ДГКС ASES | U-5
Kongres 2026
Congress 2026

doi: 10.67563/ASESCONF2026113C

Gian Paolo Cimellaro[1], Francesco Trovatelli[1]

FROM CATASTROPHE TO RESILIENCE: FORENSIC INSIGHTS AND PREDICTIVE STRATEGIES FOR SUSTAINABLE INFRASTRUCTURE MAINTENANCE

Summary: Major infrastructure failures rarely originate from a single defect, but emerge when deterioration, unfavorable load paths, limited redundancy, increasing operational demand, and incomplete knowledge interact. This paper synthesizes forensic and life-cycle evidence from two collapses: the 2018 Polcevera Viaduct in Genoa and the 2021 Champlain Towers South in Surfside, Florida. High-fidelity simulations reproduced the transition from local damage to large-displacement collapse. For Viaduct, progressive degradation analyses identified the prestressed-concrete stay system as the failure-critical subsystem. For Champlain Towers South, scenario analyses showed that localized deterioration and pool-deck system failure could overload perimeter columns, initiating progressive collapse. The paper proposes a predictive maintenance framework combining forensic digital twins, probabilistic deterioration models, structural-health information, Bayesian network risk updating, and resilience-based intervention optimization. Ultimately, collapse prevention requires explicit modeling of how local damage changes load paths and redundancy. Sustainable maintenance should prioritize interventions based on time-dependent failure probability, propagation potential, recovery consequences.

Keywords: progressive collapse, Applied Element Method, structural robustness, corrosion-fatigue, digital twin, predictive maintenance, resilience, life-cycle assessment

OD KATASTROFE DO OPORAVKA: FORENZIČKI UVIDI I PREDIKTIVNE STRATEGIJE ZA ODRŽIVO UPRAVLJANJE INFRASTRUKTUROM

Rezime: Kolaps infrastrukture retko nastaje usled samo jednog nedostatka, već preplitanjem deterioracije, nepouzdanog toka sila, ograničenih rezervi nosivosti, rastućih eksploatacionih zahteva i nedovoljnog znanja. Ovaj rad objedinjuje forenzičke dokaze i podatke o životnom ciklusu dva slučaja kolapsa: vijadukta Polcevera u Đenovi (2018) i zgrade Champlain Towers South na Floridi (2021). Simulacije visoke vernosti reprodukovale su prelazak sa lokalnog oštećenja na kolaps usled velikih pomeranja. U slučaju vijadukta, analize progresivne degradacije identifikovale su sistem kosih zatega od prednapregnutog betona čiji je otkaz bio presudan za kolaps. Analiza zgrade Champlain Towers South pokazala je da bi lokalna deterioracija i otkaz platoa bazena mogli preopteretiti obodne stubove i izazvati progresivni kolaps. Rad predlaže okvir za prediktivno održavanje koji kombinuje forenzičke digitalne blizance, probabilističke modele deterioracije, podatke o stanju konstrukcije, ažuriranje rizika pomoću Bajesovih mreža i optimizaciju intervencija zasnovanu na oporavku sistema. Naposletku, sprečavanje kolapsa zahteva modeliranje načina na koji lokalno oštećenje menja tok sila i rezervnu nosivost, te bi održavanje trebalo da daje prioritet intervencijama na osnovu verovatnoće otkaza, mogućnosti širenja oštećenja i posledica po oporavak.

Ključne reči: progresivni kolaps, metoda primenjenih elemenata, robusnost konstrukcije, zamor korozija, digitalni blizanac, prediktivno održavanje, oporavak, procena životnog ciklusa

[1] Politecnico di Torino, Turin, Italy, gianpaolo.cimellaro@polito.it

1. INTRODUCTION

Catastrophic collapse is the terminal state of a long, partially observable process. A structure may satisfy its original design assumptions and remain operational for decades while its actual safety margin is progressively reduced by corrosion, fatigue, construction imperfections, changes in use, accumulated repairs, environmental exposure, and growth in traffic or gravity demand [1,2]. The final trigger may be modest. What makes the event catastrophic is the inability of the remaining system to redistribute load and confine damage [3,4].

This distinction between trigger and cause is fundamental. The trigger is the immediate local event that initiates instability. The deeper cause is the evolving system condition that allows a local event to propagate disproportionately [5-7]. Forensic engineering must identify both. Predictive asset management must then convert that understanding into measurable decision variables before failure occurs.

The Polcevera Viaduct (Genoa, Italy) and Champlain Towers South (Surfside, USA) are particularly instructive because they represent different structural typologies, exposure conditions, and propagation mechanisms [8-11]. Yet both reveal the same governing pattern: a vulnerable interface or subsystem became a conduit through which local degradation was transformed into global collapse. In Genoa, the critical path passed through a nonredundant prestressed-concrete stay. In Surfside, the investigated mechanism passed from the deteriorated pool-deck system to perimeter columns through deep beams and then into a torsionally vulnerable building wing.

The objectives of this paper are to: (1) synthesize the mechanics revealed by high-fidelity collapse simulations; (2) connect the Morandi forensic model with a time-dependent capacity-demand model capable of estimating end of life without continuous monitoring data; (3) extract transferable design and maintenance principles; and (4) formulate an anticipatory framework in which digital twins, probabilistic models, AI-assisted inference, and resilience metrics support sustainable intervention planning based on life-cycle carbon reduction.

2. FROM LOCAL DAMAGE TO SYSTEM COLLAPSE

2.1. A SYSTEM INTERPRETATION OF COLLAPSE

A useful conceptual representation is to define a time-dependent safety margin, $M(t)$, as the difference between structural capacity $C(t)$ and demand $D(t)$:

$$M(t) = C(t) - D(t) \tag{1}$$

Collapse risk increases not only as $M(t)$ approaches zero at a component level, but also as redundancy and alternative load paths deteriorate. Consequently, a component with a moderate probability of failure may govern system risk when its loss produces a large propagation multiplier. This is why conventional condition ratings can be insufficient when they are not connected to structural topology and consequence.

Figure 1 summarizes the local-to-global pathway through which deterioration can evolve into disproportionate structural failure. Component condition represents only the first layer of the problem. The associated risk depends also on the evolution of operational and environmental demand, the availability of redundant load paths, and the dynamic response that follows local loss of stiffness or capacity. Structural topology therefore acts as a critical transition between component-level damage and system-level behavior: when alternative load paths are limited, a local failure may trigger torsion, impact, catenary action, element separation, or other nonlinear mechanisms that amplify damage propagation. The final assessment must consequently extend beyond conventional condition metrics to include the societal consequences of failure, such as casualties, downtime, network disruption, displacement, and recovery time.

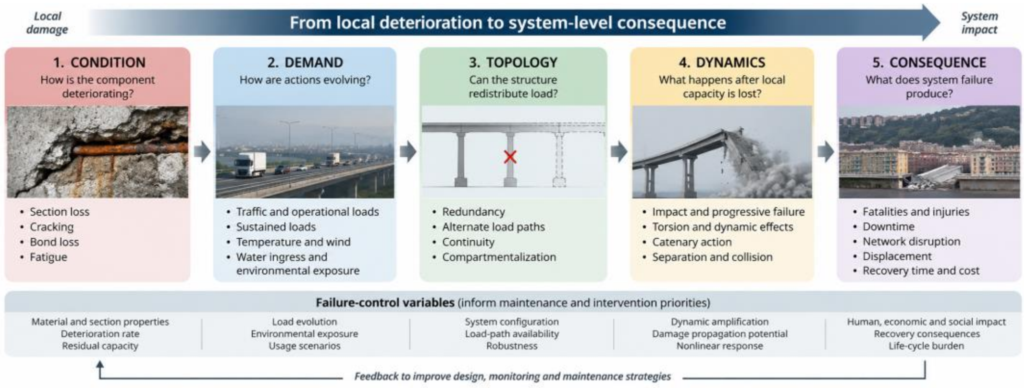

Figure 1: System variables that connect deterioration to collapse consequence

2.2. APPLIED ELEMENT METHOD FOR COLLAPSE SIMULATION

The Applied Element Method (AEM) represents a structure as an assembly of rigid elements connected by distributed normal and shear springs [12]. The springs reproduce the constitutive response of concrete and reinforcement [13,14]. As demand increases, the formulation can trace cracking, reinforcement yielding, loss of contact, element separation, rigid-body motion, impact, and debris formation. This continuity-to-discontinuity capability is essential for forensic problems in which the analyst must reproduce not simply a peak response, but the sequence by which the structure loses its original load paths [12,15].

For both case studies, the primary value of AEM was hypothesis discrimination. Multiple potential initiation scenarios were imposed, degradation was increased systematically, and the resulting collapse sequences were compared with observable evidence such as timing, global kinematics, torsional response, cracking patterns, and debris distribution. Agreement does not by itself prove a unique cause. It does, however, test whether a proposed mechanism is mechanically admissible and consistent with the available evidence.

3. POLCEVERA VIADUCT: FRACTURE CRITICALITY AND END-OF-LIFE PREDICITON

3.1. STRUCTURAL SYSTEM AND DETERIORATION CONTEXT

The Polcevera Viaduct was completed in 1967 and partially collapsed on 14 August 2018 after approximately 51 years of service. The failed balanced system at Pier 9 comprised an A-shaped tower, a prestressed box-girder deck, a reinforced-concrete trestle, Gerber connections, and a small number of prestressed-concrete stays. Unlike contemporary multi-stay cable-stayed bridges, each balanced system relied on very few large stays. Their steel tendons were encased in prestressed concrete and passed over the tower saddle, making internal deterioration difficult to observe and rendering the system highly sensitive to loss of one stay [16,17].

The exposure environment combined marine aerosol, industrial emissions, incomplete grout injection in portions of tendon ducts, and steadily increasing traffic. Archival data used in the life-cycle study indicated that heavy-vehicle average daily traffic increased from approximately 3,885 vehicles in 1968 to 24,640 in 2018. Post-collapse evidence reported severe pitting corrosion and an estimated 20% tendon mass loss in 2018. These factors created a coupled problem in which capacity declined while stress cycles and operational demand increased.

3.2. AEM FORENSIC RECONSTRUCTION

A detailed model of the Pier 9 balanced system was developed from original drawings. Prestressing tendons, reinforcement, the cellular deck, tower, trestle, stays, and Gerber girders were represented explicitly at a resolution sufficient to capture component degradation and large-displacement collapse. The model contained approximately 150,000 applied elements, each with six degrees of freedom, used five springs per face, and employed a time step of 0.001 s for dynamic collapse analysis.

The forensic strategy progressively reduced the effective section of candidate structural components. The principal result was a clear hierarchy of vulnerability. The deck, trestle, and tower exhibited appreciable redistribution capacity and developed very large, visible deformations before global collapse. In contrast, loss of a single stay caused sudden system collapse. Degradation applied along the stay identified the region near the connection with the tower saddle as especially critical (Figure 2).

The progressive degradation study showed that vulnerability was governed less by the absolute extent of local damage than by the system consequence of losing the affected component. Deck, trestle, and tower exhibited substantial residual robustness: even severe localized degradation could be accommodated through load redistribution, although at the cost of large deformations that would likely have provided visible warning. The stays represented the critical exception. Loss of a single stay immediately removed a primary support path and initiated rapid global instability, demonstrating that the balanced system possessed markedly different levels of redundancy across its subsystems. The forensic implication is therefore clear: the collapse susceptibility of Pier 9 was controlled not by the most extensively deteriorated component, but by the deterioration of the component with the highest propagation potential, the prestressed-concrete stay, particularly in the vicinity of the tower saddle.

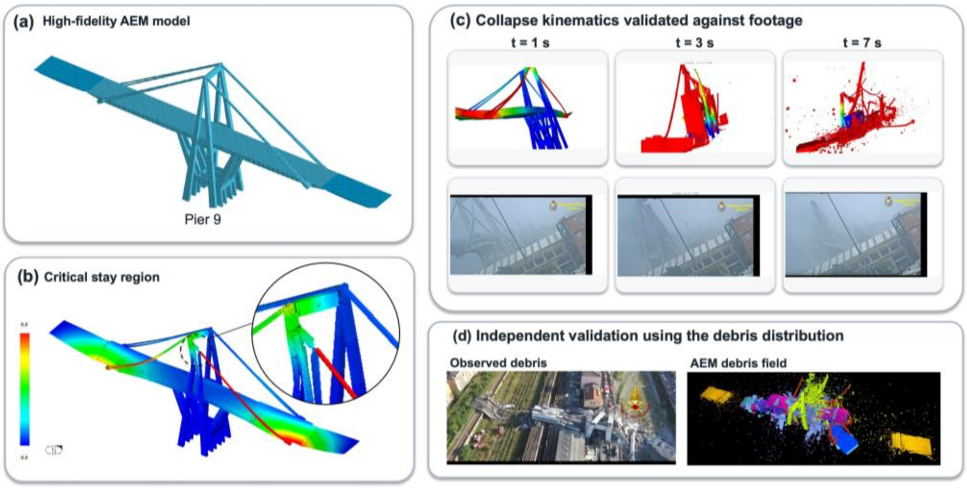

Figure 2: AEM forensic reconstruction of the Pier 9 collapse

When failure of the southeast stay was introduced, the simulated sequence reproduced the main observed features: loss of deck support, longitudinal-axis torsion due to the temporarily surviving opposite-side restraint, breakup of the deck into a V-shaped configuration, failure near the tower saddle, and a debris field broadly consistent with photographs, video frames, satellite-derived point clouds, and disposal-site observations. The analysis therefore identified stay failure as the most mechanically plausible trigger among the studied scenarios.

3.3. CAPACITY-DEMAND EVOLUTION AND REMAINING LIFE

The complementary life-cycle analysis asked a different question: could the end of structural service life have been estimated before collapse even without continuous sensor data? A three-dimensional finite-element model and classical influence lines were used to calculate the effect of representative truck axles on stay forces and other critical sections. Year-by-year demand was reconstructed from archival traffic counts and historical changes in truck configurations and axle weights.

On the capacity side, corrosion-induced mass loss reduced tendon yield and ultimate strength and increased local stress concentration. Corrosion also shifted the *S-N* relationship, decreasing fatigue life for a given stress range. Variable-amplitude damage was accumulated using the Palmgren-Miner rule:

$$D(t) = \Sigma\, n_i(t) \,/\, N_i[S_i(t), \eta(t)] \qquad (2)$$

where n_i is the applied number of cycles, N_i is the corrosion-dependent fatigue life at stress range S_i, and η is corrosion-induced mass loss. Mean-stress effects were evaluated using Goodman, Gerber, and Soderberg relationships. Although the available deterioration data required simplifying assumptions, including linearized corrosion growth and traffic evolution, the calculation produced a strikingly narrow warning window [18,19].

Figure 3: End-of-life estimates obtained from the Morandi corrosion-fatigue assessment

The significance of this result is that conventional engineering data, interpreted through a transparent time-dependent model, placed the structure inside an actionable end-of-life interval several years before failure. A monitoring system would have improved the estimate, but the absence of sensors did not preclude rational intervention.

4. CHAMPLAIN TOWERS SOUTH: PROPAGATION THROUGH STRUCTURAL INTERFACES

4.1. STRUCTURE AND MODELING STRATEGY

Champlain Towers South was a twelve-story reinforced-concrete residential building completed in 1982. The structural system consisted primarily of flat slabs supported by reinforced-concrete columns, with a basement and pool-deck structure extending beyond the tower footprint. The high-fidelity AEM model was developed from structural drawings and included slabs, columns, shear walls, transfer girders, pool-deck features, punching-shear reinforcement, and reinforcement layouts. The final model contained approximately 7.5 million concrete-interface springs, 0.85 million reinforcement springs, and more than 900,000 degrees of freedom.

Because the definitive cause was not established within the source study, the analyses were framed as scenario testing rather than a declaration of causation. Candidate scenarios included progressive column removal, intended to represent possible support loss or foundation-related effects, and localized reinforcement degradation in the pool-deck region. Loading sensitivity was addressed by varying superimposed gravity demand, while degradation was represented through progressive reduction of reinforcing-steel area.

4.2. SENSITIVITY TO PERIMETER-COLUMN LOSS AND POOL-DECK DEGRADATION

The structure was significantly more vulnerable to removal of perimeter columns than to removal of interior columns. Under the adopted assumptions and undegraded material properties, removal of as many as three interior columns did not produce progressive collapse because surrounding elements redistributed the load. Removal of two adjacent perimeter columns was sufficient to initiate collapse. This asymmetry is a crucial forensic observation because it focuses attention on mechanisms that can deliver concentrated moment and axial demand to the building perimeter.

Static analyses showed that the pool-deck area was intrinsically more flexible and more highly stressed than the tower footprint. Larger spans, limited reinforcement, and localized superimposed loads increased deflections and stresses in the punching-shear reinforcement. The pool deck was also connected to the main building at selected locations by deep beams associated with changes in slab elevation. These members created a stiff mechanical link between a one-story exterior deck exposed to water-related deterioration and the perimeter columns of a twelve-story building.

As reinforcement degradation increased, the pool-deck slab deflected and its reinforcement yielded. Numerical simulations suggest that failure of the slab and deep beam-column region imposed a concentrated bending action on perimeter columns. After local concrete crushing and loss of column capacity, the surrounding framing mobilized arch action and subsequently catenary action. The available reinforcement could not sustain the developing tensile forces, and damage propagated through the central portion of the building. The remaining eastern wing then exhibited a torsional collapse mechanism associated with the directional configuration of its core walls.

Frame-by-frame comparison showed reasonable agreement between the simulated sequence and available collapse footage in the initial failure of the central portion and subsequent torsional motion of the eastern wing. Differences in the final deformation of part of the eastern core emphasize the epistemic uncertainty associated with unknown material degradation, construction deviations, actual loads, and damage states. Such differences should be reported explicitly rather than concealed through over-calibration.

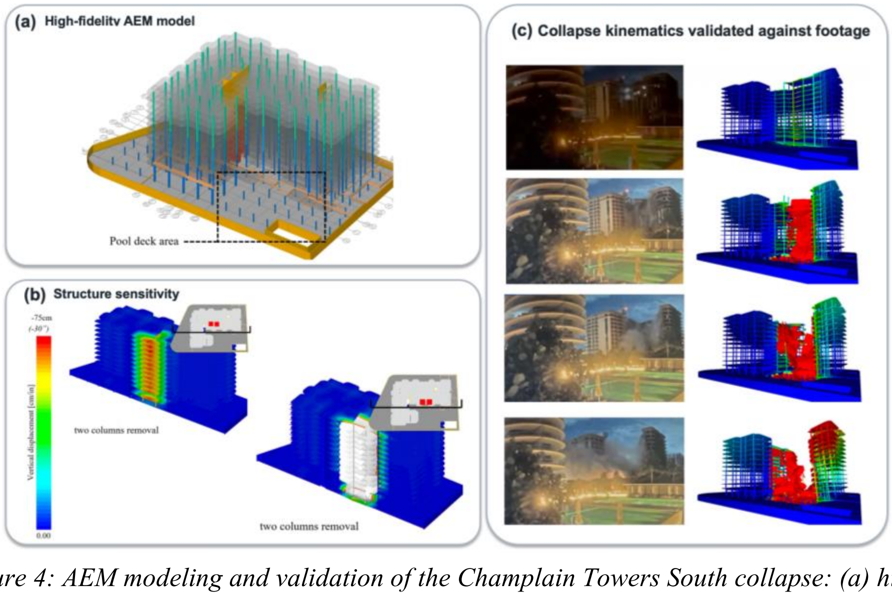

Figure 4: AEM modeling and validation of the Champlain Towers South collapse: (a) high-fidelity structural model; (b) sensitivity to adjacent perimeter-column removal; and (c) comparison of simulated collapse kinematics with available footage

4.3. COUNTERFACTUAL ROBUSTNESS MEASURES

Two alternative configurations transformed the forensic model into a design-learning instrument. First, the deep pool-deck beams were disconnected from the perimeter columns while retaining the surrounding slab concept. Under the investigated degradation scenario, the pool deck failed locally by punching and separation, but did not impose the same damaging moment on perimeter columns. Second, two additional shear walls were introduced in the east-west direction to increase torsional stiffness and strength of the eastern core. This modification prevented collapse of the eastern wing under the assumed initiation scenario.

5. CROSS-CASE FORENSIC LESSONS

Despite major differences in scale and typology, the two collapses support a common set of principles.

- Hidden deterioration is most dangerous when it affects elements with high system consequence and low inspectability.
- Redundancy must be evaluated after realistic deterioration, not only for the intact as-designed structure.
- Structural interfaces can act as propagation amplifiers. The stay-to-saddle region in the viaduct and the pool-deck-beam-to-column region in the building concentrated vulnerability.
- Visible condition and structural consequence are not equivalent. A severe defect in a redundant component may produce limited system risk, while a less extensive defect in a failure-critical component may govern collapse.
- Collapse simulations are most credible when they are tested against independent evidence, including sequence timing, deformation mode, debris distribution, and known damage observations.
- Counterfactual analysis is a central forensic tool because it converts a reconstructed failure mechanism into actionable design and retrofit principles.

In the Polcevera Viaduct, the prestressed-concrete stay in the vicinity of the tower saddle represented the fracture-critical subsystem. Loss of this support path produced a strongly asymmetric redistribution of forces, inducing deck torsion, fragmentation, and ultimately global collapse. The principal robustness implication is that components with high propagation potential must be identified explicitly and subjected to enhanced inspection, protection, and, where feasible, redundancy or independent load-path provisions.

For Champlain Towers South, the investigated failure mechanism was instead governed by the structural interface connecting the pool deck, deep beams, and perimeter columns. Local deterioration or failure within the pool-deck system could be transmitted to the primary gravity-resisting structure through concentrated moment demand, leading to perimeter-column failure, a subsequent transition from arching to catenary action, and torsional propagation within the remaining building wing. This mechanism highlights the vulnerability of strongly coupled structural subsystems with markedly different exposure conditions and consequence levels. From a resilience perspective, the analysis indicates that vulnerable secondary structures should, where practicable, be mechanically decoupled from primary load-resisting systems, while adequate and balanced torsional resistance should be ensured to limit the propagation of localized damage.

6. RESILIENCE-BASED MAINTENANCE FRAMEWORK

6.1. FORENSIC DIGITAL TWIN

The proposed framework converts forensic knowledge into an anticipatory decision process. Its purpose is not to predict a single failure date, but to maintain an updated probabilistic representation of the asset, project that state forward under evolving deterioration and demand, and select interventions before reliability or functionality thresholds are exceeded.

A predictive digital twin should not be understood as a visually appealing three-dimensional model. It is a continuously updated decision model that links four layers: asset geometry and construction history; deterioration state; structural mechanics and failure propagation; and operational consequence. The digital twin should preserve uncertainty explicitly and be able to answer both condition questions and counterfactual questions such as: Which local deterioration states can initiate disproportionate failure? Which observation would most reduce uncertainty? Which intervention most efficiently changes the system load path? Figure 5 summarizes the framework.

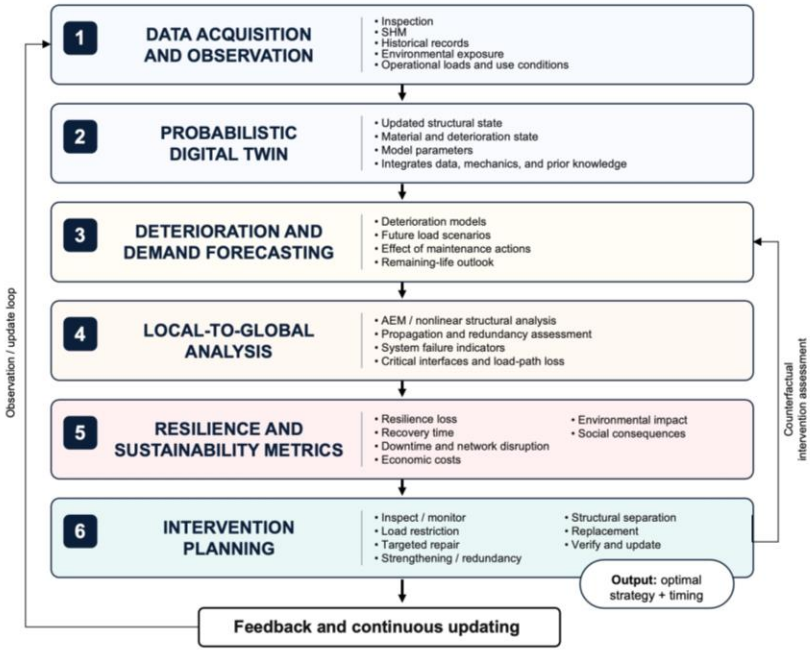

Figure 5: Framework for resilience- and sustainability-informed intervention planning through probabilistic digital twins, AI-assisted inference, uncertainty quantification, and adaptive decision updating

Let X(t) denote the uncertain state vector containing section loss, crack geometry, prestress, stiffness, load intensity, and environmental exposure. Inspection, monitoring, and testing produce observations Y(t). The digital twin updates the distribution p[X(t)|Y(0:t)] and propagates uncertainty through a structural model to estimate limit-state probability. This is more defensible than assigning a single deterministic degradation percentage because it separates variability, measurement error, model-form uncertainty, and incomplete knowledge.

6.2. FORECASTING DETERIORATION AND LOCAL-TO-GLOBAL RISK

From the posterior state, asset-specific transition models forecast corrosion, fatigue, prestress loss, cracking, stiffness degradation, and future load scenarios. Forecasts should be distributions rather than point estimates and should be updated whenever new evidence becomes available. The relevant horizon is the interval over which the probability of losing a critical load path or exceeding an operational threshold becomes actionable.

For high-consequence assets, the relevant output is not only the probability that an element reaches a conventional limit state. It is the joint probability that local failure occurs and propagates:

$$P(global\ failure, t) = \Sigma\, P(global \mid local\ state\ j) \cdot P(local\ state\ j, t) \quad (3)$$

This decomposition separates the probability of local damage from its propagation consequence. The conditional term is obtained from nonlinear local-to-global simulations, fragility surfaces, or reduced-order and surrogate models calibrated against selected AEM analyses. Screening should therefore prioritize components and interfaces with high propagation potential rather than defect severity alone. Practical outputs are remaining-life distributions, critical load-path maps, propagation fragilities, and warning indicators that can be compared with predefined action thresholds.

6.3. RESILIENCE AND SUSTAINAILITY OBJECTIVE

Maintenance optimization should minimize a life-cycle objective that includes direct cost, expected failure loss, service disruption, environmental burden, and recovery performance. A generic decision functional can be written as:

$$J(a) = C_{\mathrm{m}}(a) + E[L\_failure(a)] + C\_down(a) + \lambda_{\mathrm{e}} E\_env(a) + \lambda_{\mathrm{r}} T\_rec(a) \quad (4)$$

where a is an intervention strategy, C_m is maintenance cost, *L_failure* is consequence-weighted failure loss, C_down is disruption cost, E_env is embodied and operational environmental impact, T_rec is recovery time, and λ_e and λ_r are weighting coefficients reflecting decision-maker preferences. The decision should be constrained by acceptable reliability and robustness thresholds. In practice, this formulation favors targeted strengthening or separation of propagation-critical interfaces when such measures produce a greater risk reduction per unit of material and downtime than broad, nonselective rehabilitation.

6.4. OPERATIONAL IMPLEMENTATION, GOVERNANCE, AND LIMITATIONS

In practice, the framework can be implemented as a seven-stage closed loop: inventory the asset and its history; screen components by condition, inspectability, criticality, and consequence; diagnose critical interfaces using targeted NDT or SHM; simulate local-to-global failure scenarios; forecast deterioration and demand; optimize intervention type and timing; and verify the post-intervention response. The corresponding outputs are a traceable asset model, a priority list, an updated deterioration-state distribution, propagation and fragility surfaces, remaining-life and warning indicators, an intervention plan, and evidence that the intended load-path change was achieved.

Artificial intelligence is most valuable when it accelerates inference without replacing mechanics. Appropriate applications include anomaly detection in heterogeneous inspection records, computer-vision screening of cracks and corrosion, extraction of defects from historical reports, emulation of computationally expensive collapse simulations, and optimization of inspection or maintenance schedules. Physics-informed constraints should prevent predictions that violate equilibrium, monotonic deterioration trends, or known failure envelopes. Human review remains essential for model validation, treatment of out-of-distribution conditions, and decisions involving closure or major intervention.

Implementation can be tiered to asset criticality and data availability. Existing assets without continuous sensing can begin with drawings, inspection records, traffic and environmental histories, and targeted opening-up, as demonstrated by the Polcevera life-cycle analysis. Critical assets can add focused SHM at propagation-sensitive interfaces and periodic Bayesian updating. High-consequence assets may justify near-real-time updating and validated surrogate models for rapid scenario screening. Continuous sensing is therefore beneficial but not a prerequisite for anticipatory decision making.

Governance must connect model outputs to predefined actions. Reliability, propagation, or remaining-life thresholds should trigger specific measures, additional inspection, load restriction, shoring, repair, evacuation, or replacement, and protocols should identify model ownership, independent review, acceptable uncertainty, and authority to change operations. This prevents probabilistic forecasts from remaining advisory quantities without operational consequence.

Several limitations remain case specific. For Polcevera bridge, reconstructed traffic histories, corrosion-fatigue relationships, and simplified deterioration trends imply an end-of-life interval rather than a deterministic date; the AEM reconstruction established mechanical consistency of stay failure but not the chemical and physical history of capacity loss. For Champlain Towers South, the modeled initiation and degradation scenarios do not establish a definitive investigative cause, and the counterfactual retrofit results require project-specific verification.

More generally, Bayesian updating reduces but does not eliminate model bias or uniqueness; high-fidelity agreement cannot prove a unique hidden damage state; physics-informed surrogates may fail outside their training domain; and resilience, recovery, cost, and environmental metrics depend on boundary assumptions. The framework should therefore be used as an auditable decision architecture whose predictions are updated against new evidence.

Prospective validation should compare predicted state distributions, warning thresholds, and intervention outcomes with subsequent inspections and post-intervention response over repeated cycles. Until such evidence accumulates, forecasts should be reported as probability distributions and decision regions rather than deterministic predictions.

7. CONCLUSIONS

- The decisive variable in catastrophic collapse is often not the magnitude of local deterioration but the structural consequence of losing the affected subsystem.
- For the Polcevera Viaduct, high-fidelity AEM analyses identified stay failure as the most plausible trigger among the studied components and reproduced key features of the observed collapse and debris distribution.
- A separate corrosion-fatigue capacity-demand model placed exhaustion of stay life between 2014 and 2016, demonstrating that useful end-of-life estimates can be developed even when continuous sensor data are unavailable.
- For Champlain Towers South, the investigated pool-deck mechanism showed how deep beams could transfer local deck failure into perimeter-column overload and subsequent progressive collapse.
- Structural separation of the pool deck and increased torsional capacity of the eastern core arrested propagation in the modeled alternatives, illustrating the value of counterfactual forensic simulation.
- Predictive maintenance should integrate probabilistic deterioration, local-to-global collapse mechanics, digital-twin updating, AI-assisted inference, resilience consequences, and environmental burden.
- The transition from reactive repair to anticipatory resilience occurs when inspection data are converted into explicit forecasts of load-path loss, propagation probability, and actionable intervention thresholds.

Catastrophes become engineering knowledge only when their mechanisms are translated into future decisions. The most sustainable infrastructure is not merely the structure requiring the least material or the fewest repairs. It is the structure whose deterioration is observable, whose local failures remain confined, whose critical functions recover rapidly, and whose maintenance decisions are made before the safety margin disappears.

ACKNOWLEDGEMENTS

The author acknowledges the co-authors and technical contributors to the underlying Polcevera Viaduct and Champlain Towers South studies, including the teams at Politecnico di Torino, University of Illinois Chicago, and Applied Science International. The Polcevera research received support from the European Research Council through the IDEAL RESCUE project, Grant Agreement No. 637842. The original studies also acknowledged the Italian authorities and the City of Surfside for access to relevant documentary material.

REFERENCES

[1] ASCE. (2005). Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-05. American Society of Civil Engineers.

[2] ASCE. (2021). Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-22. American Society of Civil Engineers.

[3] Kiakojouri, F., De Biagi, V., Chiaia, B., and Sheidaii, M. R. (2020). "Progressive collapse of framed building structures: Current knowledge and future prospects." Engineering Structures, 206, 110061.

[4] Vrouwenvelder, T. (2021). "The weakness of robustness." Journal of Structural Engineering, 147(11), 02021001.

[5] CEN. (2006). EN 1991-1-7 Eurocode 1: Actions on Structures, Part 1-7: General Actions, Accidental Actions. European Committee for Standardization.

[6] Praxedes, C., and Yuan, X.-X. (2021). "Robustness assessment of reinforced concrete frames under progressive collapse hazards: Novel risk-based framework." Journal of Structural Engineering, 147(8), 04021103.

[7] Sadek, F., Bao, Y., Main, J. A., and Lew, H. S. (2022). "Evaluation and enhancement of robustness for reinforced concrete buildings." Journal of Structural Engineering, 148(1), 04021233.

[8] Calvi, G. M., Moratti, M., O'Reilly, G. J., Scattarreggia, N., Monteiro, R., Malomo, D., Calvi, P. M., and Pinho, R. (2019). "Once upon a time in Italy: The tale of the Morandi Bridge." Structural Engineering International, 29(2), 198–217.

[9] Domaneschi, M., Pellecchia, C., De Iuliis, E., Cimellaro, G. P., Morgese, M., Khalil, A. A., and Ansari, F. (2020). "Collapse analysis of the Polcevera Viaduct by the Applied Element Method." Engineering Structures, 214, 110659.

[10] Lu, X., Guan, H., Sun, H., Li, Y., Zheng, Z., Fei, Y., Yang, Z., and Zuo, L. (2021). "A preliminary analysis and discussion of the condominium building collapse in Surfside, Florida." Frontiers of Structural and Civil Engineering, 15, 1097–1110.

[11] Pellecchia, C., Cardoni, A., Cimellaro, G. P., Domaneschi, M., Ansari, F., and Khalil, A. A. (2023). "Progressive Collapse Analysis of the Champlain Towers South in Miami, Florida." Journal of structural engineering, ASCE, 150(1), https://doi.org/10.1061/JSENDH.STENG-1248.

[12] Meguro, K., and Tagel-Din, H. (2000). "Applied element method for structural analysis: Theory and application for linear materials." Structural Engineering/Earthquake Engineering, JSCE, 17(2), 215s–224s.

[13] Maekawa, K., and Okamura, H. (1985). "The deformational behavior and constitutive equation of concrete using elasto-plastic and fracture model." Journal of the Faculty of Engineering, University of Tokyo, 37, 253–328.

[14] Menegotto, M., and Pinto, P. E. (1973). "Method of analysis for cyclically loaded reinforced-concrete plane frames." IABSE Symposium on Resistance and Ultimate Deformability of Structures Acted on by Well-Defined Repeated Loads, 15–22.

[15] Grunwald, C., Khalil, A. A., Schaufelberger, B., Ricciardi, E. M., Pellecchia, C., De Iuliis, E., and Riedel, W. (2018). "Reliability of collapse simulation: Comparing finite and applied element method at different levels." Engineering Structures, 176, 265–278.

[16] Morandi, R. (1967). "Il viadotto sul Polcevera per l'autostrada Genova–Savona." L'Industria Italiana del Cemento, 37, 849–872.

[17] Ministero delle Infrastrutture e dei Trasporti. (2018). Comune di Genova, Autostrada A10: Crollo del Viadotto Polcevera, Evento Accaduto il 14 Agosto 2018. Commissione Ispettiva Ministeriale, Rome.

[18] Jiang, C., Wu, C., and Jiang, X. (2018). "Experimental study on fatigue performance of corroded high-strength steel wires used in bridges." Construction and Building Materials, 187, 681–690.

[19] Xu, F., Chen, Y., Zheng, X., Ma, R., and Tian, H. (2019). "Experimental study on corrosion and mechanical behavior of main cable wires considering the effect of strain." Materials, 12, 753.