# Structural Reliability and Resilience:

# Contextual Limitations of Risk-Informed Design

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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What might go wrong is varied and the best chance of spotting what might go wrong is to have experience of what has gone wrong

–Allan Mann, *Structural Safety - Theory and Practice* (2023)

In a statement by the American Society of Civil Engineers (ASCE) following the collapse of the Francis Scott Key Bridge that crippled vital economic channels and killed 6 construction crew workers, “A bridge collapsing after being struck by a ship is extremely rare but not without precedent” (ASCE, 2024). Although not explicitly stated, the subtext presumes that these sorts of failures are unavoidable or even acceptable. While this might be the case, this resolution is particularly unsatisfying and seems to be in direct contradiction with ASCE’s (2020) code of ethics that describes the critical responsibility of civil engineers to “protect the health, safety, and welfare of the public” (p. 2).

This is far from the only instance where this contradiction appears. In reality, structural engineers operate “within a paradigm of tradeoff between safety and expense” (Gainsburg, 2007, p. 483). While hypothetical design decisions may seem obvious based on a professional code of ethics, reality is not so simple. The difficult truth is that engineers cannot necessarily guarantee safety but only minimize the risks of failures (Mann, 2023, pp. 381-382; Pandey et al., 2025, p. 1). Every project incurs a range of risks that must be negotiated to reach an acceptable solution that appeases some societal risk tolerance.

Achieving a balance that continually prioritizes safety with finite resources can be a controversial and arduous task that requires an understanding of engineering practice, a way to evaluate societal risk preferences, and a methodology to cohesively incorporate these factors. Given the criticality of these decisions, this research evaluates cost optimization methods in structural engineering, explores how they are incorporated in risk-informed design, and provides contextual case study reviews that demonstrate practical limitations to implementation.

**The State of Structural Engineering**

Over the last century, structural design philosophies have shifted, and the implications for structural resilience along with them. The industry has navigated dramatic changes from traditional and modern design approaches. Until the mid to late 1900s, design methods were primarily based on Allowable Stress Design (ASD), which ensures the ratio of a structural member's theoretical strength to its loading conditions is equal to or exceeds a factor of safety (Pandey et al., 2025, p. 4; Melchers, 2018, pp. 2-3). These factors represent "a value judgment by code-writers based on past experience and best practices" (Ellingwood et al., 2025, p. 1). While these principles are still used in some applications today, the methodology's inability to accurately predict material behavior (Ellingwood et al., 2025, p. 1; Melchers, 2018, p. 2) and the development of more complex computational models have seen the approach fall from favor (Roësset et al., 2002, p. 4).

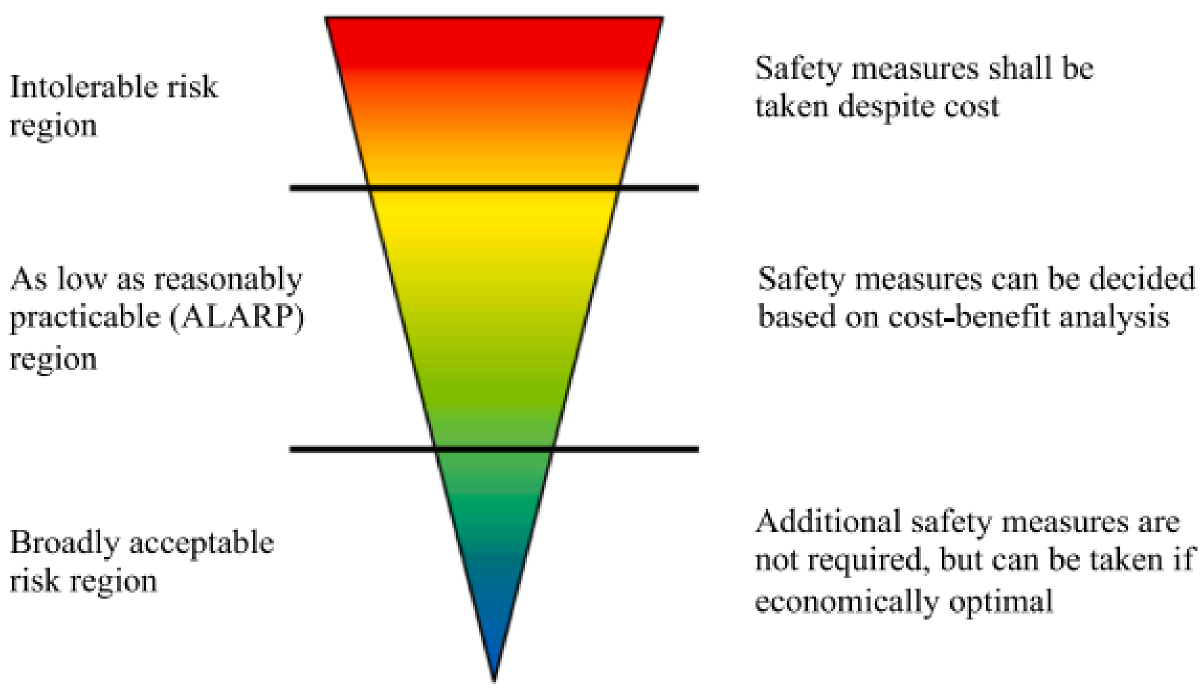
Coinciding with enhancements in understanding material behavior and the development of finite element analysis, reliability-based design (RBD) sought to implement a probabilistic approach to account for the many uncertainties during analysis, design, and construction (Fahrni et al., 2021, p. 2; Gardoni & Murphy, 2009, p. 30; Melchers, 2018, p. 4). The approach targets a limit for structural failure at some sufficiently low probability, depending on the criticality of the structure or component (Pandey et al., 2025, pp. 4-6). As described by Fahrni et al. (2021), "Modern codes use a semi-probabilistic" approach derived from reliability-based design, such as Load and Resistance Factored Design (LRFD), which provides conservative load and resistance factors that simplify calculations for practitioners (p. 2). While reliability-based design marks significant progress towards structural resilience, it is not without limitations, including the appropriate calibration of target reliability.

**Targeting Acceptable Reliability**

Initially, reliability calibration targets were often calculated based on values achieved by antiquated design methodologies rather than on "explicit optimization of either life cycle cost or life safety goals" (Pandey et al., 2025, p. 2; Melchers, 2018, p. 59). The current calibration philosophy has undergone revisions, and calibrations aim to achieve a probability of failure set As-Low-As-Reasonably Practicable (ALARP) as illustrated in the decision guide in Figure 1 (Pandey et al., 2025, p. 2).

**Figure 1**

*Risk-Informed Decision Guide*




*Note.* This figure serves as a visual representation of guidance by which to make risk-informed decisions in terms of general societal acceptability. From "Life Safety in the Reliability-Based Design and Assessment of Structures," by M. Pandey, et al., 2025, *The Joint Committee of Structural Safety*: *Past*, *Present*, *and a Perspective on the Future*, *113*, p. 2.

To apply these principles, finding an objective means to determine thresholds for intolerable risk is critical. Minimum reliability indices, directly related to a structure's probability and consequence of failure, have been calculated based on risks "associated with everyday life" (Pandey et al., 2025, p. 2). Alternatively, cost optimization methods attempt to reflect societal preferences in structural resilience decisions (Fischer et al., 2019, p. 150). Values from risk-informed design, the application of cost optimization in reliability-based design, should only be used when the resulting reliability index exceeds the minimum acceptable risk criterion (Pandey et al., 2025, p. 6). In plain language, risk-informed designs should result in lower probabilities of death than risks incurred in daily life.

These methods, however, only evaluate economic implications and require some conversion factor to account for any other considerations (Pandey et al., 2025, p. 5). Economists have produced an extensive body of work towards estimating societal risk preferences that dictate risk-informed decisions. For the purposes of this research, Marginal Life Saving Costs (MLSC), the Value of a Statistical Life (VSL), and societal willingness to pay are considered synonymous, idealized as dollar amounts that society is willing to pay in safety measures to save one statistical life, irrespective of race, gender, age, status, or any other identifiable differentiators. To provide estimates for these metrics, data was aggregated from market decisions that reflect how individual choices prioritize safety and financial incentives (Viscussi & Aldy, 2003).

In a meta-analysis by Viscusi and Aldy (2003), market data from employment, housing, and product selection was used to infer an implied value of a statistical life (pp. 7-26). From employment trends, implied VSL estimates assume that fair wage compensation is directly related to the associated risks of more dangerous jobs, as shown in Figure 2.

**Figure 2**

*VSL vs. Occupational Hazards*


*Note.* The graph was derived from general trends in market data between compensation and occupational mortality risk. Adapted from "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World," by W. K. Viscusi and J.E. Aldy, 2003, *Journal of Risk & Uncertainty*, *27*(1), p. 23.

Results varied significantly, from as low as $700,000 to as high as $69.4 million (Viscussi & Aldy, 2003, pp. 19-21, 27-28). Similarly, implied VSL estimates from other methods ranged from $770,000 to $9.9 million (Viscussi & Aldy, 2003, p. 25). For reference, the United States Department of Transportation used a VSL equal to $13.2 million in 2023 (USDOT, 2023). The inconsistencies of interpreting societal preferences, compounded with the subjectivity of the value selection in reliability-based design calibration, are cause for concern.

At least part of the reason for these variations is the way populations perceive risk. Principally, data from these VSL estimates are founded on misperceptions that assume individuals making these decisions are aware and consciously considering the risks (Gardoni &

Murphy, 2009, p. 32). Even if this were true, Clarke and Short (1993) describe an inherent "malleability of risk perception" (p. 5). Further, an example of the unreliability of risk perception exists in the bias toward the prioritization of "rare, catastrophic events" over frequent, less severe events (Gardoni & Murphy, 2009, p. 32; Pandey et al., 2025, p. 3). Likely due to the disproportionate exposure to media coverage of these events, people tend to believe that low-probability, high-consequence events should be prioritized, even if the prioritization of high-probability, low-consequence events would result in more lives saved.

These variations also extend across demographic factors such as age and socioeconomic status (Viscusi & Aldy, 2003, pp. 36-43, pp. 50-53). One flaw of these analyses is what Gardoni & Murphy (2009) describe as "adaptive preferences" (p. 32). Adaptive preferences provide context to many of the decisions that constitute implied VSL estimates and challenge the assumption that market decisions are chosen. For example, lower-income individuals may not be able to afford safer options and have little choice in the matter. This is confirmed by consistently smaller VSLs in developing countries when compared to developed countries (Viscusi & Aldy, 2003, p. 63). On an interpersonal level, it is not unreasonable to suggest that these adaptive preferences similarly restrict estimates from reaching values that may be more contextually appropriate.

**Research Approach: Economic and Historical Context**

Despite these concerns, the practices previously discussed are quite common and appropriate based on the scale of data aggregation implemented. Understanding the theory and limitations behind these approaches to risk-informed design is important. However, it is imperative to ground them towards the ultimate goal of limiting public risk exposure, preventing catastrophe, and saving lives.

While often heartbreaking, past catastrophes provide an incredible opportunity to learn from their failures (Mann, 2023, p. 381). This research analyzes events, failure mechanisms, and the safety culture surrounding several relevant structural failures. While these case studies can be helpful and particularly revealing, they cannot be used as the sole justification for any useful conclusions. Key economic context for understanding the limitations of applying idealized design codes to the United States' expansive infrastructure networks supplements the limitations and biases of the limited scope of case study reviews. With an understanding of the specific problems associated with the selected case studies and the economics of operation and maintenance on a national scale, this research contemplates the applicability of existing reliability indices in an atmosphere where funding is variable and maintenance is reactive, rather than proactive.

**Results**

Assuming that estimates for VSL and reliability indices accurately predict societal preferences using the methodologies presented herein, a significant challenge remains. The values calculated during the calibration "do not consider human error" and do not reflect "actual failure probabilities" (Pandey et al., 2025, p. 6). Human error exists in many forms; the associations typically made include flaws during design and construction, but human error also extends to the policy decisions that provide the funding for life-cycle costs, including maintenance and replacement. Although life-cycle costs are often considered during risk-informed design and cost-benefit analyses, the societal benefits of structures artificially bolster economic development without receiving appropriate resource allocation for the necessary maintenance and replacement.

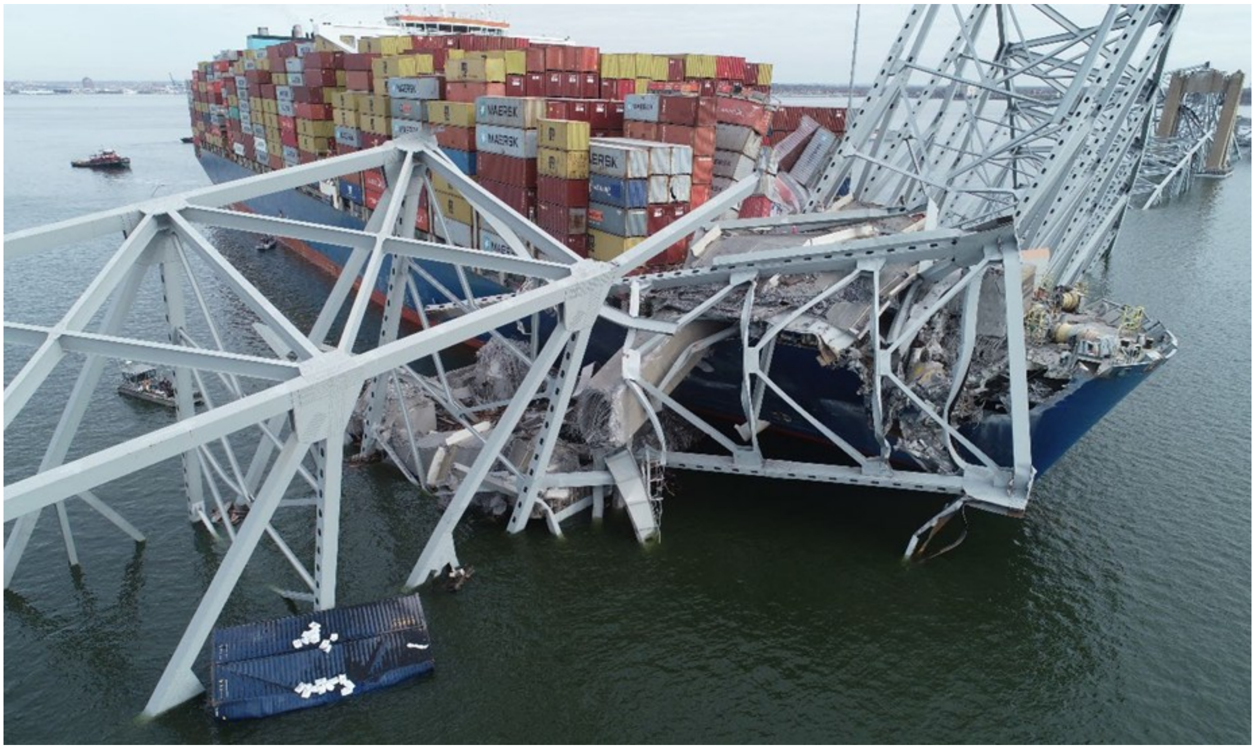
***Bridges***

The societal benefits of bridges cannot be overstated; they are the connective tissue of a vast transportation network that connects people, businesses, raw materials, and manufacturing. Despite their importance, “a third of the nation’s bridge inventory needs repair work or replacement,” and nearly “45% of bridges have exceeded their planned design lives” (ASCE, 2025, p. 28). While the age of a bridge may not necessarily indicate any structural deficiencies, reliance on earlier design standards could expose the public to more significant risks.

A recent and influential example of outdated standards in a structural failure occurred on March 26, 2024, when a container ship, the *Dali*, experienced repeated electrical failures leading to the loss of all propulsion and temporary loss of rudder controls, resulting in a collision with one of the Francis Scott Key Bridge’s piers (NTSB, 2024). The subsequent progressive collapse of the bridge’s 3 spans, shown in Figure 3, resulted in 1 injury to a *Dali* crew member, along with 1 injury and 6 deaths of a crew performing road maintenance.

**Figure 3**

*Francis Scott Key Bridge and the* Dali



*Note.* The image shows the collapsed Francis Scott Key Bridge on the *Dali*'s deck. From "Contact of Containership *Dali* with the Francis Scott Key Bridge and Subsequent Bridge Collapse," by the National Transportation Safety Board, 2024, p. 2.

Fortunately, officers performing traffic control duties for the maintenance crew were able to coordinate the bridge's closure to the public before impact. Although the bridge, constructed in 1977, was rated as satisfactory in recent inspections and had some preventative measures for vessel collision prevention, the National Transportation Safety Board's (NTSB, 2025) vulnerability assessment, according to the American Association of State Highway and Transportation Officials' (AASHTO) guidelines, demonstrated that the annual frequency of collapse from vessel collisions for the Francis Scott Key Bridge (about 3 in 1000) exceeded the threshold (1 in 10,000) around 30 times over. Since the bridge was constructed before these guidelines, MDTA was not required to perform this assessment, but unknowingly exposed the public to risk exceeding the threshold delineating the intolerable risk region.

Vessel collision, however, is only one of many factors that must be considered to minimize the risks incurred by the public. The NTSB's (1988) report following the collapse of New York's I-90 bridge over the Schoharie Creek that killed 10 on April 5, 1987, indicated that one of the pier foundations was undermined by turbulent hydrology and poor maintenance of riprap (pp. 99-101). The peak flow rates recorded at a nearby gaging station could be expected once every 70 years, otherwise known as a 70-year storm (p. 7). Despite the many revisions to inspection and design practices, around 22,420 bridges, many of which are relatively old, are still "susceptible to overtopping or having their foundations undermined during extreme storm events" (ASCE, 2025, p. 30).

While the risks posed in this section certainly are not all-encompassing, it should be clear that the ever-increasing age of bridges poses a serious problem in achieving an appropriate, uniform structural reliability. This is compounded further by their status: only "44.1% are in good condition" (ASCE, 2025, p. 27). Although funding through the Infrastructure Investment and Jobs Act has helped improve these conditions, ASCE estimates that it would take an additional investment of $373 billion over the next 10 years to recover from the funding deficit; that number will only increase if bridges are allowed to continue to deteriorate (p. 29).

***Dams***

Dams are critical for "flood control, irrigation, water supply and conservation, river navigation, [and] hydropower generation" (ASCE, 2025, p. 48). Around 70% of the nation's dams are over 50 years old and are tasked with managing flows from "increasingly severe" storm events (p. 50). There are 16,800 high-hazard dams in the United States, of which 2,500 are in “poor or unsatisfactory condition” (p. 49). High-hazard classifications are reserved for dams that would likely lead to “significant property destruction” and/or “loss of life” if they were to fail (p. 48). Furthermore, as development continues downstream, many dam hazard classifications are increasing. As a result, many of the dams with upgraded hazard classifications require expensive rehabilitation projects. Estimates for funding the rehabilitation of “non-federal dams is $165.2 billion” (p. 51).

One of the most influential dam safety incidents was the failure of the Oroville Dam spillways (IFTR, 2018). On February 7, 2017, the service spillway chute experienced severe erosion below the slab at only about 10% of its intended design flow, as shown in Figure 4. The California Department of Water Resources attempted to prevent further erosion by managing flows through the principal spillway, but eventually, the unproven emergency spillway was activated. The emergency spillway quickly began to erode and initiated a 188,000-person evacuation order. The Independent Forensics Team found that the incident resulted from failures across multiple technical and human factors. The primary technical factor was geologic mischaracterization at both the principal and emergency spillways, which led an inexperienced designer, whose work was not meaningfully verified, to a foundation design that assumed subgrades of moderately weathered rock. These issues, exacerbated by failures during construction, inspections, potential failure mode analyses, and the general overconfidence surrounding the California Department of Water Resources’ dam safety culture, highlight key assumptions in assuming competency across engineering design. Importantly, calibrated risk mitigation metrics assume an adequate and appropriate understanding of the engineering limit states, particularly in geotechnical and geologic applications, where anticipated behavior can vary and appropriate design can be, at times, open to some interpretation.

**Figure 4**

*Oroville Dam Spillway*

*Note*. The image shows the erosion at the Oroville Dam's principal spillway. From "Oroville Dam Spillway Incident," by an Independent Forensic Team, 2018, p. 27.

While widely known, the Oroville Dam spillway incident is far from the only dam safety incident in recent years. The Association of Dam Safety Officials' (ASDSO) dam incident database includes 48 high-hazard potential dam failures over the last 25 years (ASDSO, n.d.). Each of these failures had profound effects on the affected communities, incurring considerable societal costs. Another prolific example occurred on May 19, 2020, when the Edenville and Sanford dams failed after a historic yet foreseeable flooding event (IFTR, 2022). The Edenville Dam was constructed in the 1920s and did not meet the modern regulatory requirements for extreme storm events. Had sufficient funds been available to upgrade spillway capacity, the

Independent Forensics Team stated, “failure would almost certainly have been prevented” (p. S-1). Although equitable funding appropriation is complicated by the high proportion of privately owned structures, many of these issues have been inherited from older practices, considering less downstream development and less severe storm events.

Following these events, there have been some encouraging developments. Engineers have recognized the need for and begun the development of risk-informed decision-making in dam safety (ASCE, 2025, pp. 48-56). Like most infrastructure sectors, the Infrastructure Investment and Jobs Act has provided a much-needed influx of funding for dam safety programs across the nation (pp. 48-56). These investments across a wide array of infrastructure networks have provided meaningful improvements that are actively working toward reducing risks to public safety (pp. 3-4).

***Opportunities for Improvement***

There are some actionable steps the industry and policymakers can take to continue improvements towards reducing public risk exposure from structural engineering decision-making. To continue the recent momentum, practitioners can continue the development of risk-informed decision-making practices, considering realistic inspection, maintenance, and rehabilitation schedules, improve guidance for adapting risk-informed design methodologies across various market sectors, and emphasize the implementation of a comprehensive risk-informed asset management program, including funding appropriations for all lifecycle costs with escalation costs.

Finally, the nation’s neglected and aging infrastructure, which inordinately exposes the public to excessive risks, must be addressed. Despite the best efforts from engineers, it is impossible to design for the strain of chronic underfunding. The Infrastructure Investment and

Jobs Act, set to expire in 2026, has provided opportunities for significant advancement; however, an investment of about $3.7 trillion over the next 10 years is needed (ASCE, 2025, p. 10). To mitigate further deterioration and deficiencies, it is imperative to address these issues both now and in the future. According to ASCE (2025), “Every dollar spent on resilience and preparedness saves communities $13 in post-disaster costs” (p. 11). Immediate and sustained funding is critical for ensuring infrastructure resilience and public safety.

**Conclusion**

The application of risk-informed design makes critical assumptions that we have a perfect understanding of all mechanics, all future loading conditions, every material property, and most controversially, the intrinsic value of human lives. With the multidisciplinary collaboration of economists, engineers, and policymakers, newer methodologies have been calibrated and optimized to save lives while remaining good stewards of societal resources. Modern methods for modeling structural mechanics and risk-informed design techniques provide engineers with the tools to make fiscally responsible and equitable decisions that effectively minimize risks toward acceptable societal preferences; however, funding for these projects has been historically unreliable. As a result, much of our aging infrastructure has deteriorated and is not being updated or replaced to incorporate these concepts. To promote continued economic growth, increase quality of life, and ensure public safety, a concerted effort must be made toward sustained investment in infrastructure throughout its entire lifecycle.

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