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A Hybrid Safety Risk Assessment Framework Integrating Hira and Fault Tree Analysis for Complex Urban Infrastructure

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Abstract: *Safety in the construction industry remains one of the most widely discussed subjects and continues to be a focus of ongoing research. With frequent accidents occurring at construction sites, it becomes crucial to identify the underlying causes. This paper applies Job Safety Analysis (JSA), Failure Mode and Effect Analysis (FMEA), Safety Performance Monitoring, and Fault Tree Analysis (FTA) to enhance workplace safety in metro rail projects. Various Hazard Analysis and Risk analysis methodologies are used for ranking the risk by knowing its consequence and its frequency of occurrence in the Construction work place. The primary goal is to identify the hazards present in the workplace and evaluate the associated risks using various available methods to create a safer work environment.*

Keywords: Hazard Identification & Risk Assessment, Risk Ranking, Fault Tree Analysis, Job Safety Analysis, Failure Mode and Effect Analysis.

I. INTRODUCTION

The Indian construction industry is going through an exceptional developmental stage, especially with urban rapid transportation systems like Metros. Elevated metro systems are often the only viable solution in built-up urban areas. The construction process involves heavy machinery like gantry cranes, piling rigs, transit mixers, and launching girders. In India, the construction industry is the second largest employer, but it is also highly hazardous. According to the National Safety Council of India, about 7.5% of laborers are involved in the construction industry, and the fatality rate is significantly higher than in manufacturing.

Risk assessment is a careful examination of what could cause harm to people in their workplace. This research focuses on developing and applying a structured safety risk management framework for metro rail projects, emphasizing the integration of hazard identification, risk assessment, and fault tree analysis. The scope includes safety-critical risks such as construction accidents, electrical hazards, fire, and structural failures.

II. LITERATURE REVIEW

A review of literature on hazard identification and risk analysis (HIRA) reveals various methodologies. Ji-won Song et al. applied FMEA to structural steel erection work. T. Yuge and S. Yanagi discussed the qualitative evaluation of a fault tree with priority AND gates. G. Emre Gurcanli and Ugur Mungen proposed an occupational safety risk analysis method at construction sites using fuzzy sets. Limao Zhang et al. presented a probabilistic approach for safety risk analysis in metro construction. Min Cheng and Yujie Lu developed a risk assessment method combining fuzzy logic with FMEA for complex pipe jacking construction projects.

The literature indicates a need for comprehensive and integrated risk assessment models that combine qualitative and quantitative techniques to handle uncertainties and specific site conditions in construction projects.

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Literature Gap & Problem Identification

Research Gap in Current Safety Management Practices

Lack of an Integrated Hybrid Framework: While tools like JSA, FMEA, and FTA are proven effective, previous studies predominantly apply them in isolation. There is a clear gap in creating a unified, multi-tiered framework that combines baseline Hazard Identification (HIRA) with advanced failure modeling (FTA).

Complexity vs. Practical Application: Many existing advanced models (e.g., Fuzzy-AHP, Bayesian Networks) are mathematically complex and difficult for on-site engineers to implement dynamically. A practical, user-friendly framework tailored for immediate field application is required.

Inadequate Focus on Synergistic Site Risks: Current tools often evaluate risks from a predefined hierarchy and fail to capture the specific, simultaneous complexities of elevated metro construction in dense urban areas (e.g., live traffic interaction, heavy lifting, and working at heights).

Comprehensive Assessment of Critical Equipment: There is limited research that directly links general workplace hazard analysis (HIRA/JSA) with the specific mechanical failure modeling of high-risk site equipment (like tower cranes) within a single project scope.

III. AREA OF STUDY

The study focuses on a Metro Rail Project involving the construction of an elevated viaduct structure. The infrastructure at the construction site includes batching plants, canteens, worker rest rooms, hospitals, and designated areas for store and machine parking. Key equipment includes lifting tackles and cranes (e.g., Tower Cranes, Cummins Hydraulic Truck Crane CQUY550).

3.1 Crane Capacity Details (Model: CQUY550)

Table 1: Crane Details at work side

Descriptions	Unit	Data
Length of standard boom	M	13~52
Length of fixed jib	M	9.15~15.25
Max. length of boom plus fixed jib	m	43+15.25
Swing speed	r/min	High 2.7 Low 1.8
Travel speed	km/h	1.1
Max. single line pull	t	15t
Grade Ability	%	40
Weight of whole machine	t	55

Figure 1: Batching Plant Worker Welfare Machine Parking

IV. PROBLEM IDENTIFICATION

Several hazards were observed at the project site, including structural, mechanical, electrical, chemical, and biological hazards. Common construction site falls involve roof-related falls, crane falls, scaffolding falls, elevator shaft falls, and gaps in flooring. Falling objects and crane accidents also pose significant risks. Types of injuries observed include spinal cord injuries, broken limbs, blinding injuries, hearing loss, head injuries, coma, cuts, and stress injuries.

Type of Construction Hazard

This development work site had numerous exercises arranged by L&T Project administration. Specialists and machines move in the different ranges with everybody concentrated on the current workload. In such synchronous actuates at undertaking site area, development mishaps can happen regularly.

On task site, a few sorts of perils watched Such as;

- Structural
- Mechanical
- Electrical
- Chemical
- Radiant Energy
- Biological
- Automated framework present nearby.

Because of these perils specialists get by from transitory or lasting disablement or some time passing each of these mishaps, however these circumstance may totally stayed away from through compelling security measures as it were

Development Site Falls-Bits of knowledge demonstrate that improvement workers are executed each year as a result of advancement site falls. Tremendous quantities of these passing or wounds which can be expected realizing security benchmarks. All things considered, advancement site falls consolidate housetop related falls, falling articles, crane falls, system falls, lift shaft falls, falls coming to fruition as a result of openings in deck,. Fruitful Proper protection apparatus and security wellbeing measures are imperative to guarantee the lives of workers.

Roof Related Falls-In development work there are an assortment of rooftop related occupations that posture incredible danger for even the most experienced specialists, for example, bay window falls, correspondence tower falls, tumbles off of rooftop structures, falls through existing openings,. Wounds can be kept away from with legitimate security safety measure and hardware. Rooftop falls are generally normal in development work, and there are numerous reasons for these development mischances. As a standout amongst the most well-known reasons for death on the development site, rooftop falls ought to be considered important and each exertion ought to be made to keep these fetal mishaps.

Crane Falls on Construction Site-Shockingly, there are times when the use of cranes results in mischief or even downfall. Overseers can fall unprecedented statures from their cranes, and afterward again cranes can lose their equality and topple, realizing the injuries of various pros.

Scaffolding Falls-Scaffolds Platforms can achieve extensive statures and must be fabricated effectively keeping in mind the end goal to guarantee the security of those working with them. Platform falls can happen for an assortment of reasons, however a standout amongst the most appalling happens when broken framework development is to be faulted .Scaffolding is an impermanent system used to bolster development laborers and their materials amid the development or repair of extensive structures.

Elevator Shaft Falls-Amid development, lift shaft falls can happen with lethal results. Despite the fact that there have been accounted for instances of people surviving tumbles from statures may bring about lethal in a few occurrences. In any case, numerous lift shaft falls can be effortlessly counteracted through legitimate preparing and wellbeing safety measures.

Gaps in Flooring on Construction Site-Falls made by openings in ground surface or weak deck are a huge peril for any person from an improvement bunch. The advancement handle that can incite wounds or notwithstanding passing when the falls happens. Exactly when there are openings in ground surface and are not suitably stamped, then they transform into a honest to goodness wellbeing peril for even the most experienced advancement authorities.

Falling Objects- The wounds kept up from falling articles may extend from minor scratches and slices to power blackouts, visual need, or even passing. Change laborers are at danger from falling difficulties at whatever time they are underneath where overhead work is being in movement. With a specific last target to minimize the wide variety of prosperity shields should be taken some of them are the events of falling things at a progression site.

Crane Accidents-In thickly populated urban territories where there is no spot else to manufacture anyway they will find cranes are everywhere and they have to relies on to make business structures and private structures. The usage and making of cranes have allowed individuals to make structures which could have never imagined. In spite of the way that we upgraded an impressive measure in regards to cranes with the best in class development consistently, a rate of the setbacks still happen that can realize damage or death. Harmed cranes, lightning, high winds, falls, electric stun, and diverse threats associated with crane mishap while advancement at statures. Various crane disasters can be avoided with real get ready and wellbeing philosophy. In the midst of advancement, the thriving of workers is basic than various thoughts.

Construction Related Hazards

Problem noted during MPPGCL Construction activities by Plants &equipment's Clustering plant dangers

Inhalation-Breathing in the dust and crude materials at a plant can bring about various wellbeing dangers. Breathing in bond dust is accepted to add to growth and breathing in dust can likewise bring about throat and nose disturbance. Breathing in bond dust can even bring about nosebleeds and also trouble with relaxing. You can shield yourself and your workers from this danger by wearing dust fog veils

Eyes-Dust from bond and other crude materials utilized for delivering cement can likewise make harm your eyes, including aggravation and, in amazing cases, notwithstanding blazing. To secure your eyes, you ought to dependably wear defensive goggles when working with the crude materials utilized for blending concrete.

Skin-smolders and bothering-Introduction to wet cement can bring about aggravation and even severe singeing. On the off chance that you come into contact with wet solid, you ought to quickly wash it off your skin to maintain a strategic distance from damage. It is additionally prudent to wear gloves when working with wet cement.

Injuries-At the point when working with concrete and other overwhelming articles, you are at danger of harm. At a bunching plant, all specialists ought to wear hard caps and practice alert when managing overwhelming hardware.

V. METHODOLOGY

Risk assessment is the process used to determine the likelihood that people may be exposed to an injury or illness. The steps include: 1) Identify the Hazard, 2) Assess the Risks, 3) Evaluate existing controls, 4) Implement additional risk controls, and 5) Monitor and Review.

Figure 5.3: Steps in Risk Assessment

5.1 Risk Assessment Matrix

A semi-quantitative risk matrix was utilized, multiplying Likelihood (L1-L5) and Consequence (C1-C5) to determine the Risk Rating.

Risk Matrix (Likelihood x Consequence)

	Catastrophic	Major	Moderate	Minor	Insignificant
Almost Certain	25	20	15	10	5
Likely	20	16	12	8	4
Possible	15	12	9	6	3
Unlikely	10	8	6	4	2
Rare	5	4	3	2	1

Table 2: Risk Matrix

The project utilized Job Safety Analysis (JSA), Failure Mode and Effect Analysis (FMEA), and Fault Tree Analysis (FTA).

VI. RESULTS, DISCUSSION AND ANALYSIS

The Hazard Identification and Risk Assessment (HIRA) identified critical risks across various activities.

6.1 Hazard Identification and Risk Assessment (HIRA)

Table 3: Hazard Identification and Risk Assessment

Activity	Hazard	Risk Involved	Initial Risk Level (PxS)	Control Measures	Residual Risk Level
Work At Height	Unprotected leading edges	Fatal/serious injury due to falls	4x4=16	Install edge protection (guardrails, nets).	2x4=8
Storage of Explosives	Fire & explosion	Fatal/serious/ multiple injuries	4x4=16	Trained persons, approved containers, valid permits.	2x4=8
Excavation & Tunnels	Trench collapse	Fatal/serious injury due to soil collapse	4x4=16	Shoring, method statement, inspection by competent person.	1x4=4

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Confined space	Asphyxiation / Toxic gases	Fatality/unconscious	4x4=16	Permit to work, gas monitoring, ventilation.	1x4=4
Cranes & Lifting	Failure of crane / Dropped load	Serious injuries / Fatality	3x4=12	TPI, Daily checks, ASLI, lift plan, competent rigger.	1x4=4

6.2 Job Safety Analysis (JSA)

JSA was performed for tasks like Excavation, Underground Piping, Scaffolding, Erection, Welding, and Gas Cutting. Key controls for Scaffolding Erection included deploying trained scaffolders, quarterly inspection of materials, using full body harnesses, stopping work during high winds, and implementing a tag system (GREEN/RED).

JSA- In this possible result and discussion, only most hazardous activity is taken from the site to give an example of job safety analysis procedure.

Table 4 Job Safety Analysis

Activity: List the task required to perform the activity in the sequence they are carried out	**Hazards:** Against each task list the hazards that could cause injury when the task is performed	**Risk Control Measures:** List the control measures required to eliminate or minimize the risk of injury arising from the identified hazard
Job Safety Analysis for Excavation	Exposure to or contact with underground utilities (electrical cable, pipeline, etc)	1. First Refer Engg. Drawings as per site excavation Plan 2. Seek information about the underground utilities and check for the same before excavation. Obtain Excavation Permit Engineer/Supervisor shall be responsible for any violation of the requirement 3. Insulated tools, rubber hand gloves, mask, goggles and safety shoes 4. Use hand digging initially till underground facility located if drawings not available.
Job Safety Analysis for Under Ground Piping Fabrication And Installation	Incompetence Lack of knowledge Improper supports High noise Flying partials Electrocution Slip & trip,	1. Safety Induction, 2. Follow work method statement, 3. Trained work force 4. Tool box talk. 5. Place sufficient adjustable tripod stand or four legged stand with suitable/workable height. 6. Use ear protective muff. Post ear protection signage. 7. Ensure wheel guard for grinding machine, Dead man switches for the grinding machine, 8. Use tight fit safety goggle for the job.
Job Safety Analysis for Concreting	Vibration or toppling of machine. Manual handling of cement bags. Physical contact with cement slurry or wet concrete	1. Position the machine on a firm level ground with proper anchoring. 2. Helmet/Goggle/Safety shoes/Hand gloves. 3. Use mechanical means to carry cement bags from go down to site. 4. Use safe method of manual handling.

Job Safety Analysis for Rigging	Unstable ground Equipment failure	1. Ground condition shall be made suitable for crane. 2. Outriggers shall be fully extended & load bearing pads shall be used during lifting operation. 3. Crane operator has to assess lifting area with rigging supervisor before lifting operation. 4. Lifting is not allowed in harsh weather condition. 5. All lifting tools, tackles shall be protected from sharp edge to avoid damage to slings. 6. Sufficient taglines shall be used with lifting load to avoid swinging the load. 7. The lifting capacity of rigging appliances vs. job to be lifted shall be evaluated about its safe lifting. 8. Crane load chart shall be posted in operator's cabin. The SWL to be mentioned on the crane. 9. The SLI should be in working condition
Job Safety Analysis For Structural Steel Erection Selection of crane,	Mechanical failure of crane. Failure of crane tools & tackles due to overloading.	1. Quarterly inspection & current color tag for crane, man basket, lifting tools & tackles. 2. Management should authorized experienced
Lifting tools & tackles Lifting of structural steel	Improper securing & imbalanced load. Poor hand signal to the operator	Operator & riggers. 3. Daily inspection of crane by operator & reviewed by equipment supervisor. 4. Valid third party certificates for crane, man basket & lifting tools, tackles. 5. Lifting Plan to be prepared for critical lifting 6. Check the load to be lifted 7. Check the SWL of the crane with maximum boom length & radius to work. 8. Check the SWL of the slings, shackles & Chain Pulley Block. 9. Use correct slinging procedure; load should be properly balanced.
Job Safety Analysis for Confined Space entry Preparing for Entry Opening Man-hole, Nozzles, Install exhaust blower, fresh air blower	Incompetency/untrained human resources Injury to workers	1. HSE Induction training to be imparted and should be in possession of HSE Induction card. 2. Specific training on “Confined Space Entry” to be imparted. 3. Only physically and mentally fit persons allowed entering the confined space. 4. Display cautionary board “Confined Space”, “No Unauthorized Entry”. 5. Tool Box Talk to be conducted. 6. Ensure communication system. 7. PTW to be followed. 8. Ensure the emergency rescue procedure and resources are available and workers are aware. 9. Use proper standard tools, do not use fabricated tools 10. Use plant and machinery wherever possible instead of manual lifting.

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Job Safety Analysis for cutting Gas Cutting	Unsafe Storage and Handling of gas cylinders Fire and Explosion	1. The gas cylinders should be stored in separate shed having weather protection. 2. The gas cylinders should be segregated gas wise and full, empty. 3. Trolley shall be used to transport gas cylinders from place to place. 4. Ensure only trained person shall handle the gas cylinders. 5. Always store the cylinders in an upright position and chained. 6. The cylinders should be chained in the trolley also. 7. The cylinder should have valve cap/guard. 8. Fire protection and firefighting system to be available. 9. No smoking board should be displayed. 10. Cylinders should not be rolled on the ground. 11. Cylinders should not be dropped down from the vehicle. 12. Gas cutting to be done by the trained gas cutter and not by helper. 13. Oxygen and acetylene cylinders shall be stored separately in upright position and well secured, with related signs, in weather protection shed. 14. Gas cylinders should have colour code. 15. Rubber hoses should have colour code. 16. Clamps/jubilee clips should be used for connecting hoses. 17. Cap/guard shall be fixed when the cylinder not in use. 18. Valve guard should be fixed when cylinders are in use. 19. Ensure ISI/CE marked flash back arrestors are installed to the cutting torch as well as cylinder side
Job Safety Analysis for Welding Welding	Fire	1. Welding to be done by trained welder, not by helper. 2. Ensure proper house keeping all the time. 3. Ensure proper earthing connections. 4. Ensure that all cables, electrode holder, electrode ovens are in good conditions. 5. Welding return to be connected with proper clamp to job as close as possible from the welding joint. 6. Ensure fire watch, adequate firefighting equipment and fire blankets are in place. 7. Ensure the welding machines are equipped with ELCB, DB. 8. Never place electrode oven on wooden surface when in use. 9. Electrode stubs shall be properly collected in containers, tins. 10. Toolbox talks before starting the job. 11. Weather protection shed to be provided for welding machine. 12. Welding cables should be coiled properly and to be routed away (segregated) from power cable. 13. Flammable material should be removed or covered with fire retardant blanket.

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6.3 Failure Mode and Effect Analysis (FMEA)

FMEA calculates the Risk Priority Number (RPN) = Probability (P) x Gravity (G) x Control (C).

Example: Material handling with Tower Crane. Hazard: Parts drop from lifting devices. Before control: P=7, G=2, C=3, RPN=42. Countermeasure: Proper lifting technique, SOP, Training. After control: P=1, G=2, C=2, RPN=4.

6.4 Safety Performance Rating

Analysis of 5-year data (2020-2025) showed:

Table 5 Safety Performance Rating 2020-2025

Year	Accidents	Man days lost	Frequency Rate	Severity Rate	Incident Rate
2020-2021	11	23	20.31	42.48	22.83
2021-2022	7	45	12.47	80.19	8.81
2022-2023	6	19	9.48	30.02	3.90
2023-2024	5	67	6.44	86.31	12.73
2024-2025	8	36	11.43	51.45	10.60

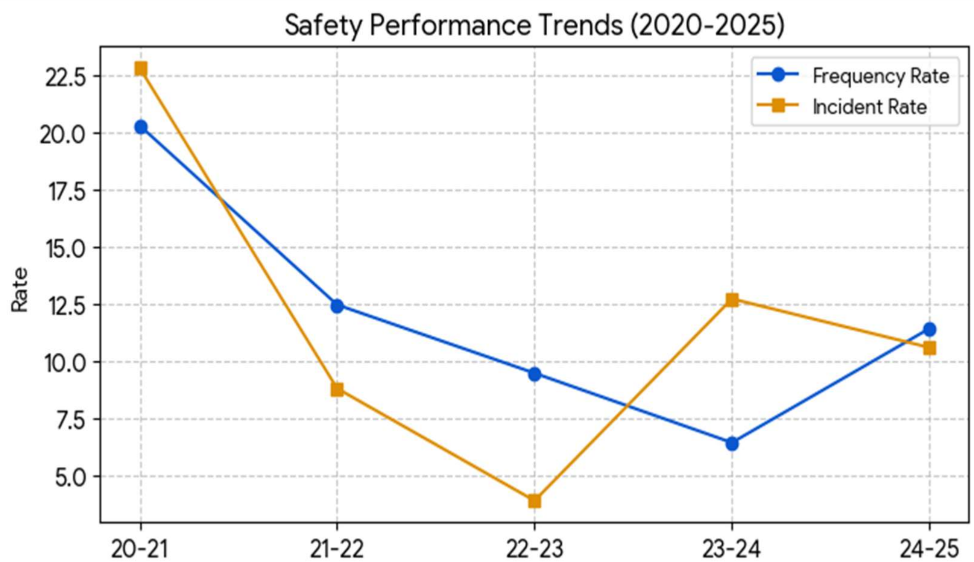

Figure 2 Safety performance trends 2020-2025

Safe T Score for 2024-25 vs 2023-24 was calculated as 0.5423. Since it is between +2 and -2, the change is not significant, indicating random fluctuation.

6.5 Fault Tree Analysis (FTA)

FTA was conducted for the Top Event: "Fall of Tower Crane". The major branches identified were Overload Upsurge, Unexpected Unloading, and Faulty Operation. Basic events included: Non-functional brake system, wrong calculation of mass, wind problems, inclined movement of arm, rope failure, arm folded, unfamiliar operation, horseplay, track gradient under adverse conditions, and loosened joint bolts. Qualitative analysis provided minimal cut sets indicating the possible approaches of mishap happening.

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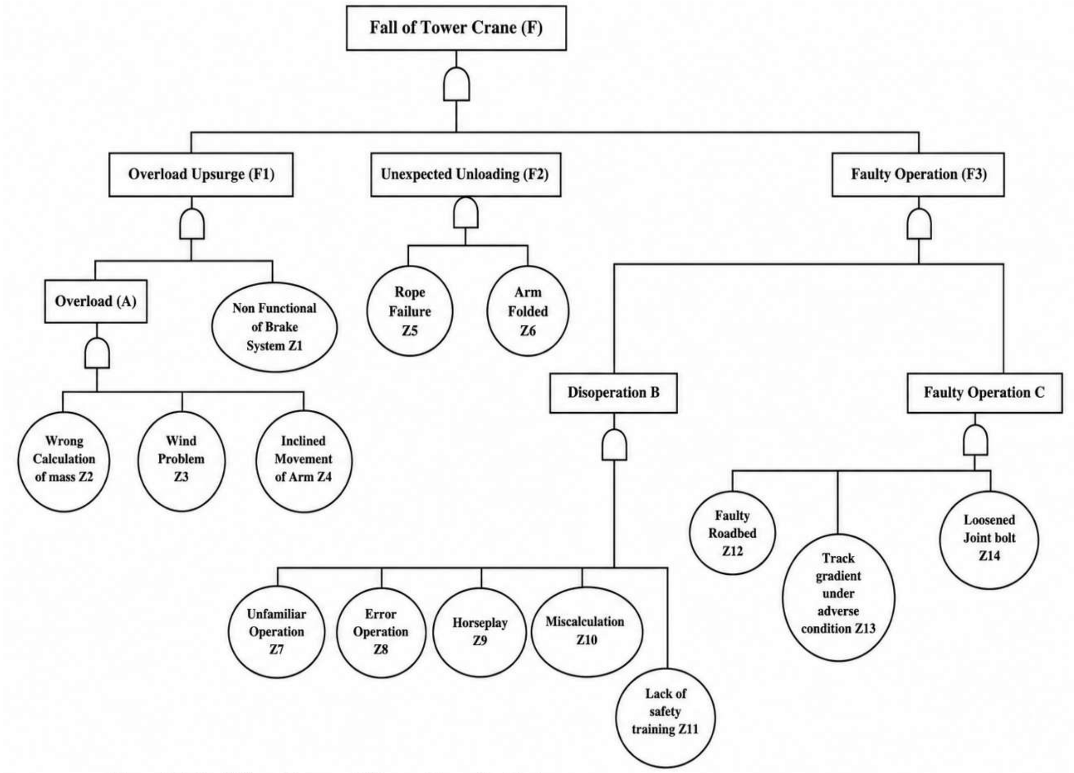

Figure 6.1: Fault Tree Diagram Of Tower Crane Accident

VII. CONCLUSION

This study successfully calculated risk and determined the accident rate, severity rate, incident rate, and safe T score to understand potential job risks. Based on risk assessment methods, risks were prioritized to recommend proper countermeasures. The FTA for potential tower crane failure highlighted minimal cut sets indicating possible mishap approaches. FMEA for crane and tack welding prioritized risk control measures. JSA provided a clear idea about specific activity risks and their countermeasures. The implementation of this integrated safety risk management framework helps ensure safety, reduce accidents, and minimize losses in complex construction projects.

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