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Worker Safety in Modular Construction: Investigating Accident Trends, Safety Risk Factors, and Potential Role of Smart Technologies

Muhammad Khan[1], Evan Mccrary[1], Chukwuma Nnaji[1*], and Ibukun Awolusi[2]

[1] *Construction Innovation Integration Laboratory (CII-Lab), Department of Civil, Construction, and Environmental Engineering, 3043 HM Comer, The University of Alabama, Tuscaloosa, AL 35487, USA.* Email: *cnnaji@eng.ua.edu*
[2] *School of Civil & Environmental Engineering, and Construction Management The University of Texas at San Antonio, San Antonio, TX 78207, USA.*

Abstract: Modular building is a fast-growing construction method, mainly due to its ability to drastically reduce the amount of time it takes to construct a building and produce higher-quality buildings at a more consistent rate. However, while modular construction is relatively safer than traditional construction methods, workers are still exposed to hazards that lead to injuries and fatalities, and these hazards could be controlled using emerging smart technologies. Currently, limited information is available at the intersection of modular construction, safety risk, and smart safety technologies. This paper aims to investigate what aspects of modular construction are most dangerous for its workers, highlight specific risks in its processes, and propose ways to utilize smart technologies to mitigate these safety risks. Findings from the archival analysis of accident reports in Occupational Safety and Health Administration (OSHA) Fatality and Catastrophe Investigation Summaries indicate that 114 significant injuries were reported between 2002 and 2021, of which 67 were fatalities. About 72% of fatalities occurred during the installation phase, while 57% were caused by crushing and 85% of crash-related incidents were caused by jack failure/slippage. IoT-enabled wearable sensing devices, computer vision, smart safety harness, and Augment and Virtual Reality were identified as potential solutions for mitigating identified safety risks. The present study contributes to knowledge by identifying important safety trends, critical safety risk factors and proposing practical emerging methods for controlling these risks.

Keywords: Modular Construction Accident, Safety risk, Smart Safety Technology, Mobile House, Prefabricated, OSHA accident database

1. INTRODUCTION

Modular construction has been an increasingly popular method of construction in recent years [1]. Though modular buildings have a history dating back to the 17th century, according to the Modular Building Institute, its most substantial increase in popularity occurred in the 1950s, with manufactured homes being a cost-efficient and affordable solution to a post-World War II housing crisis [1]. Though there are some hindrances to the expansion of modular construction, such as a lack of building codes and standards, poor supply chain integration, and lack of expertise [2], the modular construction industry has seen a compound annual growth rate of 5.69% and has an anticipated market value of $154.8 million by the end of 2023 [3], so it is evident that modular construction is on the rise. Using 21st-century technologies and manufacturing methods, companies are looking to increase this growth rate and to have a more significant presence in the construction sector.

There are many factors why modular construction is being chosen over traditional construction methods. Modular building allows for better quality control because it greatly reduces the variability associated with construction [4]. With most modular construction operating in indoor manufacturing environments, weather and its effects on construction workers and materials are much less of a concern. The ability to standardize products enhances the consistency and quality of your products. This ability to standardize products also helps reduce the total time it takes to construct a building [5]. It also allows for more efficient build times using manufacturing techniques and reduces delays associated with traditional construction methods [4]. Cost-effectiveness is significant reason project owners opt for modular construction, especially if the projects involved are repetitive [5]. Modular construction also allows improving safety and working conditions for construction workers. By moving the majority of the construction work from construction sites to manufacturing plants, workers are in a more controlled environment, where working conditions are better monitored [6].

Though modular construction seemingly provides safer working conditions, the nature of the work required could counteract some of its advantages. Falls, falling objects, and crushing incidents are the three leading causes of accidents in manufacturing and construction settings, accounting for 85% of accidents [6]. The type of work required in modular is quite conducive to these three types of accidents. Workers are often required to be on top of modules as they are being manufactured, prepared for transport, and installed where there is potential to fall off the side or through the roof, especially if there are unsecured or lose parts [6] Investigating injury and fatality accidents related to modular construction and at what stage of construction they happened is imperative to analyze modular construction's safety. Doing so will provide insight into which stages are the most dangerous and pinpoint specific points of hazard during the modular construction process. However, limited studies have analyzed accident trends associated with modular construction or proffered potential technology-driven mitigation strategies.

Technology is largely used to boost production and efficiency in the construction sector. In site supervision, advanced technologies are utilized to monitor workers, equipment, safety, quality, and efficiency [7]. Of recent, several studies have explored the role of technologies such as sensors, robots, immersive reality devices, mobile devices, and cameras in construction safety and health management [8]. However, limited attention has focused on the role of technology as a safety risk mitigation strategy within the modular construction industry. Thus, further investigation into how to resolve modular construction safety issues as well as assess the role of emerging methods, such as smart technologies, is needed.

2. RESEARCH METHODOLOGY

In this study, accidents data and safety risks associated with the modular construction industry is extracted from the Occupational Safety and Health Administration (OSHA) Fatality and Catastrophe Investigation Summaries database [9] using keywords such as "modular", "prefabricated", "manufactured", and "mobile home". The keywords were input into the database's search function, manually analyzing descriptions and abstracts from accident reports to find injuries and fatalities related explicitly to modular construction. The extracted data is classified based on search keywords, modular construction phase accidents, and accident type. In the next step, as shown in Figure 1, the statistical information is evaluated and organized to determine the critical risk factors in the modular construction industry. Furthermore, relying on an integrated review, the researchers identified potential emerging smart technologies that could mitigate the safety risks identified through the archival analysis. Finally, future research recommendations are discussed at the end of the article.

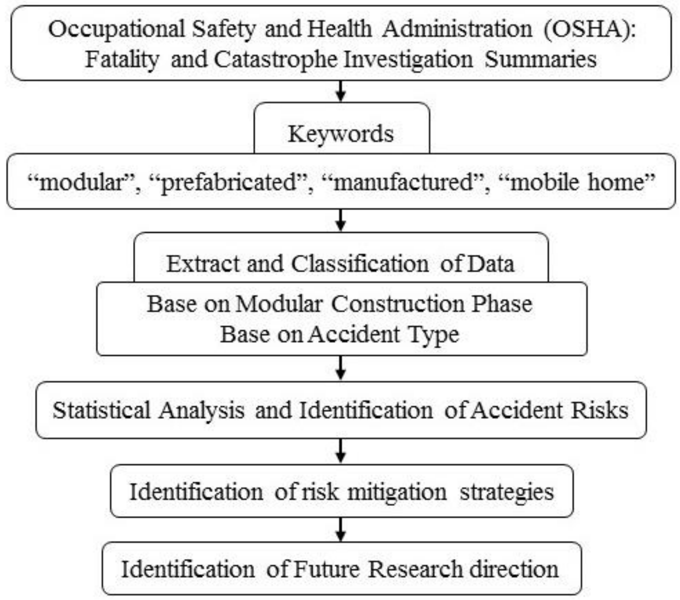

Figure 1. Research methodology for collecting and analyzing modular construction accidents.

3. FINDINGS

3.1. Archival Analysis

Keywords were input into the database's search function, analyzing descriptions and abstracts from accident reports to find injuries and fatalities related explicitly to modular construction, which yielded a total accident count of 114, with 67 resulting in a fatality. The date range for the data collected was from November 2002 - to November 2021. The data was then categorized by which phase of modular construction the injury occurred. The three phases considered were manufacturing, transportation, and installation of the modules. Table 1 provides a summary of the collected data:

Table 1. Modular construction-related accidents and accident rates at a different phase.

Phase	Number of Accidents	Accidents Rate	Number of Fatalities	Fatalities Rate
Manufacturing	27	24%	8	12%
Transportation	13	11%	11	16%
Installation	74	65%	48	72%
Total	114	100%	67	100%

An initial investigation into the breakdown of accidents related to modular construction reveals that the most dangerous phase of the modular construction process is the installation phase, accounting for 65% of accidents. In comparison, 11% of accidents occurred during the transportation phase, and 24% occurred during the manufacturing phase. The installation phase also accounted for 72% of fatalities, with the transportation phase accounting for 16% of fatalities and the manufacturing phase accounting for 12% of fatalities.

The data was then categorized by injury type. The four major injuries reported were falls, crushing incidents, falling objects, and being caught by machinery/hardware. Table 2 presents this data. An investigation into the accident and fatality rates of each accident yields the result that crushing incidents are the most common type of incidents that happen during the modular construction process, accounting for 42% of accidents, while falls account for 29%, falling objects account for 16%, and workers getting caught accounts for 4%. Being crushed was the deadliest accident, accounting for 57% of fatalities related to modular construction, with falls accounting for 22% and falling objects accounting for 15%.

Table 2. Different types of accidents in modular construction from OSHA accident database.

Accident Type	Number of Accidents	Accidents Rate	Number of Fatalities	Fatality Rate
Fall	33	29%	15	22%
Crushed	48	42%	38	57%
Falling Object	18	16%	10	15%
Caught	5	4%	0	0%
Other	10	9%	4	6%
Total	114	100%	67	100%

An analysis of the distribution of accident types between the three phases of modular construction was conducted, revealing that most of the accidents happened during the installation phase for all four major accident types. During the installation phase, 48% of falls happened, 79% of crushing incidents, 67% of falling object incidents, and 80% of workers got caught. This data is presented in Table 3:

Table 3. Accident type distribution for each phase of modular construction.

Phase	Accident Type			
	Fall	**Crushing**	**Falling Object**	**Caught**
Manufacturing	48%	2%	28%	20%
Transportation	3%	19%	5%	0%
Installation	48%	79%	67%	80%
Total	100%	100%	100%	100%

Of the 48 crushing incidents reported, 45 had a description of the cause of the incident. The causes of or safety risk factors associated with crushing incidents were jack slippage/failure with 58%, other equipment failures (block supports, lifting equipment) with 27%, a lack of safety precaution with 9%, poor weather conditions with 4%, and structural failure with 2% (see Table 4).

Table 4. Cause of crushing incidents.

Cause	Number of Incidents	Percentage of Incidents
Jack Slippage/ Failure	26	58%
Equipment Failure	12	27%
Lack of Safe Precaution	4	9%
Weather Related	2	4%
Structure Failure	1	2%

It is important to note that not all accidents related to modular construction might have been reported as such or at all. With the industry being relatively young, a lack of consistent and accurate accident reporting may exist. When searching the OSHA accident database, the keywords may not have recovered all modular-related incidents. The relatively small sample size for modular-related accidents could create an inaccurate representation of risk factors related to modular construction.

3.2. Safety Risk Mitigation Technologies

As mentioned previously, smart technologies have various applications at different construction project phases [10]. A review of existing literature suggests that several technologies could be used to improve safety management in the modular construction industry. For instance, creating an immersive environment for real-life accidents scenarios to train workers to improve hazard recognition can be achieved using augmented and virtual reality technology (AR/VR). These technologies can give the experience of the dangers associated with the modular construction industry without exposure to natural hazards. Utilizing this technology reported a significant reduction of accidents when workers got training through mixed-reality technology [11]. Recently, robots have been used to reduce workers' exposure to unsafe work environments [10].

At the execution of a modular construction project, sensor and computer vision-based technology can play a vital role in preventing accidents early. The different sensors can monitor the workers' unsafe behavior, body temperature, toxic gases exposure, activity recognitions, hook status, PPE, intrusion, and body posture in real-time [12]. Through computer vision technology, hardhat, safety waste, PPE, and hazardous activity of the workers can be monitored at a high level of accuracy and precision [13]. Recent development makes it possible to collect 3D information through the Stereo camera. Because of the Stereo camera, it is possible to overcome the ordinary camera's limitation, which contains 2D information. In the recently published article, Khan et al. [13] conclude that integrating different technology can help overcome the limitations of independent technologies, thereby increasing the precision and prediction performance of the system. Table 5 provides a list of emerging technologies that could be used as risk mitigation systems and tools in the modular construction industry.

Table 5. Potential Smart Technologies

ID	Technologies
T1	Computer vision-based monitoring
T2	Sensor-based monitoring
T3	Smart personal fall arrest systems
T4	Virtual and augmented reality for training
T5	Automated prevention through design (PtD) tools
T6	Computer vision and IoT integration
T7	Stereo camera
T8	Single-task robots
T9	Building Information Modeling

4. DISCUSSION

Statistical analysis of the OSHA accident database data regarding accidents and fatalities related to modular construction shows which phases and activities are the most dangerous. As shown in Table 1, most workplace accidents related to modular construction happen during the installation phase, with an even higher percentage of fatal accidents occurring. From one point of view, this provides credence to the idea that modular construction is safer than traditional construction. With the installation phase of modular being most similar to work conducted on traditional construction sites, reducing the total amount of work done on-site should reduce the number of accidents and fatalities. But, as discussed earlier, work conducted in the field for modular construction can be, on average, more dangerous than fieldwork for traditional construction. According to Table 2, the most common type of accident for modular construction is a crushing incident, accounting for 42% of accidents. Referring to Table 2, 57% of crushing incidents resulted in a fatality, whereas only 22% of falling incidents resulted in a fatality. The results show that work done at installation sites for modular has a higher potential to be dangerous. Accidents related to modular are more likely to be fatal. Again, a significant reason fieldwork for modular construction sites is considerably more hazardous is that the objects being lifted and transported are often multi-ton, complex units. Potential safety risks include unsecured parts, improper placement of lifting accessories, a lack of structural integrity, or bad weather conditions. In these conditions, modular units could very quickly become unattached from the lifting device and cause significant harm to the workers near it. As seen in Table 4, the most common cause of crushing incidents was jack failure, accounting for 58%. Another equipment failure is the second leading cause of crushing, accounting for 27% of incidents. High lifting/support equipment percentages show that it is often used during the installation phase of modular construction and is not as effective at preventing injury as it should be. It may be because the equipment used is not specifically designed for modular construction.

The complex and dynamic working environment exposes workers to various risks on a construction site. Although the supervisors are responsible for ensuring that safety procedures are followed in order to limit the hazards and accidents mentioned in Tables 2 and 4, it could be labor-intensive and time-consuming. Recent research has used computer vision and sensor-based techniques to automate the detection of dangerous behavior such as non-compliance with PPE [14] and the use of a safety hook [13] to prevent falls from height accidents. Table 5 proposes a combination of technologies that could play a critical role in reducing accidents across the different phases in modular construction.

Crushing accidents in the modular construction industry accounts for most accidents. This can be reduced by deploying smart technologies to monitor the workers working with objects or structures. Cushing accidents take place due to failure of tower and equipment. Therefore, tower crane layout plan plays a critical role in reducing hazards; Zhang and Pan [15] developed an innovative VR tool that gives the operators experience regarding layout feasibility, layout selection, and crane lift simulation in real-time. Such technology helps the crane operators know the importance of layout and lifting load relationships early. During the manufacturing and installation phase of modular construction, computer vision, sensor-based monitoring, or integration can help monitor and predict the worker and structure behavior before any hazard or failure occurs.

Current vision-based technologies deployed for construction safety have generalization issues i.e. they detect a specific behavior. Moreover, the supervised learning-based detection approaches have labor-intensive dataset labeling procedures. So semi-supervised approaches with generalized detection ability need to be utilized. Multiple sensor fusion techniques need to be analyzed for risk elimination with improved accuracy. In response to fall from height concerns, Khan et al. [13]monitored the worker's unsafe behavior and hook status by integrating computer vision and IoT technologies. The advantage of the integration technology is that it helps to achieve high accuracy and precision. Better monitoring of man-machine co-activity and their safety assurance can be carried out by integrating tags (April tags) with monocular/stereo visual-inertial odometry. Table 6 summarizes the different technologies that could help eliminate or reduce the safety risk associated with the modular construction. The authors believe that integrating smart technologies can help develop more accurate and precise interventions needed to overcome accidents.

Table 6. Technologies for preventing modular construction accidents

Accident Type	Phase		
	Manufacturing	Transportation	Installation
Fall	T1, T2, T3, T6,T9	T1, T2 ,T6	T3, T6,T9
Crushing	T1, T2, T5, T8	T1, T6	T5, T7,T8
Falling Object	T1,T2	T1	T1,T2
Caught	T7, T8,T9	-	T7, T2, T6

5. CONCLUSION AND FUTURE RESEARCH WORK

Modular construction can reduce the number of workplace accidents related to the construction industry. While traditional construction sites certainly have their fair share of large items with crushing potential, the unpredictability involved with the lifting and moving of modular components introduces risk variables not observed on typical building sites. Significant improvements in safety procedures and equipment quality need to happen soon. The more familiar a construction method becomes the greater capacity to implement better safety measures. An increased volume of production for modular construction will allow for standardization of safety procedures and the creation of modular-specific equipment designed; to safely handle the volume and size of products produced. Ideally, this improvement in equipment and the use of emerging technologies would drastically reduce the number of injuries and fatalities that happen during modular construction, especially during the installation phase. Specifically, an improvement in the quality of jacks and monitoring technologies used to suspend mobile homes would be essential, as jack failure was responsible for 58% of accidents during the installation phase.

As modular construction grows, a greater focus will be placed on optimizing its processes, allowing for more efficient time and resources. Just as traditional construction is starting to apply modern technologies to its practices to improve quality and reduce the risk of accidents and fatalities, modular construction is expected to follow a similar trajectory. Artificial intelligence, Building Information Modelling, robotics and automation, and other emerging technologies are being applied to construction practices to improve safety and should be utilized by the modular construction industry. Though it is not the most dangerous phase of modular construction, the manufacturing phase could become safer for workers if robotics and automation (sensor and computer vision) are implemented to processes similar to other manufacturing industries, such as the automotive industry. The implementation of more advanced technologies will come with the increase in production for modular construction and should assist in ushering in better safety procedures and the performance of safer, more reliable equipment.

Future research within this domain should expand the archival analysis using more keywords to broaden the theme-based analysis. Construction material handling at different phases (manufacturing, transportation, and installation) has additional risks. Therefore, classifying and identifying the associated risk to the type of material would lead us to identify the potential hazards and develop innovative technology that would play a vital role in eliminating accidents. In addition, case studies should be conducted to evaluate the mitigation capacity of smart technologies on safety risks and accident prevention (crush and caught accident) in the modular construction industry. Furthermore, future studies could develop tools for assessing the safety risks within the modular construction industry.

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