AI models that go beyond analyzing past data to predict future scenarios. Integrating AI with advanced computational modeling can advance risk assessment and management strategies. Such integration can lead to more comprehensive and dynamic models capable of evaluating a wider range of variables and conditions, thus providing more robust and reliable strategies for mitigating fire risks in bridge structures.

Conclusion

The critical role of bridge structures in transportation and their susceptibility to fire highlights the importance of exploring advanced fire safety measures. Correspondingly, the present research reviewed advanced CFD-FEM approaches and their integration in enhancing the fire safety and resilience of bridges. For this, a comprehensive series of articles were evaluated using NLP, whereby the 10 articles were shortlisted for more in-depth evaluation. This review particularly investigated the role of CFD, FEM, and AI in enhancing the fire resilience of bridges. Despite progress in bridge fire safety, challenges persist in current CFD-FEM models, including high computational demands and the need for more accurate thermal behavior predictions and real-time detection. Emerging technologies, such as AI and the internet of things (IoT), present opportunities for enhancing CFD-FEM assessments. Future research should focus on developing advanced CFD models that integrate real-time data and machine learning algorithms, enabling dynamic and more precise fire simulations. Addressing these gaps will not only improve the efficacy of CFD models, but also significantly contribute to the safety and sustainability of bridge infrastructures.

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