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Developing a Forensic Engineering Model for Investigation Building Construction Failures: a Literature Review

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Abstract

This study presents a systematic literature review of Scopus-indexed publications (2015–2025) on forensic engineering investigations of building construction failures, conducted under the PRISMA 2020 protocol. From 139 identified articles, 38 were analyzed through bibliometric mapping (VOSviewer) and narrative meta-synthesis. The mapping of methods and failure types indicates that specific failures tend to be examined with particular analytical tools—for example, structural collapses are modeled numerically, while procedural or human-factor failures rely on Root Cause Analysis (RCA), Failure Tree Analysis (FTA), or expert judgment. Findings reveal that research remains predominantly technical, emphasizing structural and material failures analyzed via Finite Element Analysis, load testing, and visual inspection, while managerial, procedural, and legal aspects are underexplored. Three interrelated domains—technical, managerial, and regulative—emerged as key determinants of investigative effectiveness. The study proposes an integrated forensic engineering investigation framework encompassing six sequential phases: Pre-Scene Preparation and Coordination, Scene Examination/Investigation, Laboratory and Testing, Analytical Modelling, Causal Analysis, and Reporting and Knowledge Management. Within technical, investigative, and legal-regulatory domains, ensuring methodological rigor, procedural consistency, and legal defensibility, thereby advancing a standardized, multidisciplinary model for construction failure investigations.

Keywords: Building Construction Failures; Forensic Engineering; Failure Analysis; Integrated Investigation Framework

Cite This Article

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INTRODUCTION

Forensic structural engineering serves a vital function in identifying the root causes of structural failures, providing technical guidance in the immediate aftermath of catastrophic events, and offering expert opinions when legal disputes arise [1]. The core of structural causation analysis lies in the systematic application of the forensic process, which seeks to objectively determine the technical origins of failure through the rigorous examination of available evidence. This process encompasses the systematic collection of data, formulation of failure hypotheses, evaluation of each hypothesis against physical and analytical evidence, and the identification of the most probable cause of failure—a sequence that constitutes a process of analytical reasoning rather than mere synthesis [2]. In professional practice, forensic engineers are engaged in conducting technical investigations, providing expert assessments, and, when necessary, delivering testimony in judicial proceedings. Whether failures occur during construction or throughout the service life of a structure, they are almost invariably followed by comprehensive engineering investigations aimed at diagnosing causes and supporting the resolution of related claims [3].

The technical and legal approaches to addressing structural failures—ranging from first response actions and engineering investigation procedures to damage claim management, dispute resolution, litigation, and the subsequent application of lessons learned—differ significantly across countries. [4] Although the concept of forensic engineering is recognized internationally, its institutional establishment remains limited in many regions. In several countries, the absence of professional bodies, specialized academic programs, or structured lifelong learning initiatives has impeded the systematic development of this discipline. Moreover, there are often no formal requirements defining the qualifications of forensic experts, nor standardized protocols governing the investigative process, as illustrated in Figure 1 [4] Consequently, forensic investigations are frequently conducted in a fragmented and sector-specific manner, leading to substantial variation in practice and outcomes.

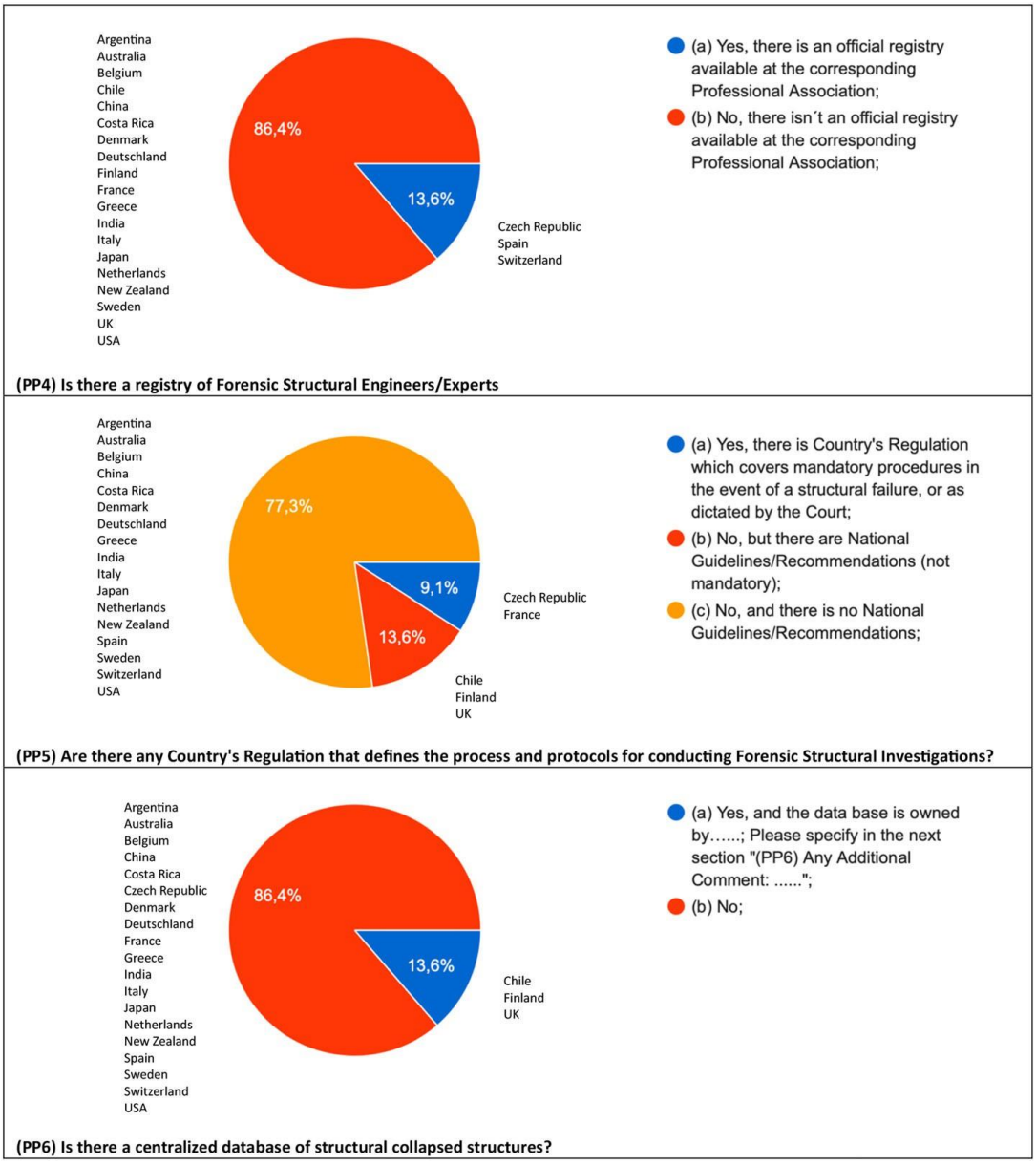

Figure 1. "Professional practice", questions PP4–PP6, Adapted from [4]

In many engineering defect investigations, the selection of a forensic failure analysis methodology is seldom subjected to critical evaluation. Analysts often determine the analytical approach based on convenience or personal preference rather than systematic justification, which may result in the adoption of methods that are neither optimal nor efficient. [5]Such practices can increase both the risk and cost associated with decision-making processes. Consequently, it becomes essential to identify and analyze the variables that influence practitioners in selecting appropriate forensic methodologies. A review of existing literature indicates the absence of clear evidence establishing which factors primarily govern this selection process [6]. Developing a structured framework for choosing suitable methodologies is therefore necessary to reduce subjectivity and improve the reliability of investigative outcomes. In the absence of international standards or universally recognized guidelines for methodology selection, forensic analysts remain vulnerable to selection bias, which heightens the risk of employing sub-optimal analytical methods—potentially extending investigation durations and undermining the accuracy of forensic conclusions [6].

According to findings reported by the IABSE Task Group 5.1 on Forensic Structural Engineering, which compiled responses from experts representing 22 IABSE member countries, only a small proportion of respondents (14%) confirmed the existence of a centralized database documenting structurally collapsed structures (Figure 2 shows question Professional practice PP6) [4] This finding underscores the critical need for establishing comprehensive failure databases that record structural collapse incidents. Such databases would enable the systematic identification and analysis of past failure patterns, thereby supporting proactive risk mitigation and enhancing the prevention of similar failures in future engineering practice.

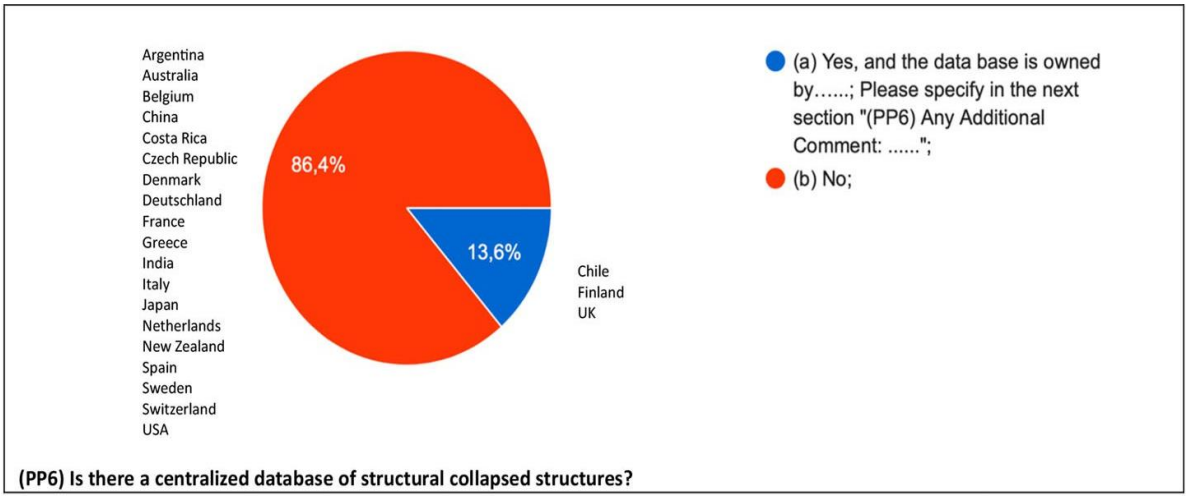

Figure 2. "Professional practice", questions PP6 Adapted from [4]

The integration of physical evidence with technical documentation in forensic engineering remains fraught with several challenges and inherent limitations. These difficulties can generally be grouped into three major areas: deficiencies in documentation, technological constraints, and barriers to interdisciplinary communication. One of the most critical issues involves transient or ephemeral physical evidence, which is often difficult to capture, preserve, and analyze in its original condition. The fragile nature of such evidence complicates both the documentation process and subsequent analytical validation, thereby increasing the risk of data loss and interpretive uncertainty during forensic investigations. [7]

The concept of the chain of custody plays a pivotal role in maintaining the integrity and reliability of evidence in engineering failure investigations. A weak or improperly managed chain of custody can compromise the credibility of findings, leading to misinterpretation or inaccurate conclusions. In essence, the chain of custody refers to a systematic procedure for preserving, handling, and recording factual information throughout the investigative process. It represents one of the most rigorous and evaluative methods of data documentation, ensuring that evidence remains authentic and traceable from the point of collection to its final analysis. Within legal contexts, this procedure is instrumental in assessing the admissibility and validity of evidence related to an incident or failure. By comparing the evidence gathered during investigation with that originally present at the scene, the chain of custody supports the verification of factual consistency. Whether tangible or intangible, such evidence constitutes a fundamental component of forensic and legal investigations, underpinning the accuracy and legitimacy of engineering failure assessments [8].

Interdisciplinary collaboration in forensic failure analysis is fundamental to accurately identifying the causes of structural failures and improving the overall quality of investigative outcomes. By integrating expertise from diverse domains, utilizing advanced analytical and diagnostic technologies, and promoting effective communication and professional training, forensic engineers can better address the complexities inherent in modern failure cases while strengthening the connection between engineering practice and the legal system in the pursuit of justice. However, in multifaceted situations—particularly those involving complex structures or multiple contributing factors—the practice of forensic engineering becomes increasingly challenging. This underscores the importance of embracing interdisciplinary approaches, as failure analysis represents not only a technical exercise but also a critical component within the broader and more intricate framework of forensic engineering [9]

Although the process of investigating construction failures has been discussed in the literature, it often lacks structure, consistency, and uniformity across countries and professional practice. This highlights a notable gap in global practices, particularly in the availability of standard models, professional associations, and regulatory frameworks. To address this gap, the current study conducts a systematic review of the literature to identify the essential elements of forensic engineering models, organize and synthesize previous findings, and develop a conceptual framework for forensic engineering investigations. The review is guided by three central questions: What types of building construction failures are most frequently investigated in forensic engineering studies? What methods and tools are commonly used in forensic engineering investigations of building failures?, What are the main challenges and gaps reported in current forensic engineering research on building failure investigations and How can existing studies contribute to developing an integrated forensic engineering model for building failure investigations?

The results of this study carry significant practical implications for post-construction failure investigations. The research offers valuable guidance for field investigators, laboratory analysts, and scholars in understanding appropriate methods and procedures for forensic examination. The structure of this paper is as follows: Section 2 outlines the methodology, including data collection, extraction, screening, quality appraisal, and the systematic review approach employed. Section 3 discusses the results, synthesizes key findings, and highlights potential directions for future research. Section 4 concludes with a concise summary of the study's contributions, particularly its relevance to forensic engineering investigations of construction failures.

METHODS

The research applied a systematic review methodology to ensure both comprehensiveness and reproducibility. A detailed search strategy was designed to capture a wide range of relevant literature. To maintain quality and replicability, the study adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which offers standardized guidelines and checklists. PRISMA further supported consistency and transparency throughout the review process. The study also established clear criteria for article selection, structured procedures for literature searches, and systematic strategies for data extraction and analysis. Each stage of the review adhered to PRISMA standards to uphold methodological rigor.

Literature search

To identify relevant studies for our research, we carried out an extensive search through multiple electronic databases, academic journals, conference proceedings, and other reputable sources. The main databases utilized in this process were Scopus, Science Direct and Google Scholar. We used a well-defined set of keywords and search strings related Forensic Engineering Model for Investigation Building Construction Failures. Keywords related include “forensic engineering”, “forensic structural engineering”, “failure investigation”, "failure analysis" , “building failure”, “construction failure”, "structural collapse", “building collapse” , “infrastructure failure”, "failure analysis", “model” , “framework”, “methodology”, “approach”. The types of data collected include both conceptual and empirical publications that specifically discuss the application of forensic engineering for Investigation Building Construction Failures.

For Scopus and Google Scholar, the search strings used were: ("forensic engineering" OR "forensic structural engineering" OR "failure investigation" OR "failure analysis") AND (model OR framework OR methodology OR approach) AND ("building failure" OR "construction failure" OR "structural collapse" OR "building collapse" OR "infrastructure failure"). In the case of ScienceDirect, the database restricts the use of boolean connectors to a maximum of eight. Accordingly, the search strategy was refined by employing a set of targeted keywords: ("forensic structural engineering" OR "failure investigation" OR "failure analysis") AND (model OR framework OR methodology) AND ("building failure" OR "construction failure" OR "structural collapse").

A validation procedure was established to ensure that the literature review captured the most relevant and significant studies related to forensic engineering investigation models. This procedure involved: (i) benchmarking against a set of well-known and highly relevant papers, (ii) refining the search strategy iteratively based on preliminary results, (iii) applying supplementary techniques to identify papers not retrieved through database searches alone, and (iv) thoroughly documenting each step to maintain transparency and reproducibility. Such an approach minimizes the likelihood of overlooking key literature and provides a systematic and transparent framework for developing and refining the search strategy. Outlines the search findings retrieved from each of the databases used in this study as shown in Table 1.

Table 1. Outlines the search findings retrieved from each of the databases used in this study.

Literatur Database	Articles
Scopus	139
Google Scholar	281
Science Direct	12

The data for this study were drawn exclusively from Scopus for three key reasons. (a) Scopus offers one of the most comprehensive collections of scholarly publications, with substantial overlap with other major databases; (b) the data exported from Scopus can be directly integrated into VOSviewer, enabling smooth bibliometric mapping and visualization; and (c) previous systematic literature reviews have consistently recognized Scopus as a reliable and widely adopted primary source of data [10] .

Inclusion and exclusion criteria

To improve the precision of our search results, we defined a set of inclusion and exclusion criteria, as shown in Table 2. These criteria served as the basis for determining the

relevance of studies included in the review. To minimize bias and avoid data duplication, we excluded review articles, editorials, book chapters, grey literature, preprints, and unpublished studies. Nonetheless, review papers were initially consulted for reference chaining to identify relevant primary studies. The search covered the period from 2015 to 2025, with the initial search conducted on October 13, 2025. The initial search identified 139 from Scopus. Records from these databases were extracted in RIS text format. The screening process began with an evaluation of titles and abstracts to identify potentially relevant studies. Subsequently, the full texts of these studies were examined against the inclusion criteria, resulting in the final set of studies included in the review. EndNote reference management software was utilized to remove duplicates and assist in the study selection process. Figure 3 shows the The PRISMA systematic review flowchart was then applied to document both the included and excluded articles, along with the reasons for their selection.

Table 2. Inclusion and exclusion criteria

Inclusion criteria	Indicator for selection
Search strategy Time period Language Document type	keywords and abstracts Between 2015 and 2025 English Peer-reviewed journal articles, theses and dissertations, technical reports, and conference papers were included for consideration.
Exclusion criteria	
Field of study Accessibility Deletion	Studies that were not related to, or lacked a clear connection with, the forensic engineering model were excluded We excluded articles that did not provide complete bibliometric data or that lacked full text access.. Duplicate records, review articles, editorials, book chapters, grey literature, preprints, and unpublished studies were excluded.

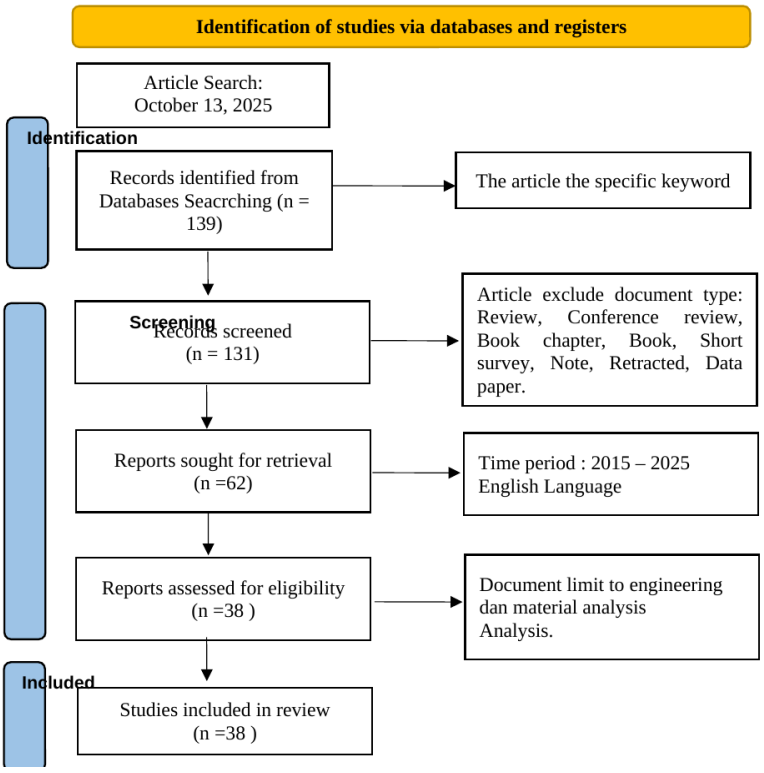

Figure 3. Literature search and selection flow chart adopted from PRISMA

RESULTS

Distribution of Publications

The distribution of publication documents by year is illustrated in Figure 4. The graph shows an upward trend in the number of publications from 2017 to 2018, followed by a decline and another rise in 2023. Meanwhile, Figure 5 presents the distribution of publications by country, revealing that the United States leads with 11 publications, followed by Italy with 8. China, Spain, Switzerland, and the United Kingdom each contributed 4 publications, while Hong Kong produced 3, and Iran, New Zealand, and Nigeria each accounted for 2 publications. This distribution underscores the dominance of the United States and several European countries in this research domain, while also highlighting the limited representation from Asia indicates the need for broader international collaboration.

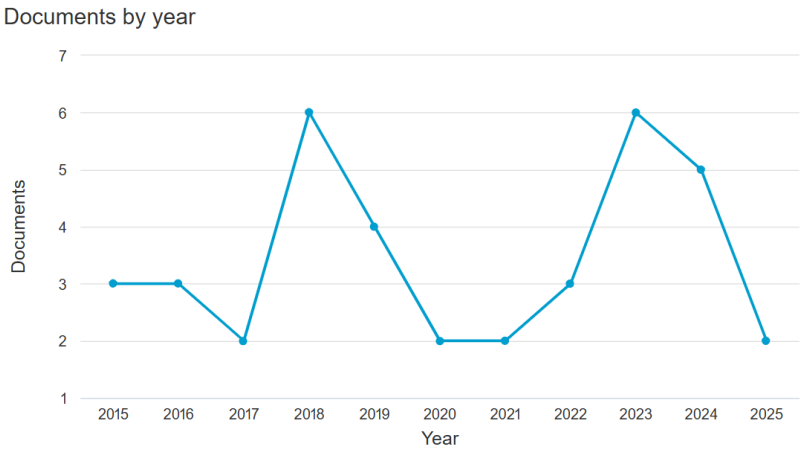

Figure 4. Distribution Document Publications by The Year

The database search yielded 38 relevant publications focused on forensic engineering investigations of building construction failures. The distribution of these studies demonstrates a noticeable upward trajectory over the past decade, indicating the increasing acknowledgment of the forensic approach as a vital framework for diagnosing and mitigating construction failures. Most of the identified studies were released between 2018 and 2025, highlighting the field's evolution into a dynamic and rapidly developing area of research.

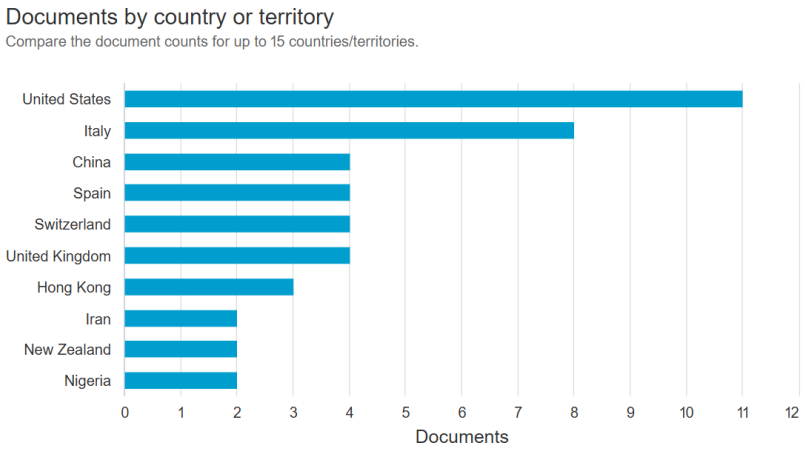

Figure 5. Distribution Document Publications By Country Or Territory

In terms of publication outlets, most of the identified studies were published in high-impact journals such as Engineering Failure Analysis, Engineering Structures, Structural

Engineering International, and Structures—the majority of which fall under the SJR Q1–Q2 categories, as summarized in Table 3 (Journal Allocation Metrics). This distribution underscores the international relevance and scientific maturity of forensic engineering within the civil and structural engineering disciplines. Furthermore, the geographical analysis of authorship reveals that the principal contributions originate from Europe, the United States, and Asia, reflecting the field's growing global engagement.

Table 3. Journal Allocation Metrics

Journal	Publications	CiteScore 2024	SJR 2024	SNIP 2024	SNIP 2024
Structural Engineering International	4	2.8	0.458	0.95	0.95
Engineering Structures	4	11.2	1.803	2.217	2.217
Engineering Failure Analysis	3	8.8	1.159	1.865	1.865
Bulletin of the New Zealand Society for Earthquake Engineering	1	2.1	0.394	0.606	0.606
Earthquake Engineering and Structural Dynamics	1				
Case Studies in Thermal Engineering	1	10	1.061	1.67	1.67
Bulletin of Earthquake Engineering	1	9	1.242	1.73	1.73
Composites Part B Engineering	1	25.6	2.961	2.673	2.673
Computer Aided Civil and Infrastructure Engineering	1	17.4	3.012	2.961	2.961
Developments in the Built Environment	1	7.6	1.516	2.069	2.069
Wind and Structures an International Journal	1				
Engineering Construction and Architectural Management	1				
IEEE Access	1				
International Journal of Mechanical Sciences	1				
Journal of Performance of Constructed Facilities	1				
Journal of Failure Analysis and Prevention	1				
Proceedings of the Institution of Civil Engineers Forensic Engineering	1				
Proceedings of the Institution of Civil Engineers Structures and Buildings	1				
Structural Safety	1	11.8	1.767	2.407	2.407
Structures	1	6.5	1.085	1.525	1.525
Tribology International	1	10.7	1.377	1.945	1.945
Water Research	1	21.2	3.843	2.363	2.363
Composite Structures	1	14.8	1.761	2.068	2.068
Annual IEEE Semiconductor Thermal Measurement and Management Symposium	1	0.6	0.12	0.709	0.709
Total	32				

As summarized in Table 4, the majority of studies reviewed adopt case study (57.9%) and experimental (23.7%) designs, with a predominant emphasis on structural and material failure investigations (around 70%), followed by numerical and experimental modeling using Finite Element Analysis (FEA). Conversely, there are relatively few publications exploring investigation procedures, human factors, or managerial contributors to failure. This trend suggests that forensic engineering research remains largely centered on technical analysis,

while procedural and organizational perspectives are beginning to surface as important frontiers for future research development.

Table 4. Research Type in literature review

Research Type	Number (n)	Percentage (%)
case study	22	57.9
Experimental	9	23.7
Analytical / Modeling	5	13.2
Interview / Survey	2	5.3

Typology of Building Construction Failures

The synthesis of 38 reviewed papers reveals that building construction failures in forensic engineering exhibit diverse characteristics in terms of causes, structural components, and project lifecycle stages. These failures can be classified into seven main typologies: (1) structural failure involving collapse of beams, columns, or slabs; (2) material failure due to degradation or corrosion; (3) design error or miscalculation; (4) human or managerial error linked to poor coordination and decision-making; and (5) combined or complex failures involving multiple simultaneous mechanisms. The Classification of Literature Based on Types of Building Construction Failures as shown in table 5.

Table 5. Classification of Literature Based on Types of Building Construction Failures

NO.	Type of Failure	Typical Causes / Description	Representative Studies (Authors & Year)	Investigation / Analysis Method Used	Remarks / Key Findings
1.	Structural Failure (29)	Insufficient reinforcement or material deterioration, Inadequate design load, poor detailing or progressive collapse of RC elements.	[11], [12], [13], [14], [4] [4], [15]. [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37]	Forensic Case Study Analysis (5), Finite Element /Numerical Simulation (20), Experimental/ Testing Investigation (2), General Analytical/ Review Method (2)	Identified Failure Mechanisms And Causes (24), Proposed or validated analytical model/framework (4), General insights on forensic or engineering investigation (1).
2	Material Failure (3)	Material degradation, corrosion, or fatigue of steel components.	[38], [39], [40].	Finite Element /Numerical Simulation (2), General Analytical / Review Method (1)	Identified Failure Mechanisms And Causes (2), Proposed or validated analytical model/framework (1)
3	Design Error / Miscalculation (4)	Incorrect load estimation, software modeling error, or design not aligned with standards.	[41], [42], [43], [44]	Finite Element /Numerical Simulation (2), General Analytical / Review Method (1), Data-driven / Statistical Analysis (1)	Identified Failure Mechanisms And Causes (4)
4	Human / Managerial Error (1)	Lack of coordination, miscommunication, or failure in safety management and documentation.	[45]	Finite Element / Numerical Simulation (1)	Identified Failure Mechanisms And Causes (1)
5.	Combined or	Interaction of	[46]	Finite Element /	Identified Failure

Complex Failure (1)	technical and managerial causes, e.g., poor design + low material quality.	Numerical Simulation (1)	Mechanisms And Causes (1)

This typological classification is crucial because each failure type demands a distinct investigative approach. Structural failures typically require quantitative modeling such as Finite Element Analysis (FEA), while managerial or procedural failures benefit from qualitative causal tools such as Root Cause Analysis (RCA) or Failure Tree Analysis (FTA). Consequently, the typology of failures provides the conceptual foundation for designing an effective and standardized forensic investigation model in the context of construction engineering. Figure 6 and Figure 7 shows the Number Of Studies By Failure Type and Distribution Of Failure Types In Forensic Engineering Type.

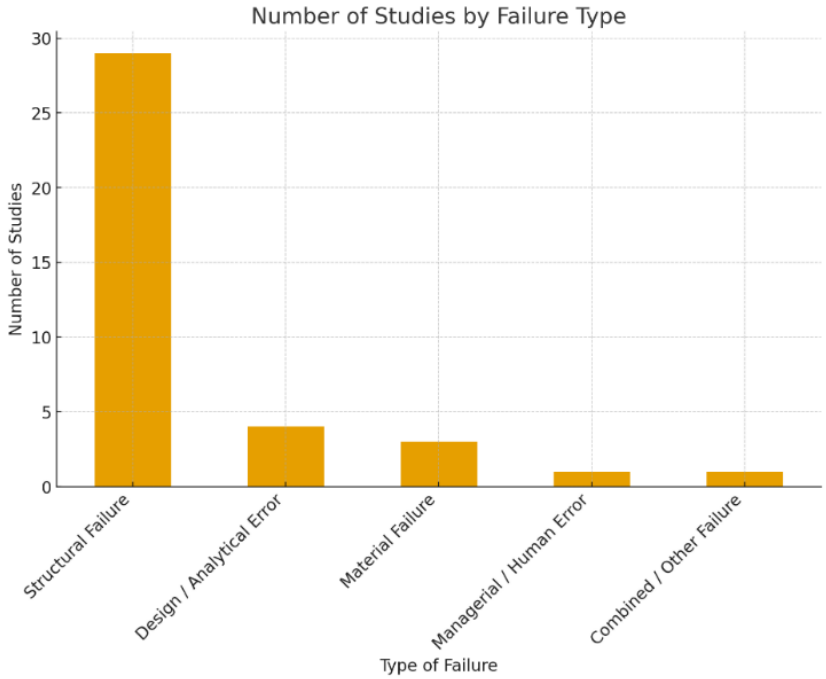

Figure 6. Number Of Studies By Failure Type

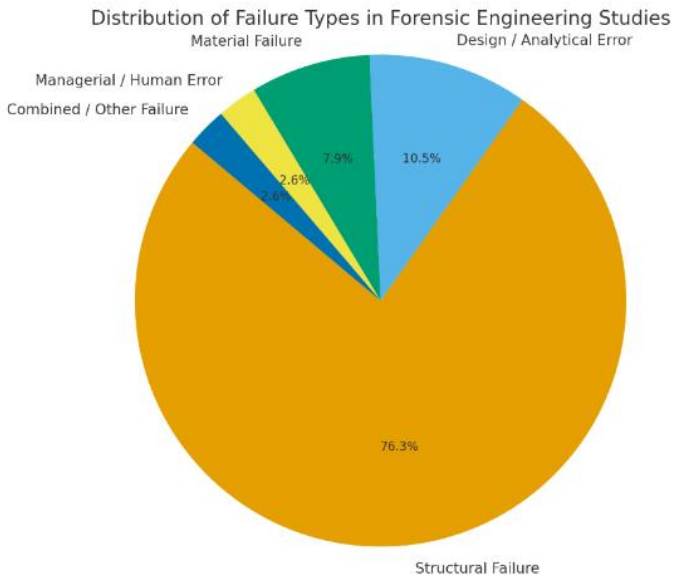

Figure 7. Distribution Of Failure Types In Forensic Engineering Type

Methods and Tools in Forensic Investigations

Findings from the reviewed literature suggest that the techniques and analytical tools employed in forensic engineering investigations differ according to the failure type, data accessibility, and specific investigative goals. In general, these methodologies fall within three overarching categories: (1) observational and in-situ testing approaches, (2) numerical and experimental analysis methods, and (3) causality-oriented and expert-based evaluation tools.

Within the observational domain, visual inspection remains the most commonly employed technique and serves as the foundational step in any forensic investigation. It enables the identification of surface anomalies such as cracking patterns, deformations, and other visible signs of structural distress. This approach is frequently supported by Non-Destructive Testing (NDT) methods—including ultrasonic pulse velocity, rebound hammer testing [47], infrared thermography, and ground-penetrating radar (GPR)—which provide quantitative insights into material integrity without causing damage to the specimen [48] The classification of the reviewed literature based on investigative tools and techniques is summarized in Table 6.

Table 6. Classification of Literature Based on Tools & Tecnique Investigation

NO.	Tools & Tecnique Investigation / Analysis Method	Main Purpose/Function	Representative Studies (Authors & Year)	Advantages	Constraints	Percentage (%)
1.	Visual Inspection (19)	Identification of damage patterns through direct field observation and on-site documentation.	Whittle, et al (2025), Rus et al (2024), Palmisano et al (2024), Caredda et al (2023). Abubakar et al (2023), Khan et al (2023), Peraza [45], Egwunatum et al (2022), Ortega I. (2022), Kizito [46], Zheng [25], Fazeres et al (2018), Boateng [42], Lu et al (2018), Gill et al (2018), Justo et al (2017), Fereshtehnejad et al (2016), Astarlioglu et al (2015).	Quick and economical; critical in the initial examination phase of an investigation.	Subjective and non-quantitative; reliant on the examiner's professional experience.	50
2	Finite Element Analysis (15)	Analyzes structural behavior and predicts failure mechanisms through numerical modeling	Wu et al (2025), Abdoh D.A. (2024), Riccio et al (2023), Pinho et al (2023), Khedmatgozar et al (2023), Possidente et al (2021), Etemadi et al (2020), Calvi et al (2019), Blaszczyński et al (2019), Piluso et al (2019), Riccio et al (2018), Ortega [30], Dai Et Al (2017), Murray et al (2016), Gao et al (2015).	Highly precise for analyzing complex loading condition; facilitates the reconstruction of failure scenarios.	Requires highly accurate material and boundary data; outcomes are sensitive to modeling assumptions.	39.5

3.	Failure Tree Analysis (FTA) (3)	Models the sequence of events leading to failure using a fault tree diagram.	Bahrami et al (2024); Martani, et al. (2020); Mieler, et al (2016)	Systematic and visually intuitive; assists in identifying critical pathways.	Requires comprehensive event data; less adaptable to changes or new condition.	7.9
4.	Expert Judgment (1)	Expert judgment applied for interpretation and decision-making throughout the investigation process.	Ortega, I. (2015)	Quick and context-based; valuable when available data are limited.	Subjective in nature; requires calibration against empirical evidence.	2.6

The Classification of Literature Based on Analysis Method and Type of Failure as shown in Table 7. In the numerical and experimental domain, Finite Element Analysis (FEA) dominates the literature, offering a means to simulate collapse mechanisms, stress distribution, and structural behavior under load. Some studies combine FEA with laboratory experiments or in-situ load testing for calibration, forming hybrid validation models that enhance the reliability of forensic conclusions.

Table 7. Classification of Literature Based on Analysis Method and Type of Failure

No.	Investigation / Analysis Method	Main Purpose/Function	Common Types of Failures Analyzed	Example Studies (Authors and Year)	Advantages	Constraints	n (studies)	Percentage (%)
1	Finite Element Analysis (FEA) / Numerical Simulation (26)	Analyzes structural behavior and predicts failure mechanisms through numerical simulation.	Structural Failure; Design/Analytical Error; Fire-induced collapse	Wu et al (2025), Abdoh D.A. (2024), Caredda et al (2023). Riccio et al 2023, Pinho et al (2023), Khan et al (2023), Khedmatgozar et al (2023), , Possidente et al (2021), Calvi et al (2019), Blaszczyński et al (2019), Piluso et al (2019), Riccio et al (2018), Lu et al (2018), Gil et al (2018), Ortega [30], Justo et al (2017), Dai Et Al (2017), Fereshtehnejad et al (2016), Murray et al (2016), Mieler et al (2016), Gao et al	Accurate for analyzing complex load conditions; assists in verifying design validity.	Requires precise material properties and boundary conditions; results are sensitive to the underlying assumptions.	26	68.4

No.	Investigation / Analysis Method	Main Purpose/Function	Common Types of Failures Analyzed	Example Studies (Authors and Year)	Advantages	Constraints	n (studies)	Percentage (%)
				(2015), Astarlioglu et al (2015). Abubakar et al (2023), Bahrami et al (2024), Peraza et al (2022), Kizito et al (2021)				
2	Forensic Case Study Analysis (5)	Case-based analysis grounded in field evidence and reconstruction methods.	Structural Failure; Construction/Execution Failure	Whittle et al (2025), Palmisano et al (2024), Rus et al (2024), Etemadi et al (2020), Fazeres et al (2018)	Contextual and practically oriented; useful for developing guidelines.	Dependent on data completeness; replication potential is limited.	5	13.2
3	General Analytical / Review Method (4)	Literature synthesis conducted to formulate a conceptual framework or model.	Combined/Complex; Structural Failure	Egwunatum et al (2022), Martani et al (2020), Zheng et al (2019), Boateng [42].	Well-structured theoretical framework; easily adaptable for further application.	Limited field evidence available.	4	10.5
4	Experimental / Testing Investigation (2)	Validation of material or element performance and verification of failure hypotheses.	Material Failure; Structural Failure	Ortega, I. (2022), Rus et al (2024)	Empirical evidence that enhances reliability and credibility.	High cost and time requirements; sample selection is critical.	2	5.3
5	Data-driven / Statistical Analysis	Identifies recurring patterns and trends derived from multiple case datasets.	Combined/Complex	Ortega, I. (2015)	Reveals relationships among variables; supports broader generalization of findings.	Requires a large dataset; does not explicitly explain the underlying physical mechanisms	1	2.6

Causal analytical tools such as Root Cause Analysis (RCA) and Failure Tree Analysis (FTA) are increasingly used to trace procedural and human errors, while expert judgment and peer review play important roles in verifying findings and ensuring interpretative neutrality.

Overall, methodological trends indicate a paradigm shift from single-method technical analysis toward integrated forensic frameworks that combine field observation, computational simulation, and managerial diagnostics. This integration enables the development of holistic and legally defensible forensic investigation models suitable for modern construction forensic failure analysis.

Identified Challenges and Gaps

Based on the analysis of 38 articles (comprising 58% case studies, 24% experimental research, 13% analytical or modeling studies, and 5% interview or survey-based investigations), several key challenges and research gaps were identified. Technical Constraint – Data and Evidence Integrity, A recurring issue involves the degradation or incompleteness of technical evidence, as many investigations are conducted long after the failure event occurred. This delay often hampers accurate root cause analysis and weakens the reliability of forensic conclusions. [4] [14]. Accordingly, there is a clear need to establish standardized protocols for field evidence preservation to ensure data integrity over time.

Modeling Assumptions and Boundary Conditions, Studies employing Finite Element Analysis (FEA) frequently rely on idealized assumptions without proper field calibration [12] [19]. Such simplifications limit the realism of simulation outcomes and may lead to inaccurate representations of actual failure conditions. Future research should therefore emphasize the integration of experimental validation with numerical simulation to improve the fidelity and applicability of forensic modeling.

Lack of Comprehensive Experimental Validation, A significant gap was observed in terms of empirical validation—only about 24% of the reviewed studies conducted direct experimental testing [38] [18]. This limitation underscores the necessity for a hybrid forensic framework that integrates simulation, experimental investigation, and field observation to enhance the accuracy and reliability of forensic interpretations. Standardization Deficiency, Another key challenge lies in the absence of a unified international reference or standard methodology for conducting forensic structural investigations [4]. The lack of consistency in investigative protocols makes cross-study comparison and methodological benchmarking difficult, highlighting the need for an internationally recognized forensic investigation standard.

Organizational and Procedural Gaps, A recurring issue is the limited integration between engineering and legal or investigative institutions. Most studies remain confined to the technical domain without establishing links to legal or criminal investigation systems [14]. Addressing this gap requires adopting a scientific crime investigation model that integrates civil engineering expertise with legal procedures and forensic investigation practices, fostering a more holistic and multidisciplinary approach to forensic failure analysis.

Weak Documentation and Knowledge Management, A clear gap was identified in the area of documentation and knowledge management. Only a small number of studies have archived failure databases or made investigation results publicly accessible [4]. This limitation highlights the need to establish a Forensic Knowledge Repository accompanied by a standardized reporting template to facilitate knowledge sharing, transparency, and cross-case learning within the forensic engineering community.

Human and Managerial Oversight, Another notable gap concerns the limited attention to managerial roles, project coordination, and supervisory practices in the context of failure investigations [20]. These aspects remain underexplored despite their significant influence on the occurrence and resolution of construction failures. Future research should therefore advance the integration of human factors and organizational behavior perspectives into forensic investigation studies, promoting a more holistic understanding of engineering failures that extends beyond purely technical dimensions.

Research Design and Methodological Gaps, The review identifies several methodological limitations within the current body of forensic engineering research. Dominance of Case Study Design, A significant proportion of studies (58%) adopt descriptive case study designs with limited application of systematic quantitative approaches. This restricts generalizability and limits the potential for theoretical integration. Therefore, there is a clear need to develop model generalization strategies that enable case study findings to be synthesized into a broader conceptual framework. Lack of Systematic Literature Reviews and Meta-Analyses, Only a small number of studies have conducted cross-case or cross-country reviews, revealing a scarcity of systematic syntheses in the field. This highlights the importance of conducting systematic literature reviews (SLR) and meta-analyses—such as the present study—to consolidate fragmented findings and construct an integrated forensic engineering model. Limited Multidisciplinary Approaches, Nearly all reviewed publications remain focused on technical dimensions—such as material and structural analysis—while managerial, legal, and social perspectives are largely overlooked. Future research should therefore pursue a holistic forensic engineering model that combines engineering principles with managerial, legal, and socio-organizational insights. Insufficient Access to Field Data, A persistent challenge involves the limited availability of primary data from actual failure sites, constraining empirical validation and forensic accuracy. Addressing this issue requires closer collaboration between academic researchers and investigative authorities to improve data access, evidence sharing, and validation capacity.

The synthesis of the reviewed literature suggests that integrating multi-source methodologies provides a strong conceptual foundation for developing a comprehensive forensic investigation model. The combination of visual inspection, Finite Element Analysis (FEA), Root Cause Analysis (RCA), and expert judgment should form the core pillars of this model, ensuring both analytical depth and practical applicability. Technical–Legal Connectivity, The linkage between technical evidence and legal verification emerges as a critical element in model formulation. A robust forensic investigation framework must accommodate both the scientific rigor of technical analysis and the evidentiary standards required for legal proceedings, bridging the gap between engineering findings and judicial interpretation. Multidisciplinary Stakeholder Involvement, Active participation of diverse stakeholders—engineers, investigators, legal experts, and academics—is essential across all phases of the investigation. Such collaboration ensures that each stage of the process, from field examination to reporting, benefits from multidisciplinary expertise and contextual understanding. Standardization and Knowledge Transfer, Finally the establishment of standardized operational procedures (SOPs) and a knowledge database based on construction failure cases represents a crucial step toward institutionalizing forensic engineering practices. These mechanisms promote consistency, transparency, and continuous learning, forming the knowledge backbone of a sustainable forensic investigation model.

Most contemporary forensic engineering research remains fragmented, with technical and procedural aspects often treated in isolation. Persistent issues such as incomplete site evidence, non-standardized investigative practices, and limited cross-disciplinary collaboration continue to hinder the development of effective investigative frameworks. Addressing these gaps calls for the establishment of a standardized and integrated forensic engineering model that harmonizes technical accuracy, procedural robustness, and organizational synergy.

ANALYSIS

Synthesis of Failure Categories and Investigation Approaches

The analytical overview derived from the meta-analysis identifies several primary failure categories: structural failure, material failure, design error or miscalculation, human or managerial error, and combined or complex failure. In parallel, the dominant investigation approaches observed include visual inspection, Finite Element Analysis (FEA), Failure Tree Analysis (FTA), and expert judgment. Analysis reviewed papers reveals a clear methodological preference linking failure types (RQ1) with corresponding investigative approaches (RQ2). Specifically, failure types with a high degree of technical complexity—such as structural or design failures—tend to employ quantitative and modeling-based methods like FEA or experimental testing. Conversely, failures involving managerial or human factors, as well as multi-causal or complex cases, are more commonly investigated through qualitative or diagnostic approaches such as RCA, FTA, and expert judgment. A Synthesis of Failure Categories and Investigation Approaches as show in the Table 8.

Table 8 Synthesis of Failure Categories and Investigation Approaches

NO	Failure Category	Dominant Investigation Approaches Found	Supporting Studies (Examples)	Analytical Link / Insight
1.	Structural Failure (29)	Finite Element Analysis (FEA), Load Testing, Visual Inspection	Wu et al. [12]; Pinho et al. [17]; Palmisano & Vitone [4]	Structural collapse, beam or slab failure are modeled through FEA to simulate stress, strain, and collapse sequence. Often supplemented by visual inspection of cracking patterns.
2	Material Failure (3)	Experimental Testing, NDT, Microscopic Analysis	Abubakar et al. [38]; Khan et al. [18]	Focus on laboratory tests (tensile, fatigue, or corrosion) to assess degradation. NDT validates in-situ material deterioration without damaging structure.
3	Design Error / Miscalculation (4)	Finite Element Analysis (FEA), Expert Judgment, Root Cause Analysis	Khedmatgozar et al. [19]; Bahrami et al. [41]	Analytical design errors are revealed through numerical re-simulation and expert review. FEA detects under-designed members or overestimated safety factors.
4	Human / Managerial Error (1)	Root Cause Analysis (RCA), Failure Tree Analysis (FTA), Interview/Survey	Egwunatum et al. (2023)	Managerial failures identified through RCA and FTA to visualize decision or supervision breakdown. Often supported by qualitative stakeholder insights.
5.	Combined or Complex Failure (1)	Integrated Hybrid Method (FEA + RCA + Expert Judgment)	Rus et al. [14]; IABSE (2018)	Complex collapses require a mixed-method: numerical simulation for physical mechanism and RCA for procedural chain of events.

The analytical synthesis can be categorized into three main dimensions. First Technical Failures and Quantitative Methods, This category encompasses structural, material, and design failures, which predominantly employ quantitative techniques such as Finite Element Analysis (FEA), load testing, and experimental approaches. The focus of these studies lies in reconstructing the mechanical behavior of structures—examining parameters such as stress distribution, deformation patterns, residual capacity, and collapse mechanisms. These investigations reflect a scientific and evidence-based orientation, emphasizing analytical rigor and quantifiable validation. Second Procedural and Organizational Failures with Qualitative Causal Methods, This dimension includes human,

managerial, and construction-related failures, which are primarily analyzed through qualitative causal approaches such as Root Cause Analysis (RCA), Fault Tree Analysis (FTA), and visual inspection. These studies emphasize human behavior, project communication, and decision-making processes, representing a qualitative and interpretative mode of investigation that seeks to understand the underlying causal dynamics beyond technical parameters. Third Hybrid or Integrated Approaches for Complex Failures, This emerging category, classified as combined or complex failures, integrates both quantitative and qualitative methods—for instance, the combination of visual inspection with FEA, RCA, and expert review. Such approaches have become increasingly evident in studies published between 2023 and 2025, marking a clear shift toward a holistic forensic framework that bridges technical precision with procedural and organizational understanding.

The implications for model development can be summarized into four key dimensions. First, Method–Failure Mapping emphasizes the need for a matrix-based toolkit that explicitly links specific types of failure to their appropriate analytical methods, ensuring methodological alignment and precision in forensic investigations. Second, a Multi-Phase Investigation Workflow is required, in which each stage—from field observation to analysis and interpretation—should integrate both quantitative and qualitative approaches to produce a comprehensive understanding of failure mechanisms. Third, Adaptive Method Selection underscores the flexibility for investigators to select analytical techniques based on the typology of failure, such as employing FEA for structural analysis and RCA for managerial or human-related issues. Finally, the Model Validation Path highlights the importance of empirically testing the proposed framework through hybrid case studies, enabling verification of methodological suitability and effectiveness across different categories of construction failures.

Mapping of Factors Influencing Investigation Effectiveness

Mapping the factors influencing investigation effectiveness is crucial for understanding the urgency and quality of forensic examinations. This mapping connects technical and managerial aspects, as well as regulatory factors, with the chosen investigation methods and their outcomes, while aligning them with the theoretical foundations of failure analysis and the forensic engineering process model. The analysis resulted in a taxonomy of factors affecting investigation effectiveness. The technical factors encompass several key dimensions: site evidence quality, including sample completeness, labeling accuracy, chain-of-custody management, and time-related degradation; structural data integrity, involving comparison between as-built and as-designed drawings, load history, and monitoring or instrumentation logs; material and element condition, referring to corrosion, fatigue, cracking, and residual capacity after events such as fire; and technical validation, which relates to the availability of Non-Destructive Testing (NDT) or experimental tests, as well as calibration of FEA parameters. The managerial or organizational factors include inter-party coordination among engineers, contractors, owners, investigators, and experts; competence and roles encompassing investigator qualifications, engineering judgment, and peer review mechanisms; documentation and knowledge management related to reporting standards, case repositories, and lessons learned; and project control, covering quality, safety, and change management. Lastly, the regulatory or institutional factors involve standards and guidelines such as ASTM, ACI, or Eurocode and technical SOPs for on-site investigation; legal compliance, including evidence-handling procedures, site access, and authority mandates; and data transparency, which covers archive accessibility, ethical dissemination, and data protection practices. Together, these interrelated dimensions form a

comprehensive framework for evaluating the factors that determine the effectiveness of forensic engineering investigations.

Table 9 Mapping of factors influencing the effectiveness of inspections in relation to applied methods and resulting outcomes.

NO	Key Factor	Direct Impact	Affected / Recommended Methods	Impact On Results	Repair (Levers)
1.	Examination of delayed or degraded crime scene evidence.	Physical evidence lacking/contaminated at the crime scene	Strengthen structured Visual Inspection, NDT for residual evidence; triangulation with RCA/FTA	Decreased accuracy of causes, increased uncertainty	SOP for crime scene preservation, rapid response kit, chain-of-custody training
2	As-built ≠ as-designed	Model/analysis bias	FEA berbasis as-is, back-calculation & expert judgment	More representative models; The collapse hypothesis is stronger	Document audit and scanning of existing conditions
3	Material parameters of evidence unknown	Speculative FEA parameters	NDT+ experimental for model calibration	Validation performance increases while model deviation decreases.	Sampling protocols and rapid testing procedures; database of local material properties.
3	Weak stakeholder coordination	Fragmented data and restricted access to the site or physical evidence.	Joint evidence walkdown and collaborative root cause analysis (RCA).	The investigation cycle slows down, leading to the emergence of narrative gaps	Cross-agency RACI framework with a designated single point of contact.
4	Investigator competencies vary across individuals and institutions.	Inconsistent interpretation of investigation results.	Peer review and expert panel evaluation.	Reliability of conclusions improves.	Investigator certification and registry of accredited experts.
5	No standardized investigation guidelines.	Variability in the quality of investigation processes and outcome reports.	Process checklist based on a forensic process model.	Low reproducibility, meaning that research results cannot be replicated or reproduced by other investigators even when using the same methods and data. This condition undermines the overall validity and credibility of scientific findings.	Standardization of format through a uniform reporting template.
6	Limited access to legal data and lack of transparency.	Limited cross-validation capability.	FTA and RCA based analysis, complemented by sensitivity testing of key assumptions.	Increased risk of bias.	Controlled data-sharing policies and data anonymization measures.

In relation to the theories of failure analysis and the forensic engineering process model, the investigative procedure can be systematically structured into a sequential workflow. The process begins with on-site examination, which includes visual inspection, measurement, and the collection of physical evidence samples in accordance with

established Standard Operating Procedures (SOPs). This stage is followed by laboratory testing, where a series of Non-Destructive Tests (NDT) and experimental analyses are conducted to obtain empirical material and structural parameters. The subsequent stage involves analytical modeling and simulation, utilizing Finite Element Analysis (FEA), what-if or sensitivity analyses, and the integration of causal diagnostic methods such as Root Cause Analysis (RCA) and Fault Tree Analysis (FTA). Finally, the investigation culminates in a reporting phase, which employs a standardized template comprising findings, analytical interpretations, conclusions, and recommendations, supplemented by peer review and the development of an evidence map to ensure traceability and scientific accountability. To establish a matrix that links failure types with their corresponding primary investigative methods and key analytical outputs, the classification has been organized and summarized as shown in Table 10.

Table 10. failure types with their corresponding primary investigative methods and key analytical outputs.

No	Failure Type	Primary Investigative Methods	Key Analytical Outputs
1.	Structural	FEA, Visual, (opsional Load test)	Collapse sequence, residual capacity, and stress hotspots.
2	Material (corrosion/fatigue)	NDT, Eksperimental, Microscopy	Degradation rate and residual stress–strain curve.
3	Design/miscalculation	FEA (as-is), Expert review, RCA	Detection of under-reinforcement and design load misapplication
3	Construction/ execution	Visual, RCA/FTA, Interview	Procedure violations and work chronology reconstruction.
4	Human/Managerial	RCA, FTA, Survey	Coordination and decision-making failure points
5	Combined/Complex	Hibrida (Visual+NDT+FEA+RCA+Expert)	Separation of technical and procedural contributions

In determining the indicators of effectiveness for evaluating the performance of forensic investigations, several measurable parameters can serve as key references. The first is the Evidence Integrity Index, which assesses the completeness of collected evidence, the maintenance of the chain of custody, and the emergency response time to the incident site. The second is the Model Validation Score, which evaluates the degree of calibration between Non-Destructive Testing (NDT) or experimental results and Finite Element Analysis (FEA) outputs. The third is the Causal Consistency Index, measuring the alignment between Root Cause Analysis (RCA) or Fault Tree Analysis (FTA) results and corresponding physical or numerical evidence. The fourth is the Reporting Quality Index, which examines adherence to standardized reporting formats, transparency of assumptions, and the inclusion of peer review. Lastly, the Lead Time to Findings indicator measures the duration from the initial on-site investigation to the completion of the final report, reflecting the efficiency and responsiveness of the overall forensic investigation process.

Thematic or Bibliometric Analysis

The keyword co-occurrence network provides a visual representation of how major terms in the research field are conceptually linked and interact with one another. [49] In the visualization, each keyword functions as a node whose size reflects its frequency within the dataset, while the thickness and distance of the connecting lines signify the degree of association among the terms. The co-occurrence network in this study was generated using VOSviewer, employing the “author keywords” and “full counting” settings, with a minimum

occurrence threshold set at one, from the 38 analyzed studies, several recurring keywords were identified. As shown in Table 11, failure (mechanical) ranked as the most prevalent term (17 occurrences; total link strength = 62), followed by failure analysis, forensic engineering, structural collapse, and safety engineering. Together, these keywords capture the breadth and interconnection of research themes within the forensic engineering domain.

Table 11. The leading keywords and the intensity of their interconnections as represented in the co-occurrence network.

NO	Keyword	Occurrences	Total link strength
1.	failure (mechanical)	17	62
2	failure analysis	17	28
3	forensic engineering	13	49
3	structural collapse	10	25
4	safety engineering	9	43
5	fracture mechanics	9	40
6	structural failure	7	38
7	reinforced concrete	7	18
8	structural integrity	6	33
9	finite element method	6	12
10	structural analysis	5	24
11	failure mechanism	5	20
12	construction failures	5	16

Figure 8 depicts the co-occurrence network of author keywords derived from 38 screened articles. The keyword failure (mechanical) occupies the central position in the network, exhibiting the highest total link strength and functioning as the conceptual nucleus of this research area. It demonstrates strong associations with forensic engineering, safety engineering, and failure analysis, reflecting the dominant and interconnected topics in the field. The visualization also reveals four major clusters representing distinct yet related research themes, which are elaborated upon in the subsequent sections.

Analysis of the Procedural & Construction Failure theme, categorized as an Underdeveloped Zone, reveals that this cluster is underrepresented, registering only five occurrences and a link strength of 16. Such low connectivity reflects the limited attention given to failures related to construction processes, human factors, and managerial issues. This underexplored area presents a clear research gap and underscores the need for further investigation—potentially leading to the development of a Forensic Construction Management Model.

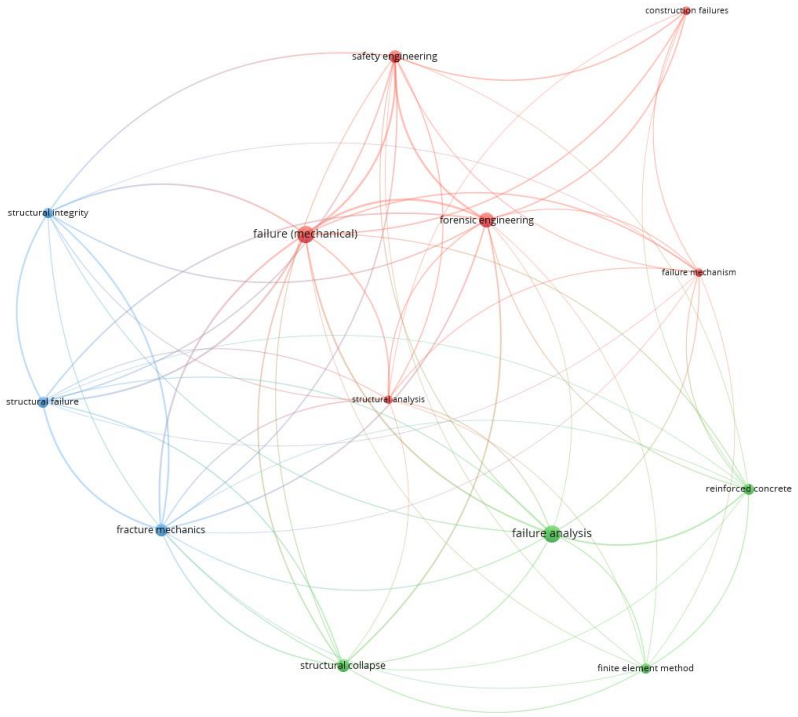

Figure 8. Keyword co-occurrence network of Failure-Forensic Engineering research visualized using VOSviewer

The VOSviewer co-occurrence map indicates that forensic engineering research remains highly concentrated on technical and structural failure analysis, especially those using FEA and mechanical modeling. However, the weak connectivity of 'construction failures,' 'human error,' and 'project management' reveals an unbalanced focus. This suggests a significant research gap in integrating procedural, managerial, and safety dimensions into a unified forensic engineering model.

DISCUSSION

Discussion of Key Findings

The systematic review of 38 Scopus-indexed papers revealed that forensic engineering research on building construction failures remains dominated by structural and material failure analyses. The most frequent keywords identified in the VOSviewer co-occurrence map: failure (mechanical), failure analysis, forensic engineering, structural collapse, and finite element method show a strong orientation toward quantitative mechanical and numerical modeling approaches.

These findings confirm that current forensic studies emphasize the "technical phase" of the forensic engineering process (analysis and modeling), while the "procedural" and "organizational" phases (evidence collection, coordination, and reporting) are less developed. Moreover, the majority of studies employ case study and experimental designs, indicating a descriptive and technical bias, with limited engagement in cross-case synthesis or multidisciplinary approaches.

Implications for Model Development

Implications for Model Development, The results of this study highlight the urgent need for a comprehensive and standardized forensic engineering model that integrates three interdependent layers. First Technical Layer, This layer focuses on structural and mechanical reconstruction through approaches such as Finite Element Analysis (FEA), Non-Destructive Testing (NDT), and experimental validation. The implication for model development is to embed hybrid analytical verification protocols that integrate field observations, laboratory testing, and numerical simulations to enhance the reliability of failure interpretation. Second Procedural Layer, The procedural dimension encompasses evidence management, documentation, and root cause or fault tree analysis (RCA/FTA). This implies the importance of formalizing standardized stages in forensic investigations, including site data collection, testing, analysis, and structured reporting, to ensure methodological consistency and traceability. Third Organizational Layer, The organizational aspect emphasizes collaboration among engineers, investigators, and legal authorities. Its implication lies in developing multidisciplinary operational frameworks that bridge engineering forensics with legal, regulatory, and safety institutions—promoting coordinated and accountable investigative practices.

Research Gaps and Future Work

The synthesis of the reviewed literature and keyword mapping reveals several enduring research gaps in the field of forensic engineering investigations. Procedural Standardization, Currently there is no unified guideline or standardized framework governing forensic investigations. Future research should focus on developing adaptable forensic investigation models that align with national regulatory frameworks and institutional contexts. Multidisciplinary Integration, Few studies have incorporated the intersection of engineering, legal, and managerial perspectives. Future efforts should aim to establish a Forensic Investigation Consortium that brings together civil engineers, legal professionals, and investigative authorities to foster interdisciplinary collaboration. Data and Knowledge Management, The absence of open or shared databases for forensic case records limits knowledge accumulation. A future direction involves developing a Forensic Failure Knowledge Repository to promote transparency, data sharing, and learning from past incidents. Validation Gap, Many studies rely heavily on numerical simulations with limited empirical or field calibration. Future work should focus on creating hybrid validation protocols that integrate experimental results with real-world field data to strengthen model reliability. Human and Managerial Factors, Discussions on supervisory practices, decision-making errors, and project management failures remain scarce. Future research should adopt Root Cause Analysis (RCA), Fault Tree Analysis (FTA), and the PMBOK framework to explore human and managerial aspects of forensic investigations. Overall, future studies are encouraged to design and empirically validate a comprehensive forensic investigation framework tested against real cases of construction failure to bridge these existing research and practice gaps.

Conceptual Model of the Forensic Engineering Investigation Framework

The forensic framework developed by [50] presents a systematic approach for investigating failures in reinforced concrete buildings. The process begins with the identification of failure and the preliminary collection of information through document review and planning. It proceeds to the site investigation stage, which includes visual inspection, eyewitness interviews, and sample collection to establish an initial failure hypothesis. Subsequent phases involve testing and verification through laboratory and field

testing, design evaluation, computational analysis, and expert consultations. The findings are synthesized to refine and confirm the final failure hypothesis, leading to the formulation of conclusions, determination of legal responsibilities, and preparation of the final report. This framework emphasizes an evidence-based and iterative investigative process that integrates technical, analytical, and legal dimensions to ensure scientific rigor, reliability, and accountability in forensic engineering investigations.

The framework developed by [51] offers a methodologically rigorous and logically coherent structure for investigating damage in concrete structures. Its notable strength lies in the integration of technical validation with procedural transparency, linking client input, data collection, and hypothesis testing through evidence-based reasoning. The model successfully operationalizes the forensic investigation as a scientific inquiry process, emphasizing falsification, iterative hypothesis refinement, and mathematical validation. However, despite its analytical depth, the framework's orientation remains predominantly technocentric, focusing on technical root causes while underrepresenting the institutional, organizational, and legal interfaces that often influence investigative outcomes. Moreover, its linear workflow may constrain adaptive decision-making in complex, multi-stakeholder investigations. To advance this approach, future frameworks should embed cross-domain coordination, legal accountability mechanisms, and feedback loops that accommodate uncertainty and emergent evidence—thus evolving from a technically sound to a holistically integrative forensic investigation model.

The conceptual model of this study presents a systematic and integrated framework for conducting forensic engineering investigations of building construction failures. The model is structured into six major phases: Pre-Scene Preparation and Coordination, Scene Examination/Investigation, Laboratory and Testing, Analytical Modelling, Causal Analysis, and Reporting and Knowledge Management. which collectively ensure that the investigative process remains scientifically valid, procedurally consistent, and legally defensible. These stages operate within three interrelated domains: the technical, investigative, and legal-regulatory domains, each defined by distinct functions, actors, and critical success factors. Figure 9. shows The Conceptual Model of the Forensic Engineering Investigation Framework.

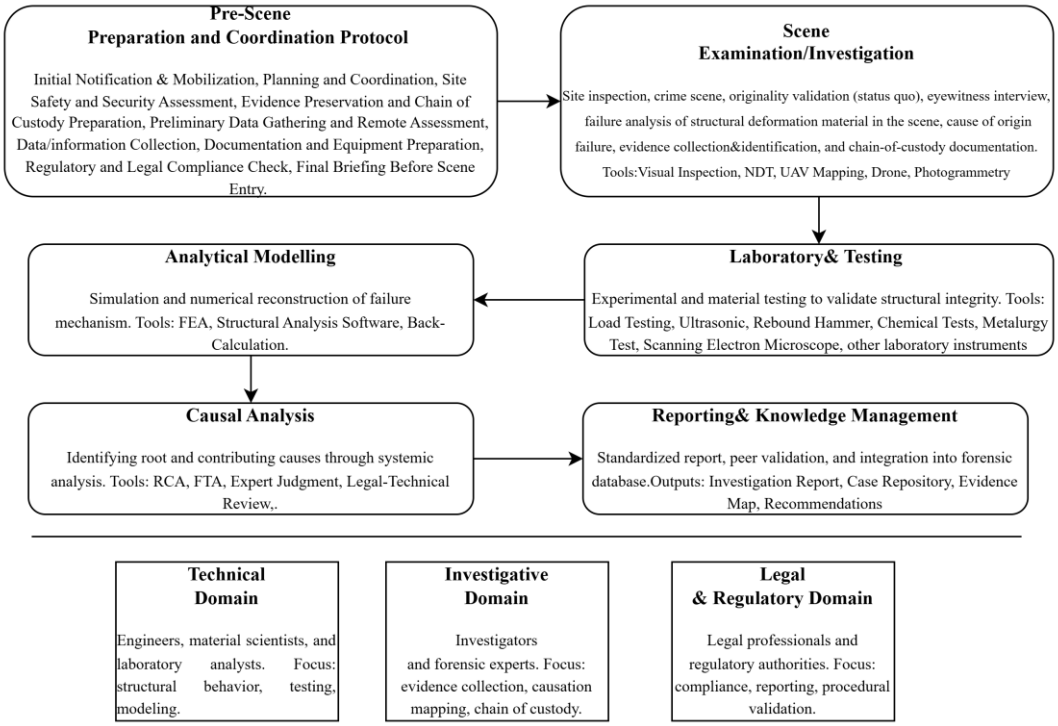

Figure 9. The Conceptual Model of the Forensic Engineering Investigation Framework

Pre-Scene Preparation and Coordination Protocol, The investigation process begins with a comprehensive preparatory phase that establishes organizational readiness, legal authorization, and technical planning. Tools employed during this stage include an Investigation Plan Template, Team Assignment Matrix (RACI), Authorization Forms and Access Permits, Stakeholder Contact Sheets, Communication Logbooks, Legal Compliance Checklists, and essential Personal Protective Equipment (PPE). Hazard assessment sheets, safety barrier systems, emergency communication devices, digital cameras, drones, and forensic evidence collection kits are also used to secure, document, and prepare the site. This preparatory protocol ensures that the subsequent scene investigation proceeds safely and in accordance with forensic engineering standards.

Inter-Domain Integration: Technical, Investigative, and Legal-Regulatory Dimensions. The model integrates three interdependent domains that collectively determine the effectiveness of the forensic investigation process. Technical Domain – This domain encompasses engineers, material scientists, and laboratory analysts. Their primary focus lies in ensuring data accuracy, equipment reliability, and model calibration. Technical rigor is maintained through structured testing, analytical modelling, and validation of structural behavior. Investigative Domain – This domain involves investigators and forensic experts responsible for coordination, documentation, and causation mapping. Their competence determines the quality of evidence collection and the integrity of the chain of custody, linking field observations to laboratory findings. Legal and Regulatory Domain – This domain comprises legal professionals and regulatory authorities who oversee compliance with standards, procedural ethics, and reporting requirements. Their role ensures that all findings are legally defensible and conform to statutory and professional obligations.

The interaction among these domains establishes a feedback-driven system in which technical accuracy supports investigative credibility, while legal and procedural compliance

sustains the admissibility of findings. Collectively, they create a comprehensive model that bridges the gap between engineering science and legal accountability in the context of construction failure investigations.

Practical Contributions

The review contributes both conceptually and practically. First Conceptual Contribution, Provides a mapping of failure categories versus investigation methods. Establishes the theoretical foundation for a Forensic Engineering Process Model combining technical, procedural, and managerial layers. Second Practical Contribution, Offers an evidence-based guideline for investigators, engineers, and policymakers in conducting systematic failure investigations. Supports standardization efforts for forensic protocols and legal systems. Provides a baseline for training and certification of forensic civil engineering professionals.

Limitations

While this systematic review offers a comprehensive overview, several limitations exist: The dataset (38 papers) may not capture the full global spectrum of forensic engineering research, particularly from non-English or non-Scopus sources. The keyword co-occurrence analysis (VOSviewer) is dependent on author-supplied keywords, which might not reflect the complete conceptual structure of each paper. The study focuses primarily on building-related failures, limiting generalization to infrastructure or transportation domains. The synthesis is interpretive, future meta-analytic quantification (e.g., co-citation and temporal trend analysis) could further validate these patterns. Data or language limitations can affect the reliability of conclusions. If the conceptual model has not yet been empirically tested or applied to real-world cases, its reliability and generalizability to field situations remain limited. Further validation is required to ensure that the research outcomes can be adopted as an official guideline

To summarize, this discussion articulates a logical pathway connecting literature synthesis with the development of a comprehensive forensic engineering model. It emphasizes that future research in this domain should transcend isolated technical studies and move toward a unified, standardized, and multidisciplinary investigative framework—one that ensures both technical precision and legal credibility in the evaluation of construction failures.

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REFERENCES

1. Brady SP. Effectively responding to structural engineering failure: Expertise and cognitive entrenchment Journal of Performance of Constructed Facilities. 28(5), Article 04014020. 2014. doi:10.1061/(ASCE)CF.1943-5509.0000458.
2. Brady SP. Role of the forensic process in investigating structural failure Journal of Performance of Constructed Facilities. 26(1), 2-6. 2012. doi:10.1061/(ASCE)CF.1943-5509.0000274.

3. Ratay RT. An overview of forensic structural engineering Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE). 27(3), 338-343. 2017. doi:10.2749/101686617X14881932437176.
4. Palmisano F, Rus L, Terwel K. The Practice of Forensic Structural Engineering in IABSE's Member Countries Structural Engineering International. 34(3), 444-455. 2024. doi:10.1080/10168664.2024.2307411.
5. Booker NK, Clegg RE, Knights P, Gates JD. The need for an internationally recognised standard for engineering failure analysis. Engineering Failure Analysis. 2020;110:104357. https://doi.org/. doi:10.1016/j.engfailanal.2019.104357.
6. Booker NK, Knights P, Gates J, Clegg RE. Applying principal component analysis (PCA) to the selection of forensic analysis methodologies. Engineering Failure Analysis. 2022;132:105937.
7. Komar DA, Davy-Jow S, Decker SJ. The Use of a 3-D Laser Scanner to Document Ephemeral Evidence at Crime Scenes and Postmortem Examinations Journal of Forensic Sciences. 57(1), 188-191. 2012. doi:10.1111/j.1556-4029.2011.01915.x.
8. Joseph CM. Forensic biology: A passport for biological evidence. Crime Scene Management within Forensic Science: Forensic Techniques for Criminal Investigations (pp. 121-153). Springer Nature. 2022. doi:10.1007/978-981-16-6683-4_16.
9. James MN. Interactive on-line resources for training forensic engineers Proceedings of the Institution of Civil Engineers: Forensic Engineering. 165(3), 143-153. 2012. doi:10.1680/feng.11.00033.
10. Laohaviraphap N, Waroonkun T. Integrating Artificial Intelligence and the Internet of Things in Cultural Heritage Preservation: A Systematic Review of Risk Management and Environmental Monitoring Strategies Buildings. 14(12), Article 3979. 2024. doi:10.3390/buildings14123979.
11. Whittle JW, odczyk IA, Danks S, Koh LSC, Fletcher DI. Investigating the effect of railway track ballast and bed conditions on the lateral resistance of timber. concrete, steel, and composite sleepers using a novel test methodology Engineering Structures. 2025;340:Article 120769. doi:10.1016/j.engstruct.2025.120769.
12. Wu ZN, Dong Y, Han XL, Ji J, Lin JC. Hysteresis elongation behavior of RC beams failing in different modes: Experimental investigation and numerical modelling using smeared crack approach Engineering Structures. 329, Article 119807. 2025. doi:10.1016/j.engstruct.2025.119807.
13. Abdoh DA. Failure analysis of bolted steel plate connections with three-dimensional flexibilities International Journal of Mechanical Sciences. 272, Article 109313. 2024. doi:10.1016/j.ijmecsci.2024.109313.
14. Rus L, Moreno C, Mohammad S, Shahid A, Ahmed I, Chowdhury T. Failure Analysis: Structural Investigation Methods and Example of Application Structural Engineering International. 34(3), 461-468. 2024. doi:10.1080/10168664.2024.2363437.
15. Caredda G, Makoond N, Buitrago M, Sagaseta J, os M, Adam JM. Learning from the progressive collapse of buildings Developments in the Built Environment. 15, Article 100194. 2023. doi:10.1016/j.dibe.2023.100194.
16. Riccio C, Remus A, Tezcan S, da Silva LC, Milani G, Perucchio R. A macroblock 2D finite element model for assessing the roots of failure of Huaca de la Luna's main pyramid (Peru) under seismic action Engineering Failure Analysis. 151, Article 107417. 2023. doi:10.1016/j.engfailanal.2023.107417.
17. Pinho R, Scattarreggia N, Orgnoni A, Lenzo S, Grecchi G, Moratti M, Calvi GM. Forensic estimation of the residual capacity and imposed demand on a ruptured concrete bridge stay at the time of collapse Structures. 55, 1595-1606. 2023. doi:10.1016/j.istruc.2023.05.114.
18. Khan AA, Khan MA, Domada RVV, Huang X, Usmani A, Bakhtiyari S, Ashtiani MJ, Garivani S, Aghakouchak AA. Fire modelling framework for investigating tall building fire: A case study of the Plasco Building Case Studies in Thermal Engineering. 45, Article 103018. 2023. doi:10.1016/j.csite.2023.103018.

19. Khedmatgozar Dolati S, Matamoros A, Ghannoum W. Evaluating the effects of loading protocol on the strength and deformation capacity of Flexure-Shear critical concrete columns Engineering Structures. 279, Article 115592. 2023. doi:10.1016/j.engstruct.2023.115592.
20. Egwunatum SI, Anumudu AC, Eze EC, Awodele IA. Total quality management (TQM) implementation in the Nigerian construction industry Engineering. Construction and Architectural Management. 2022;29(1):354-382. doi:10.1108/ECAM-08-2020-0639.
21. Ortega I. Monitoring Strategies for Construction and Operation of Facilities. 2022.
22. Possidente L, Weiss A, de Silva D, Pustorino S, Nigro E, Tondini N. Fire safety engineering principles applied to a multi-storey steel building Proceedings of the Institution of Civil Engineers: Structures and Buildings. 174(9), 725-738. 2021. doi:10.1680/jstbu.20.00110.
23. Etemadi A, Balkaya C. Collapsed-RC Building Failure Mechanisms with a Forensic Engineering Approach Journal of Performance of Constructed Facilities. 34(5), Article 04020086. 2020. doi:10.1061/(ASCE)CF.1943-5509.0001462.
24. Calvi GM, Moratti M, O'Reilly GJ, Scattarreggia N, Monteiro R, Malomo D, Calvi PM, Pinho R. Once upon a Time in Italy: The Tale of the Morandi Bridge Structural Engineering International. 29(2), 198-217. 2019. doi:10.1080/10168664.2018.1558033.
25. Zheng Y, Dong Y. Performance-based assessment of bridges with steel-SMA reinforced piers in a life-cycle context by numerical approach Bulletin of Earthquake Engineering. 17(3), 1667-1688. 2019. doi:10.1007/s10518-018-0510-x.
26. ski TZ, Sielicki PW. The influence of design and contractor errors on the failure of a tenement building Engineering Failure Analysis. 97, 676-689. 2019. doi:10.1016/j.engfailanal.2019.01.060.
27. Piluso V, Pisapia A, Castaldo P, Nastri E. Probabilistic Theory of Plastic Mechanism Control for Steel Moment Resisting Frames Structural Safety. 76, 95-107. 2019. doi:10.1016/j.strusafe.2018.08.003.
28. Riccio A, Raimondo A, Di Caprio F, Fusco M, Sanità P. Experimental and numerical investigation on the crashworthiness of a composite fuselage sub-floor support system Composites Part B: Engineering. 150, 93-103. 2018. doi:10.1016/j.compositesb.2018.05.044.
29. Fazeres-Ferradosa T, Pinto F, Romão X, Vanem E, Reis MT, das Neves L. Probabilistic design and reliability analysis of scour protections for offshore windfarms Engineering Failure Analysis. 91, 291-305. 2018. doi:10.1016/j.engfailanal.2018.04.035.
30. Ortega I. A framework to prevent construction failures due to computer-related errors. 2018.
31. Justo J, Reinoso J, Blázquez A. Experimental failure investigation of pull-off tests of single T-stiffened composite specimens Composite Structures. 177, 13-27. 2017. doi:10.1016/j.compstruct.2017.04.070.
32. Dai K, Sheng C, Zhao Z, Yi Z, Camara A, Bitsuamlak G. Nonlinear response history analysis and collapse mode study of a wind turbine tower subjected to tropical cyclonic winds Wind and Structures. An International Journal. 2017;25(1):79-100. doi:10.12989/was.2017.25.1.079.
33. Fereshtehnejad E, Banazadeh M, Shafieezadeh A. System reliability-based seismic collapse assessment of steel moment frames using incremental dynamic analysis and Bayesian probability network Engineering Structures. 118, 274-286. 2016. doi:10.1016/j.engstruct.2016.03.057.
34. Murray JA, Sasani M. Near-collapse response of existing RC building under severe pulse-type ground motion using hybrid simulation Earthquake Engineering and Structural Dynamics. 45(7), 1109-1127. 2016. doi:10.1002/eqe.2698.

35. Mieler MW, Uma SR, Mitrani-Reiser J. Using failure analysis tools to establish seismic resilience objectives for building components & systems Bulletin of the New Zealand Society for Earthquake Engineering. 49(1), 86-97. 2016. doi:10.5459/bnzsee.49.1.86-97.
36. Gao T, David M, Geer J, Schmidt R, Sammakia B. A dynamic model of failure scenarios of the dry cooler in a liquid cooled chiller-less data center. Annual IEEE Semiconductor Thermal Measurement and Management Symposium,. 2015.
37. Astarlioglu S, Marjanishvili S. Uncertainties in structural collapse mitigation. 2015.
38. Abubakar M, Abdulmajeed ISA. Characterization. Mechanical Properties and Probabilistic Failure Analysis of Reinforcement Bars Produced from Scraps in Southern and Northern Region of Nigeria Journal of Failure Analysis and Prevention. 2023;23(3):1232-1241. doi:10.1007/s11668-023-01675-y.
39. Martani C, Adey BT, Wenk K. Determining optimal intervention strategies for bridges considering both gradual deterioration and sudden events. 2020.
40. Gill WS, Matthew Barry Marshall MB, Lewis R, Hall B, Bolton S. Failure analysis of pipeline indents using steel precision balls under subsea conditions Tribology International. 118, 524-537. 2018. doi:10.1016/j.triboint.2017.06.007.
41. Bahrami M, Roghani B, Tscheikner-Gratl F, Rokstad MM. A deep dive into green infrastructure failures using fault tree analysis Water Research. 257, Article 121676. 2024. doi:10.1016/j.watres.2024.121676.
42. Boateng FG. Why the de-emphasis of wider societal factors in construction failures analysis is fatal Proceedings of the Institution of Civil Engineers: Forensic Engineering. 171(4), 137-142. 2018. doi:10.1680/jfoen.17.00019.
43. Lu L, Wang X, Ouyang Y, Roningen J, Myers N, Calfas G. Vulnerability of Interdependent Urban Infrastructure Networks: Equilibrium after Failure Propagation and Cascading Impacts Computer-Aided Civil and Infrastructure Engineering. 33(4), 300-315. 2018. doi:10.1111/mice.12347.
44. Ortega I. Prevention of construction failures: A systematic approach. 2015.
45. Peraza DB. Philadelphia Building Collapse during Demolition. 2022.
46. Kizito R, Scruggs P, Li X, DeVinney M, Jansen J, Kress R. Long Short-Term Memory Networks for Facility Infrastructure Failure and Remaining Useful Life Prediction IEEE Access. 9. 2021;67585-67594:Article 9420660. doi:10.1109/ACCESS.2021.3077192.
47. Hobbs B, Tchoketch Kebir M. Non-destructive testing techniques for the forensic engineering investigation of reinforced concrete buildings. Forensic Science International. 2007;167(2):167-172. https://doi.org/. doi:10.1016/j.forsciint.2006.06.065.
48. Gondi C, Barnes JV, Wightman MJ. Using Ground Penetrating Radar Techniques in Forensic Structural Engineering Journal of the National Academy of Forensic Engineers. 42(1), 67-75. 2025. doi:10.51501/jotnafe.v42i1.971.
49. van Eck NJ, Waltman L. Visualizing Bibliometric Networks. Y. Ding, R. Rousseau, & D. Wolfram (Eds.), Measuring Scholarly Impact: Methods and Practice (pp. 285-320). Springer International Publishing. 2014. doi:10.1007/978-3-319-10377-8_13.
50. Arafa, M., Wadi, H., & Alqedra, M. Developing a Forensic Framework for Failures in Reinforced Concrete Buildings.
51. Verbiest M. A structured approach to forensic structural investigations of concrete damages. The development of an investigation methodology to determine the technical cause of damages to concrete structures. Graduation thesis Master of Science in Building Engineering. Delft University of Technology. 2018.
52. Palmisano F, Vitone A. The Partial Collapse of the Italia Viaduct Structural Engineering International. 34(3), 358-369. 2024. doi:10.1080/10168664.2024.2322536.