A Framework for Fragility

Joan Margalef* Laura Mayoral† Hannes Mueller‡

Christopher Rauh§

September 5, 2025

Abstract

This paper develops a general framework for understanding and measuring fragility applicable across disciplines. Although the concept of fragility is widely used in research and policy, its definition and measurement remain contested even within individual fields. The framework offers a structure for thinking about fragility by examining the process through which an object fails. We conceptualize fragility as the ease of failure, distinguishing it from risk and resilience, and analyze five measures: critical stress, damage condition, conditional probability, unconditional probability, and composite index. We also provide policy guidance on developing fragility measures and illustrate the crucial role of defining failure to measure fragility and inform policy.

Keywords: Fragility, Measurement, Policy

JEL Classification: D74, D81, E61, O19

*UNU-WIDER. Email: margalef@wider.unu.edu

†IAE (CSIC), BSE and CEPR. Email: mayoralaura@gmail.com.

‡IAE (CSIC), BSE and CEPR. Email: h.mueller.uni@gmail.com.

§IAE (CSIC), BSE, University of Cambridge and CEPR. Email: cr542@cam.ac.uk.

We acknowledge financial support from the Severo Ochoa Programme for Centres of Excellence in R&D (Barcelona School of Economics CEX2024-001476-S), funded by MCIN/AEI/10.13039/501100011033. Rauh acknowledges financial support from AEI/MICINN (ATR2023-144291).

1 Introduction

The concept of fragility has become a catch-all term for describing systems prone to failure, including ecosystems, supply chains, financial systems, and states. Researchers, governments, and international organizations use fragility measures to assess potential failures and support policymaking. How fragility is framed and measured often shapes how the issue is understood and addressed. In development and security debates, for example, fragility indices from the World Bank and OECD influence decisions on aid allocation, economic stabilization, and conflict prevention.

While the notion of "being fragile" is clear for material objects, its extension to more complex and intangible systems has led to a proliferation of interpretations. Even within the same discipline, there is often no consensus on how to define or measure it.[1] Moreover, fragility frequently overlaps with the notion of risk and the opposite of resilience. This ambiguity hinders communication, collaboration, and coherent policy design. If the concept of fragility is to serve for diagnosis and guiding interventions, it is essential to work toward a shared understanding.[2]

We develop a cross-disciplinary framework for understanding and measuring fragility. Fragility commonly refers to the ease with which an object breaks. In materials science, this corresponds to fracture—the separation of a material into distinct pieces. We generalize this idea and define fragility as the ease of a system to fail, where "failure" is a clearly specified outcome; a fragility measure quantifies that "ease". We then distinguish fragility from related concepts—risk and resilience—and assess different measures. We show how these measures are used across fields, map them into our framework, and explain which types are most appropriate for particular contexts and decisions. Finally, we offer policy guidance on designing fragility metrics and on applying them in practice, illustrated with a concrete application.

Understanding fragility begins with examining the process through which an object fails. This process consists of three core components: the object, the stress applied to it, and the resulting damage. This is referred to as the stress–damage process. A fourth component,

1. See, for instance, definitional debates in state fragility (Besley and Persson 2011; UNDP 2016; Milante et al. 2023; Sanín 2011; Ferreira 2017), financial systems (Aspachs et al. 2007; Schroeder 2009), environmental fragility (Nilsson and Grelsson 1995), and health systems (Diaconu et al. 2020).

2. UNDP (2011) write: *"How fragility is defined has implications for how interventions are designed, implemented, monitored, and evaluated."*

external factors, must also be considered to ensure that fragility is properly identified. Together, these four elements provide the foundation for understanding how failure occurs and serve as the basis for quantifying fragility.

We identify and analyze five fragility measures. Two are deterministic: critical stress and damage condition. Two are probabilistic: the conditional probability of failure given a level of stress, and the unconditional probability of failure. Finally, there is a composite type, which includes indices constructed from multiple indicators. There is a trade-off across measures between causal interpretability and operational feasibility. The less a measure is required to reflect the causal structure of the failure process, the easier it becomes to construct. However, preserving the causal link is important for understanding the drivers of fragility and informing policy.

Our policy guidance clarifies the purposes fragility metrics can serve, links each to appropriate policy responses, and outlines a design protocol. The protocol begins with a precise, operational definition of failure. Once failure is defined, fragility can be measured coherently and policies targeted accordingly. Because fragility denotes the ease with which failure occurs, any ambiguity about what counts as failure propagates directly into measurement and advice. A clear failure definition is therefore a non-negotiable first step in any fragility assessment, as we illustrate in our policy exercise.

This paper contributes to the ongoing discussions on fragility. It introduces a general framework that helps reconcile fragmented debates across disciplines (Nilsson and Grelsson 1995; Aspachs et al. 2007; Milante et al. 2023). Furthermore, by incorporating existing measures, it connects to both general formulations (Taleb and Douady 2013) and field-specific measures in areas such as state fragility (OECD 2016; Ziaja et al. 2019; World Bank 2020; African Development Bank Group 2022), financial systems (Brunnermeier and Pedersen 2009; Tsomocos 2003; Van Order 2006; Demirgüç-Kunt and Detragiache 1998), health domains (Walsh et al. 2014; Feinstein 1990; Tignanelli and Napolitano 2019; Al-Asadi et al. 2024), seismic engineering (Erberik 2015; Mibang and Choudhury 2021), and network analysis (Lorenz et al. 2009; Elliott et al. 2022). Finally, this paper also contributes to conceptual debates on risk and resilience (Society for Risk Analysis 1987; Marin-Ferrer et al. 2017; Aven et al. 2018; Holling et al. 1973; Pimm 1984; Constas et al. 2014; Bosetti et al. 2016; Folke 2016). We clarify how fragility differs and complements these concepts, offering a perspective that allows their integration within a unified framework.

The paper is structured as follows. Section 2 introduces the conceptual framework of fragility, including key definitions and the description of the stress–damage process. Section 3 analyzes the different fragility measures. **Readers primarily interested in practical implications may proceed directly to Section 4**, where the framework is translated into a step-by-step design process and illustrated with an example. The final section presents the conclusions.

2 Conceptual foundations

2.1 Definitions

The term "fragile" is used to describe objects that are easily broken, or more technically, fractured.[3] In material science, a fracture is the main type of failure, referring to the separation of a material into pieces.[4] Fragility is then the quality of being fragile, which corresponds to standard dictionary definitions (M.-W. Dictionary 2025; Oxford English Dictionary 2025).

The concept has been extended—by analogy—to engineered structures (e.g., bridges and buildings) and to intangible systems (e.g., financial markets and governments). In these settings, physical fracture is not the relevant endpoint; the appropriate generalization is *failure*.

Definition 1 *Fragility is the* ***ease*** *with which an object fails.*

A fragility measure quantifies this "ease". Crucially, it is defined with respect to a well-specified failure. Whether the outcome is the collapse of a bridge, the insolvency of a bank, or the breakdown of state authority, fragility is always assessed against that outcome. Only once failure is defined can fragility be conceptualized and measured. What varies across the measures we examine is how this "ease" is interpreted and operationalized.

3. The words fragile, fracture, and fragility share the Latin root "frangere", meaning to break. In fracture mechanics, the concept in use is not fragility but rather its opposite, toughness (Callister and Rethwisch 2000), which is defined as a material's ability to absorb energy up to the point of fracture. Indeed, fragility is used differently than in common language, referring to how quickly a material's viscosity increases as it approaches the glass transition temperature (Angell 1995).

4. More specifically, fracture is the separation of a material into pieces under static stress and low temperatures. Other failure types include fatigue, caused by dynamic stresses (e.g., in bridges or aircraft), and creep, a time-dependent deformation under constant stress at high temperatures (e.g., in turbine rotors or steam lines) (Callister and Rethwisch 2000).

To better understand the boundaries of fragility, it is useful to define as well *risk* and *resilience*. We define risk as the combination of the probability of an adverse event and the severity of its consequences.[5] As we will formally show later, the probability of failure can itself be interpreted as a measure of fragility—the higher the probability, the more fragile. While fragility is anchored to the likelihood of a specific failure, risk incorporates both the probability and the impact of the failure. In this sense, risk relates more closely to an expected loss, that is, the product of probability and impact.

Definition 2 *Risk is the* ***combination*** *of the probability of an event and the severity of its consequences.*

Therefore, when the event under analysis is failure, fragility measures can be seen as a component of risk measures, which helps explain why the two often co-move: the more fragile a system is, the greater the risk—holding consequences constant. However, by combining both probability and impact, risk excludes cases where failure is likely but inconsequential. If there are no consequences to something breaking, there is no risk—yet the object may still be fragile. We rarely observe this deviation in practice because there is no reason to monitor failures that do not matter.

We define the resilience of a system as its capacity to recover.[6] Our definition is grounded in material engineering, where resilience is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered (Callister and Rethwisch 2000). The key emphasis is on elasticity, which entails the ability to return to the original shape.[7]

Definition 3 *Resilience is the* ***capacity to recover****.*

5. Many scholars have converged on this view (Lowrance 1976; Haimes 2009; Aven et al. 2018; UNISDR 2009; Bosetti et al. 2016). Several operational frameworks also measure risk through metrics that combine these two dimensions (Marin-Ferrer et al. 2017). The ISO defines risk as "the effect of uncertainty on objectives", encompassing both probability and consequences, as outcomes are evaluated relative to intended objectives (Aven et al. 2018). However, some definitions describe risk as the probability of an adverse event, which overlaps with our concept of fragility. Examples include a subset of the definitions compiled by the Society for Risk Analysis (Society for Risk Analysis 1987; Aven et al. 2018), as well as those found in standard dictionaries (C. Dictionary 2025).

6. Bosetti et al. (2016), in their review of development resilience, identify three general interpretations: (i) resilience as the capacity to avoid long-lasting adverse development outcomes; (ii) resilience as the ability to prevent transitions into undesirable well-being states; and (iii) resilience as the ability to return to equilibrium. Some approaches emphasize recovery (Holling et al. 1973; Pimm 1984; Constas et al. 2014; Birhanu et al. 2017), which would align with our definition. Others do not, and focus solely on withstanding shocks (Folke 2016), which is more closely related to the concept of fragility.

7. By contrast, plastic deformation refers to a permanent change in shape.

While fragility is concerned with failure, resilience is about bouncing back. Their relationship is not straightforward—one does not necessarily imply the other. For example, consider two materials subjected to the same force: neither breaks, so neither is fragile. Yet if one returns to its original shape and the other remains deformed, only the first is resilient. The reverse can also occur: both may easily fail, but only one recovers quickly, showing resilience despite fragility. This latter case is hard to imagine in physical materials, which, once broken, cannot restore themselves. However, other systems, such as economies, ecosystems, or even biological organisms, can recover after failure.

In Appendix B, we formalize several measures of risk and resilience that integrate with the framework presented below.

2.2 The stress-damage process

The notion of fragility is grounded in the process by which an object is damaged to the point of failure, which we refer to as the *stress–damage process*.

In general, an *object* is susceptible to being subjected to a force, referred to as *stress*, which may cause *damage* to it. If framed as a process, stress is applied as an input to the object, and the damage level is the outcome. This stress-damage process consists then of three core components:

- **Object:** The subject of analysis, such as a glass, house, crop field, bank, or state. It possesses intrinsic features that influence how stress translates into damage. These are referred to as **object characteristics**. Formally:
  - **Object characteristics:** The set of inherent properties that influences the object's response to stress, such as material composition, number of floors, crop type, number of clients, or type of government.
- **Stress:** The force applied to the object that can create damage to it, such as newtons, earthquake magnitude, droughts, debt default rates, or polarization.
- **Damage:** The effect caused by stress, such as cracked/shattered, wall cracks/structural collapse, crop withering/desertification, liquidity strain/insolvency, protests/civil war. When the damage reaches a level where the object is considered to be malfunctioning,

this is referred to as **failure**, and the stress level required to reach this state is called **critical stress**. Formally:

- **Failure:** A state in which the object is considered to have suffered enough damage for malfunctioning.
- **Critical stress:** The stress level required for failure.

The concept of the object remains fixed, while stress and damage are variables that depend on each other, with higher stress typically leading to greater damage. The notion of fragility summarizes information about an object's stress–damage process, offering a simplified and partial representation of it. For example, if deemed as very fragile, low stress values can create high damage and ultimately failure.

To understand this process, and hence, fragility measures, it is useful to formalize it. Let $\mathcal{O}$ denote the set of objects (e.g., bridges, banks, states). For each object $o_i \in \mathcal{O}$, let M_i denote its fragility measure. Stress is denoted by $s \in S$, where S is the set of all possible stress levels. While s could represent a vector of forces, assume it is a single variable for simplicity. Similarly, damage is represented by $d \in D$, where D is the set of all possible damage levels. Failure is a binary variable $y \in Y = \{0, 1\}$, where $y = 1$ indicates failure and $y = 0$ indicates no failure, and is determined by whether d reaches a predefined value, say d^*. Critical stress refers to the value of s associated with d^*, which is denoted by s^*.

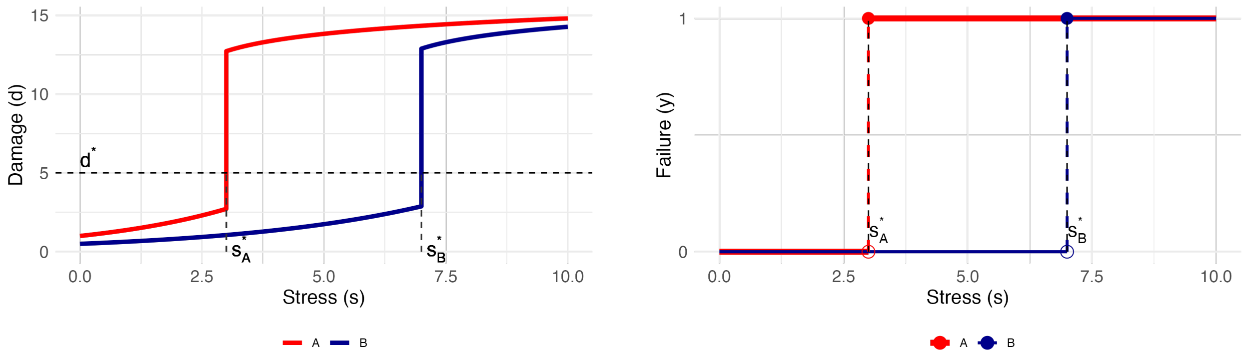
The relationship between stress and damage—how stress translates into damage—is represented by $d = f(s)$, where f denotes the functional mapping. The assumption that higher stress leads to greater damage implies that f is monotonic in s. The critical stress is obtained by inverting the function at failure: $s^* = f^{-1}(d^*)$.[8] A precise grasp of this relationship enables us to know how an object responds to different levels of stress, identify critical stress, and predict failures.

Objects respond differently to stress levels because they differ in their characteristics. Let $\mathbf{x} \in \mathbf{X}$ represent a vector of variables that describe the object's characteristics, where $\mathbf{X}$ is the set of all possible values. Then, $d = f(s, \mathbf{x})$, and the object-specific function is $f_i(s) = f(s \mid \mathbf{x}_i)$, where $\mathbf{x}_i$ represents the values of the characteristics of object i. In the view of the process, $\mathbf{x}_i$ "defines" the object.

Figure 1 illustrates an example of a monotonic stress-damage process for two objects,

8. Strict monotonicity is required for the inverse to be well defined.

$i \in I = \{A, B\}$. s_i^* represents the critical stress level of each of them. The left panel shows the outcome of the function represented as damage, while the right panel depicts the outcome as a binary failure variable.



(a) Damage (b) Failure

Figure 1: Example of a stress to damage mapping

Notes: This figure illustrates an example of the stress-to-damage function of two objects, A and B. The left panel depicts the stress-to-damage relationship, while the right panel shows the stress-to-failure relationship. The damage threshold is $d^* = 5$, which determines the critical stress point of failure, s_i^*, where $y = 1$. In this case, the critical stress levels are $s_A^* = 3$ and $s_B^* = 7$.
Sources: Authors' elaboration.

Furthermore, other *external factors* beyond stress can also affect this mapping. Given their constant presence, we consider them a fourth core component:

- **External factors:** Conditions external to the object, distinct from stress, that influence the damage outcome. Examples include temperature, soil erosion, daylight hours, central bank interventions, or international assistance.

Note that the difference between stress and other external factors is conceptual: stress is identified as the primary variable influencing the damage outcome, which is why it is treated separately. Let $\mathbf{z} \in \mathbf{Z}$ represent a vector of variables for external factors, where $\mathbf{Z}$ is the set of all such possible values. Then, $d = f(s, \mathbf{x}, \mathbf{z})$, and the object-specific function is $f_i(s, \mathbf{z}) = f(s, \mathbf{z} \mid \mathbf{x}_i)$.[9] We collectively refer to s, $\mathbf{x}$, and $\mathbf{z}$ as the *inputs* of the process. Figure 2 illustrates the interaction of the core components of the stress-damage process.

9. One can think of the analogy with a linear model:

$$d = \alpha + \beta s + \gamma \mathbf{x} + \delta \mathbf{z}.$$

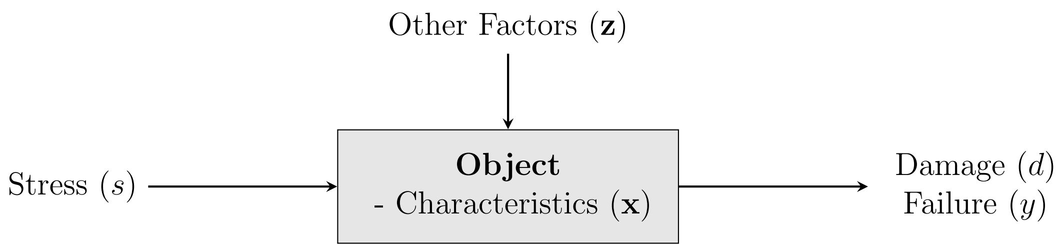


Figure 2: Stress-damage Process

Notes: This figure represents the stress-damage process, illustrating the interaction between four core components: the object, stress, damage/failure, and external factors.
Sources: Authors' elaboration.

Controlling for external factors is crucial to maintaining a one-to-one relationship between stress and damage. When these factors are omitted, identical stress levels may lead to different damage outcomes due to varying external conditions, hindering identification. Other sources that can blur this mapping include measurement errors and missing inner characteristics.

These core elements—object, stress, damage, and external factors—form the foundation of any stress-damage process. The process may differ in how these concepts are defined and their level of complexity. For instance, the analysis may incorporate many characteristics and external factors, model stress and damage in high-dimensional spaces, and account for time dependency. However, no matter how complex this process is defined, it ultimately boils down to these core concepts.

Note that the stress–damage process describes how stress translates into varying levels of damage, with failure defined as a binary condition. Fragility is concerned with reaching failure; in this sense, the concept focuses exclusively on the binary outcome.

3 Measures of fragility

A fragility measure quantifies the ease with which an object reaches failure, where failure is a well-defined outcome. This implies that the measure is constructed relative to a failure definition.

In econometrics terminology, d (or y) corresponds to the *dependent variable*, s represents the *key explanatory variable*, $\mathbf{x}$ is a vector of *inner characteristics*, and $\mathbf{z}$ consists of *external factors* that influence the mapping. $\mathbf{x}$ and $\mathbf{z}$ are referred to as *control variables*. Together, s, $\mathbf{x}$, and $\mathbf{z}$ are referred to as *regressors*. The f is assumed to be linear in the sense that it introduces the variables in a summation mode with multiplicative constant coefficients α, β, γ, and δ.

We identify three **types** of fragility measures: *deterministic measures*, which assess fragility by directly using fixed values of stress or damage; *probabilistic measures*, which account for the uncertainty of the process through probability distributions; and *composite measures*, which result from aggregating multiple variables related to the stress–damage process.

These give rise to five main fragility **measures**: (i) *critical stress* and (ii) *damage condition*, both deterministic; (iii) the *conditional probability of failure given stress* and (iv) the *unconditional probability of failure*, both probabilistic; and (v) *indexes* (or scores), which are composite measures. Table 1 provides a structured overview of the five fragility measures, organized by type and with representative examples.

Table 1: Summary of fragility measures

Type	Deterministic		Probabilistic		Composite
Measure	Critical stress	Damage condition	Conditional Prob.	Unconditional prob.	Index, scores, ...
Examples	• Materials science • Al-Asadi et al. (2024) (RCT analysis)	• Van Order (2006) (Financial economics) • Elliott et al. (2022) (Network science)	• Muntasir Billah and Shahria Alam (2015) (Seismic analysis) • Fu et al. (2016) (Structural engineering)	• Demirgüç-Kunt and Detragiache (1998) (Financial economics) • Chami et al. (2021) (State fragility)	• World Bank (2024) (State fragility) • Mastronardi et al. (2022) (Environmental science)

Notes: This table provides a structural relationship between the different types and main measures of fragility, along with examples of each.
Sources: Authors' elaboration.

3.1 Deterministic measures

A deterministic measure involves measuring fragility as a constant value of the main variables involved in the process.

One way to measure fragility is by using critical stress. In this case, a damage level (i.e., failure) is fixed, and stress serves as the measure of fragility. When comparing two objects, if one requires less stress to produce failure, it is deemed more fragile. This is the **critical stress measure**.

Measure 1 *Fragility is measured by the* ***critical stress:*** *the minimum level of stress required for failure.*

This is the measure commonly used in material science, where experiments include fracture toughness tests, in which stress is gradually increased until fracture occurs. Another example is the Fragility Index used in the health literature, particularly in RCTs, which quantifies the number of event-to-nonevent outcome changes needed to make a statistically significant result nonsignificant (Al-Asadi et al. 2024).

Formally, for a failure definition given by a threshold d^*, a measure of fragility can be expressed as $M_i = h(s_i^*)$, where $h(\cdot)$ is a strictly decreasing function of the critical stress level s_i^*. This ensures that higher stress levels correspond to lower fragility. If $s_A^* < s_B^*$, object A is more fragile than B. Figure 3 illustrates this measure.

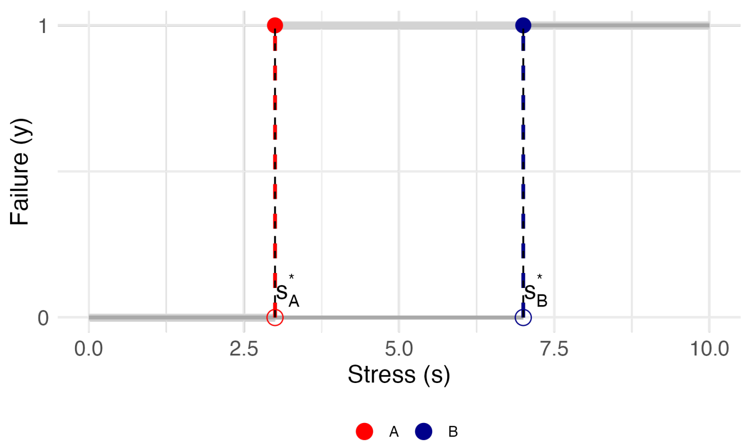


Figure 3: Representation of the critical stress measure

Notes: This figure illustrates the stress measure. From the entire mapping depicted in Figure 1, the figure emphasizes that the stress measure focuses on one specific point of it. A damage level is fixed, and the corresponding stress level is obtained. In this case, the critical stress levels are $s_A^* = 3$ and $s_B^* = 7$.
Sources: Authors' elaboration.

An alternative way to measure fragility is to fix a stress level and assess whether it leads to failure. When comparing two objects, if one reaches failure under the same stress while the other does not, it is considered more fragile. We refer to this as the **damage condition measure**.

Measure 2 *Fragility is measured by whether a* ***damage condition*** *is satisfied: the object reaches sufficient damage under a specific level of stress.*

This type of measure is commonly used in the financial literature, where fragility is defined as the condition in which a small shift in fundamentals leads to a sharp increase in illiquidity (Brunnermeier and Pedersen 2009), or when small parameter changes cause abrupt jumps in interest rates, asset prices, or market structure (Van Order 2006). A similar logic is found in network science applied to supply chains, where fragility is understood as the condition in which small, unanticipated shocks can trigger a collapse in production (Elliott et al. 2022). Taleb's notion of fragility can be understood within this type of measure, where "fragility resides in the fact that a small—or at least reasonable—uncertainty on the macro-parameter of a distribution may have dramatic consequences on the result of a given stress test." (Taleb and Douady 2013).[10]

An applied way to measure fragility in this sense is through stress testing, such as in structural engineering, where engineers place heavy trucks at critical points of a bridge and assess whether the resulting damage exceeds acceptable thresholds. A similar approach is used in the banking systems, where institutions are exposed to hypothetical shocks—such as recessions or asset price collapses—and their responses are analyzed across key indicators.[11]

In this case, for a given level of stress $\overline{s}$, fragility is measured as $M_i = g(\overline{y}_i)$, where $\overline{y}_i$ is the failure variable under that stress and $g(\cdot)$ is strictly increasing. If $\overline{y}_A > \overline{y}_B$, then object A is more fragile than B. See Figure 4 for a representation of the damage-based measure.

10. While the conceptual framing differs, the underlying idea is similar. In their framework, fragility arises when changes in stress variables beyond certain thresholds lead to disproportionate effects. This maps onto our framework by interpreting such changes as the stress itself.

11. Related to this approach is the definition of fragility fractures by WHO (2024), referring to fractures that result from low-energy trauma—mechanical forces that would not ordinarily cause a fracture—such as a fall from standing height or less.

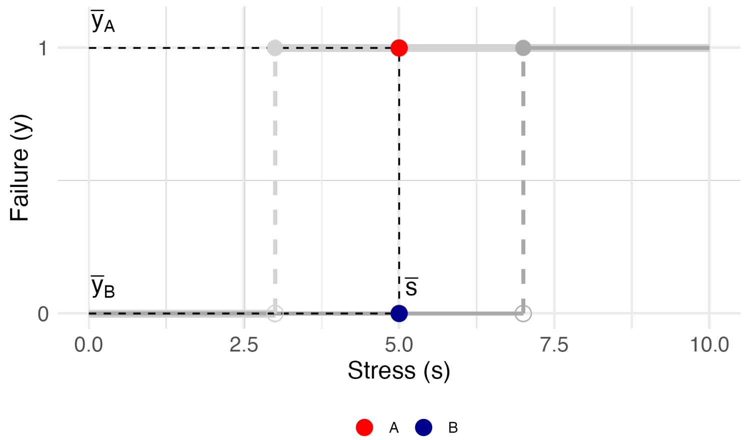


Figure 4: Representation of the damage condition measure

Notes: This figure illustrates the damage-per-stress condition measure. From the entire mapping depicted in Figure 1, the figure emphasizes that the stress measure focuses on one specific point of it. The chosen stress level is $\bar{s} = 5$ which induces $\bar{y}_A = 1$ and $\bar{y}_B = 0$.
Sources: Authors' elaboration.

The choice between a critical stress measure and a damage measure depends on how stress and damage vary relative to each other. Fixing one variable means ignoring variation in its intermediate or over-threshold values, implicitly assuming no meaningful changes occur there. If one variable changes abruptly at certain levels, exhibiting clear threshold effects, while the other varies smoothly over a range, it is usually preferable to fix the first and measure fragility using the second. For example, in material science, fracture is abrupt, with other levels of damage not being appreciable, while stress can be controlled and measured across a wide range. Conversely, when stress tends to take on common or recurring values, it is often more practical to fix a specific stress level and assess whether failure occurs. This is the logic behind stress testing.

Both deterministic measures rely on a clear understanding of the stress–damage process, that is, of the function f, which inherently ties them to the causal mechanisms of failure. This makes them particularly useful for guiding policies. Knowing which stressor levels matter, and how internal characteristics and external factors interact, is useful to inform interventions. However, deterministic measures are also compromised by the assumption of this understanding. The relationship between stress and damage must closely approximate a one-to-one mapping: each stress level corresponds to a unique damage outcome. If the function f is not one-to-one—meaning the same stress level can lead to different damage outcomes, or vice versa—then deterministic measures become unreliable. We refer to this source of uncertainty as *internal uncertainty*, as it originates within the mapping itself.[12]

Additionally, even with a perfect understanding of the stress–damage function, uncertainty about the input values can still introduce variability. That is, if we do not know which stress level will actually occur, failure cannot be precisely anticipated. We refer to this as *external uncertainty*, as it lies outside the mapping itself.

The presence of either type of uncertainty limits the applicability of deterministic measures and motivates the use of probabilistic alternatives.

3.2 Probabilistic measures

A probabilistic type measures fragility as the likelihood of experiencing failure. A higher probability means greater fragility. Since the damage on the object depends mainly on the stress level, fragility can be quantified either as a conditional probability—given a specific stress level—or as an unconditional probability. For simplicity of the argument, assume that no external factors influence the probability at first; later, we will incorporate them.

The **conditional probability measure** uses the likelihood of failure for a given stress level. Formally, for a given failure definition d^* and stress level $\overline{s}_i$, fragility is represented as $M_i = \Pr(y_i = 1 \mid \overline{s})$. Note that this measure accounts for internal uncertainty, as it captures variability in damage outcomes given the same stress level. However, it does not address external uncertainty, as it still assumes a fixed stress level without considering its own potential variability.

Measure 3 *Fragility is measured by the* ***conditional probability*** *of failure for a given stress level.*

These measures are widely used in seismic analysis, where fragility is often defined as the probability that the demand on a structure will exceed its capacity for a given intensity measure (Mibang and Choudhury 2021). A common tool in this context is the *fragility curve*, which depicts the conditional probability that structural damage will exceed a specified threshold at varying levels of ground motion intensity (Muntasir Billah and Shahria Alam

12. For instance, in material science, internal air bubbles in ceramics—undetectable during testing—can introduce significant variability in test results. These variations lead to differing critical stress levels for specimens that appear identical (Callister and Rethwisch 2000).

2015). This measure of fragility and the use of fragility curves have also been extended to structural engineering applications involving wind and rain loads (Fu et al. 2016), and fire (Gernay et al. 2016).

To account for the external uncertainty, we can measure fragility with an **unconditional probability measure**: the likelihood of failure. Formally, $M_i = \Pr(y_i = 1)$. This measure accounts for the external uncertainty related to the stress level (s) since it incorporates its distribution, as shown by the *law of total probability*:

$$\Pr(y_i = 1) = \sum_{s_j \in S} \Pr(y_i = 1 \cap s_j) = \sum_{s_j \in S} \Pr(y_i = 1 \mid s_j) \Pr(s_j) \tag{1}$$

where S is assumed to be discrete for simplicity.[13]

If, in addition, there is internal uncertainty, the unconditional probability also accounts for it because it ultimately reflects the final outcome, which is influenced by both types of uncertainty. As shown in the equation, the conditional probability forms a part of the unconditional one. Therefore, while the conditional probability accounts only for internal uncertainty, the unconditional accounts for both.

Measure 4 *Fragility is measured by the **unconditional probability** of failure.*

Importantly, the unconditional probability serves as a measure of fragility even in the absence of stress data or even a conceptualization of it. It can be estimated directly without computing conditional probabilities. For example, calculating the proportion of years a country has been at war provides an estimate of the country's probability of war using relative frequencies without relying on a specific definition of stress. This measure of fragility indirectly captures the distribution of all stress variables by incorporating observed historical patterns, assuming that future distributions will resemble the past ones. This ease of computation represents a relative advantage over conditional probabilities.

An example of this type of fragility measure is found in the financial literature, where fragility is quantified through the probability of a banking crisis (Demirgüç-Kunt and Detragiache 1998). A similar approach is used in the study of state fragility, where fragility is measured by the probability of state failure (Mueller 2018; Chami et al. 2021).[14]

13. For a continuous stress level, the formula becomes $\Pr(y_i = 1) = \int_S \Pr(y_i = 1 \mid s) f_s(s), ds$, where f_s is the density function of s.

14. Mueller (2018) defines state failure as the inability of a government to prevent an economic or political

If there is uncertainty in the external factors ($\mathbf{z}$), one can choose to condition a probability measure on their values, treating them as fixed, or leave them unconditioned to account for their uncertainty. The conditional probability measure becomes $M_i = \Pr(y_i = 1 \mid \bar{s}, \mathbf{z})$ or $M_i = \Pr(y_i = 1 \mid \bar{s})$, while the unconditional probability measure becomes $M_i = \Pr(y_i = 1 \mid \mathbf{z})$ or $M_i = \Pr(y_i = 1)$. This can be shown again by the law of total probability:

$$\Pr(y_i = 1) = \sum_{s_j \in S} \Pr(y_i = 1 \mid s_j) \Pr(s_j) = \sum_{s_j \in S} \sum_{\mathbf{z}_k \in \mathbf{Z}} \Pr(y_i = 1 \mid s_j, \mathbf{z}_k) \Pr(s_j) \Pr(\mathbf{z}_k).$$

where s and $\mathbf{z}$ are assumed to be independent and both discrete for simplicity.[15]

Similarly, one can also choose to account for uncertainty in the internal characteristics of the object ($\mathbf{x}$). The inputs of the process—$\mathbf{s}$, $\mathbf{x}$, and $\mathbf{z}$—can all carry uncertainty. Then, there is a combination of types of conditional and unconditional probabilities to account for the distinct uncertainties induced by the variables.

To illustrate the difference and the relation between the conditional and unconditional probability measures, consider the following example. Imagine the probability of a building collapsing in Japan is 0.3 when there is an earthquake, 0 when there is not, and the probability of an earthquake is 0.2. For Spain, the probability of collapse when there is an earthquake is 0.6, and 0 when there is no earthquake, but the probability of an earthquake is 0.05. Then, the conditional probability of collapse given an earthquake is higher for Spain than for Japan. However, the unconditional probabilities are given by

$$\Pr(y_{JPN} = 1) = 0.3 \cdot 0.2 + 0(1 - 0.2) = 0.06$$

crisis that threatens the welfare of its population. Chami et al. (2021) refers to a situation in which a country's governmental apparatus is of limited effectiveness in delivering a broad range of public services.

15. If s and $\mathbf{z}$ are dependent and discrete:

$$\Pr(y_i = 1) = \sum_{s_j \in S} \sum_{\mathbf{z}_k \in \mathbf{Z}} \Pr(y_i = 1 \mid s_j, \mathbf{z}_k) \Pr(s_j, \mathbf{z}_k) = \sum_{s_j \in S} \sum_{\mathbf{z}_k \in \mathbf{Z}} \Pr(y_i = 1 \mid s_j, \mathbf{z}_k) \Pr(\mathbf{z}_k \mid s_j) \Pr(s_j).$$

If s and $\mathbf{z}$ are continuous and independent the formula becomes

$$\Pr(y_i = 1) = \int_S \int_{\mathbf{Z}} \Pr(y_i = 1 \mid s, \mathbf{z}) f_s(s) f_{\mathbf{z}}(\mathbf{z}) \, ds \, d\mathbf{z}.$$

where $f_s(s)$ and $f_{\mathbf{z}}(\mathbf{z})$ are the probability density functions of s and $\mathbf{z}$, respectively. If s and $\mathbf{z}$ are continuous and dependent:

$$\Pr(y_i = 1) = \int_S \int_{\mathbf{Z}} \Pr(y_i = 1 \mid s, \mathbf{z}) f_{s,\mathbf{z}}(s, \mathbf{z}) \, d\mathbf{z} \, ds.$$

$$\Pr(y_{ESP} = 1) = 0.6 \cdot 0.05 + 0(1 - 0.05) = 0.03.$$

Although Spain has double the probability of collapsing when an earthquake occurs, it has half the probability of collapsing. This is because Spain has a lower probability of experiencing an earthquake.

Conditional probabilities require a deeper understanding of the stress–damage process, as they identify stress variables and condition the measure on their levels. This is useful for informing policy. Policies to reduce earthquake-induced collapses (e.g., seismic retrofitting, base isolators, flexible structural designs) may differ significantly from those aimed at mitigating collapse risks unrelated to seismic activity (e.g., corrosion-resistant materials, fireproofing, flood barriers). An estimated unconditional probability that abstracts from conditional probabilities—such as one based on historical data—does not provide this type of insight. However, conditional probabilities are compromised when the key stress variables are uncertain or poorly understood. If the probability of an earthquake increases, only the unconditional probability will capture this change in fragility.

Probabilistic measures relax the requirement—present in deterministic approaches—of having complete knowledge of the stress–damage process. Conditional probabilities still require identifying key stressors but not the full set of underlying mechanisms, allowing for outcome variability even at the same stress level. Unconditional probabilities go further, requiring no explicit identification of stress variables, as when using historical data. This flexibility makes probabilistic measures easier to compute and better suited to account for uncertainty. However, by not committing to a full understanding of the stress–damage process, it becomes more difficult to extract causal insights.

Note that both deterministic and probabilistic approaches demand knowledge of failures, which can be obtained through data, experiments, or simulations. However, there are cases where the object of interest has not yet failed, failures are extremely rare, difficult to operationalize, or the process cannot be realistically simulated. In such situations, these measures become highly unreliable. One alternative is to aggregate a set of indicators that are assumed to proxy the system's ease of failure. This is a composite measure.

3.3 Composite measures

A composite measure aggregates indicators related to the core components into an index or score. These indicators may reflect stress variables, object characteristics, external factors, or their distributions, and are combined using weighting schemes or other dimensionality-reduction methods. Both the choice of indicators and the aggregation method are intended to capture the object's ease of failure.

Measure 5 *Fragility is measured by a* ***composite index*** *that aggregates indicators related to the core components in a manner intended to capture the ease of failure.*

Composite measures are typically used for state fragility. The World Bank, for example, maintains a list of Fragile, Conflict, and Violence (FCV) countries.[16] To identify fragile states, the World Bank relies on several criteria. The primary one is the Country Policy and Institutional Assessment (CPIA), which scores countries on aspects of economic management, structural policies, social inclusion, and public sector management. These scores are aggregated using a weighted average to create an overall index. Countries with a CPIA score below 3.0 are classified as fragile. Other conditions are the host of a United Nations peacekeeping operation or experience high levels of forced displacement.

Mastronardi et al. (2022) defines environmental fragility as the susceptibility of an area to change as a result of a disturbance. They construct a fragility index for Italian municipalities using eight indicators, grouped into natural and anthropic components, which are relativized, normalized, and aggregated using simple averages.[17]

Composite measures offer a simple way to measure fragility. They combine variables assumed to proxy the ease of failure, with the aggregation method implicitly reflecting assumptions about how these variables interact. Even failure itself need not be explicitly

16. Formally, the World Bank defines fragility as a systemic condition characterized by an extremely low level of institutional and governance capacity, which significantly impedes the state's ability to function effectively, maintain peace, and foster economic and social development (World Bank 2024). Notably, this definition equates fragility with the existence of failure, rather than with the ease of failure. In this view, a state is classified as fragile if failure has already occurred. This reflects a core conceptual problem in defining state fragility.

17. Natural indicators include earthquake hazard, landslide hazard, and flood hazard; anthropic ones include PM10 air pollution, per capita waste generation, land consumption, presence of protected areas, and forest cover. Variables that increase fragility are directly normalised; those reducing fragility (protected areas and forests) are reverse-normalised. The Composite Fragility Index (CFI) is calculated as the average of a partial fragility score (based on risk-enhancing indicators) and a reverse score (based on resilience-enhancing indicators).

operationalized. This has made composite measures especially popular in public policy, where decision-makers face complex problems and seek simplified tools for comparison and monitoring.

However, this simplicity comes at the cost of interpretability. The aggregation produces a convoluted metric that is difficult to interpret. For example, if the World Bank index assigns Somalia a fragility score of 2 and Nigeria a score of 4, we can infer that Somalia is more fragile. But what those two points actually mean in practical terms is unclear. Moreover, because the methodology depends largely on assumptions about which variables to include and how they interact, and does not require operationalizing failure, composite measures usually offer little insight into the true drivers of fragility.

3.4 Discussion

All fragility measures aim to represent the ease of failure, making them inherently connected and, to some extent, translatable to one another. However, they vary in the degree of assumed knowledge about the underlying stress–damage process.

Deterministic measures require a complete understanding of it. They can precisely identify failure thresholds but become unreliable when key parameters are uncertain. Probabilistic measures address this uncertainty. However, they relax the causal structure by not requiring all contributing factors to be specified. Conditional probabilities rely on a principal stressor, whereas unconditional probabilities can be computed without identifying any specific stressor. Although this flexibility allows calculation without accounting for the entire stress-damage process, it limits the ability of these measures to capture the causal pathways of fragility.

Both deterministic and probabilistic measures depend on prior knowledge of failure, such as experimental data, simulations, or historical records. Composite measures, by contrast, offer a simple alternative that requires minimal knowledge. Yet this simplicity typically comes at the cost of even more clarity on the underlying drivers of fragility.

Therefore, as we move from deterministic to probabilistic and then to composite measures, a clear trade-off emerges between *causal interpretability*—the ability to explain how failure occurs—and *operational feasibility*—the ease with which a measure can be constructed with reasonable validity. Table 2 illustrates how these measures are positioned within this trade-off. The less a measure is required to reflect the causal structure of the failure process, the easier it becomes to construct. However, preserving the causal link in the model is useful for identifying key inputs and simulating counterfactuals—both essential for informing policy.

Table 2: Trade-offs in fragility measures

Type	Deterministic	Probabilistic		Composite
Measure	Critical Stress Damage Cond.	C.Prob	U.Prob	Index
Trade-off	← *Causal Interpretability*			
	Operational feasibility →			

Notes: This table illustrates the trade-offs between different types of fragility measures.
Sources: Authors' elaboration.

The recent surge in machine learning illustrates this trade-off. Supervised methods build highly non-linear functions to predict outcomes, requiring large datasets and computing power but little additional implementation cost. However, they are often "black boxes", in the sense that the estimation of the causal effect of single variables does not take center stage. This favors the use of unconditional probability measures and composite measures. The former can be obtained directly by predicting failure (y) from a broad set of relevant inputs (x, s, z) with supervised learning. While the latter benefit from machine learning's ability to process text and images, and from unsupervised methods that cluster variables to construct indices.

4 Measuring fragility for policy

We now move from the theoretical discussion to its practical application for policy. First, we describe how fragility measures can support policy responses. Then, we provide general guidelines for designing a fragility measure. Finally, we illustrate a practical application.

4.1 Fragility and policy responses

Fragility measures are valuable in the policy realm because they help identify and understand failures that often entail significant social, ecological, or human losses. For any policymaker concerned with such outcomes, developing a fragility measure serves two main purposes. First, the developed model supports the prediction of failure, enabling better targeting of resources. If a measure indicates that a particular object may soon fail, it directs attention to that case and helps determine where to intervene. Second, the model can inform the design of policy responses. Because fragility measures reflect the stress-damage process itself, they can help identify how to minimize the likelihood or impact of failure.

In this regard, it is useful to distinguish between different types of policy responses:

- *Mitigation:* policies that preemptively reduce the impact of failure (e.g., reducing exposure to failure, or insurance).
- *Prevention:* policies that avert failure (e.g., structural reinforcements, or reducing stress levels).
- *Containment:* policies that limit the propagation of failure's effects to other domains (e.g., contingency planning, or crisis management).
- *Recovery:* policies to restore normality after failure (e.g., rebuilding efforts, or compensation).

Mitigation and prevention are proactive actions taken before failure occurs, while containment and recovery are reactive responses implemented after failure has taken place. Among all response categories, prevention is the only one that directly seeks to reduce the object's fragility. This can be done by reinforcing the object's internal characteristics or by modifying the level, distribution, or nature of external stressors to make them less severe. Therefore, prevention requires knowledge of how the object fails, that is, of the stress–damage process. Models that offer a deeper understanding of this process are more valuable for prevention.

By contrast, the other types of response focus on managing the consequences of failure rather than preventing its occurrence. As such, they do not necessarily require an understanding of the failure process itself. Instead, these responses require an understanding of the consequences of failure—how different mechanisms can mitigate its impact, how failure might propagate to other sectors, and how recovery can be achieved.

Therefore, while the predictive capacity of a fragility measure is useful across all response types to determine when to act or prepare, its connection to the stress–damage process is particularly valuable for informing preventive interventions.

4.2 The design process

Before even beginning the process of developing a fragility measure, it is essential to identify the organizational goal, as this determines both the purpose of the measure and the direction of the policies. In other words, one must first define the optimization problem, whether it is maximizing population welfare or increasing economic profits.

With this in mind, the following steps guide the development of a fragility measure:

1. **Define failure.** Identify the adverse outcome of interest. Conceptualize both the object and the failure to be captured. This requires defining the damage variable (d) and the condition under which failure (y) occurs.

2. **Complete the stress–damage process.** Specify the mechanisms that lead to failure. Identify the inputs of the process: internal characteristics ($\mathbf{x}$), stress factors ($\mathbf{s}$), and external influences ($\mathbf{z}$). Predictable policy responses should also be included. This step is helpful for generating ideas about policies that influence these inputs and prevent failure.

3. **Review data.** Assess the data available to model the stress–damage process, including variables for damage (d), failure (y), internal characteristics ($\mathbf{x}$), stress factors ($\mathbf{s}$), and external influences ($\mathbf{z}$). Evaluate whether failure can be directly observed or empirically approximated.

4. **Select the appropriate measure.** Choose the fragility measure that best fits the context. Consider the purpose of the analysis, the level of understanding of the stress–damage process, the measurability of key inputs, the degree of uncertainty surrounding their distribution, and the intended scope of the policy toolbox.

5. **Build the fragility measure.** Construct the function that connects the failure definition to the measured fragility. Assess also the measure's validity using predictive metrics or by comparing it with findings from existing studies. Use the underlying model to extract insights for policy design.

While the steps provide a structured guideline, the process is iterative: recognizing the limitations of a given measure may prompt reconsideration of the failure definition. A back-and-forth between searching for data and varying the failure definition can be inevitable.

Crucially, the entire fragility framework depends on how failure is defined, which in turn shapes the policy options and their nature. Consider an actor concerned with people being affected by climate change. If failure is defined as climate change itself, then prevention involves reducing carbon emissions, while mitigation refers to relocating populations away from vulnerable coastlines. In this case, relocation does *not* reduce fragility; it only limits the consequences. However, if failure is defined as the loss of life from floods or hurricanes, then both emissions reductions and relocation become preventive measures. Mitigation now refers to preemptive actions that reduce the impact of the resulting loss of life, such as insurance schemes to support affected families.

As a result, the choice of fragility measure also shapes how trade-offs are analyzed between short-term recovery and long-term fragility. Some policies may provide immediate relief but fail to reduce fragility over time. This trade-off is central to current debates on how public and private actors should respond to climate-related challenges.[18]

4.3 Application: assessing city wildfire fragility

We now model a city mayor concerned with maximizing the well-being of citizens. In the context of the January 2025 Southern California wildfires, she seeks to reassess the threat wildfires pose to the city. This motivates a fragility assessment.

The first step would be to define what constitutes failure. We illustrate the importance of this step by discussing the entire design process and its consequences for two example definitions: (i) wildfire occurrence, and (ii) building destruction.

(i) Wildfire occurrence

The object is the entire city area, including the urban–rural interface, with its mix of woodlands, homes, and critical infrastructure. Failure can be operationalized as the occurrence of a wildfire within the municipality, defined as such if a sufficiently large area is burned.[19]

To complete the stress–damage process, the mayor's office must identify the key inputs. Internal characteristics ($\mathbf{x}$) may include vegetation coverage and type of vegetation. Stress factors ($\mathbf{s}$) could include drought indices, human activities that produce sparks, and lightning

18. See, for example, P. W. Baylis and Boomhower 2021; P. Baylis and Boomhower 2023.
19. Formally, let d denote the total burned area, and define failure as $y = 1$ if $d \geq d^* = 1$ hectare.

activity. External influences ($\mathbf{z}$) may include wind patterns and the firefighters' capacity to contain small fires before they escalate into wildfires.

Assuming the drought index is the main stress factor, a critical stress measure would identify the minimum drought level at which wildfires occur and flag those with low levels as fragile. A damage-conditioned measure would classify the area as fragile if, given a specific drought index, wildfires occur. A conditional probability measure would estimate the likelihood of an occurrence given a particular drought index. An unconditional probability measure would assign fragility based on the probability of the municipality catching fire given an expected distribution of drought stress. Finally, a composite index would combine multiple factors such as vegetation dryness, temperature anomalies, and historical fire frequency into a single score.

If the drought index were the sole relevant and well-predicted stressor, deterministic measures or conditional probabilities would be feasible. However, given the high uncertainty inherent in the process, unconditional probabilities and indices become more practical candidates. Suppose sufficient data are available to estimate Pr(Wildfire) reliably. In that case, one could train a model using inputs such as drought indices, vegetation density, the presence of barbecue or camping areas, recent lightning activity, and historical fire records.

What are the policies that could be directed with this fragility measure? Preventive policies that aim to reduce the probability Pr(Wildfire), might involve interventions such as vegetation management or fire bans. The mayor's office could direct resources to clean specific surfaces in the municipalities, for example, by putting power lines in the area underground, improving insulation, or banning barbecues in certain areas during dry seasons. Mitigation policies might involve insurance schemes for homeowners and farmers. Containment could focus on firefighting and evacuation plans, while recovery strategies may prioritize replanting.

(ii) Housing loss

In this case, the failure definition is the loss of urban infrastructure. Failure could be defined, for example, as the destruction of at least one residential structure due to a wildfire in the municipality.[20]

20. Formally, let d denote the number of residential properties destroyed due to wildfire. Failure is then defined as $y = 1$ if $d \geq d^* = 1$.

The stress–damage process now requires an understanding of how wildfires spread into urban areas and damage homes. Internal characteristics ($\mathbf{x}$) may include housing materials, urban layout, and the proximity of buildings to natural vegetation. Stress factors ($\mathbf{s}$) can be summarized by fireline intensity, which is a standard measure of wildfire destructive power that reflects fuel type and rate of spread. External influences ($\mathbf{z}$) include weather conditions and provision of firefighting support through federal coordination.

Assuming that fireline intensity is the main stressor, a critical stress measure would identify the level of fireline intensity at which housing loss occurs. A damage-conditioned measure would classify an area as fragile if even low fireline intensity levels lead to residential destruction. A conditional probability measure would estimate the likelihood of housing destruction given a specific fireline intensity. An unconditional probability measure would reflect the overall likelihood of destruction due to wildfire. Finally, a composite index could combine several factors into a single fragility score.

Given that the problem focuses on residences rather than the entire area, deterministic and conditional probability appear more feasible to construct than in the previous case. However, suppose there is still enough uncertainty about how fireline intensity translates into destruction to rule out deterministic measures. The interesting candidates are then the conditional probability $\Pr(\text{Destruction} \mid FI_i)$, where FI_i denotes a specific level of fireline intensity, and the unconditional probability $\Pr(\text{Destruction})$. While the conditional measure focuses on how wildfire penetrates the urban perimeter, the unconditional probability also accounts for the occurrence of wildfires and fireline intensities, as shown by:

$$\underbrace{\Pr(\text{Destruction})}_{\text{U.Prob of (ii)}} = \sum_{FI_i \in S} \underbrace{\Pr(\text{Destruction} \mid FI_i)}_{\text{C.Prob of (ii)}} \cdot \Pr(FI_i \mid \text{Wildfire}) \cdot \underbrace{\Pr(\text{Wildfire})}_{\text{U.Prob of (i)}} \tag{2}$$

This equation connects the three measures of fragility: the two discussed here plus the one from scenario (i). Note how $\Pr(\text{Destruction} \mid FI_i)$ focuses on how fireline intensity translates into destruction. $\Pr(\text{Wildfire})$ focuses on wildfire occurrence and $\Pr(FI_i \mid \text{Wildfire})$ models how fireline intensity builds when wildfires occur. Meanwhile, $\Pr(\text{Destruction})$ accounts for all three aspects jointly.

The choice between measures depends on data availability. The unconditional probability $\Pr(\text{Destruction})$ can be estimated directly, without explicitly modeling either the probability of wildfire, fireline intensity and the set of conditional probabilities. This can be done using data on building destruction through wildfires, urban sprawl into vegetated areas, climatic conditions, and firefighting capacities. The unconditional measure is attractive when data on destruction through wildfires is easily available, whereas wildfire data is patchy. However, it could also be that building the function Pr(Destruction | FI_i) is relatively easy because housing destruction data and data on fireline intensity are available.

In any case, the choice of fragility measure directly shapes the type of preventive policy to reduce it. If the measure is the conditional probability Pr(Destruction | FI_i), preventive efforts focus on housing characteristics, such as promoting fire-resistant construction and retrofitting vulnerable buildings. In contrast, if the measure is the unconditional probability Pr(Destruction), preventive action can also address the likelihood and spread of wildfires, for example, by managing fuel loads or limiting fire transmission from rural to urban areas. The other types of policy responses follow similar lines across both measures. Mitigation may involve collective insurance schemes. Containment would involve rapid-response logistics, evacuation plans, and temporary shelters. Recovery would focus on reconstruction and financial support for rebuilding.

Note, how the different failure definitions in (i) and (ii) lead to completely different design challenges, estimation methods, data requirements and would target different parts of the city administration for a policy response to the fragility measure.

5 Conclusion

This paper develops a general framework for defining and measuring fragility, grounded in the idea that fragility is the ease with which failure occurs. It clarifies how fragility differs from risk and resilience, while also identifying how the concepts relate. By examining the process through which an object fails, the framework offers a structured and transferable way to conceptualize fragility across domains.

The framework identifies five types of fragility measures—two deterministic, two probabilistic, and one composite—each reflecting a trade-off between causal interpretability and operational feasibility. We also present a step-by-step approach to designing fragility measures and show how they support different types of policy responses. Through both the theoretical framework and the policy application, a central message emerges: defining failure is a foundational step. Any ambiguity in what constitutes failure directly affects measurement and decision-making.

As fragility becomes a central concept in research and policymaking in many fields, this framework provides a foundation for building a shared understanding of the concept and offers guidance for developing fragility measures. The measures we identify represent a coherent set derived from our definition of fragility, which are also used in the existing literature. These measures should not be seen as exhaustive. Future work could expand the framework by identifying and integrating additional measures.

Finally, while we provide definitions for risk and resilience, our focus remains on fragility. These concepts are discussed only to distinguish them conceptually. Developing analogous frameworks for risk and resilience is a key task for future research to support a more integrated understanding.

References

African Development Bank Group. 2022. "Bank Group's Strategy for Addressing Fragility and Building Resilience in Africa (2022–2026)." Transition States Coordination Office (RDTS), *African Development Bank Group* (March). Accessed May 8, 2025. https://www.afdb.org/en/documents/bank-groups-strategy-addressing-fragility-and-building-resilience-africa-2022-2026.

Angell, C Austen. 1995. "Formation of glasses from liquids and biopolymers." *Science* 267 (5206): 1924–1935.

Al-Asadi, Mohammed, Michelle Sherren, Hassaan Abdel Khalik, Timothy Leroux, Olufemi R Ayeni, Kim Madden, and Moin Khan. 2024. "The continuous fragility index of statistically significant findings in randomized controlled trials that compare interventions for anterior shoulder instability." *The American Journal of Sports Medicine* 52 (10): 2667–2675.

Aspachs, Oriol, Charles AE Goodhart, Dimitrios P Tsomocos, and Lea Zicchino. 2007. "Towards a measure of financial fragility." *Annals of finance* 3:37–74.

Aven, Terje, Yakov Ben-Haim, Henning Boje Andersen, Tony Cox, Enrique López Droguett, Michael Greenberg, Seth D Guikema, Wolfgang Kröger, Ortwin Renn, Kimberly M Thompson, et al. 2018. "Society for risk analysis glossary."

Baylis, Patrick, and Judson Boomhower. 2023. "The Economic Incidence of Wildfire Suppression in the United States." *American Economic Journal: Applied Economics* 15, no. 1 (January): 442–73. https://doi.org/10.1257/app.20200662. https://www.aeaweb.org/articles?id=10.1257/app.20200662.

Baylis, Patrick W., and Judson Boomhower. 2021. *Mandated vs. Voluntary Adaptation to Natural Disasters: The Case of U.S. Wildfires.* Working Paper 29621. Cambridge, MA: National Bureau of Economic Research, December. https://doi.org/10.3386/w29621. http://www.nber.org/papers/w29621.

Besley, Timothy, and Torsten Persson. 2011. "Fragile states and development policy." *Journal of the European Economic Association* 9 (3): 371–398.

Birhanu, Zewdie, Argaw Ambelu, Negalign Berhanu, Abraraw Tesfaye, and Kifle Woldemichael. 2017. "Understanding resilience dimensions and adaptive strategies to the impact of recurrent droughts in Borana Zone, Oromia Region, Ethiopia: A grounded theory approach." *International journal of environmental research and public health* 14 (2): 118.

Bosetti, Louise, Alexandra Ivanovic, and Menaal Munshey. 2016. "Fragility, risk, and resilience: a review of existing frameworks." *UN University Centre for Policy Research, Background Paper, October* 3.

Brunnermeier, Markus K, and Lasse Heje Pedersen. 2009. "Market liquidity and funding liquidity." *The review of financial studies* 22 (6): 2201–2238.

Callister, William D, and David G Rethwisch. 2000. *Fundamentals of materials science and engineering.* Vol. 471660817. Wiley London.

Chami, Ralph, Raphael A Espinoza, Raphael Espinoza, and Peter J Montiel. 2021. *Macroeconomic policy in fragile states.* Oxford University Press.

Constas, Mea, Timothy R Frankenberger, John Hoddinott, Nancy Mock, Donato Romano, Chris Bene, and Dan Maxwell. 2014. "A common analytical model for resilience measurement: Causal framework and methodological options." *Resilience Measurement Technical Working Group, FSiN Technical Series Paper* 2:52.

Demirgüç-Kunt, Asli, and Enrica Detragiache. 1998. *Financial liberalization and financial fragility.* 1917. World Bank Publications.

Diaconu, Karin, Jennifer Falconer, Nicole Vidal, Fiona O'May, Esther Azasi, Kelly Elimian, Ibrahim Bou-Orm, Cristina Sarb, Sophie Witter, and Alastair Ager. 2020. "Understanding fragility: implications for global health research and practice." *Health policy and planning* 35 (2): 235–243.

Dictionary, Cambridge. 2025. *Risk.* Accessed May 7, 2025. https://dictionary.cambridge.org/us/dictionary/english/risk.

Dictionary, Merriam-Webster. 2025. *Fragility.* Accessed May 7, 2025. https://www.merriam-webster.com/dictionary/fragility.

Elliott, Matthew, Benjamin Golub, and Matthew V Leduc. 2022. "Supply network formation and fragility." *American Economic Review* 112 (8): 2701–2747.

Erberik, Murat Altug. 2015. "Seismic Fragility Analysis." In *Encyclopedia of Earthquake Engineering,* edited by M. Beer, I. Kougioumtzoglou, E. Patelli, and I.K. Au. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-36197-5_387-1. https://doi.org/10.1007/978-3-642-36197-5_387-1.

Feinstein, Alvan R. 1990. "The unit fragility index: an additional appraisal of "statistical significance" for a contrast of two proportions." *Journal of Clinical Epidemiology* 43 (2): 201–209.

Ferreira, Ines A. 2017. "Measuring state fragility: a review of the theoretical groundings of existing approaches." *Third World Quarterly* 38 (6): 1291–1309.

Folke, Carl. 2016. "Resilience (republished)." *Ecology and society* 21 (4).

Fu, Xing, Hong-Nan Li, and Gang Li. 2016. "Fragility analysis and estimation of collapse status for transmission tower subjected to wind and rain loads." *Structural safety* 58:1–10.

Gernay, Thomas, Negar Elhami Khorasani, and Maria Garlock. 2016. "Fire fragility curves for steel buildings in a community context: A methodology." *Engineering Structures* 113:259–276.

Goodhart, Charles AE, Pojanart Sunirand, and Dimitrios P Tsomocos. 2006. "A model to analyse financial fragility." *Economic Theory* 27:107–142.

Haimes, Yacov Y. 2009. "On the complex definition of risk: A systems-based approach." *Risk Analysis: An International Journal* 29 (12): 1647–1654.

Holling, Crawford S, et al. 1973. *Resilience and stability of ecological systems.*

Lorenz, Jan, Stefano Battiston, and Frank Schweitzer. 2009. "Systemic risk in a unifying framework for cascading processes on networks." *The European Physical Journal B* 71:441–460.

Lowrance, William W. 1976. *Of Acceptable Risk: Science and the Determination of Safety.* Los Altos, California: William Kaufmann, Inc. ISBN: 0913232300.

Marin-Ferrer, Montserrat, Laura Vernaccini, and Karmen Poljansek. 2017. *Index for Risk Management INFORM Concept and Methodology Report — Version 2017.* Technical report EUR 28655 EN. Publications Office of the European Union. https://doi.org/10.2760/094023.

Mastronardi, Luigi, Aurora Cavallo, and Luca Romagnoli. 2022. "A novel composite environmental fragility index to analyse Italian ecoregions' vulnerability." *Land Use Policy* 122:106352.

Mibang, Durga, and Satyabrata Choudhury. 2021. "Seismic Reliability of Structures Based on Fragility Analysis: A Review." In *International Conference on Advances in Structural Mechanics and Applications,* 535–551. Springer.

Milante, Gary, Zina Nimeh, Kaj Thomsson, et al. 2023. "Why do we still measure state fragility?"

Mueller, Hannes. 2018. "Fragility in the Data." *Background paper for Paul Collier, Tim Besley, and Adnan Khan (eds.)*

Muntasir Billah, AHM, and M Shahria Alam. 2015. "Seismic fragility assessment of highway bridges: a state-of-the-art review." *Structure and infrastructure engineering* 11 (6): 804–832.

Nilsson, Christer, and Gunnell Grelsson. 1995. "The fragility of ecosystems: a review." *Journal of Applied Ecology,* 677–692.

OECD. 2016. *States of Fragility 2016: Understanding Violence.* Technical report. Report. Paris: OECD Publishing. Accessed May 8, 2025. https://doi.org/10.1787/9789264267213-en.

Oxford English Dictionary. 2025. *fragility, n.* Accessed May 7, 2025. https://www.oed.com/dictionary/fragility_n.

Pimm, Stuart L. 1984. "The complexity and stability of ecosystems." *Nature* 307 (5949): 321–326.

Sanín, Francisco Gutiérrez. 2011. "Evaluating state performance: a critical view of state failure and fragility indexes." *The European Journal of Development Research* 23:20–42.

Schroeder, Susan. 2009. "Defining and detecting financial fragility: New Zealand's experience." *International Journal of Social Economics* 36 (3): 287–307.

Society for Risk Analysis. 1987. *1987 Annual Meeting to Address National, Individual Risks.* Published in RISK Newsletter, Vol. 7, No. 3. Society for Risk Analysis.

Taleb, Nassim Nicholas. 2012. *Antifragile: Things That Gain from Disorder.* New York: Random House. ISBN: 9781400067824.

Taleb, Nassim Nicholas, and Raphaël Douady. 2013. "Mathematical definition, mapping, and detection of (anti) fragility." *Quantitative Finance* 13 (11): 1677–1689.

Tignanelli, Christopher J, and Lena M Napolitano. 2019. "The fragility index in randomized clinical trials as a means of optimizing patient care." *JAMA surgery* 154 (1): 74–79.

Tsomocos, Dimitrios P. 2003. "Equilibrium analysis, banking and financial instability." *Journal of mathematical economics* 39 (5-6): 619–655.

UNDP. 2011. *Governance for Peace: Securing the Social Contract.* UNDP Report 978-92-1-126335-0. New York, NY: United Nations Development Programme. https://www.undp.org/publications/governance-peace-securing-social-contract.

———. 2016. *UNDP Offer on SDG Implementation in Fragile Situations.* UNDP Report. Accessed April 25, 2025. New York, NY: United Nations Development Programme. https://www.undp.org/sites/g/files/zskgke326/files/publications/SDG_Implementation_in_Fragile_States.pdf.

UNISDR. 2009. *UNISDR Terminology on Disaster Risk Reduction.* Technical report. English version. United Nations.

Van Order, Robert. 2006. "A model of financial structure and financial fragility." *Journal of Money, Credit and Banking,* 565–585.

Walsh, Michael, Sadeesh K Srinathan, Daniel F McAuley, Marko Mrkobrada, Oren Levine, Christine Ribic, Amber O Molnar, Neil D Dattani, Andrew Burke, Gordon Guyatt, et al. 2014. "The statistical significance of randomized controlled trial results is frequently fragile: a case for a Fragility Index." *Journal of clinical epidemiology* 67 (6): 622–628.

WHO. 2024. *Fragility Fractures.* Technical report. Fact sheet, published 25 September 2024. World Health Organization, September. Accessed May 7, 2025. https://www.who.int/news-room/fact-sheets/detail/fragility-fractures.

World Bank. 2020. *World Bank Group Strategy for Fragility, Conflict, and Violence 2020–2025.* Technical report. Strategy Document. Washington, DC: World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/844591582815510521.

———. 2024. *Classification of Fragility and Conflict Situations (FCS) for World Bank Group Engagement.* Accessed: 2025-05-22. https://thedocs.worldbank.org/en/doc/fb0f93e8e3375803bce211ab1218ef2a-0090082023/original/Classification-of-Fragility-and-Conflict-Situations-FY24.pdf.

Ziaja, Sebastian, Jörn Grävingholt, and Merle Kreibaum. 2019. "Constellations of fragility: An empirical typology of states." *Studies in Comparative International Development* 54:299–321.

Appendices

A List of fragility definitions across fields

Table A1: List of fragility definitions

Domain	Author	Definition
Environmental science	Mastronardi et al. (2022)	Environmental fragility is the susceptibility of an area to change as a result of a disturbance.
Environmental science	Nilsson and Grelsson (1995)	Fragility is the inverse of stability.
Financial economics	Brunnermeier and Pedersen (2009)	Fragility is the property that a small change in fundamentals can lead to a large jump in illiquidity.
Financial economics	Demirgüç-Kunt and Detragiache (1998)	Fragility is the likelihood of a banking crisis.*
Financial economics	Tsomocos (2003), Goodhart et al. (2006), and Aspachs et al. (2007)	Fragility is the combination of probability of default together with bank profitability.
Financial economics	Van Order (2006)	Fragility is the condition when small parameter changes can lead to discontinuous changes in interest rates, asset prices, and market structure.
General / cross-domain	Taleb (2012)	Fragility is the susceptibility to harm from variability, shocks, or disorder.*
General / cross-domain	Taleb and Douady (2013)	Fragility is the condition in which a small—or at least reasonable—uncertainty on the macro-parameter of a distribution may have dramatic consequences on the result of a given stress test, or on some measure that depends on the left tail of the distribution.*

Health – clinical	WHO (2024)	Fragility, from fragility fracture, is the structural weakness of bones that predisposes them to fractures from minimal trauma.*
Health – statistical	Feinstein (1990), Walsh et al. (2014), Al-Asadi et al. (2024), and Tignanelli and Napolitano (2019)	Fragility is the susceptibility of a statistically significant result to lose significance due to minimal changes in event data.*
Health – systems	Diaconu et al. (2020)	Fragility is the breakdown or dysfunction in the interaction between health systems and the communities they serve, marked by a lack of trust, stigma, inequity, bias, and reinforcing power imbalances between providers and patients.*
Network science	Lorenz et al. (2009)	Fragility is defined as the inverse or opposite of the node's health.*
Network science - supply chain	Elliott et al. (2022)	Fragility is the condition when small unanticipated shocks can trigger a collapse in production.*
Seismic analysis	Erberik (2015)	Fragility is the proneness of a structural component or a system to fail to perform satisfactorily under a predefined limit state when subjected to an extensive range of seismic action.
State fragility	African Development Bank Group (2022)	Fragility is a condition where the exposure to internal or external pressures exceeds existing capacities to prevent, respond to, and recover from them, creating risks of instability.
State fragility	Chami et al. (2021)	Fragility is the probability of becoming a failed state, which is a situation in which a country's governmental apparatus is of limited effectiveness in delivering a broad range of public services.

State fragility	Mueller (2018)	Fragility is defined as the likelihood of state failure, which is the inability of a state to prevent an economic or political crisis that threatens the welfare of its population.
State fragility	OECD (2016)	Fragility is the combination of exposure to risk and insufficient capacity of the state, system, or community to manage, absorb, or mitigate those risks.
State fragility	World Bank (2024)	Fragility is defined as a systemic condition or situation characterized by an extremely low level of institutional and governance capacity, which significantly impedes the state's ability to function effectively, maintain peace, and foster economic and social development.
State fragility	Ziaja et al. (2019)	Fragility is defined as deficiencies in one or more of the three core functions of the state. These functions include state authority, state capacity, and state legitimacy.
Structural engineering	Mibang and Choudhury (2021)	Fragility may be defined as the probability of exceedance of the demand acting on the structure over the structure's capacity for a specified intensity measure.

Note: This table presents a selected—not exhaustive—set of field-specific definitions across different domains that explicitly define fragility. *Interpretation of the authors' notion of fragility, based implicitly on terms like "fragile" or the measure of fragility, and the conceptual context of the cited work.

Source: Authors' elaboration.

B Measures of risk and resilience

Risk combines the probability of an event with its negative consequences. Let $y \in \{0, 1\}$ denote occurrence of the event, and let L be the loss random variable. By the *law of total expectation*,

$$\mathbb{E}[L] = \underbrace{\mathbb{E}[L \mid y = 1] \Pr(y = 1)}_{Risk} + \mathbb{E}[L \mid y = 0] \Pr(y = 0)$$

Here, risk is the expected incremental loss due to the event: $Risk = \mathbb{E}[L \mid y = 1] \Pr(y = 1)$. If there is no loss when the event does not occur ($\mathbb{E}[L \mid y = 0] = 0$), then $Risk = \mathbb{E}[L]$.

When the event of analysis is a failure, an increase in the fragility measure ($\Pr(y = 1)$) will raise risk, holding impact constant. This also shows that risk can remain small even when fragility is high if the impact is low. The consequences of failure, represented by L, need not be the object's damage; they may capture any dimension affected by the failure. If L is the object's damage at failure, then $Risk = d^* \cdot \Pr(y = 1)$. If L is the binary indicator of failure itself, then $Risk = \Pr(y = 1)$, which coincides with the fragility measure.

Resilience refers to the capacity of a system to recover from damage and has an intrinsic time dimension. Let t denote time, and define s_t as the stress applied at time t, and d_{t+a} as the damage level at time $t + a$, with $a \geq 0$. This implies that stress is applied at least at or before the damage occurs. Let $\underline{d}$ represent the reference (or baseline) damage level, which could be zero or any predefined target. Define also the recovery time a^* such that $d_{t+a} > \underline{d}$ for all $a < a^*$, and $d_{t+a} \leq \underline{d}$ for all $a \geq a^*$. Then, a possible set of deterministic resilience measures includes:

- **Time to recovery:** $Resilience = h(a^*)$, where $h(\cdot)$ is a decreasing function.
- **Maximum stress in elastic range:** $Resilience = g(s_t^*)$, where $g(\cdot)$ is an increasing function, such that for all $s_t \geq s_t^*$, it holds that $a^* > \overline{a}$, with $\overline{a} \in (0, \infty)$ representing the maximum allowable time to wait for recovery.
- **Maximum damage in elastic range:** $Resilience = h(d_t^*)$, where $h(\cdot)$ is a decreasing function, such that for all $d_t \geq d_t^*$, it holds that $a^* > \overline{a}$, with $\overline{a} \in (0, \infty)$ representing the maximum allowable time to wait for recovery.

A possible set of probabilistic resilience measures includes:

- **Conditional probability of recovery:** $\Pr(d_{t+\overline{a}} \leq \underline{d} \mid s_t)$ with $\overline{a} \in (0, \infty)$ representing the maximum allowable time to wait for recovery.
- **Unconditional probability of recovery:** $\Pr(d_{t+\overline{a}} \leq \underline{d})$ with $\overline{a} \in (0, \infty)$ representing the maximum allowable time to wait for recovery.

An index measure can also be constructed by aggregating indicators that proxy for the elements involved in these measures.