Stakeholder-Based Risk Priority Assessment of Construction Accident Causes: A Comparative FMEA, RPN and t-Test Analysis

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Abstract

This study presents a quantitative, stakeholder-based assessment of construction accident risks using Failure Mode and Effects Analysis (FMEA), Risk Priority Number (RPN), risk-rating comparison and t-test significance analysis. Primary survey data were obtained from 1,250 respondents equally distributed among five construction stakeholder groups—architects, design engineers, site engineers, site supervisors and construction workers (250 in each group) in Tamil Nadu, India. Twenty-three accident causes were classified into five cause domains—ergonomic, planning, physical, person and management—and assessed against eight accident categories: Falling from Height; Slips, Trips and Falls; Struck by Objects; Electrocution; Caught in Between; Faulty Tools; Collapses/Cave-ins; and Fire / Explosions. The overall mean risk-rating results identify Slips, Trips and fall (14.77) and Struck by Objects (14.23) as the two highest risks, followed by Falling from Height (13.00) and Caught in Between (12.17). Cause-wise t-tests reveal substantial stakeholder differences, with the largest reported values occurring for Fatigue–Caught in Between (t = 79.000), Material Quality–Collapses/Cave-ins (t = 24.000), Monotony–Falling from Height (t = 21.000), Vibration–Caught in Between (t = 19.000), Carelessness–Caught in Between (t = 18.779), Negligence–Electrocution (t = 18.779), and Work Assignments–Struck by Objects (t = 17.963). At the cause-category level, all five domains show statistically significant differences across the reported risks at α = .05. The findings demonstrate that construction safety is simultaneously technical, behavioural, environmental and managerial, and that multi-stakeholder risk assessment can reveal risk priorities that may be obscured by single-group evaluation.

Keywords: Construction Safety; Occupational Safety; FMEA; Risk Priority Number; Stakeholder Perception; t-test; Construction Hazards; Risk Assessment

1. Introduction

Construction is a dynamic production environment in which design decisions, temporary works, material handling, equipment operation, workforce behaviour, site conditions and management practices interact continuously. Unlike static industrial environments, construction sites change as the project progresses, so the hazard profile can change from one activity to another and from one project phase to the next. This dynamic character makes construction safety a systems problem rather than a problem attributable to a single unsafe act. Reviews of construction accident causation have shown that worker actions, workplace conditions, equipment, project management, risk management and supervision frequently interact in producing accidents (Haslam et al., 2005[1]; Winge et al., 2019)[2].

Accident prevention therefore requires both identification of hazardous conditions and an understanding of the mechanisms through which risks develop. Abdelhamid and Everett (2000)[3] distinguished among unsafe conditions, unsafe acts and management-related root causes, emphasizing that effective prevention requires attention to underlying causes rather than only immediate accident events. More recent reviews similarly show that safety performance is shaped by interacting factors at personal, workgroup, project and organizational levels (Mohammadi et al., 2018[4]; Newaz et al., 2021)[5].

The Indian construction sector presents an especially important context for such investigation. Rapid infrastructure and building development is accompanied by large and heterogeneous workforces, subcontracting, temporary work arrangements and substantial variation in safety-management capability. Indian studies have identified weaknesses in safety implementation and emphasized the importance of management involvement, safety training, supervision and worker interaction (Singh & Misra, 2021[6]; Samanta & Gochhayat, 2023)[7]. The problem is therefore not simply the presence of hazards, but the ability of project organizations to recognize, prioritize and control them consistently.

Risk perception adds another dimension. Architects, designers, site engineers, supervisors and workers occupy different positions in the construction system. They encounter different hazards, possess different information and have different responsibilities. Zhao et al. (2016)[8] demonstrated that safety-critical construction stakeholders can disagree significantly in their judgments of risk. Such differences should not automatically be treated as error; they can provide diagnostic information about blind spots and competing interpretations of risk.

FMEA provides a practical mechanism for converting expert and practitioner judgments into a structured risk-prioritization process. Conventional FMEA evaluates Occurrence (O), Severity (S) and Detection (D), commonly combining them into $RPN = O \times S \times D$. The method is transparent and comparatively easy to communicate, although the conventional RPN has recognized limitations related to ordinal scales, equal weighting and possible ranking ambiguities (Liu et al., 2013)[9]. Construction-specific applications have therefore developed enhanced FMEA approaches, including fuzzy FMEA and fuzzy AHP (Abdelgawad & Fayek, 2010)[10]. The present study retains conventional FMEA because the objective is not to replace the established risk-rating process but to complement it with multi-stakeholder comparison and statistical validation.

Accordingly, this research examines 23 specific construction accident causes across eight accident categories using the perceptions of five stakeholder groups. The study moves beyond a simple hazard ranking by identifying which individual causes produce the strongest differences in stakeholder perceptions and whether those differences are statistically significant. The analysis also aggregates the 23 causes into five broader domains—ergonomic, planning, physical, person and management—to determine whether stakeholder disagreement is concentrated in a particular causal domain.

2. Literature Review

2.1 Construction Accident Causation as a Systems Problem

Early construction safety research often concentrated on immediate unsafe acts and physical hazards. However, systems-based research has demonstrated that accidents frequently emerge from combinations of organizational decisions, work conditions and human actions. Haslam et al. (2005)[1] demonstrated that based on the investigation of construction accidents, identified management, workplace, equipment, worker and work-team influences. Abdelhamid and Everett (2000)[3] likewise argued that root-cause analysis should distinguish management failures from unsafe conditions and unsafe acts. Winge et al. (2019)[2] subsequently demonstrated causal connections among worker actions, risk management and immediate supervision, showing that supervision can function as a bridge between organizational decisions and frontline behaviour.

2.2 Human, Ergonomic and Behavioural Factors

Manual handling, prolonged static postures, repetitive activities, fatigue and time pressure are common characteristics of construction work. Causes such as Repetitive handling, Heavy lifting, prolonged single position, long working hours, Monotony and Fatigue can influence attention, physical capability and decision-making. Choudhry et al. (2008)[11] emphasized that unsafe work behaviour is influenced by a combination of individual and situational factors rather than being reducible to individual irresponsibility. This is important for the present study because Carelessness and Negligence are examined as empirical causes within a broader safety system, not as moral judgments about workers.

2.3 Planning, Design and Management Influences

Planning decisions influence safety before workers reach the site. Structure and design, project scheduling, budget allocation and material quality can shape constructability, sequencing, temporary works and resource availability. Mohammadi et al. (2018)[4] reviewed 90 studies and identified 113 sub-factors grouped within 13 main factors, demonstrating that safety performance is determined by interactions across hierarchical levels. Newaz et al. (2021)[12] further reviewed 2,574 articles and 75 quantitative surveys and identified 38 interrelated safety-management factors across individual, workgroup and organizational levels. Their review argued for greater attention to organizational and cultural factors rather than treating physical hazards as isolated technical problems.

Management-related causes are especially important because they determine how plans are translated into work execution. Work assignments, vendor management, worker competence and supervision influence the actual conditions under which tasks are performed. Winge et al. (2019)[2] found immediate supervision and risk management to be central causal connections. This supports the inclusion of Work Assignments, Untrained and Incompetent Workers, and Ineffective Supervision and Examination in the present study.

2.4 FMEA and RPN in Construction Safety

FMEA is a structured preventive technique that identifies potential failure modes, evaluates their causes and effects, and prioritizes corrective action. In construction, Abdelgawad and Fayek (2010)[10] demonstrated the application of FMEA to construction risk management and combined it with fuzzy AHP to address some limitations of conventional RPN. Liu et al. (2013)[9], in a review of 75 FMEA papers, showed that conventional RPN has important limitations and that alternative approaches have been developed using fuzzy logic, multi-criteria decision-making and other methods. These limitations notwithstanding, conventional RPN remains attractive in practice because its calculation and interpretation are straightforward.

The present study uses the FMEA logic as a transparent common language across stakeholder groups. Each respondent assesses Occurrence, Severity and Detection on a ten-point scale, after which risk ratings/RPNs are compared. The emphasis is therefore on relative prioritization and stakeholder differences rather than claiming that RPN is an absolute probability of accident occurrence.

2.5 Stakeholder Risk Perception

Risk perception is shaped by professional role, exposure, responsibility, experience and access to information. Zhao et al. (2016)[8] provided empirical evidence of intergroup discordance among construction stakeholders and concluded that effective risk management requires attention to these differences. The present study extends this line of inquiry by comparing five groups within one empirical framework: architects, design engineers, site engineers, site supervisors and construction workers. This broader representation captures the project lifecycle from design through planning, execution, supervision and direct work exposure.

2.6 Indian Construction Safety and Management

Indian evidence reinforces the importance of management and worker-level factors. Singh and Misra (2021)[6] developed a safety-performance evaluation framework for the Indian construction industry and reported that management involvement, interaction with workers and safety training were important for safety performance. Samanta and Gochhayat (2023)[7] reviewed occupational safety and health in the Indian construction sector and highlighted challenges including under-reporting, manual work, transient workforces and weaknesses in safety implementation. Bhagwat and Delhi (2022)[13] also reported differences in safety perceptions across multiple organizational levels in the Indian construction industry. Together, these studies justify a multi-level stakeholder design for the present research.

2.7 Emerging Proactive Safety Management

Contemporary construction safety research increasingly emphasizes leading indicators and proactive management. Xu et al. (2021)[14] identified 16 safety leading indicators and argued for combining qualitative and quantitative measures while considering organizational, operational and behavioural issues. Alkaissy et al. (2020)[15] reviewed 20 years of safety risk modeling and noted the growing importance of integrated modeling approaches. Digital technologies such as BIM, computer vision, wearable and predictive analytics can strengthen hazard detection, but they do not eliminate the need for managerial interpretation and stakeholder participation. The current study contributes to this proactive perspective by treating statistically significant differences in risk perception as a signal for targeted safety review.

2.8 Research Gap

Three gaps emerge from the literature. First, many studies examine accident causes or safety-management factors without simultaneously comparing multiple stakeholder groups. Second, FMEA applications often emphasize final RPN ranking without investigating whether stakeholder perceptions differ significantly. Third, broad causal domains can conceal important cause-specific relationships. The present study addresses these gaps by retaining 23 individual causes, eight accident categories and five stakeholder groups, and by combining risk-rating evidence with cause-wise and cause-category-wise t-tests.

3. Research Objectives and Hypotheses

3.1 Objectives

1. To identify and assess 23 constructions accident causes against eight major construction accident categories.
2. To compare construction risk perceptions among architects, design engineers, site engineers, site supervisors and construction workers.
3. To identify cause–risk combinations that exhibits the largest differences in stakeholder risk perception.

4. To test the statistical significance of stakeholder differences at the individual-cause and cause-category levels.
5. To develop an integrated, stakeholder-informed basis for construction safety prioritization and management intervention.

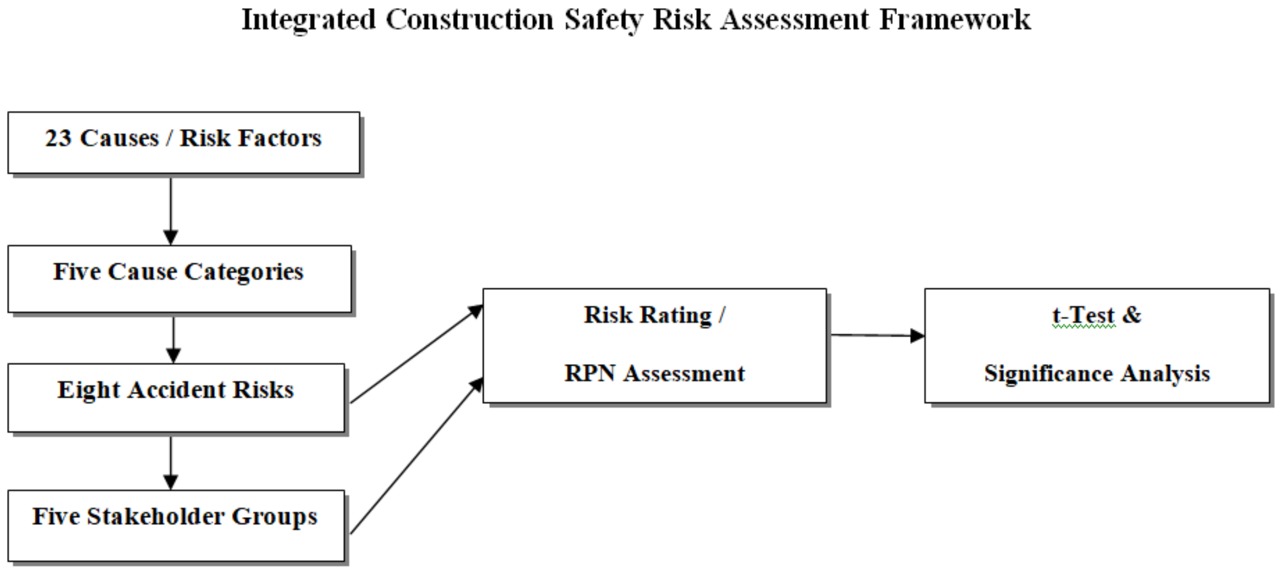
3.2 Hypotheses

1. H1: Stakeholder perceptions of construction accident risk differ significantly across the five stakeholder groups.
2. H2: The 23 identified accident causes exhibit statistically significant differences in perceived contribution to the eight accident categories.
3. H3: Ergonomic, planning, physical, person and management cause categories are significantly associated with differences in stakeholder RPN perceptions.
4. H4: Multi-stakeholder risk assessment provides additional safety-prioritization information beyond a single-stakeholder assessment.

4. Conceptual Framework

The conceptual framework positions construction activities as the operational context, the 23 causes as explanatory risk factors, the eight accident categories as safety outcomes, and the five stakeholder groups as distinct perception sources. FMEA-based risk assessment provides the quantitative measurement layer. RPN/risk-rating comparisons establish priority, while t-tests establish whether stakeholder differences are statistically significant. The resulting evidence is translated into targeted safety-management actions.

Figure 1. Conceptual framework for stakeholder-based construction accident risk assessment.



5. Research Methodology

5.1 Research Design

The study employed a quantitative, cross-sectional survey design. The research was structured around a stakeholder-based FMEA approach in which respondents independently evaluated construction accident risks. The design is perception-based: the statistical results quantify differences in professional judgments rather than estimating population accident probabilities.

5.2 Study Context and Target Population

The study was conducted in the context of construction projects in Tamil Nadu, India. The target population comprised professionals and workers actively involved in construction projects. Five stakeholder groups were selected to represent distinct stages and responsibilities in the construction lifecycle: architects, design engineers, site engineers, site supervisors and construction workers.

5.3 Sampling and Sample Size

Purposive sampling was adopted because the study required respondents with direct construction experience and familiarity with construction safety and hazard management. Inclusion criteria comprised active involvement in construction activities, practical experience, familiarity with safety practices and willingness to participate. The final dataset contained 1,250 respondents, equally distributed across the five stakeholder groups.

Table 1. Survey sample composition. Source: Primary survey data.

Stakeholder group	Sample size (n)	Percentage
Architects	250	20.0
Design Engineers	250	20.0
Site Engineers	250	20.0
Site Supervisors	250	20.0
Construction Workers	250	20.0
Total	1,250	100.0

5.4 Questionnaire Development

A structured questionnaire was developed from construction-safety literature, FMEA principles, expert consultation and the study's identified hazard structure. It comprised a demographic/professional section and a risk-assessment section. Section B asked respondents to assess Occurrence, Severity and Detection for the identified construction hazards using a ten-point ordinal scale. Higher ratings indicated greater occurrence, greater severity or greater difficulty of early detection, respectively. The questionnaire was reviewed by academic researchers, construction safety specialists and experienced engineering professionals.

5.5 Pilot study, Validity and Reliability

A pilot study was conducted to assess clarity, wording, sequencing and practicality. Content validity was established through expert review, while face validity was examined during pilot administration. Internal consistency was assessed using Cronbach's alpha, with 0.70 treated as the minimum acceptable threshold. The supplied study record states that the instrument demonstrated satisfactory reliability and content validity; however, because the numerical alpha value was not supplied in the dataset used for this manuscript, no numerical reliability coefficient is introduced here.

5.6 Data Collection and Quality Control

Primary data were collected through structured questionnaire administration using field visits, professional interactions and organizational contacts. Participants were informed of the study purpose and the voluntary and confidential nature of participation. Completed questionnaires were screened for completeness and consistency; substantially incomplete or inconsistent responses were excluded before analysis. The final analytical dataset comprised 1,250 respondents.

5.7 Risk Categories

Table 2. Eight construction accident/risk categories assessed in the survey.

No.	Accident / risk category
1	Falling from Height
2	Slips, Trips and Falls
3	Struck by Objects
4	Electrocution
5	Caught in Between
6	Faulty Tools
7	Collapses / Cave-ins
8	Fire / Explosions

5.8 Twenty-three causes and five causal domains

Table 3. Classification of the 23 accident causes into five causal domains.

Cause domain	Specific causes
Ergonomic	Repetitive handling; Heavy lifting; Prolonged single position; Carelessness; Negligence
Planning	Structure and design; Project Schedule; Inadequate Budget; Material Quality
Physical	Site nature; Climate; Noise; Vibration; Exposure to materials
Person	Long working hours; Tight Deadlines; Monotony; Fatigue; Inter-personal relationships
Management	Work assignments; Vendor miss-management; Untrained and Incompetent workers; Ineffective supervision and examination

5.9 FMEA and RPN

Risk Priority Number was defined using the conventional FMEA expression:

$$RPN = O \times S \times D \quad (1)$$

Where, O is Occurrence, S is Severity and D is Detection. Stakeholder-specific RPN values were calculated or reported from the primary dataset. The analysis uses the supplied RPN/risk-rating outputs and does not reconstruct respondent-level values where those values were not explicitly supplied.

5.10 Statistical Analysis

Descriptive comparison was used to summarize risk priorities. Independent-sample t-test outputs supplied in the study were used to examine differences in stakeholder RPN perceptions. Statistical significance was evaluated at $\alpha = .05$; $p < .05$ was interpreted as statistically significant. The reported t-values are treated as indicators of the magnitude of the tested difference, while p-values determine statistical significance. Because respondent-level raw data, degrees of freedom and the exact t-test specification were not supplied with the tabulations, no additional effect sizes or confidence intervals were calculated.

5.11 Activity-level Validation

The study also examined twelve construction activities—Investigation, Site Cleaning, Earthwork, Foundation, Masonry, Concrete, Scaffolding, Electrical, Plumbing, Finishing, Painting and Final Cleaning—against the eight accident categories. In the supplied activity-level significance table, 96 activity–risk relationships were tested. Using p < .05 as the criterion, 92 relationships were statistically significant and four were not significant. The non-significant relationships were Investigation–Struck by Objects (p = .067), Investigation–Electrocution (p = .056), Investigation–Faulty Tools (p = .056), and Earthwork–Fire/Explosions (p = .061).

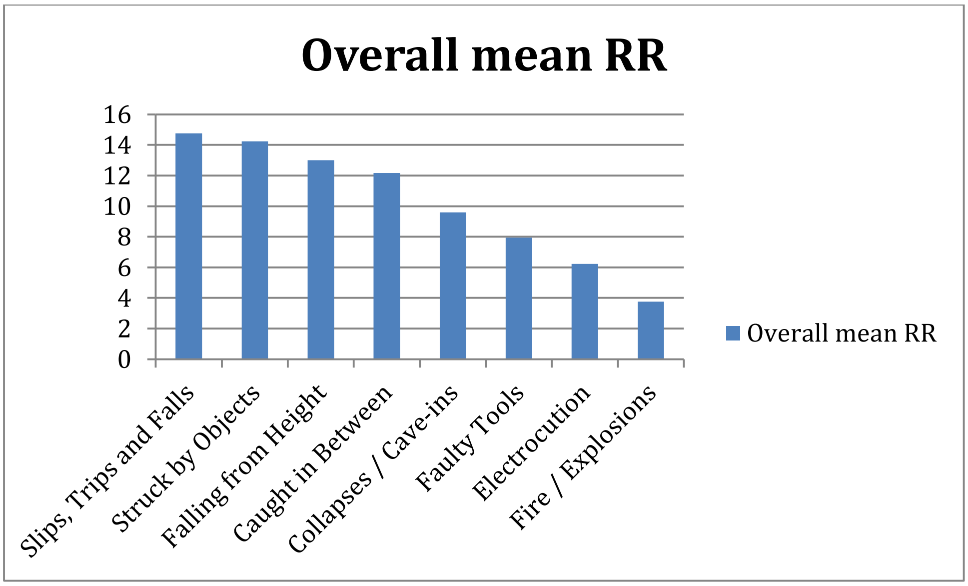
6. Results

6.1 Overall Risk-rating Comparison

Table 4. Overall ranking of the eight construction accident risks. Source: Primary survey data.

Rank	Accident risk	Overall mean RR	Risk level
1	Slips, Trips and Falls	14.77	Very High
2	Struck by Objects	14.23	Very High
3	Falling from Height	13.00	High
4	Caught in Between	12.17	High
5	Collapses / Cave-ins	9.60	Moderate
6	Faulty Tools	7.95	Moderate
7	Electrocution	6.23	Low–Moderate
8	Fire / Explosions	3.75	Low

Figure 2. Overall mean risk-rating comparison across accident categories.



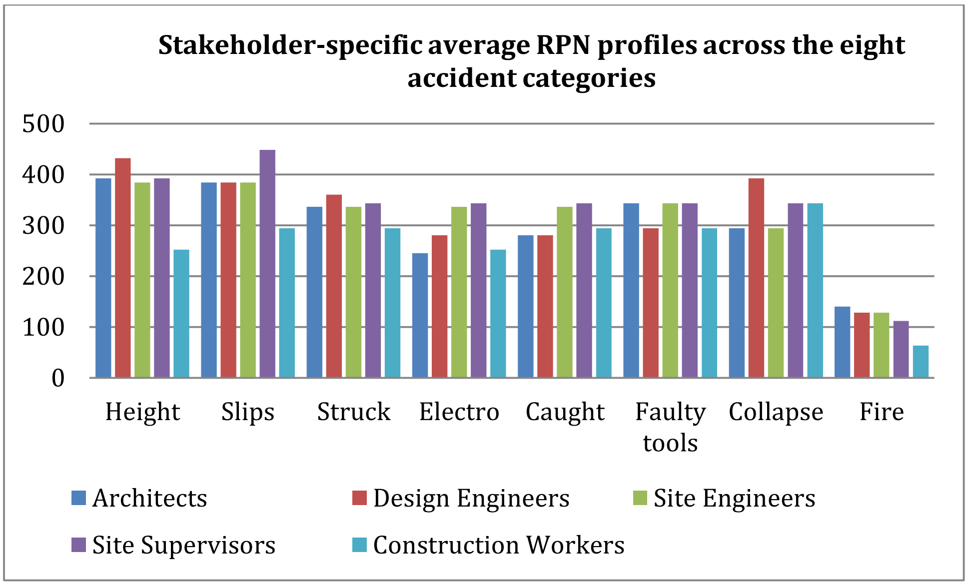
The overall risk-rating pattern establishes a clear priority structure. Slips, Trips and Falls is ranked first (14.77), followed by Struck by Objects (14.23). Falling from Height (13.00) and Caught in Between (12.17) form the next high-risk group. Collapses/Cave-ins (9.60) and Faulty Tools (7.95) fall into the moderate range, while Electrocution (6.23) and Fire/Explosions (3.75) receive comparatively lower overall ratings. The lower ranking of a hazard should not be interpreted as absence of danger; rather, it indicates lower relative risk rating within the present dataset.

6.2 Stakeholder-Specific RPN Profiles

Table 5. Stakeholder-specific average RPN profiles across the eight accident categories. Source: Primary survey data.

Stakeholder	Height	Slips	Struck	Electro	Caught	Faulty tools	Collapse	Fire
Architects	392	384	336	245	280	343	294	140
Design Engineers	432	384	360	280	280	294	392	128
Site Engineers	384	384	336	336	336	343	294	128
Site Supervisors	392	448	343	343	343	343	343	112
Construction Workers	252	294	294	252	294	294	343	63

Figure 3. Stakeholder-specific average RPN profiles across the eight accident categories



The stakeholder profiles show both convergence and divergence. Architects report their highest average RPN for Slips, Trips and fall (392), closely followed by Falling from Height (384). Design Engineers identify Falling from Height (432) as the highest, with Collapses/Cave-ins (392) and Struck by Objects (360) also prominent. Site Engineers report equal highest values for Falling from Height and Slips, Trips and Falls (384 each), followed by Faulty Tools (343). Site Supervisors assign the highest average to Slips, Trips and fall (448), followed by Falling from Height (392). Construction Workers show a more distributed profile, with Collapses/Cave-ins at 343 and Slips, Struck by Objects, Caught in Between and Faulty Tools at 294 & Fire/Explosions are lowest for every stakeholder group.

These patterns support the proposition that professional role and exposure shape risk perception. The design-oriented groups emphasize height and structural issues, operational stakeholders emphasize movement and equipment-related risks, while workers show a more distributed perception reflecting simultaneous exposure to multiple hazards.

6.3 Cause-wise t-Test Values

Table 6. t-test values of RPN differences among stakeholder perceptions for the 23 causes and eight accident risks. Source: Primary survey data.

Cause / risk	Height	Slips	Struck	Electro	Caught	Faulty	Collapse	Fire
Repetitive handling	4.274	5.701	5.615	2.236	3.301	7.741	5.019	2.712
Heavy lifting	5	4.846	4.757	3.13	3.413	4.1	14	3.029
Prolonged single position	4.257	4.3	6.708	2.982	2.123	3.944	3.28	5.715
Carelessness	4.529	6.246	12.147	12.364	18.779	8.615	14.143	5.876
Negligence	5.751	14.143	12.364	18.779	17.963	8.091	9.889	5.013
Structure and design	4.52	6.482	6.068	4.635	5.286	4.899	4.237	4.216
Project Schedule	7.75	5.241	5.327	4.325	2.994	4.913	13.88	6.5
Inadequate Budget	3.965	6.771	7.364	4.077	3.283	6.091	7.926	4.494
Material Quality	4.635	8.5	5.308	7.902	7.233	8.944	24	12.649
Site nature	7.632	5.327	4.041	6	4.333	3.9	3.268	3.415
Climate	3.83	5.85	3.737	4	3.727	5.286	3.841	3.674
Noise	5.729	11	5.013	8.573	3.81	6.882	3.055	2.34
Vibration	4.468	11.952	14.697	3.475	19	7.738	14.697	14.697
Exposure to materials	5.013	6.708	3.902	6.328	9	11	2.638	11.677
Long working hours	9.892	10.113	6.046	5.286	7.233	21	3.792	—
Tight Deadlines	5.917	4.593	6.029	3.465	6.755	4.844	13.88	3.792
Monotony	21	6	17.963	7.695	7.738	7.757	4.518	5.013
Fatigue	10.113	6.39	8.525	7.571	79	10.156	3.589	3.521
Inter-personal relationships	5.25	3.301	2.123	2.994	2.135	6.5	4.472	3.255
Work assignments	9.662	7.926	17.963	3.796	11	7.738	12.649	4.692
Vendor mis-management	2.24	6.403	5.715	9.594	8.045	7.738	11.225	14.697
Untrained and Incompetent workers	5.549	8.091	9.707	11.677	11.677	11.677	8.663	7.059
Ineffective supervision and examination	6.186	8.317	5.578	12.124	3.852	11	11	4.867

The largest supplied t-value is associated with Fatigue and Caught in Between (t = 79.000). Other exceptionally high differences occur for Material Quality and Collapses/Cave-ins (t = 24.000), Monotony and Falling from Height (t = 21.000), Vibration and Caught in Between (t = 19.000), Carelessness and Caught in Between (t = 18.779), Negligence and Electrocution (t = 18.779), and Work Assignments and Struck by Objects (t = 17.963). Heavy lifting also produces a high value for Collapses/Cave-ins (t = 14.000), while Project Schedule is high for Collapses/Cave-ins (t = 13.880). These values indicate that the greatest stakeholder differences are concentrated in specific cause–risk combinations rather than being uniform across all hazards.

6.4 Significance of Cause-wise Stakeholder Differences

Table 7. Significance values for cause-wise t-tests of RPN among stakeholders (α = .05). Source: Primary survey data.

Cause / risk	Height	Slips	Struck	Electro	Caught	Faulty	Collapse	Fire
Repetitive handling	0.013	0.005	0.005	0.089	0.030	0.001	0.007	0.053
Heavy lifting	0.007	0.008	0.009	0.035	0.027	0.015	0.000	0.039
Prolonged single position	0.013	0.013	0.003	0.041	0.101	0.017	0.031	0.005
Carelessness	0.011	0.003	0.000	0.000	0.000	0.001	0.000	0.004
Negligence	0.005	0.000	0.000	0.000	0.000	0.001	0.001	0.007
Structure and design	0.011	0.003	0.004	0.010	0.006	0.008	0.013	0.014
Project Schedule	0.001	0.006	0.006	0.012	0.040	0.008	0.000	0.003
Inadequate Budget	0.017	0.002	0.002	0.015	0.030	0.004	0.001	0.011
Material Quality	0.010	0.001	0.006	0.001	0.002	0.001	0.000	0.000
Site nature	0.002	0.006	0.016	0.004	0.012	0.018	0.031	0.027
Climate	0.019	0.004	0.020	0.016	0.020	0.006	0.018	0.021
Noise	0.005	0.000	0.007	0.001	0.019	0.002	0.038	0.079
Vibration	0.011	0.000	0.000	0.025	0.000	0.002	0.000	0.000
Exposure to materials	0.007	0.003	0.018	0.003	0.001	0.000	0.058	0.000
Long working hours	0.001	0.001	0.004	0.006	0.002	0.000	0.019	—
Tight Deadlines	0.004	0.010	0.004	0.026	0.003	0.008	0.000	0.019
Monotony	0.000	0.004	0.000	0.002	0.002	0.001	0.011	0.007
Fatigue	0.001	0.003	0.001	0.002	0.000	0.001	0.023	0.024
Inter-personal relationships	0.006	0.030	0.101	0.040	0.100	0.003	0.011	0.031
Work assignments	0.001	0.001	0.000	0.019	0.000	0.002	0.000	0.009
Vendor mis-management	0.089	0.003	0.005	0.001	0.001	0.002	0.000	0.000
Untrained and Incompetent workers	0.005	0.001	0.001	0.000	0.000	0.000	0.001	0.002
Ineffective supervision and examination	0.009	0.004	0.011	0.001	0.031	0.002	0.002	0.017

Most cause–risk combinations are statistically significant at the 5% level. Carelessness and Negligence are particularly consistent, with significant results across all eight accident categories. Material Quality is also significant across all eight categories. Vibration is significant across all reported risks, while Untrained and Incompetent Workers and Ineffective Supervision and Examination show significant differences across all eight risks. A smaller number of relationships are not significant, including Repetitive handling–Electrocution (p = .089), Repetitive handling–Fire/Explosions (p = .053), Prolonged single position–Caught in Between (p = .101), Inter-personal relationships–Struck by Objects (p = .101), Inter-personal relationships–Caught in Between (p = .100), Vendor miss-management–Falling from Height (p = .089), and Exposure to materials–Faulty Tools (p = .188). These non-significant relationships suggest comparatively closer stakeholder judgments for those specific cause–risk combinations.

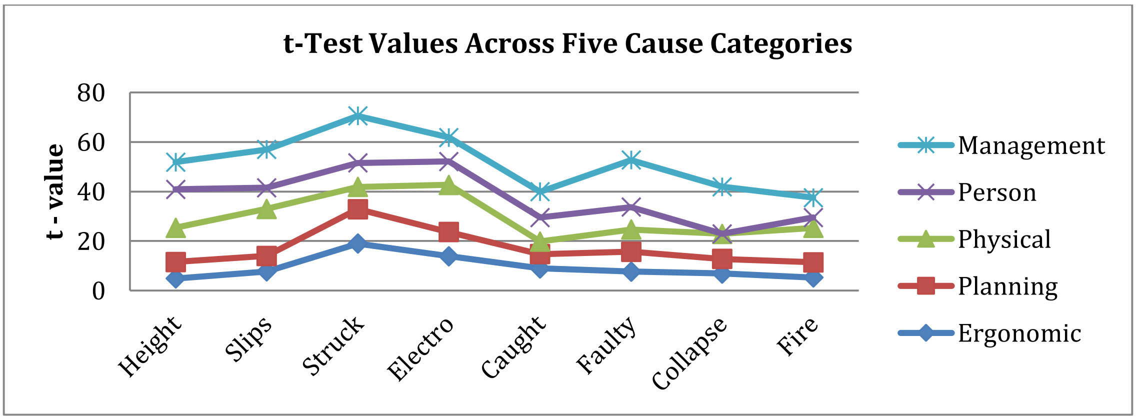
6.5 Cause-category-level t-test

Table 8. t-test values by the five cause categories and accident risks. Source: Primary survey data.

Cause category	Height	Slips	Struck	Electro	Caught	Faulty	Collapse	Fire	Significance
Ergonomic	4.884	7.741	19.000	13.880	9.003	7.698	6.882	5.286	All significant
Planning	6.675	6.274	13.880	9.798	5.702	8.000	5.920	6.150	All significant
Physical	13.860	19.000	9.003	19.000	5.137	9.003	10.124	13.880	All significant
Person	15.493	8.500	9.690	9.487	9.662	9.003	—	4.226	Reported p-values significant where supplied
Management	10.956	15.493	19.000	9.662	10.429	19.000	19.000	7.980	All significant

At the aggregated level, the Ergonomic causes show the highest t-value for Struck by Objects (19.000), followed by Electrocution (13.880). Planning causes show their highest value for Struck by Objects (13.880). Physical causes demonstrate very high differences for Slips, Trips and fall and Electrocution (19.000 each). Person-related causes show the strongest supplied value for Falling from Height (15.493), while Management causes reach 19.000 for Struck by Objects, Faulty Tools and Collapses/Cave-ins. The result is important because it shows that stakeholder disagreement is not concentrated in one domain: different causal domains become prominent for different accident mechanisms.

Figure 4. Comparison of t-test values across the five cause categories.



7. Activity-Level Statistical Validation

Table 9. Activity-level significance summary across eight accident categories. Source: Primary survey data; $p < .05$ criterion.

Construction activity	Significant relationships	Observation
Investigation	5 of 8	Struck by Objects, Electrocution, Faulty Tools not significant; remaining significant
Site Cleaning	8 of 8	All eight significant
Earthwork	7 of 8	Fire/Explosions not significant
Foundation	8 of 8	All eight significant
Masonry	8 of 8	All eight significant
Concrete	8 of 8	All eight significant
Scaffolding	8 of 8	All eight significant
Electrical	7 of 8	Collapses/Cave-ins not significant
Plumbing	8 of 8	All eight significant
Finishing	8 of 8	All eight significant
Painting	8 of 8	All eight significant
Final Cleaning	8 of 8	All eight significant

The activity-level results reinforce the cause-wise analysis. Site Cleaning, Foundation, Masonry, Concrete, Scaffolding, Plumbing, Finishing, Painting and Final Cleaning show significance across all eight accident categories. Investigation shows five significant relationships, while Earthwork and Electrical show seven each. Thus, statistical differences in perceived accident risk are not confined to particular hazard types; they occur throughout the construction process.

8. Discussion

The central finding is that construction safety risk is both shared and differentiated. The overall risk-rating analysis shows a clear consensus around movement-related and impact-related hazards: Slips, Trips and fall, Struck by Objects, Falling from Height and Caught in Between occupy the leading positions. This agrees with systems-based construction safety literature, which identifies the interaction of site conditions, work organization, human actions, equipment and management as important contributors to accidents (Haslam et al., 2005[1]; Mohammadi et al., 2018[4]; Winge et al., 2019[12]).

The stakeholder-specific RPN profiles demonstrate why a single aggregate score can be insufficient. Architects and design engineers emphasize height and structural risks, whereas site engineers and supervisors show stronger concern for movement, tools and active site conditions. Workers display a more distributed risk profile, which is consistent with their simultaneous exposure to multiple hazards. This is broadly consistent with Zhao et al. (2016)[8], who demonstrated that construction stakeholders can differ systematically in risk judgments.

The cause-wise t-test analysis adds a second layer of evidence. Fatigue–Caught in Between produces the largest supplied t-value (79.000), indicating an exceptionally large difference in stakeholder assessment.

Importantly, this should not be interpreted as evidence that fatigue itself causes 79 times more risk; the t-value is a statistical test output reflecting the tested difference. The same caution applies to other large values. Material Quality–Collapses/Cave-ins, Monotony–Falling from Height, Vibration–Caught in Between, Carelessness–Caught in Between and Negligence–Electrocution all show strong disagreement. These relationships point toward specific areas in which professional perspectives diverge and therefore warrant joint review.

The management-related findings are especially relevant to engineering management. Work Assignments, Untrained and Incompetent Workers, and Ineffective Supervision and Examination show significant differences across many accident categories. This supports the literature that places management, safety leadership, supervision and organizational factors upstream of frontline unsafe conditions (Newaz et al., 2021[5]; Singh & Misra, 2021[6]). In practical terms, safety management should not rely solely on worker training; it must also examine how tasks are assigned, how competency is verified, how vendors are controlled and how supervision is organized.

The results also support the use of leading-indicator thinking. Xu et al. (2021)[8] argued that proactive safety management requires indicators that identify potential incidents before they occur. In the present study, statistically significant differences in stakeholder perception can themselves function as a diagnostic leading indicator: when architects, engineers, supervisors and workers disagree sharply about a particular cause–risk relationship, that relationship can be subjected to additional hazard review, site observation or control verification.

Finally, the findings support integrated rather than purely technological safety management. Although advanced risk modeling and digital technologies are increasingly important (Alkaissy et al., 2020)[21], the effectiveness of any technology depends on how project participants interpret information and act on it. The present framework therefore treats FMEA/RPN as an analytical core and stakeholder comparison as a validation layer, rather than assuming that numerical risk rankings alone are sufficient for decision-making.

Consolidated Stakeholder Comparison

Table 10. Consolidated comparison of stakeholder risk perceptions.

Stakeholder	Highest average RPN	Next priority	Interpretive emphasis
Architects	Slips, Trips and Falls (392)	Falling from Height (384)	Design-stage/site circulation and height-safety concerns
Design Engineers	Falling from Height (432)	Collapses/Cave-ins (392)	Structural stability, sequencing and design coordination
Site Engineers	Falling from Height (384); Slips (384)	Faulty Tools (343)	Operational control, housekeeping and equipment
Site Supervisors	Slips, Trips and Falls (448)	Falling from Height (392)	Continuous monitoring and enforcement
Construction Workers	Collapses/Cave-ins (343)	Slips/Struck/Caught/Faulty (294 each)	Exposure-driven, simultaneous operational risks

The consolidated comparison demonstrates that there is neither complete agreement nor complete disagreement among stakeholders. Instead, there is a pattern of partial convergence around major hazards combined with role-specific prioritization. This is a useful management finding: safety systems should establish a common minimum set of critical controls while allowing stakeholder-specific concerns to inform detailed intervention planning.

10. Practical and Engineering Management Implications

- Prioritize Slips, Trips and fall, Struck by Objects, Falling from Height and Caught in Between in project-level risk-control plans.
- Strengthen housekeeping, access routes, edge protection, scaffolding controls and work-at-height systems.
- Use joint design–construction safety reviews to address Structure and design, Project Schedule and Material Quality before execution.
- Strengthen fatigue management, work-rest planning, task rotation and behavioural safety controls for Long working hours, Monotony and Fatigue.
- Use competency verification, induction, refresher training and task-specific authorization for Untrained and Incompetent Workers.
- Review Work Assignments and supervision arrangements for high-risk activities rather than treating unsafe behaviour as solely a worker-level issue.
- Introduce stronger material inspection and quality-control processes because Material Quality shows high stakeholder differences for several severe risks.
- Use statistical disagreement as a trigger for toolbox discussion, joint risk assessment and targeted site inspection.
- Integrate worker feedback into design-stage and planning-stage safety reviews to reduce the gap between intended and experienced safety controls.
- Use FMEA/RPN as a prioritization tool while recognizing its limitations and complementing it with field observations, incident data and, where feasible, leading indicators.

11. Proposed Stakeholder-Based Construction Safety Risk Prioritization Framework

Based on the empirical findings, the study proposes a Stakeholder-Based Construction Safety Risk Prioritization Framework (S-CSRPF). The framework follows eight steps: (1) identify construction activities; (2) identify hazards and causes; (3) obtain independent assessments from five stakeholder groups; (4) rate Occurrence, Severity and Detection; (5) calculate and compare RPN/risk ratings; (6) test stakeholder differences statistically; (7) translate validated priorities into engineering-management actions; and (8) monitor and reassess the risks continuously.

Phase 1: Construction activity identification.
Phase 2: Hazard and cause identification.
Phase 3: Multi-stakeholder assessment.
Phase 4: FMEA rating of Occurrence, Severity and Detection.
Phase 5: RPN/risk-rating prioritization.
Phase 6: Statistical validation of stakeholder differences.

Phase 7: Engineering-management intervention and resource allocation.Phase 8: Continuous monitoring, feedback and risk reassessment.

12. Conclusions

This study provides an empirical, stakeholder-based assessment of construction accident risks using 1,250 survey responses from architects, design engineers, site engineers, site supervisors and construction workers. Twenty-three causes were examined against eight accident categories through FMEA-based risk assessment and t-test analysis.

Four principal conclusions emerge. First: the overall risk-rating analysis identifies Slips, Trips and fall (14.77), Struck by Objects (14.23), Falling from Height (13.00) and Caught in Between (12.17) as the principal priorities. Second: stakeholder-specific RPN profiles demonstrate meaningful differences in priority, with design-oriented stakeholders emphasizing height and structural concerns and site-based stakeholders emphasizing operational risks. Third: the cause-wise t-tests reveal especially strong differences for Fatigue–Caught in Between, Material Quality–Collapses/Cave-ins, Monotony–Falling from Height, Vibration–Caught in Between, Carelessness–Caught in Between, Negligence–Electrocution and Work Assignments–Struck by Objects. Fourth: all five broad causal domains—ergonomic, planning, physical, person and management—show statistically significant differences across the reported accident risks at the aggregate level.

The research therefore supports a shift from single-stakeholder or purely hazard-based safety assessment toward an integrated approach that combines hazard ranking, cause-specific analysis, stakeholder comparison and statistical validation. The practical value of this approach lies in using differences in perception as diagnostic information. Where stakeholder judgments diverge sharply, project organizations can undertake targeted review, verify controls and develop interventions that address both design-stage and execution-stage conditions.

13. Limitations and Future Research

The study is based on the supplied aggregate survey tables. Although the sample size and stakeholder distribution are available, the dataset used for this manuscript does not include respondent-level observations, degrees of freedom, confidence intervals, or the exact specification of every t-test. Consequently, the manuscript does not introduce unsupported effect sizes or inferential statistics. The numerical reliability coefficient is also not reproduced because the supplied study record reports satisfactory reliability without providing the alpha value.

Future studies should preserve the five-stakeholder structure while collecting respondent-level data that permit effect-size estimation, confidence intervals, post-hoc comparisons and multivariate modeling. Longitudinal studies could examine whether risk perceptions change as projects move from design to execution. Further research could also integrate incident records, safety leading indicators, BIM-based hazard identification and real-time monitoring to validate whether high-perception cause–risk relationships correspond to observed incident frequencies.

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