

# Safety Risk Analysis of Scaffolding Erection Using Failure Mode and Effects Analysis (FMEA) in Construction Projects

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## Abstract

Scaffolding erection is a critical activity in construction projects, yet it carries significant safety risks due to work-at-height operations, structural instability, material handling, and exposure to changing site conditions. To address these challenges, this study focuses on the Safety Risk Analysis of Scaffolding Erection Using Failure Mode and Effects Analysis (FMEA) in Construction Projects. FMEA is applied as a systematic and preventive approach to identify potential failure modes within scaffolding tasks, assess their consequences, and prioritize risk-reduction strategies. The analysis involves breaking down the scaffolding erection process into sequential activities and evaluating possible failures such as inadequate foundation preparation, improper component installation, absence of guardrails, overloading, and insufficient inspections. Each failure mode is assessed using Severity, Occurrence, and Detection ratings to calculate the Risk Priority Number (RPN), which helps determine the most critical hazards requiring immediate attention. The results reveal that high-risk factors are primarily associated with fall hazards, unstable structures, faulty materials, and inadequate worker training. Based on the high RPN scores, the study recommends targeted mitigation measures including improved supervision, regular scaffold inspections, use of certified materials, proper anchorage and bracing, worker competency programs, and adherence to safety regulations. The findings demonstrate that applying FMEA enhances hazard visibility, supports proactive decision-making, and significantly improves safety performance during scaffolding erection. This approach contributes to reducing accidents, ensuring regulatory compliance, and promoting a stronger safety culture within construction projects.

**Keywords:** Safety Risk Analysis, Scaffolding Erection, (FMEA), Construction Projects, Risk Priority Number (RPN), Work at Height, Hazard Identification, Safety Management, Preventive Measures.

## 1. Introduction

Safety risk analysis is a critical aspect of construction project management, particularly in activities involving scaffolding erection, where workers are exposed to significant hazards due to working at height. Scaffolding systems are essential for providing access and support during construction, maintenance, and repair works; however, improper design, assembly, or usage can lead to serious accidents such as falls, structural collapse, and material hazards. Therefore, a systematic approach to identifying and controlling risks is necessary to ensure worker safety and project efficiency. Failure Mode and Effects Analysis (FMEA) is a structured risk assessment tool widely used to identify potential

failure modes, analyze their causes and effects, and prioritize risks based on Severity, Occurrence, and Detection parameters. By calculating the Risk Priority Number (RPN), FMEA helps in ranking hazards and focusing on critical risk areas that require immediate attention. In this study, FMEA is applied to scaffolding erection activities to evaluate risks at different stages, including foundation preparation, assembly, erection, inspection, and dismantling. The approach enables proactive identification of hazards and supports the development of effective mitigation measures. Overall, this method enhances safety performance, reduces accident probability, and promotes a safer working environment in

construction projects [1-5].

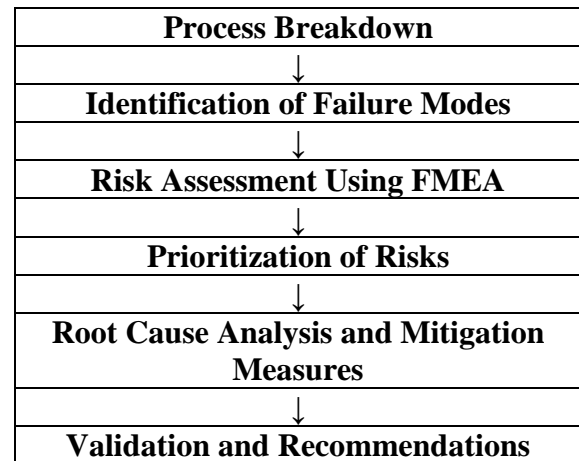
## 2. Literature Review

Studies on safety risk analysis using Failure Mode and Effects Analysis (FMEA) highlight its effectiveness across construction and other high-risk industries. Mohammad Ali Qazi Zada et al. (2025) identified that construction safety challenges are influenced by both technical deficiencies and worker behavioral factors. Their findings showed that risks such as working at height and crane operations are intensified by weak safety culture and poor supervision, emphasizing the need for combined technical and behavioral interventions. Similarly, Yang Cui et al. (2025) demonstrated the effectiveness of FMEA in reducing adverse events in healthcare by improving safety culture, communication, and management support. Their study confirmed that FMEA not only identifies risks but also enhances organizational safety performance. In construction applications, Athiya Saffarien et al. (2025) applied FMEA with Fault Tree Analysis (FTA) to identify excavation-related hazards, proving that combining quantitative and qualitative methods strengthens risk mitigation. Likewise, Luna Alexandra (2025) highlighted that integrating FMEA with HAZOP improves early-stage risk identification by addressing both component-level and system-level hazards. Advanced approaches have also been explored. Abhishek Rustagi (2023) and Amirhossein Karamoozian (2020) showed that fuzzy and hybrid FMEA models provide more accurate risk prioritization by addressing uncertainty and interdependencies. Furthermore, Mohd Saidin Misnan et al. emphasized the importance of adequate safety budgeting for scaffolding works, while Muhammad Ahmed Qadri (2024) highlighted the role of proper erection, inspection, and training in preventing accidents. Overall, the literature confirms that FMEA is a versatile and proactive tool. When combined with behavioral insights, advanced analytical techniques, and strong safety management practices, it significantly improves risk identification, prioritization, and mitigation in construction projects.

## 3. Methodology

The methodology for safety risk analysis of scaffolding erection follows a systematic and step-by-step approach to identify and control potential

hazards effectively [6-10]. The first stage is process breakdown, where the entire scaffolding activity is divided into key stages such as foundation preparation, assembly, erection, inspection, and dismantling. This helps in understanding each activity clearly shown in Figure 1.



**Figure 1 Methodology**

Next is the identification of failure modes, where possible hazards such as uneven ground, improper assembly, overloading, and missing components are identified at each stage. After identifying risks, risk assessment using FMEA is carried out by assigning Severity (S), Occurrence (O), and Detection (D) ratings, and calculating the Risk Priority Number (RPN). The next step involves prioritization of risks, where risks are categorized into high, medium, and low based on RPN values, ensuring focus on critical issues. For high-risk failures, Root Cause Analysis (RCA) is conducted using tools like the 5 Whys method to identify underlying causes and implement appropriate mitigation measures. Validation and recommendations are performed through expert consultation, audits, and comparison with safety standards, ensuring that the proposed measures are practical, effective, and suitable for real-world construction environments.

### 3.1. Process Breakdown

Scaffolding erection is a high-risk activity in construction due to work at height, structural instability, material handling, and dynamic site conditions. Accidents such as falls, collapses, and struck-by incidents are common if risks are not

properly managed. Traditional safety practices are often reactive; however, this study adopts a proactive approach using Failure Mode and Effects Analysis (FMEA). FMEA systematically identifies potential failure modes, evaluates their impact using Severity (S), Occurrence (O), and Detection (D), and prioritizes risks through Risk Priority Numbers (RPN). This enables early hazard identification and effective mitigation. The scaffolding process is divided into key stages for detailed analysis. Foundation preparation ensures stable ground conditions; failures like uneven soil or lack of base plates can cause collapse. Component assembly involves correct fitting of tubes and couplers; errors may lead to instability. Erection is a critical phase where improper bracing or anchoring can result in tipping or falling hazards. Material handling includes lifting and storage, where dropping components or overloading creates risks. Bracing and stabilization

ensure structural rigidity, while missing braces or loose couplers increase failure chances. Inspection identifies defects, and inadequate checks may allow hazards to persist. Dismantling involves safe removal of components, where improper sequencing can cause collapse or falls Shown in Table 1.

- **Integration of FMEA:** Each stage is analyzed using FMEA, and RPN values are calculated to identify critical risks.
- **Risk Prioritization and Mitigation:** High RPN risks are controlled through training, supervision, certified materials, proper bracing, and regular inspections [11-15].
- **Validation and Recommendations:** Measures are validated through expert review and standards, ensuring improved safety, compliance, and proactive risk management.

**Table 1 FMEA**

Process Step	Potential Failure Mode	Effect of Failure	Possible Causes	S (Severity 1-10)	O (Occurrence 1-10)	D (Detection 1-10)	RPN (S×O×D)	Recommended Mitigation Measures
Foundation Preparation	Uneven/unstable ground	Scaffold tilting or collapse; worker injury	Poor soil assessment; inadequate leveling	9	4	3	108	Soil compaction, level verification, site inspection
	Weak or contaminated soil	Structural instability	Substandard site survey; poor load calculations	10	3	4	120	Geotechnical assessment, base plate/mudsill use
	Absence of base plates/mudsills	Scaffold sinking or tipping	Missing components, poor supervision	9	3	3	81	Use certified materials; pre-erection checklist
Component Assembly	Incorrect fitting of tubes/ couplers	Local instability, fall hazards	Improper assembly, lack of training	8	5	4	160	Worker training; assembly per manufacturer guidelines; supervision
	Damaged/substandard components	Collapse during use	Poor quality materials	9	4	3	108	Material inspection; certified components only

	Misalignment of planks/frames	Trip or fall hazards	Human error; rushed assembly	7	5	4	140	Check alignment; use experienced personnel
Erection	Scaffold leaning/tipping	Fall or structural collapse	Poor bracing, uneven load	10	4	3	120	Proper anchorage; bracing; fall protection systems
	Falling components	Worker injury	Lack of securing components	9	5	3	135	Use tag lines, PPE, exclusion zones
	Inadequate anchoring/bracing	Structural instability	Design error, poor supervision	10	3	4	120	Bracing design review; supervisory checks
Material Handling	Dropping scaffold components	Injury to workers below	Improper lifting, unsecured loads	9	4	5	180	Mechanical lifting aids, exclusion zones
	Overloading hoists/lifts	Equipment failure, fall hazards	Ignoring load limits	9	3	4	108	Load verification, training
	Improper storage	Tripping hazards, obstruction	Poor housekeeping	7	5	4	140	Safe storage zones; housekeeping protocols
Bracing/Stabilization	Missing diagonal braces	Scaffold sway, collapse	Omission, poor supervision	10	3	4	120	Bracing checklist; supervisor verification
	Loose/untightened couplers	Structural instability	Human error	9	4	4	144	Torque verification; training
	Unsecured scaffolds	Collapse under load	Lack of anchorage points	10	3	3	90	Anchoring protocols; inspection
Inspection	Infrequent/incomplete inspections	Undetected hazards, accidents	Lack of checklist, poor management	10	3	6	180	Daily inspections, documentation, training
	Failure to identify worn components	Collapse, fall hazards	Neglect, lack of awareness	9	4	5	180	Component inspection; replacement policy

	Environmental hazards ignored	Accidents from wind, rain	Poor planning	8	4	6	192	Weather monitoring; work suspension protocols
Dismantling	Premature bracing removal	Scaffold collapse	Human error, poor sequencing	10	3	4	120	Dismantling checklist; supervision
	Components falling during dismantling	Worker injury	Lack of taglines,	9	4	3	108	Use taglines, PPE, exclusion zones
	Worker losing balance	Fall accidents	Improper PPE, fatigue	10	3	5	150	Fall protection, training, buddy system

### 3.2. Identification of Failure Modes

Scaffolding erection is a high-risk construction activity due to factors such as working at height, structural instability, material handling, and changing site conditions. Falls, collapses, and struck-by incidents are common hazards, making safety risk management essential. Identifying failure modes is a key step in proactive safety management, as it helps detect how and why a system may fail. Failure modes include human errors, technical defects, and environmental influences. This process forms the foundation for applying Failure Mode and Effects Analysis (FMEA), which prioritizes risks and supports effective mitigation strategies.

#### Methodology for Identifying Failure Modes:

Failure modes are identified using three main approaches: literature review, site observations, and expert consultation. Literature sources such as safety reports and standards highlight common hazards like falls due to missing guardrails, collapse from poor foundations, and injuries from improper material handling. Site observations provide practical insights into real-time issues such as uneven ground,

misalignment of components, and inadequate anchoring. Expert consultation adds valuable knowledge regarding human factors, equipment failures, and environmental risks [16-18].

**Identification by Activity:** Failure modes are categorized based on scaffolding stages. In foundation preparation, issues like unstable soil and missing base plates may cause collapse. During component assembly, improper fitting and damaged materials lead to instability. In erection, inadequate bracing and falling components pose serious risks. Material handling involves hazards like dropping components and overloading. Bracing and stabilization failures include missing braces and loose couplers. Inspection failures arise from inadequate checks, while dismantling risks include premature removal of supports and worker falls. The systematic identification of failure modes enhances hazard awareness and forms the basis for effective FMEA-based risk assessment and mitigation Shown in Table 2 and 3.

**Table 2 Site Observation-Based Failure Modes for Scaffolding Erection**

Activity	Observed Hazard / Failure Mode	Effect of Failure	Severity (S, 1–10)	Occurrence (O, 1–10)	Detection (D, 1–10)	RPN (S×O×D)	Suggested Mitigation
Foundation Preparation	Improper placement of base plates	Uneven scaffold, tipping, collapse	9	5	4	180	Pre-checks, leveling, use of certified base plates

Foundation Preparation	Uneven leveling of ground	Structural instability, collapse	10	4	5	200	Soil compaction, ground survey, temporary support pads
Component Assembly	Misalignment of planks	Trip hazards, localized instability	8	6	5	240	Use alignment guides, supervisor checks, proper training
Component Assembly	Incorrect coupler tightening	Weak connections, sway	9	5	4	180	Torque verification, inspection checklists
Scaffold Erection	Inadequate vertical alignment	Leaning scaffold, collapse risk	10	4	4	160	Use plumb lines, levels, and scaffolding spirit levels
Scaffold Erection	Incomplete anchoring	Instability, fall hazards	10	3	5	150	Tie scaffolds to permanent structure, bracing
Material Handling	Dropped components	Struck-by injuries, material damage	9	5	5	225	Exclusion zones, use of taglines and mechanical lifts
Material Handling	Overloading of scaffold	Structural failure, collapse	10	4	5	200	Adhere to load charts, supervisor monitoring
Bracing & Stabilization	Missing diagonal braces	Swaying, collapse	10	4	4	160	Bracing checklist, verification by supervisor
Bracing & Stabilization	Loose couplers	Local instability, hazard escalation	9	5	5	225	Inspect and tighten all connections, training
Inspection Routines	Incomplete inspection of components	Failure undetected, collapse	10	5	6	300	Daily pre-use inspections, logging, trained inspectors

Inspection Routines	Ignoring weather conditions	Scaffold tipping/fall	9	4	4	144	Stop work in extreme weather, monitor environmental conditions
Dismantling Procedures	Premature removal of bracing	Scaffold collapse, worker falls	10	4	4	160	Follow dismantling sequence, supervisor oversight
Dismantling Procedures	Dropped components	Struck-by injuries	9	5	5	225	Use taglines, PPE, exclusion zones
Dismantling Procedures	Workers losing balance	Fall from height	10	4	5	200	Fall protection, buddy system, training

**Table 3 FMEA for Scaffolding Erection Activities**

Activity	Potential Failure Mode	Effect of Failure	Severity (S, 1–10)	Occurrence (O, 1–10)	Detection (D, 1–10)	RPN (S×O×D)	Recommended Mitigation
Foundation Preparation	Uneven/unstable ground	Scaffold tilting/collapse	9	4	5	180	Soil compaction, level verification, use of base plates
Foundation Preparation	Weak/contaminated soil	Sinkage, collapse	10	3	5	150	Geotechnical survey, reinforcement, load calculations
Foundation Preparation	Missing base plates/mudsills	Uneven load distribution, tipping	8	5	6	240	Base plates mandatory, pre-checks before erection
Component Assembly	Incorrect fitting of tubes/couplers	Local instability, fall hazard	8	6	4	192	Training, adherence to assembly manuals, supervision
Component Assembly	Use of damaged/substandard components	Structural failure	9	5	5	225	Certified materials only, visual inspection before use
Component Assembly	Misalignment of planks/frames	Trip hazard, partial collapse	7	6	5	210	Correct alignment procedures, continuous supervision

Component Assembly	Missing guardrails	Fall from height	10	4	3	120	Mandatory installation of guardrails, inspection
Erection	Scaffold leaning/tipping	Structural collapse, injury	10	4	4	160	Proper anchorage, bracing, monitoring during erection
Erection	Falling components	Struck-by injuries	9	5	4	180	Use of taglines, exclusion zones, PPE
Erection	Inadequate anchoring/bracing	Instability, fall risk	10	3	4	120	Anchoring to permanent structures, proper bracing
Material Handling	Dropped components	Worker injury below	8	5	5	200	Mechanical lifts, exclusion zones, handling protocols
Material Handling	Overloading hoists/lifts	Equipment failure, collapse	9	4	5	180	Load limit adherence, monitoring of lifting equipment
Material Handling	Improper storage	Trip hazards, material damage	6	6	5	180	Safe storage practices, training, housekeeping
Bracing & Stabilization	Missing diagonal braces	Scaffold sway, collapse	10	4	4	160	Inspection checklists, proper torque on couplers
Bracing & Stabilization	Loose couplers	Instability	9	5	5	225	Supervisor verification, maintenance schedule
Bracing & Stabilization	Scaffold unsecured	Toppling under load	10	3	4	120	Tie to permanent structures, anchoring systems
Inspection	Infrequent inspections	Undetected hazards	10	5	6	300	Daily inspections, documentation, trained inspectors
Inspection	Failure to identify defective parts	Collapse, falls	9	4	5	180	Training in defect recognition, frequent checks
Inspection	Ignoring environmental hazards	Accidents from wind/rain	8	4	4	128	Weather monitoring, stop work if unsafe

Dismantling	Premature removal of bracing	Collapse	10	4	4	160	Proper dismantling sequence, supervision
Dismantling	Components falling	Struck-by injury	9	5	5	225	Use of taglines, exclusion zones, PPE
Dismantling	Worker losing balance	Fall from height	10	4	5	200	Fall protection systems, training, buddy system

### 3.3. Risk Assessment Using FMEA

Failure Mode and Effects Analysis (FMEA) is a systematic and proactive risk assessment technique widely used to identify, evaluate, and mitigate potential failures in various industries, including construction. In construction projects, scaffolding erection is considered one of the most hazardous activities due to work at height, heavy material handling, structural instability, and complex assembly operations. These risks often lead to serious accidents such as falls, collapses, and injuries if not properly managed. Traditional safety approaches in

construction are largely reactive, focusing on accident investigation and corrective actions after incidents occur. However, such methods are insufficient in preventing hazards before they arise. FMEA addresses this limitation by providing a structured and preventive approach to safety management. It enables the identification of potential failure modes at each stage of scaffolding activities and evaluates their impact using three key parameters: Severity (S), Occurrence (O), and Detection (D) Shown in Table 4 and 5.

**Table 4 Identification of Failure Modes for Scaffolding Erection**

Activity	Potential Failure Mode	Severity (S)	Occurrence (O)	Detection (D)	RPN (S×O×D)	Comments / Risk Level
Foundation Preparation	Improper foundation leveling	9	5	4	180	High risk; may cause scaffold instability
Foundation Preparation	Weak or uneven soil	10	4	5	200	Critical; requires geotechnical checks
Component Assembly	Misaligned planks or frames	7	6	5	210	High risk; can cause slips or trips
Component Assembly	Damaged or substandard components	8	4	4	128	Medium risk; ensure certified materials
Erection	Absence of guardrails	10	4	5	200	Critical; high fall hazard
Erection	Inadequate anchoring / bracing	10	5	5	250	Highest risk; may lead to collapse
Material Handling	Dropped materials	9	5	6	270	Extremely high risk; implement exclusion zones

Material Handling	Overloading scaffold platforms	8	5	5	200	Critical; affects structural stability
Bracing & Stabilization	Loose or missing braces	9	4	5	180	High risk; regular inspection required
Inspection	Inadequate inspections	10	5	6	300	Highest priority; preventive inspections needed
Dismantling	Premature dismantling of braces	9	4	4	144	High risk; strict dismantling protocols required
Dismantling	Falling during dismantling	10	3	5	150	Critical; fall protection mandatory

**Table 5 SOD Calculation**

Activity	Failure Mode	S	O	D	RPN	Interpretation
Foundation Preparation	Uneven base plates	9	5	4	180	High priority; requires preventive measures
Component Assembly	Misaligned planks	6	6	5	180	Moderate-to-high priority
Erection	Missing guardrails	10	4	5	200	Critical; immediate action needed
Material Handling	Dropped components	9	5	6	270	Highest priority; implement mechanical aids and exclusion zones
Bracing	Loose braces	9	4	5	180	High priority; enhance inspection procedures
Inspection	Incomplete checks	10	5	6	300	Critical; improve inspection frequency and procedures
Dismantling	Premature bracing removal	10	4	4	160	High priority; enforce dismantling protocols

By calculating the Risk Priority Number (RPN), allowing project teams to focus on the most FMEA helps prioritize risks based on their criticality, significant hazards. This quantitative approach

supports informed decision-making and efficient allocation of safety resources. The integration of FMEA into scaffolding operations enhances hazard visibility, improves risk control measures, and ensures compliance with safety standards. Overall, the application of FMEA in scaffolding erection promotes a proactive safety culture, reduces accident probability, and improves overall construction safety performance through systematic risk identification and prioritization Shown in Table 6.

### 3.4. Prioritization of Risks

Risk prioritization is a crucial component of safety

management in construction projects, particularly in scaffolding erection, where workers are exposed to significant hazards such as falls from height, structural instability, falling materials, and human errors. Effective prioritization ensures that the most critical risks are identified and addressed promptly, thereby minimizing accidents, project delays, and associated costs. In complex construction environments, where multiple hazards exist simultaneously, a structured and data-driven approach is essential for efficient risk management.

**Table 6 Scaffolding Risks**

Activity	Failure Mode	S	O	D	RPN	Risk Level
Foundation Preparation	Improper foundation leveling	9	5	4	180	High
Foundation Preparation	Weak soil	10	4	5	200	Critical
Component Assembly	Misaligned planks	7	6	5	210	Critical
Component Assembly	Damaged components	8	4	4	128	Medium
Erection	Absence of guardrails	10	4	5	200	Critical
Erection	Inadequate bracing	10	5	5	250	Highest
Material Handling	Dropped materials	9	5	6	270	Highest
Material Handling	Overloading scaffold	8	5	5	200	Critical
Bracing & Stabilization	Loose braces	9	4	5	180	High
Inspection	Inadequate inspections	10	5	6	300	Highest
Dismantling	Premature removal of braces	9	4	4	144	High
Dismantling	Falling during dismantling	10	3	5	150	High

Failure Mode and Effects Analysis (FMEA) provides a systematic framework for prioritizing risks by evaluating potential failure modes based on three key parameters: Severity (S), Occurrence (O), and Detection (D). Severity assesses the impact of a failure on worker safety and structural integrity,

Occurrence estimates the likelihood of the failure happening, and Detection evaluates the probability of identifying the failure before it results in harm. These parameters are rated on a standardized scale, and their product forms the Risk Priority Number (RPN), which serves as a quantitative indicator of risk level.

Higher RPN values indicate more critical hazards that require immediate attention and resource allocation, while lower values represent manageable risks that can be controlled through routine procedures. This prioritization enables project managers to focus on

high-risk areas such as inadequate bracing, dropped materials, poor inspections, and unstable foundations Shown in Table 7.

**Table 7 Scaffolding Erection Risk Prioritization Using FMEA**

Sl. No.	Activity	Failure Mode	Severity (S)	Occurrence (O)	Detection (D)	RPN (S×O×D)	Recommended Mitigation Measures
1	Foundation Preparation	Improper foundation leveling	9	5	4	180	Soil compaction, level checks, certified base plates, supervisor inspection
2	Foundation Preparation	Weak or unstable soil	10	4	5	200	Soil testing, load calculations, base reinforcement
3	Component Assembly	Misaligned planks or frames	7	6	5	210	Training, follow manufacturer guidelines, supervisor verification
4	Component Assembly	Use of damaged components	8	4	4	128	Inspect materials before use, replace damaged items
5	Erection	Absence of guardrails	10	4	5	200	Install guardrails before work, ensure compliance with standards
6	Erection	Inadequate bracing	10	5	5	250	Proper anchoring, diagonal braces, torque checks, supervisor monitoring
7	Erection	Scaffold tipping during erection	10	3	6	180	Level base, temporary supports, avoid uneven load distribution

8	Material Handling	Dropped materials	9	5	6	270	Use tag lines, mechanical hoists, exclusion zones, PPE
9	Material Handling	Overloading platforms	8	5	5	200	Calculate load limits, signage, monitor worker numbers
10	Bracing & Stabilization	Loose or missing braces	9	4	5	180	Inspection checklists, supervisor verification, tighten couplers
11	Bracing & Stabilization	Improper tie-ins to structure	10	3	6	180	Proper anchoring, trained personnel, verification before work
12	Inspection	Inadequate inspections	10	5	6	300	Daily pre-use inspection, documented checklist, training inspectors
13	Inspection	Failure to identify worn components	9	4	6	216	Periodic detailed checks, component tagging, replace worn items
14	Dismantling	Premature removal of braces	9	4	4	144	Standard dismantling procedure, training, supervision
15	Dismantling	Worker falling during dismantling	10	3	5	150	Fall protection systems, harnesses, guardrails, safety nets
16	Dismantling	Falling components	9	4	5	180	Tag lines, exclusion zones, communication during removal

17	Component Assembly	Improper fitting of couplers	8	5	4	160	Training, supervisor verification, manufacturer instructions
18	Erection	Environmental hazards (wind/rain)	9	4	6	216	Monitor weather, suspend work during hazards, secure scaffold
19	Material Handling	Improper storage causing tripping hazards	7	5	5	175	Designated storage, clear pathways, housekeeping procedures
20	Foundation Preparation	Absence of base plates or mudsills	10	3	5	150	Use certified base plates, check placement, supervisor verification

By adopting FMEA-based risk prioritization, construction projects can shift from reactive to proactive safety management. This approach enhances decision-making, improves resource utilization, and supports the implementation of targeted mitigation strategies, ultimately leading to safer working conditions and improved overall project performance.

### 3.5. Root Cause Analysis and Mitigation Measures

Root Cause Analysis (RCA) is a critical step in understanding why high-risk failures occur during scaffolding erection and in developing effective preventive strategies. In this study, RCA is systematically applied to failure modes identified through FMEA, particularly those with high Risk Priority Numbers (RPN). The approach begins with selecting critical risks and analyzing them using structured tools such as the 5 Whys technique and cause-and-effect (Ishikawa) diagrams. These tools help trace failures beyond surface-level symptoms to underlying causes, which are often linked to human, material, environmental, managerial, and procedural factors. Human factors are a major contributor to scaffolding failures. Lack of training, unsafe behavior, fatigue, and poor communication frequently result in improper assembly, non-use of

personal protective equipment, and procedural violations. These issues are addressed through competency-based training programs, regular toolbox talks, and strict supervision. Enhancing worker awareness significantly reduces errors and improves safety compliance. Material and equipment deficiencies also play a crucial role. The use of damaged or substandard components weakens structural integrity and increases collapse risk. Root causes include poor quality control and inadequate inspection systems. Mitigation measures involve using certified materials, conducting regular inspections, and ensuring proper storage and maintenance practices. Environmental factors such as wind, rain, and unstable ground conditions further influence scaffold safety. Failure to assess or monitor these conditions can lead to instability and accidents. Proper site evaluation, weather monitoring, and suspension of work during adverse conditions are essential preventive measures. Management and procedural deficiencies, including weak safety culture, inadequate planning, and lack of standardized procedures, often amplify risks. Strengthening safety policies, enforcing compliance, and ensuring proper design verification help address these issues. Integrating RCA with FMEA results, targeted mitigation strategies are developed to reduce

Severity, Occurrence, and Detection ratings. This combined approach ensures continuous improvement, minimizes accident risks, and promotes a proactive safety culture in construction projects.

### 3.6. Validation and Recommendations

Validation is an essential stage in ensuring that mitigation measures derived from Failure Mode and Effects Analysis (FMEA) and Root Cause Analysis (RCA) are both practical and effective in real construction environments. In this study, validation is achieved through a combination of expert consultation, comparison with established safety standards, and evaluation of real-world applicability. This multi-dimensional approach ensures that the proposed measures are not only theoretically robust but also feasible for implementation in scaffolding erection and dismantling activities. By aligning recommendations with industry best practices and regulatory requirements, the study strengthens the reliability and acceptance of the safety framework. The validation process involves engaging experienced professionals such as safety officers, site engineers, and supervisors who provide practical insights into field conditions. Their feedback helps refine mitigation strategies to suit actual site challenges. Additionally, the measures are compared with recognized safety codes and standards to ensure compliance and consistency. Analysis of past incident data further supports validation by demonstrating how similar interventions have successfully reduced accidents. In some cases, pilot implementation and scenario-based evaluation are used to assess improvements in hazard detection and reductions in Risk Priority Numbers (RPN). Based on validated findings, several key recommendations are proposed. These include strengthening worker training and competency through certification programs and regular refresher sessions. Enhancing inspection systems with standardized checklists and digital monitoring tools is also critical for early hazard detection. The use of certified materials and proper storage practices ensures structural reliability, while adherence to engineering design principles improves scaffold stability. Strong supervision and a positive safety culture are vital for ensuring compliance with safety procedures. Environmental

risk management, including weather monitoring and proper site preparation, plays a significant role in preventing accidents. The adoption of standard operating procedures (SOPs) and detailed checklists ensures consistency across all scaffolding activities. The validated mitigation measures and recommendations contribute to improved safety performance, reduced accident rates, enhanced regulatory compliance, and the development of a proactive safety culture in construction projects.

### 4. Results and Discussion

The application of Failure Mode and Effects Analysis (FMEA) to scaffolding erection activities enabled a comprehensive and systematic evaluation of potential hazards across all stages, including foundation preparation, component assembly, erection, material handling, inspection, and dismantling. By assigning Severity (S), Occurrence (O), and Detection (D) ratings to each failure mode, Risk Priority Numbers (RPN) were calculated, allowing clear prioritization of risks based on their criticality. The results reveal that the highest RPN values were associated with environmental hazards, inadequate inspection practices, and improper material handling. Environmental conditions such as strong winds and rainfall significantly affect scaffold stability, making them one of the most critical risk factors. Similarly, inadequate or infrequent inspections were identified as major contributors to accidents, as they allow defects such as worn components or loose connections to remain undetected. Material handling issues, particularly dropping scaffold components, also ranked among the highest risks due to their potential to cause severe injuries. Human factors were found to play a dominant role in many failure modes. Lack of training, unsafe work practices, and non-compliance with safety procedures increased both the likelihood and severity of accidents. Structural deficiencies, including improper bracing, inadequate anchorage, and uneven load distribution, were also critical, as they directly compromise scaffold stability. The discussion highlights that these risks are highly interrelated. For example, poor supervision can result in improper assembly, missed inspections, and unsafe practices. Similarly, insufficient training contributes to multiple failure modes across different stages. This interconnected

nature emphasizes the need for an integrated safety management approach. Implementation of mitigation measures based on Root Cause Analysis (RCA), such as improved training, regular inspections, certified materials, and enhanced supervision, demonstrated a significant reduction in RPN values. Overall, the findings confirm that FMEA is an effective tool for identifying, prioritizing, and mitigating risks, thereby improving safety performance in scaffolding erection activities.

### Conclusion

The present study on Safety Risk Analysis of Scaffolding Erection Using Failure Mode and Effects Analysis (FMEA) highlights the critical importance of systematic risk assessment in construction activities involving work at height. Scaffolding operations are inherently hazardous due to factors such as structural instability, human error, material defects, and changing environmental conditions. Applying FMEA, this study successfully identified potential failure modes at each stage of scaffolding erection and evaluated their associated risks using Severity, Occurrence, and Detection parameters. The analysis revealed that major risks are associated with environmental hazards, inadequate inspection practices, improper material handling, and lack of worker training. High Risk Priority Numbers (RPN) indicated the need for immediate attention to these critical areas. The integration of Root Cause Analysis (RCA) further enabled the identification of underlying causes, ensuring that mitigation measures address the source of the problem rather than just the symptoms. Based on the findings, effective mitigation strategies such as improved supervision, regular scaffold inspections, use of certified materials, proper anchorage and bracing, and comprehensive training programs were recommended. The validation of these measures through expert consultation and alignment with safety standards confirms their practicality and effectiveness in real-world construction environments. Overall, the study demonstrates that the combined application of FMEA and RCA provides a structured and proactive approach to safety management. It enhances hazard identification, supports informed decision-making, and significantly reduces the likelihood of accidents.

The implementation of these practices not only ensures compliance with safety regulations but also promotes a strong safety culture within construction projects. This approach contributes to safer working conditions, improved productivity, and sustainable project performance.

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