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Bridge Failures and their Causes: A Narrative Review of Structural, Environmental, and Human Factors

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Abstract: Bridges are critical components of transportation networks, yet catastrophic collapses continue to occur, sometimes in structures that were previously judged acceptable by conventional inspection and evaluation practices. This narrative review synthesizes bridge failure mechanisms reported between 1970 and 2024 and organizes them into structural, environmental, and human-organizational domains. The synthesis indicates that environmental hazards frequently act as the immediate trigger, with hydraulic scour repeatedly emerging as a dominant initiating mechanism, while severe outcomes are often enabled by latent vulnerabilities such as deterioration, limited redundancy, constructability and inspectability limitations, and gaps in inspection, communication, and maintenance decision-making. By integrating failure case evidence with reliability and lifecycle perspectives, the review highlights how capacity declines over time can intersect with changing demands and extreme events, increasing the likelihood of rapid, disproportionate collapse. The paper also discusses climate non-stationarity as a growing challenge for hazard characterization and emphasizes opportunities for proactive asset management through enhanced monitoring, data integration, and decision-support tools. The proposed synthesis framework supports more consistent failure attribution and informs strategies for resilient design, inspection planning, and risk-based maintenance policy.

Keywords: *Bridge Failure; Bridge Collapse; Forensic Engineering; Scour; Fatigue and Fracture; Corrosion; Asset Management.*

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I. INTRODUCTION

Bridges are critical nodes in transportation networks, enabling mobility, commerce, and emergency response. In the United States alone, the Federal Highway Administration (FHWA) National Bridge Inventory tracks more than 620,000 bridges on public roads. While condition trends have improved gradually in many jurisdictions, a substantial subset of bridges remains in poor condition and requires major rehabilitation or replacement. For example, the American Road & Transportation Builders Association (ARTBA) reports that roughly 42,400 bridges are rated in poor condition and carry tens of millions of crossings each day, underscoring the continuing exposure of the traveling public and the economy to service disruptions and safety risks [1], [2].

Bridge collapses are rare relative to the size of the inventory, but their consequences can be catastrophic, including loss of life, long-term detours, and cascading economic impacts. Evidence across decades of failures shows that collapse typically reflects the alignment of an initiating demand, a latent structural vulnerability, and a weakness in detection or decision-making. Large-sample and review-based studies highlight recurring drivers such as scour, impact, fatigue and fracture, corrosion, design and construction errors, and inspection or maintenance breakdowns [3], [4], [5].

A central challenge for prevention is that the most hazardous vulnerabilities are not always obvious during routine operations. Foundation undermining can progress rapidly during floods, brittle fracture can occur with limited warning in low-redundancy configurations, and corrosion can localize section loss in components that are difficult to inspect directly. These realities are compounded by aging infrastructure, rising demand, and evolving hazards, underscoring the importance of systematic learning from past failures.

This review synthesizes major bridge failure case studies and technical evidence to support practical prevention. Rather than classifying events solely by trigger, the paper emphasizes a multidimensional view that links triggers to the primary structural vulnerability and the organizational pathway that

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allowed risk to persist. This framing aligns bridge safety with a socio-technical perspective in which engineering performance depends on both physical capacity and the reliability of inspection, governance, and decision escalation [6].

The contributions of the paper are fourfold. First, it compiles and synthesizes bridge failure evidence from 1970 through 2024 using a structured review process that includes peer-reviewed literature and authoritative agency reports. Second, it proposes a classification framework that separates initiating events, latent vulnerabilities, and organizational gaps to improve cross-case comparability. Third, it summarizes recurring failure signatures using a synoptic table and focused narratives for high-impact mechanisms. Fourth, it translates these findings into preventive strategies relevant to design, inspection, maintenance, and operational controls.

II. METHODOLOGY

➢ *Review Design and Synthesis Approach*

This paper uses a structured narrative review with scoping features to synthesize evidence across peer-reviewed publications and authoritative technical reports on bridge failures. A structured approach was selected because the evidence for bridge collapse is heterogeneous in form and quality, ranging from forensic investigation reports to discipline-specific studies in hydraulics, structural engineering, and construction management. To improve transparency and reproducibility, we report the search, screening, and inclusion steps in a manner consistent with PRISMA 2020 reporting guidance, adapted to the aims of a narrative synthesis rather than a meta-analysis [7].

The review process followed widely used scoping-review planning principles: defining the review questions, identifying relevant sources, applying explicit eligibility criteria, charting key variables, and synthesizing findings into an interpretable framework [8], [9]. Where applicable, reporting elements recommended for scoping reviews were also used to improve clarity of objectives, screening decisions, and outputs [10].

➢ *Information Sources and Search Strategy*

Literature searches were conducted in major engineering and multidisciplinary databases, including Scopus and Web of Science, supplemented by targeted searches in discipline-specific repositories and publisher libraries. To capture high-consequence failures primarily documented outside peer-reviewed venues, the review also included government and agency sources, such as National Transportation Safety Board (NTSB) investigation materials and FHWA guidance and technical reports.

Search terms were developed iteratively by combining keywords such as bridge failure, bridge collapse, progressive collapse, scour, allision, impact, overheight vehicle strike, fatigue, fracture, corrosion, design error, construction failure, and inspection. Backward and forward snowballing was used for key sources to identify additional relevant records not retrieved through database queries.

➢ *Eligibility Criteria and Study Selection*

The temporal scope covers incidents and publications addressing bridge failures from 1970 through 2024. Eligible sources included peer-reviewed journal articles, books, conference papers, standards and guidance documents, and official investigation or inquiry reports that provided sufficiently specific technical descriptions of the initiating event, the structural failure mechanism, or the organizational and programmatic context. Items were excluded when they lacked a clear bridge context, reported only minor damage without implications for safety or serviceability, or provided insufficient detail to support classification.

Records were screened in two stages. First, titles and abstracts were reviewed to remove clearly irrelevant items and duplicates. Second, full texts were assessed against the eligibility criteria. When multiple sources described the same event, the most authoritative and technically detailed sources were prioritized, and additional sources were used to corroborate mechanism descriptions or organizational findings.

For each included event, data were charted using a consistent extraction template. Extracted fields included bridge type and context, year and location, initiating trigger, primary structural mechanism, contributing deterioration or demand factors, and documented organizational or governance gaps. This charting step supports comparability across cases and enables cross-case pattern analysis.

A thematic synthesis was then performed. Events were coded into the proposed classification framework by mapping triggers, vulnerabilities, and organizational gaps, and the results were summarized through cross-case narratives and synoptic tables. Quantitative aggregation was not pursued because of heterogeneity in reporting detail and inconsistent availability of comparable variables across investigations. The primary output is a framework-driven synthesis intended to support practical prevention strategies and to motivate more consistent failure reporting in future studies.

III. CLASSIFICATION FRAMEWORK FOR BRIDGE FAILURE CAUSES

➢ *Rationale for a Multi-Dimensional Classification*

Bridge failure taxonomies have often emphasized the initiating event (for example, flood, collision, or earthquake) because triggers are easy to label and compare across cases. However, large-sample studies show that similar triggers can produce very different outcomes depending on latent vulnerabilities, such as low redundancy, deterioration, limited inspectability, and weak decision controls [3], [4], [5]. A classification framework that explicitly separates triggers from vulnerabilities is therefore better aligned with how collapses develop over the bridge life cycle.

In this review, we adopt a vulnerability-centered, socio-technical view: collapses are treated as the alignment of (i) a demand or disturbance, (ii) a structural susceptibility that reduces tolerance to that demand, and (iii) an organizational pathway that allows the susceptibility to persist or remain undetected. This logic parallels safety science models that

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distinguish active failures from latent conditions and emphasize defensive layers in complex systems [6].

➢ *Tripartite Framework for Failure Drivers*

The framework groups failure drivers into three interacting domains: structural and mechanistic drivers (geometry, detailing, redundancy, degradation, and load paths), environmental and hazard drivers (hydrologic, seismic, wind, fire, and other extreme events), and human and organizational drivers (design review, construction control, inspection quality, communication, and governance), as shown in Figure 1 and Table 1. This tripartite structure is consistent with bridge-collapse reviews that separate natural and human factors while emphasizing their coupling in real events [4], [11], [5].

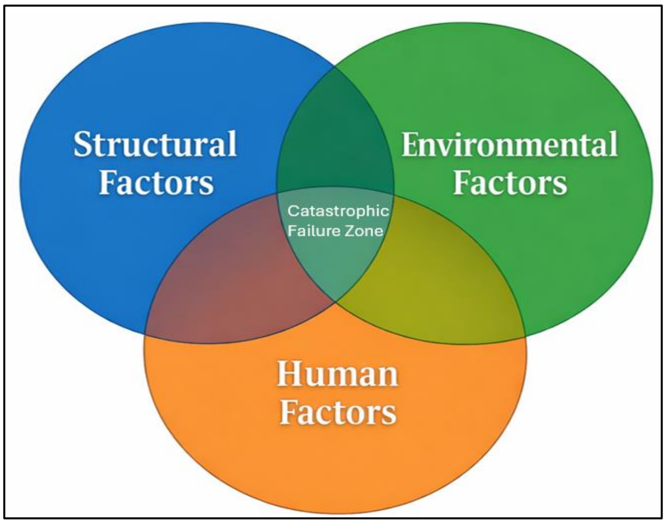

Fig 1 The Tripartite Risk Interaction Model

Table 1 Integrated Framework for Failure Analysis

Domain	Sub-Category	Primary Failure Mechanisms
Structural	Degradation	Corrosion, Fatigue, ASR
	Design	Lack of redundancy, FCMs
Environmental	Hydraulic	Scour, Debris, Flooding
	Geotechnical	Seismic, Liquefaction
Human	Systemic	Funding gaps, Poor inspection
	Operational	Overloading, Collisions

➢ *Interaction Effects and Cascading Failure Pathways*

Bridge collapses rarely follow a single-cause narrative. Instead, triggers and vulnerabilities interact, and secondary effects can accelerate loss of capacity. For example, scour can undermine foundations during high flow while debris accumulation increases local hydraulics; collision can remove a critical pier or truss member and force the remaining system to redistribute demand; and corrosion can localize section loss at details that are already fatigue sensitive [12], [13], [14]. To capture these interactions in a consistent way, each case is coded by (a) the initiating event, (b) the primary structural vulnerability (foundation, member, connection, or system-level robustness), (c) the predominant organizational gap (design verification, construction-stage controls, inspection and maintenance, or operational management), and (d) the collapse magnitude (component, functional, or global). Coding the same event along multiple dimensions reduces the risk of over-assigning causality to a single label and supports cross-case comparisons across bridge types and life-cycle stages [11], [5].

➢ *Reliability and Defensive Layers*

The Swiss cheese model is used as a conceptual aid to represent how multiple defensive layers can fail in sequence, as shown in Figure 2. In the bridge context, these layers include design checks, construction quality assurance, routine and special inspections, load rating and operational controls, and emergency response. Catastrophic collapse becomes more likely when weaknesses align across several layers rather than when a single barrier is breached [6].

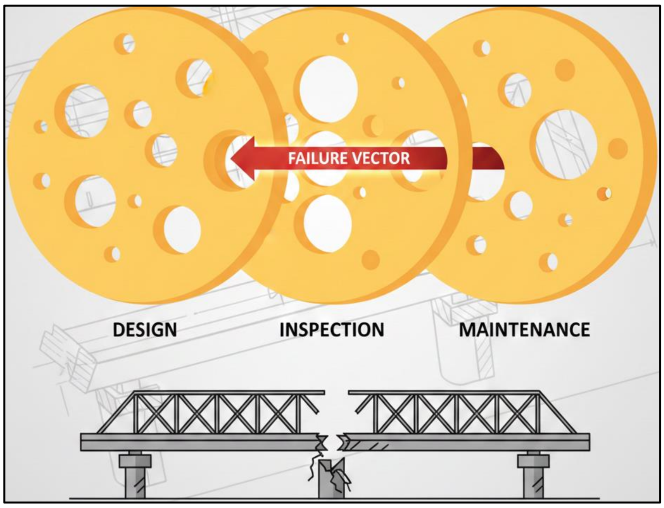

Fig 2 The Swiss Cheese Model of Bridge Failure

This view complements systems-theoretic safety perspectives that treat accidents as the result of inadequate control and feedback in socio-technical systems, not only as component malfunctions. Such perspectives are useful for bridge programs because they emphasize communication pathways, responsibility boundaries, and decision escalation when indicators of distress appear [15].

➢ *Failure Magnitude and Consequence Categories*

Finally, failures are classified by consequence level: component failure (localized damage without immediate loss of service), functional failure (loss of capacity or serviceability that requires closure or major restriction), and total collapse (loss of global stability or load path). Differentiating magnitude

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clarifies why robustness and redundancy matter: structures that can tolerate localized damage without disproportionate collapse provide additional time for detection and intervention [16], [5].

IV. CAUSES OF BRIDGE FAILURE

Bridge failures are rarely explained by a single isolated mechanism. Most collapses reflect an interaction between a triggering event or demand, a pre-existing structural vulnerability, and one or more organizational breakdowns that allow the vulnerability to persist or go unnoticed [3], [4], [6]. This section summarizes common causes grouped into structural, environmental, and human factors, emphasizing how risk concentrates when multiple layers of defense fail at the same time.

➢ *Structural Causes*

Structural causes include deficiencies in design and detailing, deterioration of materials and connections, fatigue and fracture of steel details, and construction-stage vulnerabilities. These mechanisms often remain hidden until a disturbance pushes the system beyond a reduced reserve capacity [11], [4].

- *Latent Design Deficiencies*

Design and detailing deficiencies can function as latent conditions that remain dormant for decades, particularly in nonredundant or fracture-critical systems where local damage cannot be redistributed [6], [11]. The I-35W Mississippi River Bridge collapse illustrates how an under-capacity connection detail can become critical when combined with added dead load and construction staging. The National Transportation Safety Board concluded that undersized gusset plates were the primary structural deficiency and that the deficiency was not identified through design review or in-service evaluations [17]. Because traffic volumes, truck weights, and retrofit histories evolve, managing latent design risk requires periodic re-evaluation of critical members, explicit checks for redundancy and fracture-critical behavior, and clear escalation when calculations or inspection findings indicate low reserve capacity [4]. Figure 3 shows the I-35W Mississippi River bridge collapse.

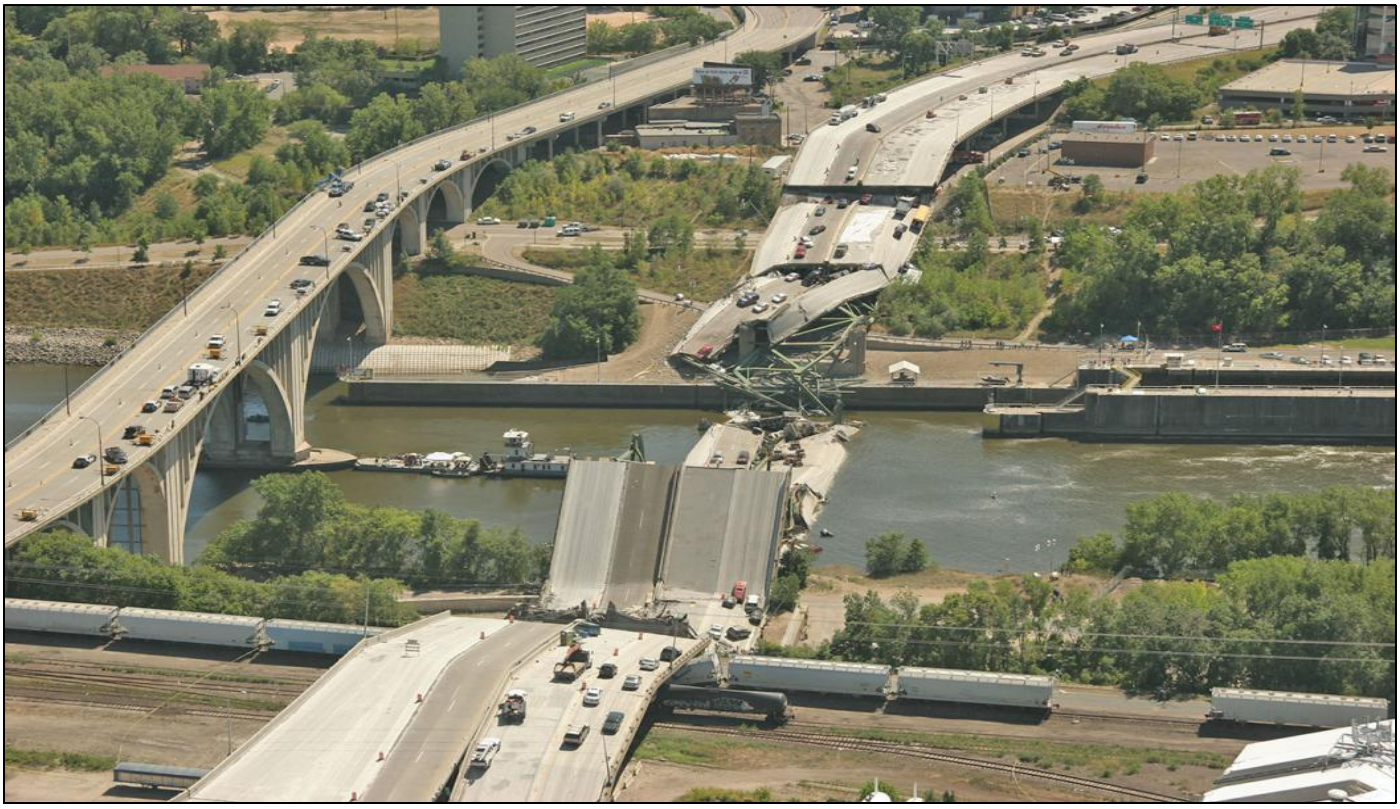

Fig 3 The I-35W Mississippi River Bridge Collapse

- *Material Degradation*

Material degradation reduces capacity gradually but can produce sudden collapse when deterioration affects fracture-critical elements, bearings, or connections that lack redundancy. Corrosion-induced section loss and impaired connections are recurring contributors in failure databases and forensic case studies [3], [11]. In steel bridges, corrosion can concentrate at drainage paths, deck joints, and connection details, while in reinforced concrete, it can initiate reinforcement corrosion, reducing bond and strength. Life-cycle reliability studies show that uncertainty in corrosion initiation and propagation can mask declining safety margins and delay intervention [18].

Recent investigations of the Fern Hollow Bridge collapse (shown in Figure 4) emphasized long-term corrosion and section loss in a fracture-critical member, coupled with maintenance and inspection shortcomings, as causal factors in the loss of structural integrity [19].

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Fig 4 The Fern Hollow Bridge Collapse

- *Fatigue and Fracture Mechanics*

Fatigue is progressive damage caused by repeated stress cycles, often initiating at weld toes, attachments, and other stress concentrations. Even when nominal stresses are modest, local detail behavior can drive crack initiation and growth [20], [14].

Fracture is most hazardous in low-redundancy systems because there is limited opportunity for load redistribution after a crack reaches a critical size. The resulting failure can be abrupt, with little warning unless inspection and monitoring are targeted at known fatigue-prone details [20], [11]. Prevention relies on damage-tolerant detailing, access for close-up inspection of fatigue-critical details, and risk-based inspection planning that reflects redundancy, consequence, and uncertainty rather than uniform intervals [14].

- *Construction and Workmanship Errors*

Construction-stage failures frequently involve temporary load paths, sequence-dependent behavior, and quality control breakdowns. Errors in falsework, connections, or concrete placement can rapidly destabilize a system that has not yet achieved its final design configuration [3], [11]. The NTSB investigation of the FIU pedestrian bridge collapse (shown in Figure 5) documented that cracking observations and engineering assessments were not effectively escalated and that the bridge remained in place over live traffic until failure, highlighting the importance of construction-stage risk management and decision-making authority [21].

Fig 5 The FIU Pedestrian Bridge Collapse

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- *The Bathtub Curve of Infrastructure*

From a systems perspective, failure risk often follows a bathtub-shaped pattern over an asset's life: early failures linked to design and construction defects, a lower but nonzero midlife risk, and increasing risk later as deterioration and accumulated damage dominate [22]. For bridges, the late-life phase is strongly influenced by environmental exposure, drainage and protective systems, inspection effectiveness, and the timing and quality of maintenance actions that arrest deterioration before it reaches fracture-critical regions. Figure 6 shows the Conceptual Visualization of the Reliability Bathtub Curve for Bridges.

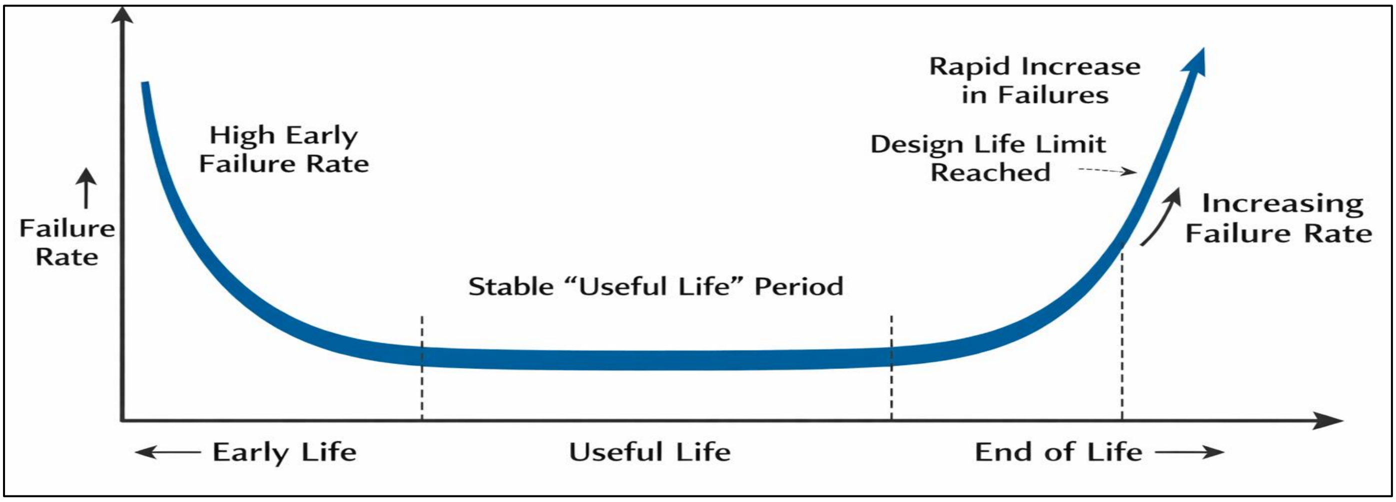

Fig 6 Reliability Bathtub Curve for Bridges.

➢ *Environmental Causes*

Environmental causes act as external demands that can rapidly overwhelm reduced reserve capacity, particularly during floods, earthquakes, and wind events [4], [11].

- *Hydraulic Scour*

Scour is the erosion of streambed material around foundations and is a leading natural cause of bridge collapse. During high flows, scour can progress rapidly and is difficult to visually confirm, making foundations especially vulnerable as channel geometry and debris conditions change over time [23], [13]. FHWA's HEC-18 guides evaluating scour at piers and abutments, identifying scour-critical bridges, and selecting countermeasures and inspection approaches [23]. The Schoharie Creek Bridge collapse (as shown in Figure 7) remains a widely cited example of foundation undermining during flooding [24]. Effective mitigation combines hydraulic assessment with repeatable field protocols such as underwater inspection where warranted, monitoring at scour-critical sites, and explicit consideration of channel migration and debris accumulation [13], [23].

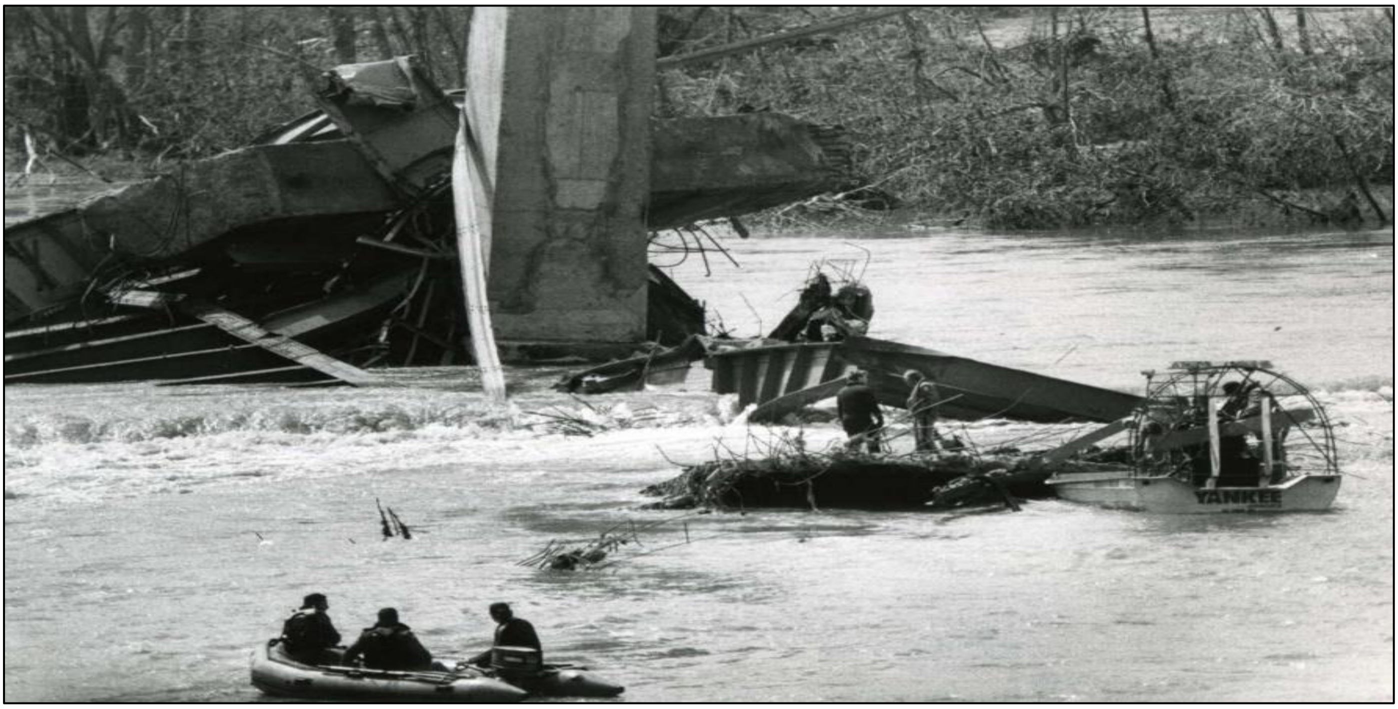

Fig 7 The Schoharie Creek Bridge Collapse

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- *Seismic and Geotechnical Instability*

Earthquakes can trigger collapse through inertial demands, unseating, connection failure, and soil failures such as liquefaction and slope instability. Lessons from major events show that older detailing and inadequate ductility can produce disproportionate damage, motivating seismic retrofit programs for vulnerable inventories [25], [4]. Geotechnical hazards also include settlement and lateral spreading that can compromise foundations even without complete superstructure failure, reinforcing the need to integrate site conditions into bridge risk screening and retrofit prioritization [25].

- *Wind and Aerodynamic Instability*

Long-span bridges are susceptible to aerodynamic phenomena such as flutter, vortex-induced vibration, and buffeting. The Tacoma Narrows collapse remains a defining example of aeroelastic instability and the need to couple structural dynamics with aerodynamic design [26], [27]. Modern practice uses wind tunnel testing, damping and stiffness requirements, and continuous monitoring to manage wind-induced vibration and serviceability demands in long-span systems [27].

- *Climate Change*

Climate change can influence bridge risk by shifting the frequency and intensity of extreme precipitation, flooding, and other hazards that drive scour, erosion, and hydraulic loading. The IPCC Sixth Assessment Report documents observed and projected increases in heavy precipitation in many regions, which can amplify hydrologic extremes relevant to bridge performance [28]. Transportation risk reviews emphasize incorporating nonstationary hazard assumptions into screening and prioritization, including flood and scour exposure under changing precipitation regimes [29].

- *Hydrological Extremes and Debris*

Beyond scour depth, floods can damage bridges through debris accumulation, impact on superstructure elements, and rapid changes in flow alignment that create unanticipated local loading. Guidance emphasizes that debris and channel evolution can be as consequential as peak discharge [23], [24]. Operational measures such as traffic closure protocols during high water, debris management near critical openings, and post-event inspection of foundations and bearings provide practical layers of defense when direct verification during the event is infeasible [11].

➢ *Human Causes*

Human and organizational factors shape whether structural and environmental threats are detected early and acted upon. Investigations repeatedly show that collapse risk increases when warnings are normalized, inspection findings are not escalated, or responsibilities are fragmented across agencies and contractors [6], [17], [21].

- *The Normalization of Deviance*

Normalization of deviance describes a process in which abnormal conditions gradually become accepted as normal because they do not immediately produce failure. Over time, repeated exposure to risk signals can erode safety margins and reduce the likelihood of decisive intervention [6]. In bridge contexts, this pattern can appear when recurring corrosion, cracking, or movement is documented but repeatedly deferred, particularly when uncertainty is high and ownership or funding responsibilities are unclear [19].

- *Inspection Subjectivity*

Visual inspection is essential but inherently subjective. Access limitations, lighting, and inspector experience influence defect detection and condition ratings, and some critical deterioration mechanisms occur in concealed or difficult-to-access locations [11]. For fatigue- and fracture-critical details, targeted hands-on inspection, nondestructive evaluation, and, where appropriate, structural health monitoring can reduce reliance on indirect indicators and help prioritize interventions [20].

- *Maintenance Funding and Politics*

Maintenance and rehabilitation decisions compete with other budget priorities, which can delay corrective actions even when deterioration is recognized. Case investigations show that repeated recommendations may go unaddressed when agencies lack dedicated resources or clear accountability for follow-through [19]. Risk-informed asset management aims to link funding to consequence and condition, but it depends on accurate data, transparent prioritization, and sustained oversight.

- *Communication and Contractual Barriers*

Communication failures can emerge at interfaces between designers, contractors, owners, and inspectors. When responsibility for evaluation and decision-making is ambiguous, critical observations may not trigger timely action [21]. Establishing clear stop-work authority, escalation pathways, and independent review for critical findings are recurring recommendations in failure investigations [21], [17].

- *Training and Institutional Memory*

Bridge safety programs rely on institutional knowledge about common failure modes, inspection limitations, and system-specific vulnerabilities. Staff turnover and inconsistent training can erode this knowledge over time [11]. Standardized training, checklists for known failure signatures, and knowledge management systems that capture lessons learned from failures can strengthen organizational resilience [6], [4].

V. SYNTHESIS OF MAJOR BRIDGE FAILURE CASE STUDIES

➢ *Cross-Case Analysis and Patterns*

Synthesizing major bridge failures over the last several decades shows that collapses rarely result from a single isolated mechanism. Instead, they recur as recognizable failure signatures, meaning repeatable combinations of (i) an initiating demand or disturbance, (ii) a latent structural vulnerability that reduces tolerance to that disturbance, and (iii) an organizational gap that allows the vulnerability to persist or remain undiscovered. Large-sample and review-based studies consistently show that natural hazards and operational events often serve as triggers, while the severity of outcomes is strongly shaped by hidden weaknesses such as limited redundancy, deterioration, constrained inspectability, and breakdowns in inspection and maintenance decision pathways [3], [4], [24], [5].

Across cases, hydraulic scour remains one of the most persistent and consequential signatures because it undermines foundations, frequently during high-flow conditions when visibility is poor and direct confirmation is difficult. Authoritative guidance emphasizes that scour risk is dynamic and shaped by channel evolution, debris effects, and the vulnerability of specific foundation types [12], [13]. A second signature involves impact and collision, including vessel allisions and overheight vehicle strikes. In these events, the initiating demand is abrupt, and the outcome depends on pier protection, redundancy, and the ability of the superstructure to sustain localized damage without disproportionate collapse [11], [5]. A third recurring signature is fatigue and fracture. Cracks initiate at details with high stress concentrations and may propagate toward brittle fracture, especially in low-redundancy configurations where load redistribution is limited. This pattern reinforces the central role of damage-tolerant detailing and inspection access to fatigue-prone details [20], [14]. Finally, several modern failures highlight a corrosion and inspectability signature. Here, progressive capacity loss is most dangerous when critical components are difficult to inspect directly, leading to increased reliance on assumptions and delayed decisive intervention. For the Polcevera Viaduct (Morandi Bridge), multiple peer-reviewed studies discuss deterioration mechanisms, inspection and monitoring challenges, and the value of condition observability using structural assessment and remote sensing [30], [31], [32], [33].

These cross-case patterns indicate that prevention is not only a matter of refining hazard models or strengthening components. Effective risk reduction also requires organizational controls that reliably surface, interpret, and act on risk signals, including clear escalation pathways for anomalous findings and independent review for critical elements. This supports viewing bridge safety as a socio-technical reliability problem rather than a purely structural one [6], a point that is consistent with recurring findings from major NTSB investigations [17], [21], [19].

Table 2 Synoptic Review of Significant Bridge Failures (1970-2024)

Bridge (Location)	Year	Primary Driver	Structural Trigger	Organizational Gap
Sunshine Skyway Bridge (Florida, US)	1980	Collision	Vessel allision leading to span loss	Limited vessel-impact protection and navigation risk management
Mianus River Bridge (Connecticut, US)	1983	Deterioration	Pin-and-hanger connection failure	Inspection and maintenance deficiencies for critical connections
Schoharie Creek Bridge (New York, US)	1987	Scour	Foundation undermining during flood conditions	Underwater inspection and scour assessment gaps
Cypress Street Viaduct (California, US)	1989	Seismic	Column and connection failures leading to progressive collapse	Seismic detailing and retrofit shortcomings in legacy systems
I-10 Escambia Bay Bridge (Florida, US)	1993	Collision	Barge allision and span collapse	Limited operational controls under low visibility and protection provisions
Seongsu Bridge (Seoul, South Korea)	1994	Fatigue	Connection fracture and collapse	Quality assurance and fatigue-critical vulnerability management
Queen Isabella Causeway (Texas, US)	2001	Collision	Vessel impact and span loss	Navigation safety controls and impact protection planning
I-40 Bridge at Webbers Falls (Oklahoma, US)	2002	Collision	Barge allision and superstructure collapse	Waterway operational risk controls and pier protection strategy
I-35W Mississippi River Bridge (Minnesota, US)	2007	Design deficiency	Gusset plate capacity shortfall at critical nodes	Design verification and lifecycle re-check failures; load management and escalation breakdowns
Skagit River Bridge (Washington, US)	2013	Operational impact	Overheight vehicle strike on truss	Routing and enforcement controls for overheight loads; vulnerability of fracture-critical members.
FIU Pedestrian Bridge (Florida, US)	2018	Construction and design	Progression of cracking at critical node and collapse	Risk communication and decision escalation failures; inadequate peer review.
Polcevera Viaduct (Genoa, Italy)	2018	Deterioration and observability	Capacity loss in critical system and collapse	Inspectability and monitoring limitations; delayed decisive intervention
Fern Hollow Bridge (Pittsburgh, Pennsylvania, US)	2022	Corrosion and section loss	Failure initiated by severe corrosion and section loss in critical steel component	Maintenance and oversight failures; inspection quality gaps; load rating issues.

➤ *Scour-Driven Failures and Inspection Challenges*

Scour remains one of the most consequential bridge collapse mechanisms because it attacks foundations, often invisibly. Standard guidance emphasizes that scour risk is not static: it evolves with river morphology, flood intensity, and debris accumulation [12], [13]. The Schoharie Creek collapse is frequently cited as a canonical illustration of the scour signature, in which extreme hydraulics interacted with foundation-level vulnerability and insufficient underwater evaluation practices [12], [24]. The broader lesson across scour

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cases is that preventing collapse requires more than modeling a design flood. It requires targeted identification of scour-critical foundations, repeatable inspection protocols that include underwater assessment where warranted, and explicit consideration of debris and channel evolution [13], [12].

- *Fatigue-Driven Failures and Damage Tolerance*

Fatigue failures underscore that bridges can appear serviceable while cracks grow at details that are difficult to observe and that concentrate stress, such as weld toes, attachments, and connection regions. Fracture mechanics research and failure statistics show that sudden fracture is most dangerous in systems with limited redundancy because there is little opportunity for load redistribution and little warning time [20], [14], [5]. The Seongsu Bridge failure is widely used to illustrate how fatigue and connection vulnerability, combined with inadequate quality assurance and inspection effectiveness, can lead to abrupt collapse [14]. Across the fatigue signature, the preventive emphasis is clear: prioritize damage-tolerant detailing, ensure robust inspection access to fatigue-prone details, and treat redundancy as a deliberate safety feature rather than an optional efficiency trade.

- *Corrosion-Driven Failures and Inspectability Limits*

The Morandi Bridge collapse remains a defining modern case because it demonstrates how conventional deterioration processes can become catastrophic when critical components are difficult to inspect and when risk signals are normalized over time. Multiple forensic and review sources highlight that corrosion and degradation progressed in a system where direct condition verification of key elements was not straightforward, increasing reliance on assumptions and indirect indicators [34]. This case reinforces two preventive principles. First, inspectability and maintainability should be treated as core design requirements for primary load paths. Second, governance and oversight must ensure that known deterioration in critical components triggers decisive interventions rather than incremental deferrals, especially when uncertainty is high [35].

- *Redundancy, Robustness, and Operational Controls*

Across the reviewed failures, redundancy repeatedly emerges as the most reliable structural "buffer" against disproportionate collapse. Robustness is not simply higher strength; it is the ability to sustain localized damage without cascading to total failure [16], [5]. This perspective also clarifies why operational factors such as chronic overloading can be so damaging: repeated exceedance of intended demands accelerates fatigue and deterioration, compressing the margin between capacity and demand [18], [4]. From a prevention standpoint, this supports a dual strategy: design and retrofit for robustness where feasible, and strengthen enforcement and monitoring of operational demands using modern sensing and analytics where appropriate [35].

VI. DISCUSSION

A recurring insight across the reviewed cases is the growing mismatch between structural capacity and external demand. This squeeze is driven by two simultaneous trends: capacity steadily declines through aging mechanisms such as corrosion and fatigue, while demand increases due to intensifying environmental hazards and heavier traffic loads. Many failures occur when an extreme action strikes a structure that has been progressively weakened over time, even though it likely would have tolerated the same action when it was in as-built condition. In this context, conventional safety factors function as a static response to a dynamic problem. A more defensible approach is to adopt time-dependent reliability models that estimate when performance margins are likely to collapse and to update these forecasts using structural health monitoring measurements so that reliability reflects actual in-service condition rather than assumed deterioration trajectories.

At the system level, failure risk increases when the inspection and maintenance feedback loop does not function as intended. In principle, inspection findings should trigger maintenance actions that restore capacity. In practice, this loop is often weakened by fragmented data systems, subjective reporting, and persistent funding constraints. Once the loop degrades, infrastructure can enter a self-reinforcing decline where the condition worsens faster than corrective actions can keep pace, leading to functional loss or collapse. Addressing this requires data-centric asset management. Agencies can move away from disconnected reports and archives toward unified digital platforms that link inspection records, monitoring streams, maintenance actions, and design information within a consistent digital representation, enabling lifecycle traceability and continuous risk management.

These challenges are compounded by the fact that many infrastructure failures arise not from a single dominant cause, but from the complexity of interactions in tightly coupled technical and organizational systems. Under tight coupling, small disruptions can cascade rapidly across components, defeating checks that assume limited interaction pathways. This points to the need to design not only for quantifiable risk, but also for deeper uncertainty, acknowledging that rare combinations of factors can dominate consequences. Resilience, in this framing, depends on both buffer capacity within the structural system and agile response capability within the organizational system, so that shocks can be absorbed and managed before they become catastrophic.

Within this landscape, forensic engineering should be treated as more than a post-failure activity. When applied proactively, forensic reasoning becomes a diagnostic approach for identifying pre-failure signatures in operating structures. These signatures can include patterns of distress, anomalies, or performance drift that indicate rising vulnerability. However, scaling this learning process can conflict with legal and insurance incentives that discourage transparency after near-misses. Establishing stronger norms and formal mechanisms for non-punitive reporting of structural anomalies would reduce information loss, accelerate learning across agencies, and improve prevention at the network level.

Ultimately, these themes converge on public safety as the defining performance metric. Engineering ethics require that safety take precedence over cost, yet modern delivery pressures such as limited budgets, compressed schedules, and political constraints can erode independent technical judgment and

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weaken safeguards. Strengthening public safety outcomes, therefore, depends not only on better models and technologies but also on institutional protections for independent safety audits, clearer accountability, and regulatory structures that ensure technical warnings are acted upon rather than deferred for short-term expediency.

VII. FUTURE DIRECTIONS AND PREVENTIVE STRATEGIES

Future progress in bridge safety will depend on shifting from reactive investigations after major incidents to proactive, lifecycle risk management that treats failures as socio-technical outcomes. This means combining better hazard modeling, stronger structural robustness, and more reliable decision workflows that reduce subjectivity in inspection and maintenance planning.

A key technical direction is tighter integration of physics and data. Rather than using machine learning as a stand-alone predictor, hybrid approaches that embed mechanics, boundary conditions, and conservation laws can produce estimates that are more stable under sparse data and changing environments. In practice, this can support more trustworthy inference of hidden states such as stiffness loss, connection degradation, or scour-sensitive foundation behavior, while also improving uncertainty quantification so that outputs are actionable for engineers.

A second priority is building an end-to-end digital ecosystem that supports traceability from design intent to in-service reality. A digital-twin-ready workflow should connect inspection records, sensor streams, geometry and metadata, repair history, and known vulnerabilities into a living asset record that can be updated over time. The value is not in creating a single "model" but in establishing a consistent pipeline for data capture, validation, and decision support so that deterioration trends and risk signals are visible early and comparable across inspectors, districts, and years.

Preventive strategies should also evolve from time-based routines to risk-based inspection and maintenance. Inspection intervals, monitoring intensity, and retrofit prioritization should be driven by consequence, exposure, redundancy, known degradation mechanisms, and hazard context. This includes explicit attention to extreme events and compounding risks, such as flooding combined with debris impact, temperature effects combined with fatigue, or corrosion combined with connection detail sensitivity. A practical goal is to standardize decision rules that translate condition evidence into clear actions, while keeping uncertainty visible rather than hidden.

Policy and governance reforms are equally important because many bridge failures reflect systemic human and organizational factors. Agencies can reduce risk by strengthening quality control for inspection documentation, improving training and calibration for defect identification, and enforcing transparent thresholds for load posting, retrofit triggers, and emergency closures. Funding models should better support preventive maintenance and targeted retrofits, since deferring small repairs often increases long-term risk and cost. Procurement and contracting practices can also be improved by requiring stronger construction oversight, clearer responsibility for temporary works, and more consistent review of changes that affect capacity and stability.

Finally, materials and retrofit innovations offer promising complementary defenses. Durable systems that reduce corrosion susceptibility, improve fatigue resistance at critical details, and increase redundancy through retrofit load paths can reduce the likelihood that localized damage escalates into collapse. For existing bridges, the most impactful advances are often not exotic materials but scalable retrofit strategies, better protection of critical components, and monitoring plans that focus on the highest-risk details.

Taken together, these directions point to a practical prevention agenda: strengthen robustness through redundancy, anticipate evolving hazards, make inspection evidence more objective and traceable, and adopt risk-based planning that links data to timely intervention. The overarching aim is resilience-focused bridge management, where early warning, graceful degradation, and life safety are preserved even under uncertainty.

VIII. CONCLUSION

Bridge failures are rarely attributable to a single trigger; rather, they emerge from the interaction of environmental demands, structural vulnerabilities, and human-organizational decisions across the lifecycle. Consistent with the synthesis in this review, hydraulic scour remains the dominant collapse driver, and its risk profile is increasingly amplified by climate non-stationarity, which undermines traditional assumptions used in hydrologic and scour design and evaluation

Across the case evidence, the most robust technical defense against disproportionate collapse is redundancy. Bridges that provide alternate load paths and tolerate localized damage are far more likely to avoid sudden, catastrophic outcomes, even when degradation or extreme actions occur. However, technical robustness alone is insufficient: many failures persist because human error is systemic rather than individual, arising from inspection subjectivity, deferred maintenance, fragmented accountability, and recurring funding constraints.

Accordingly, prevention should be framed as closing the socio-technical subjectivity gap by moving from intermittent, qualitative assessments toward risk-based inspection regimes supported by objective sensing, data integration, and analytics. Deploying modern structural health monitoring, AI-enabled defect detection, and digital-twin-style lifecycle traceability can make deterioration visible earlier, improve decision consistency, and support timely intervention. Ultimately, the field must continue shifting from designing for nominal safety to engineering for resilience, systems that provide actionable warnings, preserve life safety, and degrade gracefully under extreme and uncertain future demands.

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