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A Study on the Analysis of Accident Risk Factors and the Development of Safety Management Frameworks for Modular Construction Sites

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Abstract

This research seeks to formulate integrated risk mitigation strategies by identifying inherent risk factors specific to each construction phase of Modular Construction—the cornerstone of Off-Site Construction (OSC), which is increasingly adopted to enhance productivity and site safety. While modular construction yields positive outcomes, such as a reduction in overall accident frequency compared to traditional Reinforced Concrete (RC) methods due to shortened onsite work hours, it concurrently introduces unprecedented categories of major accident risks, particularly during the lifting of heavy modules and high-altitude assembly.

To address these challenges, this study structuralizes the modular construction process into four distinct stages—Delivery, Lifting, Assembly, and Finishing—and identifies critical risk factors for each stage through a dual approach involving domestic and international case analyses alongside expert Failure Mode and Effects Analysis (FMEA). The findings indicate that the most critical risk factor in modular construction is the dynamic instability of modules during the lifting phase caused by center-of-gravity imbalances. Specifically, in cases of asymmetric modules where internal finishes and MEP (Mechanical, Electrical, and Plumbing) systems are concentrated on one side, a high probability of unexpected tilting was identified, which can lead to crane overturns or module falls. Furthermore, the assembly and jointing stages were found to be primary drivers of human casualties, such as falls and crushing accidents, due to frequent high-altitude tasks performed on module tops and within confined connection spaces.

To fundamentally mitigate these risks, this study proposes a three-tier response framework based on the Hierarchy of Controls. First, as an Engineering Control, worker exposure to hazards must be inherently blocked by implementing BIM-based pre-lifting simulations and adopting smart equipment such as self-leveling spreader beams and auto-release hooks. Second, as an Administrative Control, the establishment of specialized and standardized lifting plans is required, incorporating Design for Safety (DfS) to integrate safety facilities from the design phase and the deployment of dedicated modular signalers. Third, as an Educational Control, workers' risk perception must be enhanced through cross-safety training between the fabrication factory and the site, as well as VR-based virtual safety experience programs for high-risk processes.

This study suggests a paradigm shift in the safety management of modular construction sites—from a reactive approach to a proactive, prevention-oriented system centered on design and factory fabrication. The proposed mitigation strategies are expected to serve as foundational academic data for establishing practical occupational safety and health management guidelines for future modular projects.

Keywords : Modular Construction, OSC(off-site construction), DFS(Design for Safety)

1. Introduction

1.1. Background and Necessity of the Research

The contemporary construction landscape is navigating a critical inflection point, characterized by a burgeoning shortage of skilled labor, an aging workforce, and increasingly stringent legal frameworks such as the Serious Accidents Punishment Act (SAPA). As a strategic alternative to these structural challenges, Modular Construction—a hallmark of Off-Site Construction (OSC)—has emerged prominently. This methodology involves the pre-fabrication of primary structural components and interior/exterior finishes within a factory setting, followed by rapid onsite assembly. By sequestering approximately 70–80% of the workload within a controlled environment, modular construction offers significant safety dividends, theoretically minimizing worker exposure to traditional site hazards, such as prolonged high-altitude tasks inherent in Reinforced Concrete (RC) methods.

However, the transition to modularization does not inherently eliminate all occupational risks; rather, it shifts the risk profile from the site to the factory-to-site interface. The industry is witnessing the emergence of idiosyncratic hazards previously unseen in conventional RC projects. These include the risk of overturning during the transport of massive modules, center-of-gravity (CoG) imbalances during the precision lifting of multi-ton units, and the complexities of high-altitude joining processes required for structural integration. As the domestic modular market trends toward high-rise and large-scale developments, the potential for catastrophic accidents increases. Despite this evolution, current safety management protocols remain disproportionately anchored in traditional methods. Consequently, there is an urgent imperative to establish a specialized safety management model tailored to the unique exigencies of modular construction.

1.2. Purpose and Scope of the Research

The primary objective of this study is to perform a rigorous engineering analysis of the unique risk factors inherent in modular construction sites and to derive efficacious risk mitigation strategies. To achieve this, the study deconstructs the modular construction lifecycle into four operational phases: (1) Delivery and Preparation, (2) Lifting, (3) Assembly and Joining, and (4) Subsequent Finishing.

The specific research objectives are as follows:

- Identification of Risk Factors: To define and categorize the distinct risk variables

associated with modular methods through a comprehensive review of existing literature and empirical accident case studies.

- Quantification of Hazards: To quantify the frequency and severity of identified risks by leveraging expert surveys and specialized risk assessments (e.g., FMEA) targeting practitioners and designers with modular project experience.
- Proposing Integrative Countermeasures: To formulate a multifaceted suite of engineering, administrative, and educational measures. This involves integrating Design for Safety (DfS) principles with cutting-edge Smart Safety Technologies to proactively address high-risk elements.

The scope of this research is delimited to the Stacked Modular Method, which prevails in the domestic market, with a concentrated focus on establishing safety management frameworks during the onsite assembly phase. The findings of this study are expected to serve not only as a practical safety and health manual for field managers but also as a foundational academic resource for future revisions of safety regulations and standard specifications.

2. Identification of Key Hazards by Construction Stage of the Modular Method

The construction process of the modular method is categorized into four primary stages: Preparation and Delivery, Lifting, Assembly and Joining, and Finishing. This study aimed to identify common risk variables by synthesizing previous literature on modular construction. The analysis confirmed that "Center-of-Gravity(CoG) imbalance" and "overturning of lifting equipment" are consistently identified as core risk factors across the majority of existing studies, primarily due to the frequent handling of heavy-duty units.

Furthermore, an analysis of accident case studies from modular housing sites over the past five years, alongside disaster investigation reports from the Ministry of Employment and Labor (MOEL), revealed that accidents unique to the modular method—such as "crushing (caught-in/between) accidents" during module seating and "overturning during transport"—account for a higher proportion of incidents than simple falls.

In relation to these findings, in-depth interviews were conducted with a panel of subject matter experts (SMEs), including construction safety managers, modular site engineers, and foremen. These experts were tasked with selecting items from traditional Reinforced Concrete (RC) risk factors that exhibit the highest "volatility" and "potential for major accidents" within a modular context. Notably, they underscored the urgency of addressing

"access road gradients" and "fall protection facilities on module tops." Ultimately, priority was given to risks that necessitate Elimination or Engineering Controls, rather than those relying on worker attentiveness. Consequently, core risk factors stemming from the physical structural characteristics of modular units (such as asymmetry and exposure to heights) were selected and are presented in Table 1.

Table 1: Risk Factors by Construction Stage of the Modular Method

Construction Stage	Detailed Process	Key Hazard Factors	Expected Accident Type	Risk Grade
Preparation & Delivery	Ground leveling & Module unloading	- Lack of ground bearing capacity under outriggers - Traffic interference between delivery vehicles and site equipment - Collision and damage between modules during unloading	Crane overturning, Entrapment, Fall	Medium
Lifting	Sling fastening, Hoisting, Slewing	- Tilting due to asymmetrical center of gravity of the module - Dynamic oscillation of the module during bad weather (strong winds, etc.) - Defects or breakage of lifting wire ropes/sling belts	Module fall, Crane overturning, Flying objects	High (Critical)
Assembly & Connection	Unit placement, Bolting/Welding	- Lack of fall prevention facilities during work on top of the module - Getting caught between the descending module and the installed module - Poor installation of temporary scaffolds and work platforms	Worker fall, Entrapment (Getting caught)	High (Critical)
Post-Assembly Finishing	Facility connection & Exterior finishing	- Poor working posture in narrow spaces between modules (Shafts, etc.) - Collision and overturning when moving high-altitude work platforms (TL, SKY) - Falling of materials and tools from above	Musculoskeletal disorders, Fall, Flying objects	Medium

2.1. Analysis of Risk Characteristics and Causal Relationships by Process and Stage

The modular construction process is characterized by a specialized workflow involving the logistical transit of factory-complete units and their subsequent onsite integration. The risk factors emergent in this sequence are not confined to isolated mechanical malfunctions; rather, they manifest as a synergistic complexity involving design tolerances, site-specific topographical variables, and human performance factors. To facilitate a rigorous investigation, this study deconstructs the construction lifecycle into four discrete phases—Foundation Preparation and Delivery, Lifting, Assembly and Joining, and Finishing—conducting a granular analysis of the core hazards inherent in each stage..

2.1.1. Ground Stability and Logistics Risks in the Preparation and Delivery Stage

Construction safety at modular sites begins with ensuring the ground bearing capacity of the setting area for

large lifting equipment and the waiting area for modules before modules are delivered.

① Overturning risk due to lack of ground bearing capacity: Compared to the general RC (Reinforced Concrete) method, modular sites use large cranes more frequently. Poor compaction of the ground under the crane outriggers or insufficient verification of underground buried objects were identified as fatal risk factors causing equipment overturning during the lifting process.

② Interference and collision risks within the lifting radius: When multiple modules are delivered sequentially in a narrow site, there is a risk of collision and entrapment accidents with workers due to overlapping movement paths between vehicles waiting for unloading and moving construction machinery, and poor control within the working radius.

2.1.2. Physical Instability and Falling Risks in the Lifting Stage

The lifting stage is the section with the highest degree of risk in the entire modular process, where risks

attributable to the physical characteristics of the module are concentrated.

① Lack of center of gravity management due to asymmetrical loads: "Modular units are frequently characterized by a spatial asymmetry in which internal components including MEP (Mechanical, Electrical, and Plumbing) systems, bathroom pods, and fenestration are concentrated on specific planes. This configuration results in a pronounced discrepancy between the unit's geometric centroid and its actual center of gravity (CoG). The subsequent emergence of eccentric loading during the hoisting phase can precipitate abrupt tilting, inducing a state of dynamic instability. These conditions act as direct precursors to catastrophic failures, such as the tensile rupture of hoisting cables or the mechanical overloading of the crane apparatus."

② Inability to control slewing due to weather factors (strong winds): "Modular units possess a high surface-area-to-volume ratio, rendering them exceptionally susceptible to wind-induced loads. When hoisting operations are conducted in environments exceeding critical wind velocities, these units are prone to uncontrolled rotation and pendular oscillation, creating a substantial risk of collision with adjacent structures. Furthermore, this dynamic instability elevates the probability of secondary accidents, specifically involving workers who may suffer 'struck-by' or 'caught-in-between' injuries while attempting manual intervention to stabilize the swaying module."

2.1.3. High-altitude Work and Human Error Risks in the Assembly and Connection Stage

The horizontal/vertical correction and fastening process that takes place after the module is placed in the designated position is a stage that heavily relies on the worker's safety behavior.

Lack of fall prevention facilities and risk of falling: When performing joining (connection) work on the top of

modules, it is often difficult to install scaffolding or handrails. Particularly in the stacked method, workers must wait in unstable postures until just before the upper module is placed. If appropriate safety belt attachment facilities (Life-lines) are not secured at this time, the possibility of a fall accident is very high.

Entrapment and getting caught due to gaps between modules: At the moment the module is lowered to join with the lower module, entrapment accidents where a worker's body parts (hands, fingers, etc.) performing fine adjustments get caught between the joining surfaces were analyzed as a major risk factor.

2.1.4. Enclosed Space and Temporary Work Risks in the Post-Assembly Finishing Stage

"Distinctive safety challenges persist even in the post-structural integration phases, particularly during the coupling of MEP (Mechanical, Electrical, and Plumbing) systems and the execution of exterior envelope finishing."

Working environment risks in narrow spaces: Waterproofing and facility connection work performed in the clearance spaces between modules or in the shaft area is restricted by the narrow space, which potentially involves musculoskeletal disorders and the risk of suffocation due to poor ventilation.

Overturning and upper entrapment (crushing) risks of High-altitude Work Platforms (Table Lift): When using scissor-type or articulated high-altitude work platforms for finishing exterior joints, installing exterior materials, and connecting vertical pipes for electricity and facilities, the ground flatness changes rapidly due to frequent movement. Overturning risks during equipment movement are very high due to steps or unevenness scattered around the module foundation. Furthermore, when raising equipment in narrow sections with severe interference between the modular structure and temporary materials, there is a high risk of being crushed between the protruding part of the upper module and the work platform guardrail.

2.2. Analysis of Accident Cases by Modular Construction Stage

Table 2: Accident Cases by Modular Construction Stage

Accident Type	Date / Site Name	Accident Summary & Cause / Implications
[Case 1] Fall during lifting	May 2022, Yongin, Gyeonggi-do High-tech modular housing site	Summary: Module overturning and fall due to asymmetrical load during hoisting. Cause: Misjudgment of center of gravity due to concentration of internal facilities (bathrooms, etc.) and poor lifting wire angle.
[Case 2] Fall during assembly	Jan 2021, Near Sejong City 6-3 Life Zone Modular integrated public rental site	Summary: Worker fall (9m) during joining work on top of module. Cause: Failure to reflect lifeline anchor points for high-altitude work in the design stage and worker's failure to fasten safety belt.
[Case 3] Overturning during delivery	Nov 2023, Incheon New Town Modular parking lot/ Annex delivery road	Summary: Delivery trailer overturned while passing through a slope on the access road. Cause: Insufficient simulation of site access road gradient (Slope) and insufficient strength of module lashing devices.

[Case 4] Entrapment during stacking	Mar 2023, Icheon, Gyeonggi-do Module yard within apartment construction site	Summary: Collapse of module support frame due to ground subsidence and entrapment. Cause: Insufficient verification of bearing capacity of filled ground and fatigue failure of temporary materials due to long-term stacking.
[Case 5] Overturning during finishing	Mar 2023, Cheonan, Chungnam Modular dormitory construction site	Summary: High-altitude work platform (TL) overturned during exterior finishing work between modules. Cause: Sudden equipment slewing in a narrow space and overturning due to floor unevenness.

*Source: Based on the Construction Safety Management Integrated System (CSI) of the Ministry of Land, Infrastructure and Transport.

2.3. Risk Assessment by Modular Construction Stage

Table 3: Risk Grade Calculation and Evaluation Criteria

Risk Score (RS)	Risk Grade	Action Level	Actions and Response Strategies
16 or higher	Critical	Immediate Action	Fundamental measures (engineering controls) must be prepared before work, and work is conducted under the residence of a supervisor.
10 ~ 15	Major	Planned Improvement	Promote risk reduction through the establishment of specific Job Safety Analysis (JSA) and the introduction of smart safety equipment.
6 ~ 9	Moderate	Caution & Inspection	Periodically check compliance with Standard Operating Procedures (SOP) and strengthen on-site safety training.
5 or lower	Low	Maintain Current	Maintain the current safety management state and conduct continuous monitoring.

Table 4: Risk Assessment Results

Construction Stage	Key Risk Factor	Frequency (F)	Severity (S)	Risk Score (RS)	Risk Grade	Rank
Lifting	4. Tilting during hoisting due to asymmetrical internal load (eccentricity)	4.1	4.9	20.09	Critical	1
Assembly	7. Lack of temporary facilities for fall prevention during work on top of module	3.9	4.9	19.11	Critical	2
Assembly	8. Entrapment (getting caught) of body parts between joints during module placement	4.1	3.9	15.99	Critical	3
Prep	2. Narrow access road for delivery vehicles and poor gradient (slope)	2.9	4.7	13.63	Major	4
Lifting	6. Defects or breakage of hoisting tools such as wire ropes and sling belts	2.6	4.7	12.22	Major	5
Assembly	9. Overturning and falling of temporary scaffolds and work platforms during correction	2.3	4.6	10.58	Major	6
Prep	1. Lack of underground bearing capacity and subsidence in the crane mounting section	2.1	4.8	10.08	Major	7
Finishing	11. Collision and overturning when moving high-altitude work platforms (TL, SKY)	2.4	3.7	8.88	Moderate	8
Prep	3. Collision and damage between modules during unloading	2.8	3.1	8.68	Moderate	9
Lifting	5. Slewing and shaking of module due to sudden weather changes like strong winds	2.2	3.8	8.36	Moderate	10
Finishing	12. Falling of materials and tools from above	2.3	3.1	7.13	Moderate	11
Finishing	10. Poor working posture in narrow spaces (Shafts, etc.) for facility/ waterproofing	1.9	3.2	6.08	Moderate	12

* Results utilize surveys and risk assessments targeting modular-related construction, design, and experienced personnel. The risk grade is classified into four levels based on the Risk Score (RS) calculated by the product of frequency (F) and accident severity (S) collected through surveys.

3. Mitigation Strategies

3.1. Engineering Controls: Fundamental Blocking and Replacement of Physical Hazard Sources

Engineering controls are the highest level of reduction measures that physically remove or isolate risk factors within the work environment through changes in design or advancement of equipment.

First is the utilization of BIM (Building Information Modeling)-based pre-lifting simulation and digital twin technology. A virtual lifting simulation is performed by inputting the actual weight distribution and mass of each member into the 3D model built in the design stage.

Through this, asymmetrical loads and eccentricity that may occur during module hoisting are quantitatively calculated, and interference within the crane's rated load and rotation radius is verified in advance, thereby fundamentally preventing overturning and fall accidents during lifting.

Second is the introduction of smart lifting gear and automation technology. 'self-leveling spreader beam' equipped with horizontal maintenance sensors is used to control the lifting horizontality of asymmetrical modules in real-time, and 'automatic hook release devices' operated remotely from the ground are applied. This is expected to block the fundamental occurrence mechanism of fall accidents by eliminating high-risk high-altitude work where workers move to the top of the module to manually release connections.

3.2. Administrative Controls: Standardization of Processes and Strengthening of Control Systems

Administrative controls focus on standardizing work procedures and building organizational monitoring and control systems to minimize human error.

First is the integration of on-site safety facilities and a pre-verification system from the DfS (Design for Safety) perspective. This is a method where safety handrail anchors, fall prevention lifelines, and footboards for top-side work are pre-installed in the factory during the module manufacturing stage. This omits the temporary facility installation process on-site, thereby shortening workers' risk exposure time and minimizing high-altitude work on-site. Additionally, the actual center of gravity position is marked on the surface of the delivered module in advance so that site managers can intuitively judge safety before lifting.

Second is the dynamic management of smart logistics and high-risk zones (Red Zones). IoT sensors and drones are used to monitor the movement of module delivery vehicles in real-time, and a smart tag (RFID) system is operated to forcibly restrict worker entry into the crane lifting radius. In particular, during high-risk time slots when lifting and placement occur, the work area is physically isolated (Zoning) to strengthen the system for preventing entrapment and fall accidents that may occur when heavy objects fall.

3.3. Educational Controls: Enhancing Risk Perception Capacity and Spreading Safety Culture

Educational controls aim to heighten workers' safety awareness and ensure professional proficiency to respond to risks unique to the modular method.

First is the operation of a factory-site linked cross-safety education program. Due to the nature of modular construction, site workers find it difficult to accurately grasp the internal structure. Therefore, a process in which on-site assembly (construction) personnel visit the manufacturing factory to directly check the unit's internal frames, lifting points, and buried piping locations is reflected and implemented in the education program. Through this, the capacity to prevent member damage or unexpected load transfer due to careless fastening during lifting is increased.

Second is VR (Virtual Reality)-based high-risk scenario experience education. Breaking away from general safety education, special situations most frequently occurring during modular construction such as 'module tilting during lifting,' 'hand entrapment at joints,' and 'module rotation during strong winds' are implemented in VR for emergency response training. This helps to heighten workers' risk sensitivity through repetitive learning in a virtual environment similar to actual accidents and enables rapid and accurate evacuation and action in case of unexpected situations.

4. Conclusion

It can be said that the modular method shifts the paradigm of construction safety from 'on-site response' to 'prevention in the factory and design stages.' Accordingly, this study identified unique risk factors occurring in the construction stage and proposed systematic response measures to reduce them, in line with the spread of the modular method, which is drawing attention as an innovative alternative for the construction industry. The core results of the study are summarized as follows.

First, as a result of analyzing the modular construction process into four stages 'Delivery and Preparation, Lifting, Assembly and Connection, and Finishing' 'heavy object lifting instability' and 'high-altitude work exposure at joints,' which are differentiated from the existing RC (Reinforced Concrete) method, were derived as core risk groups.

Second, as a result of the risk assessment, it was confirmed that failure to manage the asymmetrical center of gravity during the lifting stage is the most critical factor that can lead to large-scale collapse accidents.

Third, it was proven that the integrated application of engineering (BIM and smart equipment), administrative (DfS and logistics control), and educational (cross-education and VR experience) measures proposed to control these risks is an effective way to minimize residual risks.

Furthermore, this study provides the following important implications from academic and practical perspectives.

From an academic perspective, it is significant that modular construction safety, which had been discussed fragmentarily, was systematized by applying it to the 'Hierarchy of Controls.' In particular, it theoretically supported the need to shift the traditional site-response safety management paradigm to 'Prevention by Design' linked to the design and factory production stages. From a practical perspective, specific reduction measures applicable to the site were presented based on practical insights as an on-site safety and health team leader.

The combination of BIM simulation, digital twins, and smart lifting equipment, as well as education programs connecting the factory and the site, will serve as practical guidelines to solve communication breakdown and lack of proficiency, which are chronic problems at modular sites. This is expected to present a specific response model for construction-related companies required to have advanced safety management systems following the implementation of the Serious Accidents Punishment Act. In addition, this study has limitations in that it focused on safety management during the on-site assembly stage, centered on the stacked modular method.

In future research, risk assessments specialized for each method, such as the In-fill method or timber modular, which are other pillars of the modular method, should be carried out in parallel.

Furthermore, if a quantitative analysis of the cost-benefit of the smart safety equipment and BIM-based simulation proposed in this study is conducted as follow-up research, it could provide a strong incentive for construction companies hesitant to introduce the modular method on-site. Going further, it is expected to expand into empirical research on an 'unmanned assembly safety system' that completely eliminates human judgment errors by building an AI-based real-time lifting monitoring system.

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