Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26223-cd

Dynamic time-dependent vulnerability of infrastructure: critical review and modelling framework proposal for NaTech risk assessment

Sylvain ARNAUD
Univ. Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, France
Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-Lab, France. E-mail: sylvain.arnaud@grenoble-inp.fr

Jean-Marc TACNET
Univ. Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, France. E-mail: jean-marc.tacnet@inrae.fr

Pierre GEHL
BRGM, France. E-mail: p.gehl@brgm.fr

Jérémy ROHMER
BRGM, France. E-mail: j.rohmer@brgm.fr

Christophe BERENGUER
Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-Lab, France.
E-mail: Christophe.berenguer@grenoble-inp.fr

Infrastructure vulnerability is crucial to predict the consequences after a NaTech event. This metric is subjected to temporal evolution due to numerous factors, e.g. multi-hazards, ageing, maintenance, fatigue. The consideration of these dynamic effects is often overlooked. The present paper proposes a concise literature review and a framework being able to include, account for time-dependent, parametrized vulnerability/fragility curves. Therefore, we show the importance of these dynamic effects across short- and long-term horizons and compare the risk assessment with a static case. Two simple examples are given and demonstrate significant differences. Precautions should be taken due to intrinsic uncertainties and necessary working assumptions.

Keywords: NaTech risks, civil engineering, damage potential, multi-hazard vulnerability, time-dependent modelling.

1. Context

The 2019 earthquake in France's Rhône Valley (Le Teil) has e.g. raised concerns due to the presence of critical infrastructure (nuclear power plants, road networks, railways...) and ageing, poorly maintained buildings in a region with high levels of urbanization. Despite relatively limited damages, this event serves as a reminder of how important it is to take into account the evolution of vulnerability into risk management.

That fact motivates the objective of this work : propose a framework for integrating dynamics in the NaTech risk assessment.

The consideration of dynamic effects in risk assessment is a topic that is already well established in the literature (e.g. Frangopol and Akiyama (2024),Argyroudis et al. (2020), Borre et al. (2025)).

Risk is classically defined as the combination of the probability of occurrence of a hazard and the severity of its consequences for human, environmental, or material assets. It therefore results from the interaction among three fundamental components: the hazard, the exposure, and the vulnerability of the affected elements. This perspective is consistent with UNDRR [a] formulation of risk, expressed as:

$$\text{Risk} = \text{Hazard} \otimes \text{Vulnerability} \otimes \text{Exposure} \quad (1)$$

where the symbol $\otimes$ denotes a combination or interaction, rather than a simple arithmetic product, between the three components.

[a] United Nation Disaster Risk Reduction

In industrial/technological systems, this conceptualization is presented as a combination of frequency and severity. Risk assessment in each domain is already complex because of interactions, uncertainties but appears as even more when natural events are triggering or aggravating technological accidents, leading to what are known as NaTech risks (Natural Hazards Triggering Technological Accidents).

Complexity results notably from the dynamic and often badly known features of risk components over time including the evolving structural vulnerability of assets. Those two aspects are developed below :

1.1. *Dynamic risk evolution*

Risk (incl. NaTech) is not a static quantity; each of its components evolves across both time and space. Spatially, the distribution and intensity of natural hazards vary according to geographical context, while exposure depends on the location and density of infrastructure. Temporally, the evolution of risk can be driven by natural factors linked to the phenomenon evolution (seasonality, long term related for instance to climate change), physical factors (ageing, deterioration), socio-economic factors related to exposure (industrial development, urbanization), or organizational factors (maintenance, modification of operating procedures, technological upgrades).

Temporal dynamics therefore play a crucial role in transforming risk's components, making it essential to analyze dynamic risk evolution rather than relying on a fixed initial state. For example, Riedel et al. (2014) evaluates the potential impact of the 1909 earthquake in southern France on current urban patterns and shows losses increase in that context.

Within this multidimensional framework, the structural vulnerability of infrastructure components plays a central role. It constitutes a key parameter of the damage potential, understood as the ability of hazard to cause significant harm compromising the integrity of installations or leading to major accidental scenario. Based on Equation 1, the dynamic evolution of risk can be due to hazard, vulnerability and exposure. In our work, we focus on the dynamic evolution of vulnerability.

1.2. *Time-dependent vulnerability*

Beyond its structural dimension, vulnerability is a multifaceted concept : direct vulnerability refers to the immediate physical or functional damage inflicted on assets when exposed to a natural hazard ; indirect vulnerability captures the secondary effects that emerge from disrupted interdependencies, such as supply chain interruptions, loss of utilities, or cascading failures across interconnected infrastructure.

Vulnerability can also be distinguished according to the nature of the affected assets : tangible vulnerability concerns measurable and material elements—equipment, buildings, processes, and economic losses—while intangible vulnerability relates to non-material consequences, including impacts on human health, organizational performance, social trust, or environmental services. Together, these different dimensions illustrate that vulnerability extends far beyond physical fragility alone; it shapes the severity and propagation of NaTech events through a combination of physical, functional, economic, and socio-organizational mechanisms.

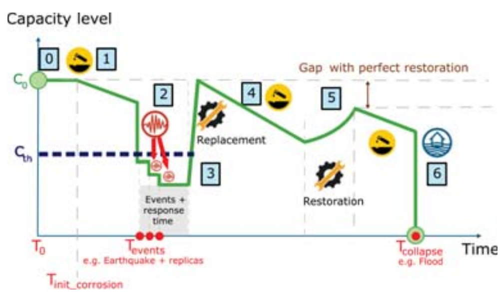

Fig. 1. Schematic overview of the time-dependent capacity level (labeled numbers 0-6 correspond to a stage of this life-cycle and are described below)

Figure 1 illustrates an example of a virtual structure's life cycle and shows the time-dependent evolution of its structural state, denoted as its capacity level. The latter starts at its initial level C_0 (Label 0 i.e. $\boxed{0}$) and gradually degrades due to corrosion after an initiation period ($\boxed{1}$).

The structure is then subjected to an earthquake following by its aftershocks ($\boxed{2}$). The capacity level becomes sufficiently low (e.g. below an acceptable threshold C_{th}) to justify replacing the structure after the seismic events and the associated response time (even without collapse) ($\boxed{3}$); after this major maintenance, the initial level is restored. Corrosion occurs again ($\boxed{4}$), then a light repair ($\boxed{5}$) is performed (the initial level is not reached this time : imperfect maintenance). Finally, a severe flood causes the structure to collapse ($\boxed{6}$).

This vulnerability is not constant : it varies over time under the influence of multiple mechanisms. On the one hand, installations may be exposed to multiple hazards—seismic events, floods, extreme winds, heatwaves, accelerated corrosion—whose interactions alter the structural resistance of systems. On the other hand, intrinsic degradation processes, linked to material ageing or adverse environmental conditions, progressively weaken installations. Finally, maintenance strategies—whether preventive, corrective, or condition-based—strongly influence the trajectory of vulnerability evolution.

1.3. *Objectives*

In classical operational situations, very simplified vulnerability curves are used to assess risk. This work aims at going far beyond but also aims to explicit gaps and situations where detailed approaches are helpful.

Studying the evolution of structural vulnerability is therefore essential for improving our understanding of NaTech risk. Such an approach moves beyond a static view of danger and highlights the need for models that integrate temporal variability, multi-hazard exposure, and the cumulative effects of degradation and maintenance.

Within this perspective, this work proposes a methodological approach for vulnerability dynamics modelling suitable for the different lifecycle stages of a system whose deterioration states evolve along time.

The remaining of this paper is organized as follows. Section 2 addresses analysis tools used in risk assessment and how they can be time-dependent. Section 3 proposes a framework to quantify vulnerability evolution. Section 4 provides numerical application for two simple examples. Conclusions and perspectives are given in Section 5.

2. State of art: from static to dynamic vulnerability assessment

In practice, risk assessment concerns events, objects: it roughly consists of comparing the capacity of a structure (linked to its vulnerability) with an external demand (conditioned by hazard effect, intensity and frequency) and it extrapolates this comparison to assess probabilistic consequences. In order to analyze vulnerability, among the most commonly used tools are fragility curves and vulnerability curves.

Next, we will define them and show how they can help us to assess dynamic risk by making them time-dependent.

2.1. *Vulnerability, fragility, losses*

The definitions and equations presented below are extracted and adapted from Baker et al. (2021).

A vulnerability curve is a function that relates the intensity measure (IM) of a hazard (phenomenon) to the mean expected loss L (or mean damage ratio DR) of an asset. It provides the direct link between hazard intensity and damage ratio (or expected economic loss) and is denoted as : $E[L|IM]$ or $E[DR|IM]$.

The fragility curves consider uncertainty in particular on physical asset's parameters and describe the probability $\mathbb{P}_f(IM)$ that the damage state (DS) of a structure will reach or exceed a specified damage state (ds_i) for a given level of hazard IM. It is analytically described as (the second equality is provided as an example for the case of a log-normal distribution) :

$$\mathbb{P}_f(IM) = \mathbb{P}(DS \geq ds_i | IM = x) = \phi(\frac{ln(x/\theta_i)}{\beta_i}) \quad (2)$$

where ϕ is the CDF of the normal distribution, ds_i is the i_{th} damage state (e.g. ds_1 for light damage, ds_2 for moderate damage, ds_3 for significant damage and ds_4 for collapse), and the fragility parameters θ_i (median) and β_i (standard-deviation) are specified for each damage state.

Fragility and vulnerability curves can be related by a damage-to-loss (or consequences) model (adapted from Martins et al. (2016)) :

$$E[L|IM] = \sum_{i=1}^{n} E[L|ds_i]\mathbb{P}(DS = ds_i|IM) \tag{3}$$

where $E[L|ds_i]$ is the mean loss L for a given damage state ds_i and

$$\mathbb{P}(DS = ds_i|IM) = \mathbb{P}(DS \geq ds_i|IM) - \mathbb{P}(DS \geq ds_{i+1}|IM). \tag{4}$$

Both fragility and vulnerability curves can be derived from numerical simulations—such as structural modeling under variable loading—or obtained from empirical databases and established engineering charts. The state of art (e.g. platforms of vulnerability's computation like HAZUS, GEM, CAPRA, Risk-EU[b]) provides considerable quantity of those two informations, depending of the structure, type of hazard, . . .

It is important to note that the terminology ”Vulnerability curve” is not universal : it is also sometimes referred to as a damage function, loss function or a consequence function.

With these informations, coupled to hazard curves, working assumptions and uncertainties, we are able to compute the expected annual losses according to the classic static risk assessment. A dynamic approach to this analysis is introduced in the next section.

2.2. *Temporal evolution*

Dynamic vulnerability assessment requires quantitative methods capable of capturing its temporal evolution.

Several studies (e.g. : Iervolino et al. (2016), Gehl et al. (2024)) have explicitly introduced a time-dependent or damage-dependent formulation of fragility/vulnerability curves, acknowledging that the resistance of assets evolves as a function of ageing, cumulative degradation, or repeated hazard exposure. These studies are specific for a given kind of structure and/or a risk scenario and they focus on vulnerability assessment, not necessarily extending to risk assessment. Following a similar approach, the present work adopts a dynamic representation of vulnerability, in which its evolution is governed by both temporal processes and damage accumulation mechanisms. Beyond vulnerability assessment alone, this framework can be further extended to a comprehensive evaluation of NaTech risk, allowing its temporal evolution to be quantified. Finally, the dynamic risk estimates are translated into economic terms, enabling an assessment of the associated costs and their evolution over time.

By looking at the life cycle of a structure (Figure 1), we can qualitatively link each event to a vulnerability/fragility curves transformation :

- Degradation, which can be continuous [1] and [4] (corrosion, fatigue) or discrete [2] and [6] (sudden event).
- Improvement due to replacement or maintenance [3], [5].

The amplitude of these transformations over time can be obtained by computation, expert's opinion or measurement.

Figure 2 illustrates this concept of temporal evolution for a virtual vulnerability curve : the original static vulnerability of an infrastructure is in green, it becomes weaker due to degradation (for a same intensity I_{event}, the damage is more important : $D_d > D_0$, ”curve shifts to the left”) or stronger due to maintenance ($D_i < D_0$, ”curve shifts to the right”).

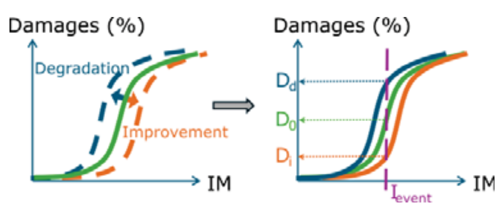

Fig. 2. Vulnerability curves transformation

[b] `https://coast.noaa.gov/digitalcoast/tools/hazus-mh.html`, `https://www.globalquakemodel.org/`, `https://ecapra.org/`, `https://eu-risk.eucentre.it/`

The main idea is to use time-dependent parameters of the vulnerability (or fragility) curve. This dependence takes into account life-events of the considered asset.

3. Methodological framework

We have now all the components to propose a framework to assess the dynamic vulnerability of a structure. Figure 3 summarizes the different steps of this method.

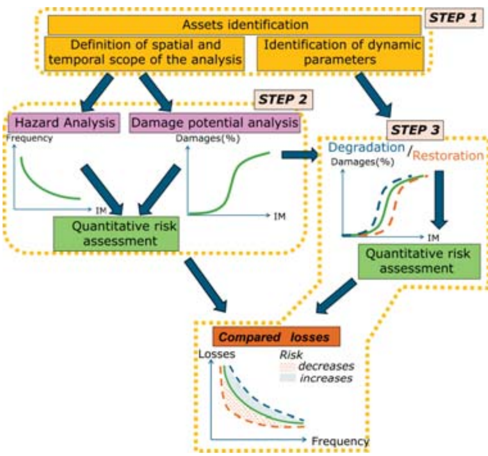

Fig. 3. Dynamic risk assessment framework proposal. Losses can be expressed in economic, functional, or casualties metrics. Uncertainties are not shown

Step 1 The first step constitutes the pre-analysis and can be done as a brainstorming with experts, stakeholders, decision maker, ... (Methods like PRA or SWIFT [c] could be used). At this stage, the spatial and temporal perimeters of the study have to be defined for assets and hazards :

- Which assets ? (e.g. a whole city), how they are designed then built ? Did they already experience events (constructive or destructive) before the study?
- Which hazards could happen on these assets during the considered temporal period? (e.g. subjected to floods and earthquakes).
- What is dynamic ? (e.g. global warming, maintenance, corrosion), what kind of information do we have and what are their accuracies ? (e.g. concrete behavior in bridge's abutment or expert's opinion), what are the required working assumptions ? Is it possible to cumulate damages of different nature ? (e.g. seismic event after an avalanche or two windstorms with distinct wind directions).

These preliminary questions are crucial and it is impossible here to list them exhaustively for a general case.

Step 2 A "classic" static analysis involves combining a hazard curve and a damage potential curve to derive a quantitative risk assessment. These curves are not necessarily continuous; in practice, frequency, intensity and damage may be expressed in discrete/qualitative forms as scalars, classes or intervals (see Figure 4, extracted from Tacnet et al. (2022)), which can likewise be used for risk assessment.

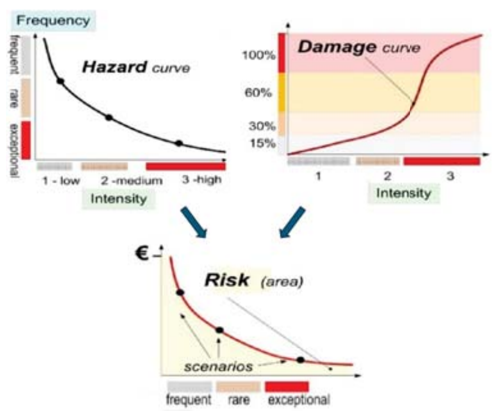

Fig. 4. Risk assessment methodology extracted from Tacnet et al. (2022)

Step 3 This step aims at including dynamic factors (identified in Step 1) into vulnerability assessment. As showed in the previous section, we define temporal fragility/vulnerability functions by using time-dependent parameters (e.g. the median

[c]Preliminary Risk Analysis or Structured What-If Technique

of log-normal distribution is a function of time). This choice allows to model a wide variety of temporal dynamics. It is now possible to compute the dynamic analysis, and finally compare losses with the static case of Step 2. The output metrics could be economic, functional, human casualties.

This latter step is the key of this study: under realistic assumptions, one can model all kinds of events (natural event, maintenance, gradual degradation) during the life-cycle of the considered asset.

It is important to note that to maintain a generic framework capable of incorporating the processes driving the temporal evolution of vulnerability described above, while also accounting for the uncertainties inherent to this type of analysis, a set of simplifying assumptions is required. In this study, hazard analysis itself is outside the scope : instead, the assessment relies on existing hazard characterization curves available in the literature or provided by relevant authorities, which are used as inputs to the proposed framework. Accordingly, the proposed methodology enables a quantitative risk assessment of the temporal evolution of structural vulnerability associated with a structure throughout the different stages of its life cycle, subject to explicit assumptions and uncertainties. These uncertainties should be assessed depending on required level of detail and assumptions are significant and may be reduced depending on the depth of analysis adopted—except for irreducible aleatory uncertainty—which itself is constrained by the time and resources allocated to the study. Based on this framework, two illustrative case studies are subsequently presented, focusing on a bridge exposed to multiple types of loadings, hazards, and maintenance strategies.

4. Simple examples of dynamic risk assessment

We consider here two examples which illustrate the influence of a temporal evolution of vulnerability on resulting risk level. In the first case, it corresponds to two successive shocks resulting in an aggravated level of damage inducing an increased level of risk. In the second example, increased vulnerability results from material ageing, and the effect of maintenance is also tackled.

In these two cases, indirect vulnerability and casualties are not taken into account.

4.1. *Example 1: Bridge subjected to seismic mainshock and aftershocks – degradation effect*

Let's consider a hypothetical bridge which gives access to a critical infrastructure, with a given seismic vulnerability curve (Figure 5, log-normal with 2 parameters : median μ_0 and standard-deviation β_0). We assumed no corrosion, no maintenance, no other hazards except earthquake.

Hazard : The bridge is subjected to an earthquake mainshock inducing a Peak Ground Acceleration (PGA) equal to 0.35g, then aftershocks with a PGA equal to 0.25g.

We assume that experts consider a mean degradation of the bridge's structural capacity between 30% and 40% after a 0.35g PGA-mainshock earthquake. We translate this information by decreasing the median value of the vulnerability function: $\mu_{aftershock} = \mu_0.(1 - [0.3 - 0.4]), \beta_0$ kept constant. This scenario is equivalent to the label $\boxed{2}$ in the life-cycle example of Figure 1.

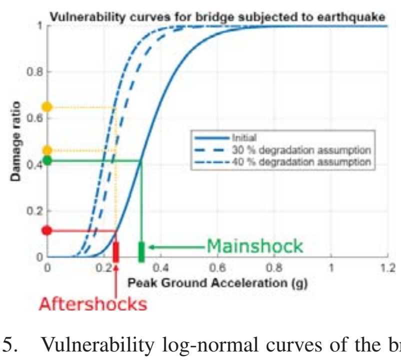

Fig. 5. Vulnerability log-normal curves of the bridge (New – solid line curve, 30% and 40% median μ_0 decrease – dashed-lines, standard-deviation β_0 kept constant)

In Figure 5, we consider the solid line curve representative of the bridge's vulnerability as new. For a PGA equal to 0.35g during mainshock, mean damage ratio (with initial strength properties) equal to 42% (green dots).

When an aftershock happens, mean damage ratios become :

- **13%** without considering degradation from mainshock (static value, red dots),
- **[46% - 65%]** considering mainshock degrades [30% - 40%] median log-normal distribution (orange dots).

In this example, the vulnerability value including degradation differs between 33% and 52% from its value excluding degradation. This vulnerability gap (ΔV) between static and dynamic analysis could be translated into a gap average annual cost ($GAAC$) by weighting by the hazard occurrence (f_{IM}) and the bridge cost (C) : $GAAC = f_{IM}.C.\Delta V$.

Furthermore, this illustrative example shows also that the aftershock could induce greater damages than the mainshock for a lower intensity when mainshock degradation is considered.

4.2. *Example 2: Bridge subjected to flood – corrosion and maintenance effects*

Let's now consider a hypothetical reinforced-concrete bridge subjected to flood, its piers have a given vulnerability curve (Figure 6, black curve, log-normal with 2 parameters : median μ_0 and standard-deviation β_0).

Scenario is gradual corrosion (labels [1] or [4] in Figure 1), maintenance at 50 years old (label [5]), no other hazards except flood. Chloride corrosion model could be used from Duracrete (1998) in order to define a corrosion initiation time then the iron mass decrease rate in reinforced concrete. To simplify the example, we will use here : $\mu_t = \mu_0 e^{-\alpha t}$ with t represents structure's age in years and α an illustrative mean decay rate.

We assume that empirical feedback yields that maintenance works will restore the bridge's piers to 80% of their original capacity : $\mu_m = 0.8\mu_0$.

Let's now consider a flood height equal to 3 m (corresponding to an exceedance water level). Figure 6 illustrates the temporal evolution of the bridge's piers vulnerability : curve for the new bridge is the solid black line. The color gradient expresses the gradual degradation due to corrosion among years. Finally, the red curve represents the bridge's piers vulnerability after maintenance works (light green : 50 years-old).

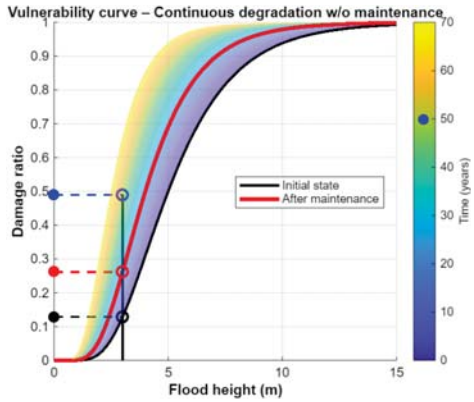

Fig. 6. Vulnerability curves of the bridge's piers subjected to flood, time-dependence with corrosion (colour gradient) and maintenance (red curve)

- On the new structure, one can expect a damage ratio of **13%** (black dots).
- On the 50 years-old structure, damage ratio becomes **49%** (blue dots).
- On the 50-years old bridge after maintenance works, damage ratio is assessed at **26%** (red dots).

In addition, as in the previous example, we can connect directly these values to the cost expectation given the flood intensity (23% less if maintenance works are done at 50 years old).

These examples demonstrate how the dynamic part of structural vulnerability is important and can be translated into economic indicators that help guide prevention strategies, investment decisions, and long-term risk-management planning.

5. Conclusion

Vulnerability, particularly in its dynamic form, plays a central role in the assessment of NaTech and multi-hazard risks. Accounting for its temporal evolution, for interactions between hazards, and for restoration mechanisms leads to more realistic and operational risk estimates. Time-dependent fragility/vulnerability curves and expected-loss calculations offer practical tools for prioritizing maintenance, optimizing resource allocation, and reducing potential economic and social losses. The methodology presented here provides a conceptual basis for integrated risk-assessment frameworks that reconcile scientific rigor with practical applicability by integrating a temporal component in the fragility/vulnerability curves parameters.

Only simple examples presented here, and many issues remains such as :

- Analyzing damage consistency and aggregation possibility : What criteria would allow to combine damage from several hazards? Their effect and their chronology must be taken into account.
- Considering uncertainties : taking into account uncertainties of multiple origins (e.g. Beven et al. (2018)) and different forms of quality information (imperfection, inaccuracy, incompleteness), which could increase considerably with the complexity of the dynamics (e.g. Pescaroli and Alexander (2018)), in particular the lack of understanding of how existing interrelationships evolve over time and what new interrelationships emerge.
- Presence of a protective structure : How its dynamic vulnerability will affect the asset's reach probability ?
- Introducing dynamics in indirect vulnerability and lethality modelling.

These topics will be addressed in future work within a more in-depth analytical framework.

Acknowledgement

This work received government funding managed by the Agence Nationale de la Recherche for France 2030 under reference number ANR 22 EXIR 0003 & ANR 22 EXIR 0006.

References

Argyroudis, S., S. Mitoulis, L. Hofer, M. Zanini, E. Tubaldi, and D. Frangopol (2020). Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Science of the Total Environment 714*, 3–19.

Baker, J., B. Bradley, and P. Stafford (2021). *Seismic Hazard and Risk Analysis*. Cambridge University Press.

Beven, K. J., S. Almeida, W. P. Aspinall, P. D. Bates, S. Blazkova, E. Borgomeo, J. Freer, K. Goda, J. W. Hall, J. C. Phillips, M. Simpson, P. J. Smith, D. B. Stephenson, T. Wagener, M. Watson, and K. L. Wilkins (2018). Epistemic uncertainties and natural hazard risk assessment – part 1: A review of different natural hazard areas. *Natural Hazards and Earth System Sciences 18*(10), 2741–2768.

Borre, A., D. Ottonelli, E. Traforini, T. Ghizzoni, G. Zoppi, G. Boni, and S. De Angeli (2025). A mathematical framework for quantifying physical damage over time from concurrent and consecutive hazards. *EGUsphere*. in press.

Duracrete, E. (1998). Duracrete: Probabilistic performance based durability design of concrete structures. Technical report, European Union, Brite EuRam III, Project BE95-1347. Final Report and related deliverables; probabilistic performance-based durability design project of concrete structures.

Frangopol, D. M. and M. Akiyama (2024). Life-cycle risk, resilience, and sustainability of individual and spatially distributed structures. In *4th International Conference "Coordinating Engineering for Sustainability and Resilience" & Midterm Conference of CircularB "Implementation of Circular Economy in the Built Environment"*, Volume 489 of *Lecture Notes in Civil Engineering*, pp. 3–19. Springer, Cham.

Gehl, P., K. Trevlopoulos, and C. Negulescu (2024). Damage state-dependent fragility models for rc buildings exposed to flood and seismic hazards. In *18th World Conference on Earthquake Engineering*.

Iervolino, I., M. Giorgio, and E. Chioccarelli (2016). Markovian modeling of seismic damage accumulation. *Earthquake Engineering & Structural Dynamics 45*, 441–461.

Martins, L., V. Silva, M. Marques, H. Crowley, and R. Delgado (2016). Development and assessment of damage-to-loss models for moment-frame reinforced concrete buildings. *Earthquake Engineering & Structural Dynamics 45*, 797–817.

Pescaroli, G. and D. Alexander (2018, 06). Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. *Risk Analysis 38*.

Riedel, I., P. Guéguen, F. Dunand, and S. Cottaz (2014). Macro-scale vulnerability assessment of cities using association rule learning. *Seismological Research Letters 85*(2), 395–305.

Tacnet, J.-M., S. Carladous, F. Sassus, E. Ripert, P. Lageize, A. Stephan, C. Calmet, and V. Gil (2022). Practical risk and resilience assessment: a methodology for implementation of mountain risk management and prevention strategy (steprim). *60th ESREDA Seminar - 2022*.