Health and Safety Challenges in Bridge Construction: A Comprehensive Review of Workplace Accidents

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Abstract: The construction of bridges is a critical component of infrastructure advancement; however, it is accompanied by considerable occupational risks. This review article investigates the common types, underlying causes, and repercussions of global accidents in bridge construction projects. The study of data derived from diverse case studies, industry analyses, and scholarly publications identifies prevalent risk factors, including falls from heights, equipment malfunctions, and structural failures. The discussion extends to the ramifications of these incidents on worker safety, project schedules, and financial implications. Additionally, the paper assesses existing safety measures and their efficacy in risk reduction. It also emphasizes innovative technologies and best practices that hold the potential for improving safety conditions in bridge construction. By integrating this information, a thorough insight into the industry's challenges and suggestions for strategies for enhancing safety protocols are provided. This research is vital in minimizing occupational hazards and fostering safer work environments in bridge construction initiatives.

Key-Words: Occupational safety; Bridge construction; Workplace accidents; Risk assessment; Engineering hazards; Construction fatalities

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1 Introduction

The construction of bridges plays a crucial role in the advancement of infrastructure, serving to link communities and enhance transportation across both natural and artificial barriers [1]. Nevertheless, this essential sector encounters considerable challenges regarding occupational safety. The intricate nature of bridge construction projects, which often involves working at elevated heights, operating heavy machinery, and managing complex structural components, fosters an environment that is susceptible to various accidents and hazards [2].

In recent decades, a multitude of incidents have brought to light the dangers associated with bridge construction. These range from structural collapses during the building phase to falls from scaffolding, resulting in injuries, fatalities, and significant financial repercussions.

One can mention the construction of the Golden Gate Bridge in the 1930s, which resulted in the deaths of 11 workers, 10 of them in one day [3]. Figure 1 depicts the Golden Gate Bridge.

Figure 1. The Golden Gate Bridge and its Memorial Plaque dedicated to the dead bridge workers [3]

In another and more recent example, a portion of the bridge at the entrance to Patras (Greece) collapsed on 2023/7/23. Situated along the ‘Perimetriki Odos’ (Peripheral Road) of Patras, specifically at the 205th kilometer of the Athens-Patras national highway, the bridge had a history of structural integrity issues. Due to extensive damage to the reinforced concrete bridge, mainly due to severe cracking, it was decided to demolish it in a controlled manner. However, the demolition process led to an unexpected collapse (see Fig. 2) resulting in injuries to two demolition workers who worked on the bridge. In addition, there was the injury of three others and the death of two people who were underneath the bridge collecting scrap metal at the time of the collapse.

Figure 2. Collapse due to uncontrolled demolition of a bridge at the North entrance to Patras (Greece) collapsed on 2023/7/23 (Author's photographs).

The necessity of addressing safety issues in bridge construction is paramount. In addition to the profound human toll, workplace accidents in this sector can lead to project delays, heightened insurance costs, legal repercussions, and damage to the reputations of the companies involved. Furthermore, such incidents can undermine public trust in infrastructure initiatives and the construction industry at large [4].

This review paper intends to thoroughly examine workplace accidents during bridge construction. By analyzing historical data, case studies, and contemporary industry practices, the objective is to identify prevalent types of accidents, their root causes, and their extensive consequences. The paper will investigate various factors that contribute to these incidents, including human error, equipment malfunctions, design deficiencies, and environmental influences.

This review will evaluate the efficacy of current safety protocols and regulations in addressing the risks inherent in bridge construction. It will explore the various approaches taken by different nations and organizations in managing safety within this field, emphasizing both successful strategies and areas that require enhancement.

Recent advancements in technology and engineering methodologies have provided new instruments and techniques aimed at improving safety in the workplace. This paper will analyze innovative technologies such as Building Information Modeling (BIM), the use of drones for site inspections, and wearable safety devices, assessing their potential to lower accident rates and enhance overall safety performance.

By integrating findings from scholarly articles, industry analyses, and expert insights, this review seeks to offer meaningful perspectives for construction practitioners, policymakers, and researchers. The main objective is to support ongoing initiatives aimed at fostering safer working conditions in bridge construction, thereby decreasing the incidence and severity of workplace accidents in this vital sector.

The following sections of this paper will outline the methodology employed in this review, present comprehensive findings regarding the types and causes of accidents, evaluate the effectiveness of current safety measures, investigate technological advancements in safety management, and conclude with suggestions for future research and industry practices. Through this thorough examination, the main objective is to close the gap between existing safety standards and the goal of achieving an accident-free work environment in bridge construction.

2 Methodology and scope of review

This extensive examination of workplace accidents occurring during bridge construction utilizes a systematic methodology to collect, analyze, and integrate relevant information from diverse sources. The approach is designed to offer a comprehensive understanding of the topic while incorporating the most up-to-date and significant data.

The scope of the search was confined to publications from the last 10 years to emphasize current issues, while also integrating foundational works from earlier eras to provide historical context. Alongside academic literature, industry reports, government documents, and case studies from esteemed engineering and construction entities are also utilized. This approach facilitates a more pragmatic understanding of the challenges encountered within the discipline.

The selection of studies and reports was guided by their pertinence to the safety of bridge construction, the robustness of their methodologies, and the comprehensiveness of their analyses. It emphasizes the inclusion of peer-reviewed publications, extensive surveys, and formal accident investigation documents. While the primary focus was on materials published in English, notable contributions in other languages were also considered, provided they were accompanied by English abstracts or translations.

Data about accident types, frequencies, causes, and outcomes were extracted from the reviewed literature. This information was systematically categorized and analyzed to discern patterns, trends, and common themes associated with bridge construction accidents. Particular emphasis was placed on studies that offered quantitative data or thorough qualitative analyses of specific incidents.

To illustrate these findings and enhance understanding, several notable bridge construction accidents for in-depth case study analysis are selected. These incidents were chosen due to their significant impact, the presence of detailed investigation reports, and their representation of various accident types and geographical contexts.

This review covers various aspects of accidents in bridge construction, including:

- Types of accidents (e.g., falls, equipment-related incidents, structural failures)
- Common causes and contributing factors
- Immediate and long-term consequences of accidents
- Current safety practices and their effectiveness
- Regulatory frameworks and their impact on safety
- Emerging technologies and innovative approaches to safety management
- Economic impacts of accidents on projects and the industry
- Psychological effects on workers and safety culture

This review predominantly emphasizes large-scale bridge construction initiatives; however, pertinent information from smaller bridge projects is incorporated as necessary to ensure a thorough understanding of the sector. It is crucial to acknowledge the limitations inherent in this review. The accessibility and quality of accident data differ markedly among various countries and regions. The construction industry is well aware of the underreporting of minor incidents, which could potentially compromise the comprehensiveness of this analysis. Furthermore, the swift evolution of technology in construction implies that some of the latest advancements may not yet be captured in the existing literature.

The concluding phase of this methodology entails the integration of the gathered data to discern significant trends, deficiencies in existing knowledge, and potential avenues for future inquiry. From this integration, recommendations aimed at enhancing safety in bridge construction, taking into account both short-term actionable measures and long-term strategic initiatives are developed.

Through adherence to this thorough methodology, the objective is to provide a thorough and detailed comprehension of the challenges and prospects associated with enhancing workplace safety in bridge construction. The following sections of this review will articulate the findings, analyses, and recommendations derived from this methodological framework.

3 Types and causes of accidents in bridge construction

This comprehensive review of accidents in bridge construction reveals a complex landscape of hazards and risk factors [5, 6]. This section presents the primary types of accidents encountered in bridge construction projects and analyzes their underlying causes.

3.1 Types and causes of accidents

3.1.1. Falls from Height

Falls continue to be the primary contributor to fatalities and severe injuries within the realm of bridge construction. An examination of incident reports spanning the last twenty years reveals that around 35% of all significant accidents in this field are associated with falls. Such incidents predominantly take place during activities

conducted on elevated structures, scaffolding, or temporary platforms.
Common scenarios include:

- Falls through unprotected openings or edges
- Collapses of temporary structures or scaffolding
- Falls during the installation or removal of formwork
- Accidents involving personal fall arrest systems

Contributing elements frequently encompass insufficient fall protection measures, misuse of safety gear, and a deficiency in adequate training [7, 8]. Additionally, environmental factors, especially strong winds and slippery surfaces, often intensify the risks associated with falls.

3.1.2. Struck-by Incidents

Accounting for roughly 25% of serious accidents, struck-by incidents form the second most common category. These typically involve workers being hit by falling objects, swinging loads, or moving equipment.
Key scenarios include:
Objects falling from overhead work areas
Crane or hoist accidents during material handling
Incidents involving moving construction vehicles
Collapse of partially completed structures

The main factors identified consist of ineffective communication among work teams, inadequate safeguarding of tools and materials, and a lack of awareness regarding surrounding activities [9].

3.1.3. Caught-in/between Accidents

Accounting for roughly 15% of severe incidents, these accidents occur when workers become trapped, crushed, or compressed between various objects or machinery.
Common occurrences include:

- Entrapment in collapsing structures or excavations
- Accidents involving heavy machinery or moving parts
- Compression between large structural elements during assembly

The fundamental issues frequently stem from the absence of effective lockout/tagout protocols, poor communication during essential operations, and inadequate barriers around dangerous zones [10, 11].

3.1.4. Electrical Accidents

Although they occur less often, electrical accidents represent approximately 10% of serious incidents and tend to be particularly severe when they do happen. Such incidents usually involve interactions with overhead power lines, unprotected wiring, or malfunctioning equipment.
Key scenarios include:

- Crane or equipment contact with overhead power lines
- Electrocution during welding operations
- Accidents involving temporary power systems

The underlying factors often involve insufficient identification and labeling of electrical hazards, inadequate insulation, and the neglect of appropriate grounding practices [12].

3.1.5. Structural Collapses

While structural collapses during construction are infrequent, their occurrence can lead to devastating consequences. This analysis reveals that these incidents represent around 5% of severe accidents, yet they contribute to a significantly higher proportion of fatalities.
Notable scenarios include:

- Collapse of falsework or temporary support structures
- Failure of partially completed bridge sections
- Overloading of structures during construction phases

The fundamental causes often include design flaws, errors in estimating load-bearing capacities, insufficient temporary support structures, and the untimely removal of supports [13, 14].

3.1.6. Health-related Incidents

Although they may not always be categorized as accidents, health-related incidents represent a considerable issue in the realm of bridge construction. Such incidents encompass exposure to toxic materials, musculoskeletal disorders resulting from repetitive activities or heavy lifting, as well as illnesses associated with extreme heat [15].
Common issues include:

- Respiratory problems from concrete dust or welding fumes
- Hearing loss from prolonged exposure to high-noise environments
- Skin conditions from contact with irritant materials

3.2. Underlying causes

Underlying causes often relate to inadequate personal protective equipment (PPE), insufficient ventilation in confined spaces, and lack of proper ergonomic considerations in task design [16-18].

Underlying Systemic Causes:

This analysis reveals several systemic factors that contribute to accidents across all categories:

- Time Pressure: Tight project deadlines often lead to rushed work and corner-cutting on safety measures.
- Inadequate Training: Many accidents are linked to workers' lack of proper safety training or understanding of specific job hazards.
- Communication Breakdowns: Poor coordination between different teams or language barriers in multinational crews frequently contribute to accidents.
- Fatigue: Long work hours and night shifts are associated with increased accident rates.
- Safety Culture: Projects with weak safety cultures and inadequate management commitment to safety show higher accident rates.
- Economic Pressures: Cost-cutting measures sometimes lead to compromises in safety equipment or procedures.
- Regulatory Compliance: Variations in safety regulations across different regions and inconsistent enforcement contribute to uneven safety standards.
- Environmental Factors: Challenging weather conditions, particularly in extreme climates, significantly impact accident rates.
- Technology Integration: While new technologies often enhance safety, their improper implementation or over-reliance can sometimes create new risks.
- Human Factors: Individual behaviors, including risk-taking, complacency, and failure to follow established safety procedures, remain significant contributors to accidents.

3.3. Discussion

This comprehensive analysis of accident types and causes in bridge construction underscores the multifaceted nature of safety challenges in the industry [19]. While certain accident types, such as falls and struck-by incidents, predominate, the underlying causes reveal a complex interplay of technical, organizational, and human factors. Addressing these issues requires a holistic approach that encompasses improved engineering controls, enhanced safety management systems, and a strong focus on cultivating a positive safety culture [20]. The subsequent sections of this review will explore current safety practices, regulatory frameworks, and emerging technologies aimed at mitigating these risks and enhancing overall safety in bridge construction projects [21, 22].

4 Current safety practices and emerging technologies in bridge construction

The bridge construction sector continues to confront ongoing issues related to workplace accidents, prompting the development of various safety protocols and advanced technologies. This section analyzes contemporary safety management strategies and investigates innovative technologies that hold the potential for decreasing accident occurrences and improving overall safety in bridge construction endeavors [23-30].

4.1. Safety Management Systems (SMS)

Contemporary bridge construction initiatives are progressively incorporating extensive Safety Management Systems. These systems amalgamate safety policies, procedures, and practices into every facet of project planning and implementation.

Key components of effective SMS include:

- Clear safety policies and objectives
- Systematic hazard identification and risk assessment processes
- Defined roles and responsibilities for safety management
- Regular safety audits and performance monitoring
- Incident reporting and investigation procedures
- Continuous improvement mechanisms

This analysis of projects implementing robust SMS indicates a 30-40% reduction in accident rates compared to those without such systems [23, 24].

4.2. Training and Competency Programs

Advanced training initiatives have emerged as a fundamental element in the enhancement of safety measures [25-27]. These initiatives extend beyond mere introductory safety training to encompass:

- Task-specific safety training
- Simulation-based training for high-risk activities

- Regular refresher courses and safety drills
- Competency assessments for critical roles

Innovative training techniques, particularly those involving virtual reality (VR) simulations, have demonstrated significant potential. Research involving 500 employees who underwent VR training for fall protection revealed a 70% decrease in incidents related to falls when contrasted with conventional training approaches.

4.3. Personal Protective Equipment (PPE) Advancements

Innovations in PPE have significantly enhanced worker protection [28]. Notable advancements include:

- Smart helmets with built-in communication systems and impact sensors
- Self-retracting lifelines with improved fall arrest capabilities
- Ergonomically designed safety harnesses for improved comfort and compliance
- High-visibility clothing with integrated cooling systems for hot environments

4.4. Engineering Controls and Safe Design

The notion of "Prevention through Design" has become increasingly prominent, highlighting the importance of integrating safety considerations from the initial phases of project development. This methodology encompasses [29-32]:

- Designing temporary works with the same rigor as permanent structures
- Prefabrication of large components to reduce on-site assembly risks
- Incorporation of permanent fall protection systems into bridge designs
- Use of Building Information Modeling (BIM) to identify and mitigate safety risks during the design phase

4.5. Advanced Monitoring and Warning Systems

Technology-driven monitoring systems are increasingly deployed to enhance site safety:

- Proximity warning systems to prevent collisions between workers and equipment
- Structural health monitoring systems to detect early signs of instability
- Environmental monitoring for hazardous conditions (e.g., high winds, lightning)
- Wearable devices that track workers' vital signs and environmental exposures

A new model combining rough set theory, sparrow search algorithm, and least squares support vector machine was proposed by Li et al. [33] to improve early warnings in bridge construction safety. The model optimized the selection of early warning factors, reducing complexity and enhancing accuracy and Fig. 3 depicts the proposed flowchart.

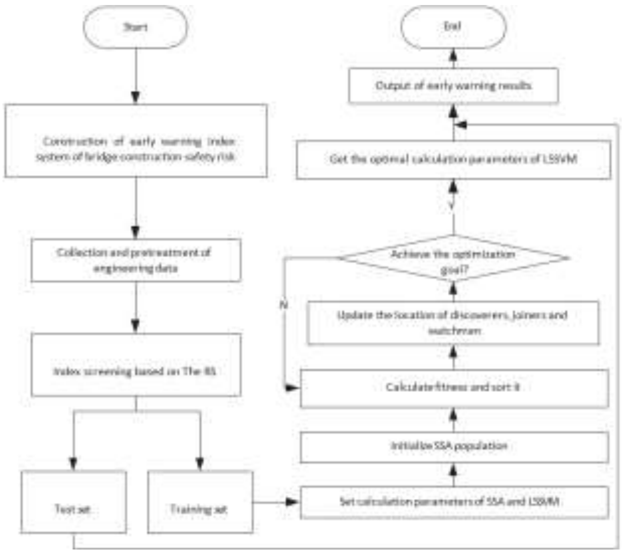

Figure 3. Flow chart of the early-warning model proposed by Li et al. (2021) [33]

4.6. Drone Technology

Unmanned Aerial Vehicles (UAVs) or drones have revolutionized site inspections and monitoring:

- Conducting aerial surveys of hard-to-reach areas, reducing the need for workers to access dangerous locations
- Real-time monitoring of construction progress and potential hazards
- Thermal imaging to detect structural issues or equipment overheating

A case study of a major bridge project in Europe reported a 60% reduction in working-at-height hours through the use of drone inspections [34].

4.7. Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) applications are emerging as powerful tools for safety management [35-40]:

- Predictive analytics to identify potential safety risks based on project data
- Automated analysis of safety inspection reports to identify trends and areas for improvement

- Computer vision systems for real-time detection of safety violations (e.g., PPE non-compliance)

4.8. Mobile Applications and Digital Platforms
Digital tools have streamlined safety processes and improved communication [41-44]:
- Safety observation and near-miss reporting apps
- Digital job hazard analysis tools
- Real-time safety dashboards for project management
- QR code-based systems for equipment inspections and certifications

4.9. Exoskeletons and Assistive Devices
To reduce physical strain and prevent musculoskeletal injuries, some projects are piloting the use of [45-48]:
- Passive exoskeletons to support workers during lifting and overhead work
- Power-assisted tools to reduce repetitive stress injuries

4.10. Advanced Materials and Equipment
Innovations in materials and equipment design contribute to safer work environments [49]:
- Self-consolidating concrete to reduce the need for vibration and improve placement safety
- Modular scaffolding systems with integrated fall protection
- Automated rebar-tying machines to reduce repetitive stress injuries

4.11. Safety Culture Initiatives

Recognizing the importance of human factors, many organizations are implementing programs to foster a positive safety culture [50-53]:

- Behavior-based safety programs
- Leadership safety commitment initiatives
- Peer-to-peer safety observation programs
- Safety incentive schemes that reward proactive safety behaviors rather than just accident-free periods

4.12. Collaborative Safety Approaches
Industry-wide collaborations are emerging to address safety challenges :
- Shared lessons learned databases
- Industry-specific safety standards and best practices
- Joint research initiatives on emerging safety technologies

4.13. Challenges and Limitations
Despite these advancements, several challenges remain [54-56]:
- High initial costs of implementing new technologies
- Resistance to change among some workers and managers
- Need for continuous training to keep pace with technological advancements
- Potential for over-reliance on technology at the expense of fundamental safety practices
- Ethical and privacy concerns related to worker monitoring technologies

4.14 Discussion
The domain of safety practices and technologies in bridge construction is undergoing significant transformation [57-60]. While foundational methods such as comprehensive safety management systems and thorough training initiatives continue to play a vital role, the advent of new technologies presents innovative possibilities for enhancing safety measures [61-64]. The amalgamation of these cutting-edge tools with established best practices holds the promise of markedly decreasing accident rates and elevating overall safety performance in bridge construction endeavors [65-68]. Nevertheless, it is imperative to acknowledge that technology in isolation is insufficient. The most successful safety strategies are those that integrate technological advancements with a robust safety culture, strong management commitment, and active worker participation [69, 70]. As the sector progresses, continuous research, collaboration, and adaptability will be critical in tackling ongoing safety issues and capitalizing on emerging opportunities for enhancement [71-76].

5 Conclusion and recommendations for improving health and safety in bridge construction
This extensive examination of workplace accidents in the context of bridge construction has uncovered a multifaceted array of challenges, prevailing practices, and innovative solutions. Upon synthesizing the results of this analysis, it is evident that, despite notable advancements in safety

measures, considerable opportunities for further improvement persist. The concluding section encapsulates essential insights and provides recommendations for various stakeholders within the bridge construction sector [46-50].

5.1. Key Findings

In the following, the key findings from the above comprehensive analysis are provided:

- Persistent Risks: Falls from height, struck-by incidents, and caught-in/between accidents continue to be the leading causes of serious injuries and fatalities in bridge construction.
- Systemic Factors: Time pressure, inadequate training, communication breakdowns, and weak safety cultures contribute significantly to accident occurrence.
- Technological Promise: Emerging technologies, including AI, drones, and advanced monitoring systems, show considerable potential in enhancing safety outcomes.
- Holistic Approach: The most effective safety strategies combine robust management systems, advanced technologies, and a strong safety culture.
- Economic Impact: While safety improvements often require significant upfront investment, they ultimately lead to cost savings through reduced accidents, improved productivity, and enhanced reputation.

5.2. Recommendations

Based on these findings, the following recommendations for improving safety in bridge construction can be proposed:

Integrate Safety in Design:

- Mandate the use of Prevention through Design (PtD) principles in all bridge projects.
- Utilize Building Information Modeling (BIM) to identify and mitigate safety risks during the design phase.
- Design permanent fall protection systems as integral parts of bridge structures.

Enhance Training and Competency Programs:

- Implement virtual reality (VR) and augmented reality (AR) training simulations for high-risk activities.
- Develop industry-wide competency standards for critical roles in bridge construction.
- Establish mentorship programs pairing experienced workers with newcomers.

Leverage Advanced Technologies:

- Invest in AI-powered predictive analytics for proactive risk management.
- Expand the use of drone technology for inspections and monitoring.
- Implement wearable technologies to monitor worker health and environmental conditions.

Strengthen Safety Management Systems:

- Develop industry-specific SMS guidelines tailored to bridge construction challenges.
- Implement digital platforms for real-time safety reporting and analytics.
- Establish cross-project learning mechanisms to share best practices and lessons learned.

Foster a Positive Safety Culture:

- Implement behavior-based safety programs that emphasize positive reinforcement.
- Develop leadership training programs focused on safety communication and engagement.
- Establish recognition programs that reward proactive safety initiatives.

Enhance Collaboration and Standardization:

- Develop industry-wide safety standards specific to bridge construction.
- Establish a global database for sharing accident data and near-miss reports.
- Create collaborative research initiatives involving industry, academia, and regulatory bodies.

Improve Regulatory Framework:

- Advocate for harmonized safety regulations across different regions to ensure consistent standards.
- Implement performance-based safety regulations that encourage innovation in safety practices.
- Enhance enforcement mechanisms, including increased site inspections and meaningful penalties for non-compliance.

Prioritize Mental Health and Wellbeing:

- Implement comprehensive mental health programs addressing stress, fatigue, and work-life balance.
- Provide resources for substance abuse prevention and treatment.
- Conduct regular assessments of psychosocial risks in the workplace.

Enhance Supply Chain Safety:

- Extend safety requirements and training to subcontractors and suppliers.
- Implement pre-qualification processes that prioritize safety performance in vendor selection.
- Develop collaborative safety initiatives across the entire project supply chain.

Invest in Research and Development:

- Allocate resources for ongoing research into emerging safety technologies and practices.
- Collaborate with academic institutions to study the long-term health impacts of bridge construction work.
- Explore applications of emerging technologies like robotics and nanotechnology in enhancing safety.

Improve Emergency Response and Recovery:

- Develop comprehensive emergency response plans tailored to bridge construction environments.
- Conduct regular drills simulating various accident scenarios.
- Implement post-accident support programs for affected workers and families.

Address Environmental and Climate Challenges:

- Develop specific safety protocols for extreme weather conditions.
- Integrate climate change considerations into long-term safety planning for bridge projects.
- Invest in equipment and PPE designed for changing environmental conditions.

5.3. Future Outlook

The outlook for safety in bridge construction is encouraging, driven by advancements in technology and an increasing recognition of the necessity for thorough safety management practices. Achieving this potential, however, demands a unified commitment from all parties involved - project owners, contractors, laborers, regulatory bodies, and technology developers. As the sector progresses, it is imperative to strike a balance between embracing innovative technologies and adhering to the core tenets of safety management. The human factor - cultivating a safety-oriented culture, providing adequate training, and ensuring constant vigilance - will continue to be vital, even as automation and artificial intelligence gain prominence. Furthermore, as bridge construction initiatives grow in complexity and ambition, new challenges will emerge.

Ongoing research, flexibility, and collaboration will be critical in tackling these evolving risks and sustaining the positive trend in safety enhancements. In summary, despite notable advancements in safety within bridge construction, there is a pressing need for continuous improvement. By adopting these strategies and maintaining a strong focus on worker safety, the industry can strive toward eradicating workplace accidents and fostering a safer environment for all participants in the essential work of bridge construction. The journey to this goal will necessitate persistent effort, investment, and innovation.

Nevertheless, the potential benefits - measured in lives saved, injuries avoided, and projects executed safely and effectively - underscore the significance of this pursuit for the entire construction sector.

5.4. Epilogue

The insights gained from bridge construction incidents highlight the paramount significance of safety in environments characterized by high risk. It is essential to strictly follow safety protocols and best practices, alongside the careful selection and utilization of equipment, particularly in areas with heavy traffic. The implementation of redundant safety measures can avert disastrous failures, while a comprehensive review and validation of construction plans can identify potential design deficiencies. The use of contemporary, safe materials for bridge infrastructure, including utilities, is of utmost importance. Furthermore, it is critical to provide adequate protection and support for workers engaged in demolition and renovation activities, as well as to invest in cutting-edge safety equipment and technologies. Ensuring that all construction phases are guided by clear, documented plans is necessary, and any safety issues must be promptly and effectively addressed. Recognizing the evolving nature of safety standards, remaining informed about regulations, and taking into account environmental considerations and specific hazards associated with each project are vital. Emphasizing worker training and enforcing adherence to safety protocols are crucial components. By reflecting on past accidents, the industry can strive to prevent similar occurrences in the future, thereby safeguarding workers and facilitating the successful completion of projects.

References:

[1] Shan, Z., Qiu, L., Chen, H., & Zhou, J. (2023). Coupled analysis of safety risks in bridge construction based on nk model and SNA. Buildings, 13(9), 2178.

[2] Chai, G., Ding, S. S., & Liu, X. Y. (2012, August). Risk assessment of bridge construction stage based on FCE. In 2012 2nd International Conference on Uncertainty Reasoning and Knowledge Engineering (pp. 256-259). IEEE.

[3] The Official Website of Golden Gate Bridge - San Francisco. (2024, August 22). https://www.goldengate.org/

[4] Wang, Y., & Xiao, D. (2022). General Standard Model for Safety Risk Assessment of Highway Bridge Construction. In Green Connected Automated Transportation and Safety: Proceedings of the 11th International Conference on Green Intelligent Transportation Systems and Safety (pp. 675-687), Springer, Singapore.

[5] Sun, B., Zhou, H., Dong, F., Ruan, W., & Zhang, X. (2022). Risk assessment of bridge construction safety considering multi-information fusion. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 8(4), 04022045.

[6] Qin, X., Zha, X., Wu, Z., & Zhang, L. (2023). Grey fuzzy comprehensive evaluation of bridge risk during periods of operation based on a combination weighting method. Applied Sciences, 13(15), 8964.

[7] Sun, B., Zhou, H., Cao, W., Chen, W., Chen, B., & Zhuang, Y. (2023). Vertical and Horizontal Combined Algorithm for Missing Data Imputation in Bridge Health Monitoring System. Journal of Bridge Engineering, 28(6), 04023033.

[8] Ren, X., & Wang, J. (2020, August). Safety Risk Assessment of Bridge Construction Based on Risk Coupling Mechanism. In International Conference on Construction and Real Estate Management 2020 (pp. 140-147). Reston, VA: American Society of Civil Engineers.

[9] Yue, Y. (2024). Construction risk of highway bridges in plateau and mountainous areas based on safety risk assessment. Journal of Computational Methods in Sciences and Engineering, 24(3), 1617-1630.

[10] Chen, F., Ji, H., & Wei, Y. (2019). Using network theory to explore the risk characteristics of bridge-tunnel hybrid construction. IEEE Access, 7, 116038-116046.

[11] Ran, R., Wang, S., Fang, J., & Wang, Y. (2024). Safety Risk Analysis of Urban Viaduct Construction Based on Dynamic Weight. Buildings, 14(4), 1014.

[12] Chen, F., Wu, X., & Wei, Y. (2022). Causation analysis for bridge-tunnel hybrid construction accident based on FISM-DEMATEL. IFAC-Papers On Line, 55(10), 1429-1434.

[13] Fu, X., Yang, M., Liu, H., Wang, L., & Li, Q. (2024). Risk Analysis and Simulation of Large Bridge Construction Based on System Dynamics. Buildings, 14(5), 1488.

[14] Wu, C., Yan, Y., Yang, S., Huang, Y., Ren, X., Wu, H., ... & Zhu, S. (2021, August). Research on Safety Risk Evaluation Model of Bridge Construction Based on Analytic Hierarchy Process. In Journal of Physics: Conference Series (Vol. 2005, No. 1, p. 012183). IOP Publishing.

[15] Su, H., Guo, C., Han, T., Li, R., Liu, Z., Su, F., & Shang, L. (2023). Research on Safety State Evaluation of Cable-Stayed Bridge Structures across the Sea. Journal of Marine Science and Engineering, 11(11), 2034.

[16] Li, Q., Zhou, J., & Feng, J. (2022). Safety risk assessment of highway bridge construction based on cloud entropy power method. Applied Sciences, 12(17), 8692.

[17] Wang, L., Jin, R., Zhou, J., & Li, Q. (2023). Construction Risk Assessment of Yellow River Bridges Based on Combined Empowerment Method and Two-Dimensional Cloud Model. Applied Sciences, 13(19), 10942.

[18] Su, H., Guo, C., Wang, Z., Han, T., Kamanda, D. B., Su, F., & Shang, L. (2024). Research on safety condition assessment methodology for single tower steel box girder suspension bridges over the sea based on improved AHP-fuzzy comprehensive evaluation. Scientific Reports, 14(1), 12079.

[19] Lu, Y., Nie, C., Zhou, D., & Shi, L. (2023). Research on programmatic multi-attribute decision-making problem: An example of bridge pile foundation project in karst area. Plos one, 18(12), e0295296.

[20] Yao, B., Wang, L., Gao, H., & Ren, L. (2024). Bridge Construction Risk Assessment Based on

Variable Weight Theory and Cloud Model. Buildings, 14(3), 576.

[21] Yang, H., Jiang, L., Xu, F., Gu, J., Ye, Z., Peng, Y. & Cheng, R. (2024). Safety Evaluation for Fabricated Small Box Girder Bridges Based on Fuzzy Analytic Hierarchy Process and Monitoring Data. Sensors, 24(14), 4592.

[22] Kim, J. M., Kim, T., & Ahn, S. (2020). Loss assessment for sustainable industrial infrastructure: Focusing on bridge construction and financial losses. Sustainability, 12(13), 5316.

[23] Ran, R., Zhou, H., & Fang, J. (2023). Safety Risk Analysis of Precast Bridge Deck Hoisting Construction Based on Structural Entropy Weight Method. In ICCREM 2023 (pp. 956-963).

[24] Zeng, X., Yin, H., & Li, Y. (2015, December). Application of modified LEC method in the large municipal bridge construction hazard evaluation. In 2015 8th International Symposium on Computational Intelligence and Design (ISCID) (Vol. 2, pp. 614-617). IEEE.

[25] Liu, B. (2024, March). Application of Improved Random Subspace Algorithm in Bridge Overall Risk Assessment System. In 2024 International Conference on Distributed Computing and Optimization Techniques (ICDCOT) (pp. 1-5). IEEE.

[26] Man, X., Wang, W., Wang, X., & Wang, Y. (2022, June). Risk Detection System of Bridge Construction Based on Fast ICA Algorithm. In International Conference on Applications and Techniques in Cyber Intelligence (pp. 36-44). Cham: Springer International Publishing.

[27] Sherif Elrifaee, M. (2023). Enhancing construction safety training of bridges using augmented reality and virtual reality. MSc Thesis, School of Sciences and Engineering, American University in Cairo, Cairo, Egypt.

[28] The Minsitry of Construction. (2019). Safety Control Manual For Road & Bridge Construction (1st ed., p. SF-8). The Republic of the Union of Myanmar.118

[29] Cui, H., Zhang, L., & Wang, H. (2011, June). Safety management of reinforced concrete bridges in China and evaluation methods for strength of existing RC bridges with crack. In 2011 International Conference on Remote Sensing, Environment and Transportation Engineering (pp. 3445-3448). IEEE.

[30] _Chen, F., Wei, Y., Ji, H., & Xu, G. (2024). A multiplex network based analytical framework for safety management standardization in construction engineering. Advanced Engineering Informatics, 59, 102278.

[31] McPheron, D., McCullouch, B., & Bowman, M. D. (2012). Structural impact of construction loads (No. FHWA/IN/JTRP-2012/18). Purdue University. Joint Transportation Research Program.

[32] Li, R. Y. M., Ho, D. C. W., & Tang, B. (2018). Factors which affect construction safety in different types of construction work. In Advances in Safety Management and Human Factors: Proceedings of the AHFE 2017 International Conference on Safety Management and Human Factors, July 17–21, 2017, The Westin Bonaventure Hotel, Los Angeles, California, USA 8 (pp. 67-76). Springer International Publishing.

[33] Li, G., Ran, R., Fang, J., Peng, H., & Wang, S. (2021). Early warning for the construction safety risk of bridge projects using a RS-SSA-LSSVM model. Advances in Civil Engineering, 2021, 1-14. doi:10.1155/2021/4449451

[34] Zhang, L., Li, R., Wang, H., & Shi, Y. (2011, April). Problems on safety management of bridges in China and its improving measures. In 2011 International Conference on Electric Technology and Civil Engineering (ICETCE) (pp. 6088-6090). IEEE.

[35] Latupeirissa, J. E., Wong, I. L. K., & Tiyow, H. C. (2021, November). Causes of work accidents and its impact on the road and bridge construction projects. In IOP Conference Series: Earth and Environmental Science (Vol. 907, No. 1, p. 012023). IOP Publishing.

[36] Bilim, A., & Celik, O. N. (2018). Assessment of work accidents in highway, street and bridge construction. International Multidisciplinary Scientific GeoConference: SGEM, 18(6.4), 333-339.

[37] Wu, Y., & Lu, P. (2022). Comparative analysis and evaluation of bridge construction risk with multiple intelligent algorithms. Mathematical Problems in Engineering, 2022(1), 2638273.

[38] Ichwan, N. E., Sutoni, A., & Khoerunnisa, S. T. (2021, February). Analysis of occupational safety and health systems in bridge construction development logistics systems: case study at cibeureum bridge, sukabumi. In Journal of Physics: Conference Series (Vol. 1764, No. 1, p. 012173). IOP Publishing.

[39] Bu, Z., Zhang, G., & Guo, Q. (2024). Study on Construction Risks of Prefabricated Assembly of Urban Bridge Substructures. In 2023 5th International Conference on Civil Architecture

and Urban Engineering (ICCAUE 2023) (pp. 283-298). Atlantis Press.
[40] Chen, T. T., & Wang, C. H. (2017). Fall risk assessment of bridge construction using Bayesian network transferring from fault tree analysis. Journal of Civil Engineering and Management, 23(2), 273-282.
[41] Tanner, P., Hingorani, R., Bellod, J. L., & Sanz, D. (2018). Thoughts on construction risk mitigation and acceptance. Structural Engineering International, 28(1), 60-70.
[42] Bolpagni, M., Bosché, F., de Boissieu, A., Akbarieh, A., Shaw, C., Mêda, P., ... & Sacks, R. (2022, July). An explorative analysis of European standards on Building Information Modelling. In 2022 European conference on computing in construction. European Council on Computing in Construction (EC3).
[43] Wildenauer, A., Mbabu, A., Underwood, J., & Basl, J. (2022). Building-as-a-service: Theoretical foundations and conceptual framework. Buildings, 12(10), 1594.
[44] Sibenik, G., Mizumoto, J., Bosche, F., Meda, P., Puust, R., Akbarieh, A., & Bolpagni, M. (2023, July). Adoption of BIM-related international standards across Europe. In EC3 Conference 2023 (Vol. 4, pp. 0-0). European Council on Computing in Construction.
[45] Gao, B., Ma, Z., Gu, J., Han, X., Xiang, P., & Lv, X. (2024). Fusing multi-source quality statistical data for construction risk assessment and warning based on deep learning. Knowledge-Based Systems, 284, 111223.
[46] Kim, J. M., Lim, K. K., Yum, S. G., & Son, S. (2022). A deep learning model development to predict safety accidents for sustainable construction: a case study of fall accidents in South Korea. Sustainability, 14(3), 1583.
[47] Kim, J. M., Bae, J., Son, S., Son, K., & Yum, S. G. (2021). Development of model to predict natural disaster-induced financial losses for construction projects using deep learning techniques. Sustainability, 13(9), 5304.
[48] Kim, J. M., Adhikari, M. D., Bae, J., & Yum, S. G. (2024). A deep neural network algorithm-based approach for predicting recovery period of accidents according to construction scale. Heliyon.
[49] Bae, J., Yum, S. G., & Kim, J. M. (2021). Harnessing machine learning for classifying economic damage trends in transportation infrastructure projects. Sustainability, 13(11), 6376.
[50] Supriyatna, H., Kurniawan, W., & Purba, H. H. (2020). Occupational safety and health risk in building construction project: literature review. Operational research in engineering sciences: theory and applications, 3(1), 28-40.
[51] Kurnia, R. F., Latief, Y., & Riantini, L. S. (2018, March). The Development of Risk Based Standardized WBS (Work Breakdown Structure) for Cost Estimation of Concrete Precast Bridge Construction. In Proceedings of The International Conference on Industrial Engineering and Operations Management. Bandung, Indonesia (pp. 731-739).
[52] Widiastuti, I. E., Purba, H., & Purba, A. (2020). Identification of safety risk in construction project: A systematic literature review. Advance researches in civil engineering, 2(3), 24-40.
[53] Handoko, F., Wijayaningtyas, M., Kusuma, I. H. A., Hidayat, S., Ismail, A., & Abdullah, Z. (2020). The occupational health and safety effect on road construction worker performance. Civil Engineering and Architecture, 8(5).
[54] Satrio, G., & Latief, Y. (2018). Development of risk-based standardized WBS (Work Breakdown Structure) for safety planning of cable-stayed bridge project. In Proceedings of the international conference on industrial engineering and operations management (Vol. 12, No. 2, pp. 110-117).
[55] Ramadhansyah, M. F., YD, N. A., & Onny, S. (2020). Dust Exposure and Symptomps of Respiratory Disorder on Worker of Sikatak Bridge Development Project. In E3S Web of Conferences (Vol. 202, p. 12002). EDP Sciences.
[56] Riyanta, S., Hartiwiningsih, H., & Rachmi, I. G. (2019, May). Community Rights in Taking the Legal Effort of the Accidents of Government Infrastructure. In First International Conference on Progressive Civil Society (ICONPROCS 2019) (pp. 28-33). Atlantis Press.
[57] Saputri, L. D., & Prajitno, A. F. H. (2022). Time and Cost Estimation of Watu Sewu Bridge Construction on the South Cross Road LOT 7 Project Blitar. Jurnal Transportasi: Sistem, Material, dan Infrastruktur, 5(2), A247-A253.
[58] Saputra, P. D., Laksmi, A. A., Purwanti, N., & Fansuri, M. H. (2022, February). Development of Activity-Based Safety Plan for Precast Parapet Panel Work in Elevated Construction. In Proceedings of the Second International Conference of Construction, Infrastructure, and Materials: ICCIM 2021, 26 July 2021, Jakarta,

Indonesia (pp. 459-470). Singapore: Springer Nature Singapore.
[59] Do, Q., Le, T., & Le, C. (2024). Text Mining-Based Approach for Identifying Critical Accident Causes in Highway Construction. In Computing in Civil Engineering 2023 (pp. 1105-1112).
[60] Chan, A. P., Wong, F. K., Hon, C. K., & Choi, T. N. (2020). Construction of a Bayesian network model for improving the safety performance of electrical and mechanical (E&M) works in repair, maintenance, alteration and addition (RMAA) projects. Safety science, 131, 104893.
[61] Widiantoro, V., Riantini, L. S., & Ichsan, M. (2023, May). Identification of factors that affect the delay in the production cycle time of precast box girder. In AIP Conference Proceedings (Vol. 2706, No. 1). AIP Publishing.
[62] Wu, K., Zhang, J., Huang, Y., Wang, H., Li, H., & Chen, H. (2023). Research on safety risk transfer in subway shield construction based on text mining and complex networks. Buildings, 13(11), 2700.
[63] Lauridsen, J., & Larsen, E. S. (2018). Quality objectives for the operation and maintenance of bridges and tunnels. In Operation and Maintenance of Large Infrastructure Projects (pp. 49-59). Routledge.
[64] Purwayudhaningsari, R., Oetomo, W., Tjendani, H. T., & Rumihin, O. F. (2023). Risk and Cost Analysis Study Occupational Health and Safety (K3) On Passenger Terminal Building Works New Mentawai Airport Development Project. Jurnal Ekonomi Teknologi dan Bisnis (JETBIS), 2(8), 590-603.
[65] Yustisia, H., Putri, N. T., & Abdi, M. (2023). The Effect of The Implementation Construction Occupational Health and Safety on The Implementation Time Of The Muaro Mais–Lubuk Gobing Bridge Construction Project Using Smart PLS. CIVED, 10(3), 1208-1216.
[66] Indriyani, I., & Kusumojanto, D. D. (2020). An occupational safety and health management system to minimize work accidents. JBMI (Jurnal Bisnis, Manajemen, Dan Informatika), 17(2), 162-166.
[67] Sutapa, I. K., Kader, I., Santiana, I., Wibawa, I., Yasa, I., & Suasira, I. W. (2021). Work Accident Risk Analysis with FMEA (Failure Mode and Effect Analysis) Method on Steel Frame Bridge Project. Int. Journal of Physical Sciences and Engineering, 5(3), 52-60.
[68] Güney, K. M. (2020). Public health risks of the uneven urban development In Istanbul: Urban inequality, environmental degradation, and earthquake risk. Urban Anthropology and Studies of Cultural Systems and World Economic Development, 1-38.
[69] Fikri, M., Aryani, S., & Pulungan, A. (2023). Feasibility Study Of Wireless Sensor Nodes On Bridges. Management Studies and Entrepreneurship Journal, 4(5), 7678-7692.
[70] Tanne, Y. A., & Indrayani, N. L. A. (2023). Review of Construction Automation and Robotics Practices in Indonesian Construction State-Owned Enterprises: Position in Project Life Cycle, Gap to Best Practice and Potential Uses. Architecture, Structures and Construction, 3(3), 373-389.
[71] Elizabeth, G. L. P., & Pagoray, G. L. (2022, June). Implementation of Occupational Safety and Health Systems Mameh–Windesi Road Development Project in West Papua Province. In WICSTH 2021: Proceedings of the 1st Warmadewa International Conference on Science, Technology and Humanity, WICSTH 2021, 7-8 Sept. 2021, Denpasar, Bali, Indonesia (p. 461). European Alliance for Innovation.
[72] Jamil, M., Maulina, F., & Hasan, M. (2020, September). The influence of occupational safety and health program on the manpower performance of construction company in Banda Aceh city. In IOP Conference Series: Materials Science and Engineering (Vol. 933, No. 1, p. 012005). IOP Publishing.
[73] Pagoray, G. L. (2021, February). Analysis of risk K3 preservation of the reconstruction Gresik–Lamongan–Babat roads in East Java Province. In IOP Conference Series: Materials Science and Engineering (Vol. 1088, No. 1, p. 012092). IOP Publishing.
[74] Bria, T. A., Chen, W. T., Muhammad, M., & Rantelembang, M. B. (2024). Analysis of Fatal Construction Accidents in Indonesia—A Case Study. Buildings, 14(4), 1010.
[75] Suraji, A., & Arman, U. D. (2023). No failure no accident in man-made disasters in construction. In E3S Web of Conferences (Vol. 464, p. 07009). EDP Sciences.
[76] Ramdani, E. W. P., Tutuko, P., & Budiyanto, H. (2020). Mitigation of the Work Accident Risk on Construction Industry. 5th ICGSS.

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