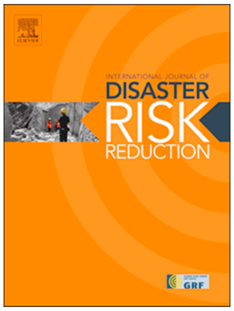

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# Resilience Stress Testing for Critical Infrastructure

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## Abstract

Critical infrastructure is vulnerable to systemic long-term stressors such as climate change, as well as shocks from extreme weather events, economic disruptions, and cyber failures. The complexity and interdependencies across critical infrastructure domains makes it susceptible to cascading failures, with the SARS-CoV-2 pandemic is the most recent example of disruptions in supply chains, healthcare and emergency facilities. Stress testing offers a conceptual framework and methodology for identifying risks associated with cascading failures and selecting mitigation and recovery strategies. This paper reviews the fundamentals of stress-testing science and practice in different fields (medicine, engineering, economics) and identifies challenges associated with the application of existing methodologies to infrastructure systems. The currently practiced risk-based stress testing approaches may only be of limited use because they merely aim to identify the components of failing systems by varying stress loads. Adding a systems-thinking perspective and consideration of interconnectedness across system domains facilitates resilience stress testing (i.e., the impact of disruptions on the system's ability to recover and adapt). We propose combining risk and resilience stress testing into a tiered approach applicable to complex, interconnected infrastructure.

**Keywords**
Stress testing; critical infrastructure; resilience

## 1. Introduction

More than ever, society is dependent upon complex and interconnected infrastructure to fulfill all the functions of modern life. Infrastructure centralization and interconnectivity has harnessed efficiencies that provide faster, less expensive, and more advanced service capabilities for developed and developing nations alike[1]. Yet, the same nested network dependencies that enable advanced infrastructural services equally enable systemic failure – fostering extensive societal losses more debilitating than in decades past [2, 3]. Where the trend towards nested infrastructure dependencies is only accelerating, a critical question has emerged: what can societies do to better safeguard themselves from systemic risks affecting infrastructure?

Many national and international organizations have grappled with the need to anticipate catalysts that may degrade or destroy various forms of critical infrastructure. For example, the United Nations' Sustainable Development Goal #9 (SDG 9) calls to "build resilient infrastructure, meaning decision-makers must seek to create infrastructure that can "resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner" [4, 5]. Target D of the Sendai Framework complements this SDG, calling for the substantial reduction of disaster damage to critical infrastructure [6]. Other documents such as the 2022 UN Global Assessment Report (GAR), have further highlighted the need for shifting toward a more holistic approach to address the systemic nature of risk, particularly given a region's exposure to compounding vulnerabilities [7]. In response to this international imperative for analyzing the intricate interaction of systemic risk and infrastructure, stress testing has been offered as a response.

A necessary first step to address this question must include an analysis of the single-points-of-failure that arise when systems affecting the infrastructure system (environment, society, etc.) operate beyond normal conditions. Known colloquially as ‘stress testing’, this methodology seeks to identify the conditions where infrastructure system failure is possible. A “stress” as it refers to stress an episodic or prolonged disruptive event, have previously relied upon scenario analyses for validation. In the documents released by the Dent [8], stress testing is calibrated on the conditions of “severe but plausible” events and the tolerance of organizations for disruptions, assuming the event will happen.

Borrowing concepts from medicine and engineering [9-11], stress testing has emerged as one of the prominent regulatory mechanisms in the financial and nuclear industries after catastrophes [12, 13]. In these applications, stress testing identifies risks that must be avoided, such as the collapse of the housing market or nuclear reactor meltdown. These risk-focused stress test exercises are important to understand how to prepare and absorb a similar shock, but as systems become more intricate, their levels and modes of disruption increase and spread [14, 15]. Stress testing must evolve to not only incorporate these risks and determine how to withstand their impacts, but to overcome them.

The risk stress testing methodology does not scale well as the system becomes larger and more interconnected. An example of a system which is too large to model in this fashion is the global supply chain, in which modeling every component is not feasible. In critical infrastructure, such component level stress-related analysis may be especially limited because of interconnected nature of complex infrastructure systems often affected by compounding threats resulting in cascading failures [16, 17]. However, as critical infrastructure becomes increasingly interconnected, it is becoming imperative to develop methods which can scale to understand how infrastructural systems collapse and recover in the midst of crises.

Unlike risk assessment that starts with specific threat scenario and focus on vulnerabilities at component level, resilience analytics favors a more threat agnostic approach – evaluating the structure and interdependencies of a system to assess how the system performs under degraded conditions [18]. Implicit within resilience are considerations of how systems with degraded functionality (disrupted nodes or severed/degraded links) can recover and adapt after a range of potential stressors – particularly those akin to a ‘one hundred year event.’ For disciplines from economics and finance to physical infrastructure, both methodologies are necessary and useful, yet systems analysis using resilience analytics has only recently become a more commonly requested practice.

To both (a) establish a method to stress test resilience of critical infrastructure, and (b) scale that methodology to maximize its accessibility for a range of users, this paper describes a tiered approach that guides the assessment of both risk and resilience that is under development by UN Office of Disaster Risk Reduction [19]. For any infrastructure resilience stress test, it is imperative to balance customizability of the analysis (analyzing conditions as close to the real-world as possible) against practicality (the time and resource constraints to conduct such assessment for a range of stakeholders). In turn, a tiered approach provides transparency and structure to infrastructure stress testing, while utilizing available quantitative and qualitative information to inform where and how infrastructure systems may buckle under pressure.

## 2. Stress Testing Origins, Methodological Framing and Use in Different Sectors

To assess state of application of stress testing methodology at system level, a representative literature search was conducted through Web of Science, which encompasses scholarly literature from all major engineering, infrastructure, and associated hard and soft science journals. Key terms that were included into the search as the review became more focused include: risk, resilience, vulnerability, infrastructure, and economy. Top-hit, highly cited papers were used to reformulate search parameters. For example, one search included following sequence of terms:

*“stress test*” >> “stress test*” resilience infrastructure >> “stress test*” resilience risk econ* infrastructure*

As the result, 120 papers were selected and sectioned into the following application sectors: financial, critical infrastructure (transportation, water, energy, telecommunications, and disaster relief), medical, manufacturing, sociopolitical, nuclear science and engineering, and computing (hardware and software).The literature review found similarity among the sectors for defining and operationalizing stress testing. Table 1 provides definitions of stress testing across each sector, but in general, a stress test can be referred to as: an analysis of how an object or system copes under pressure, typically by modeling a range of adverse scenarios that may be episodic or systemic [8]. In other words, stress testing employs a “what-if” analysis on a system and summarizes the feedback from the analysis through quantitative measures [20]. A synthesis of current stress testing literature follows.

**Table 1**. Representative stress testing based on sector with some of the methods used

| Sector | Context Behind the Definition | Methods | Representative References |
|---|---|---|---|
| Financial | “Stress testing is a process to evaluate the potential impact on company balance sheets of a specific event and/or movement in a set of financial variables. It is a simulation technique used on asset and liability portfolios to determine their reactions to different financial situations” [12] | Basel stress tests, reverse stress tests, federal stress tests | Jokivuolle et al., 2008, Grigat & Caccioli, 2017, Blundell-Wignall & Slovik, 2010; Dent, 2016; Kenett et al., n.d. [8, 22-25] |
| Critical Infrastructure | Stress tests employ low-probability, high-consequence events on critical infrastructure systems (telecommunication, transportation, and water networks) to tabulate their vulnerability and resilience from the event [26] | Decision support tools Boolean networks Indices MCDA | Croope & McNeil, 2011, Sabeur et al., 2017, Tsionis et al., 2016, Galbusera et al., 2018, Comes et al., 2013; EPA, 2015; Esposito, 2016; Lam, 2019; Nikolopoulos, 2022 [27- 35] |
| Medical | Stress testing requires patients to undergo activity while having certain vitals monitored to provide an indication of overall or specified health [9] | Trier Social Stress Test, Coronary stress tests | Narvaez Linares et al., 2020, Miller et al., 2001 [36, 37] |
| Engineering | Stress tests place increasing loads on materials to determine their durabilities | Material stress tests | Atrens et al., 1993; Bai et al., 1989; Liu et al., 2013, 2022; Winzer et al., 2008; [38-42] |
| Manufacturing | Stress tests place infrequent, high-impact disruptions on supply chains in order to identify where weakness exists to make more resilient supply chains [43] | Risk exposure indices | Hacke, 2019; Simchi-Levi et al., 2014, 2015, 2018, 2019 [43-47] |
| Sociopolitical | Stress tests analyze the effects on groups from theoretical natural or malicious hazards to inform more resilient generations [48] | Resilience matrices, Agent based modeling Vulnerability assessments | Uda & Kennedy, 2018, Sobiech, 2012, Buckle et al., 2000; Matsuyama et al., 2020 [49-52] |

| | | | |
|---|---|---|---|
| Nuclear Industry | Stress tests determine the state of nuclear system by assessing performance beyond normal operating procedures | Biaxial material stress tests Gap analyses | Shinozaki et al., 2014, Jeong & Yun, 2018 [12, 53] |
| Computing | Hardware stress tests evaluate the performance of processors under specific load on the computer, whereas a software stress test evaluates an application's ability to perform efficiently in high-stakes scenarios [54, 55] | Processor load tests<br>Software stress tests | Hackenberg et al., 2013; Schöne et al., 2021, Ester & Pedreschi, 2018 [56 -58] |

### *2.1 Early Roots: Medicine and material science*

The concept of stress testing has intellectual roots in the medical and material science sectors. To determine strength of materials, increasing tensile or compressive loads are placed on the materials [11, 38, 41]. These principles have been adopted for decades, taking form as strain tests [58]. The concept of stress testing is still maintained: apply increasing pressure to the system of interest, analyze its response, and conclude how that system may react under similar conditions. This example of stress testing takes place at a finer lens of engineering, whereas more recent developments in critical infrastructure use stress testing at a coarser view from a systems approach.

Ellestad [9] provides an introduction to the history of stress testing in the medical sector, starting in the early 20th century by monitoring a patient's heart rate before and after exercise. In general, the medical sector's principle of stress testing has remained consistent over time: monitor certain vitals or bodily response after a specific stimulus. While differing from the evaluation of stress and collapse of infrastructural systems, medical stress is grounded upon related precepts that humans are inherently complex, whose operations consist of interconnected, organic systems subject to systemic or episodic shocks and stresses [37, 57]. Human health, just like infrastructure systems, possesses ample opportunity to test a person's overall wellness before disruptive health events occur, allowing a patient time and opportunity to take corrective action if any triggers are revealed to have the potential for total system failure.

### *2.2 Post-disaster: Finance and nuclear industry*

Stress testing has been deployed in the aftermath of disasters and disruptions, particularly in response to the Global Financial Crisis (2007-2009). Dodd-Frank Act (2008) set up legal requirement for major banks in the USA to perform stress tests [59]. As stated by then-Federal Reserve chair Janet Yellen, the colloquialized *too big to fail* economy prior to the recession needed to be replaced by a resilient financial system, which is necessary for a dynamic economy [13]. While stress testing principles in the financial sector precede the financial crisis [60], the prevalence of stress-testing research from this literature review came after 2008.

Stress tests in financial industry are meant to preserve the vitality of the financial system to prevent future collapses, becoming a key part of the bank regulatory toolkit  [22, 61]. While the methodology is often scenario based, dozens of key variables are classified into an interconnected model to assess overall market risk. In other words, stress testing the financial sector is a strategy to supervise market activity to ensure more resilient behavior [25, 62]. Several strategies have been created by researchers to simplify this process, such as Basel stress testing scenarios, which were used routinely on the US bank system after the 2008-2009 recession, resulting in several revisions to the methodology itself over the years [22, 63-64]. More recent application of financial stress testing connect with climate change impacts [65] . Unlike for a typical stress test that focus on the pass or fail of banks and link the results with additional capital requirement, IMF [65] analysis aims to examine the potential magnitude of stress to banks in the event of extreme disasters and climate change. This is an example of connecting financial infrastructure to a broader range of stressors and outcomes.

Stress testing in nuclear industry was discussed following Three Mile Island (1979) and Chernobyl (1986) accidents [66], but the Fukushima nuclear accident in March 2011 resulted in a concerted international call for comprehensive stress testing procedures. Just months after, Japan announced the use of stress testing for all nuclear infrastructure [67]. The push for stress testing was felt in the EU, with the European Nuclear Safety Regulators Group (ENSREG) developing and advocating a stress-test methodology [68]. Shortly after, the EU published a comprehensive stress test assessment for all nuclear infrastructure, finding that more structure needs to be put in place for catastrophic events, such as major floods and earthquakes. The stress test was peer-reviewed over a year-long process by 17 participating countries, highlighting the need to analyze failure paths such as: initiating events, loss of safety functions, and management for severe actions [69]. ENSREG adopted these recommendations from the stress test, putting forth an action plan to renovate or restructure nuclear infrastructure or revise management and operation practices [70-71]. Stress tests continue to be used in this regard, as with the inclusion of the infrastructure's resilience stemming from the Fukushima accident [72].

### *2.3 Systems: Manufacturing, computing, and sociopolitical*

Stress testing manufacturing systems focuses on the organization and management of production through the optimization of supply chains. A range of stress tests have been proposed for the stages of the manufacturing process, such as risk mitigation for the good, developing more resilient manufacturing networks, and increasing flexibility throughout the network [44-47, 73-74]. In other words, the supply chain is broken down into singular pieces, a stress test is performed on the singular pieces, modes of improvement are adopted, and the system is made more resilient [43].

Stress tests follow a similar approach to other sectors including hardware and software. For both, a stress test is referred to as a load test that evaluates the system's ability to respond to surges in demand [55-56, 75]. Software applications apply stress testing by evaluating the performance of a system under high-pressure scenarios, such as an airborne collision avoidance system developed by NASA [54].

The sociopolitical stress testing process focuses on the movement of people in the aftermath of geopolitical disruptions and natural disasters [48. 76]. More recently the focus shifted to climate-related research, focusing on how societies can adapt to a changing climate [52, 77]. Primarily, this focuses on resilience and impact of climate change on critical infrastructure is emerging in discussions [40, 78].

### *2.4 Critical infrastructure*

The term "critical infrastructure" covers any transportation, utility, or engineered system [79]. Evaluation of such a broad range of physical infrastructure and modes of engineering has led to many applications of stress testing. Risk-based tools exist, such as stress testing for water, transportation, telecommunication, and energy [35, 41, 80]. Some of these stress tests consider critical infrastructure in isolation from other infrastructure, for example, Ray et al. [81] stress tests hydro-electric infrastructure against financial, climate, and geophysical shocks. Guo et al. [82] applied stress testing to airports against a range of disturbances to assess resilience. However, a combined approach to evaluate several sectors has also been discussed in the past decade [29-31]. These combined approaches begin to analyze how components of critical infrastructure fail in disruptive events such as the Texas Freeze [83]. Linkov et al. [19] call for the need of resilience-based stress testing tools to assess critical infrastructure systems' abilities to respond to increasingly severe disruptive events, underscoring the importance of how critical infrastructures are interdependent.

Stress testing has been operationalized by assessing the infrastructure's ability to respond to a specified threat scenario at component level. For example, European Commission's STREST project assessed critical infrastructure components as a system against a variety of disruptors [26, 84-86]. A changing climate presents a range of environmental threat scenarios, which denotes the need for stress-testing tools that assess climate's impact on critical infrastructure [87]. The World Bank Group created a risk-based stress test tool that functions as a cost-benefit analysis of critical infrastructure components' response to climate-induced shocks and stresses [88-89]. Monte Carlo algorithms [90], game theory and graph theory [79, 91-92], and the creation of various indices to tabulate vulnerable assets [93-96] are a few examples of the methods that have been formed to evaluate stress testing for critical infrastructure.

### *2.4 Stress Testing for Resilience*

The literature presents numerous applications of stress testing in different fields, but the focus is primarily on stress testing for risk. The goal is to gain understanding on how the system responds to different amounts of disruptions. Comparable to risk assessment and management where risk is quantified in comparison to acceptable performance thresholds, risk stress testing increases level of stress to identify point of systemic failure. A system under small and acceptable stress should perform well. Yet, as the amount of stress imposed across interconnected nodes and links increases, far more resources are required to sustain system functions and performance. At a given point, the stress placed upon the system becomes too great to bear, saturates across its critical functions, and collapses. Stress-strain relationship developed in materials science has been generalized for infrastructure for construction safety in general as well as disaster response in particular [97-98].

Stress testing is about understanding the point at which the system is not able to cope with the amount of load imposed on it [99]. Through such improved understanding, stakeholders can reduce system bottlenecks that hasten collapse, or identify avenues to adapt in the midst of disruption to (a) extend the system's lifespan, and/or (b) soften the degradation process via a gradual rather than abrupt decline [100].

Resilience terminology has been used in multiple studies, but connection to ability of the systems recover and adapt from threat at cross-domain level is rarely addressed. Tabletop exercises and scenario building can be used for identifying common point of failures to different threats and concurrencies, assessing escalation points that could cause "knockout" disruptions across sectors [101]. A direct consequence of this approach is in development of resilience in the financial industry, for which stress testing has been adopted to support the capacity to recover from disruptions in capital markets [102]. Recovery was analyzed by evaluating post-disruption contingency plans from low-probability, high-risk shocks in automotive manufacturing [45, 47]. Specific companies have become more concerned with stress testing in response to COVID-19 and import/export debacles, leading to measures to quantify supply chain resilience [103]. Similarly, the US Department of Energy has begun stress testing the network of electrical supply chains to evaluate the response and likelihood of catastrophic failure [104].

## **3. Proposed Tiered Methodology for Resilience Stress Testing**

Tiered assessment approaches have been applied to risk management in various applications in order to make a transparent, repeatable, and scientifically-informed governance process that aids regulatory evaluation. Linkov et al. [18] proposed to extend tired risk analytics approach towards resilience, but operationalization and application of this proposal are limited at best. Linkov et al. [18] argued that extending risk tiers towards resilience requires evaluation of different disruption scenarios, but stopped short of devising stress testing approach. Figure 1 builds on the ideas presented in Linkov et al. [18], but specifically operationalizes combined risk and resilience stress testing. Scaling from least to greatest analytical requirements (and, likewise, least to greatest granularity in evaluating infrastructure system performance under stress), these include:

- Tier 1 is a screening level assessment framing critical system functions and analyzing changes in system connectivity in response to shocks and stressors,
- Tier 2 utilizes simplified system models to understand and quantify connections across various domains and their impacts on critical system functions,
- Tier 3 utilizes advanced modeling techniques (e.g. network science and AI) to further assess changes in interconnected networks in response to random and targeted threats and attack scenarios.

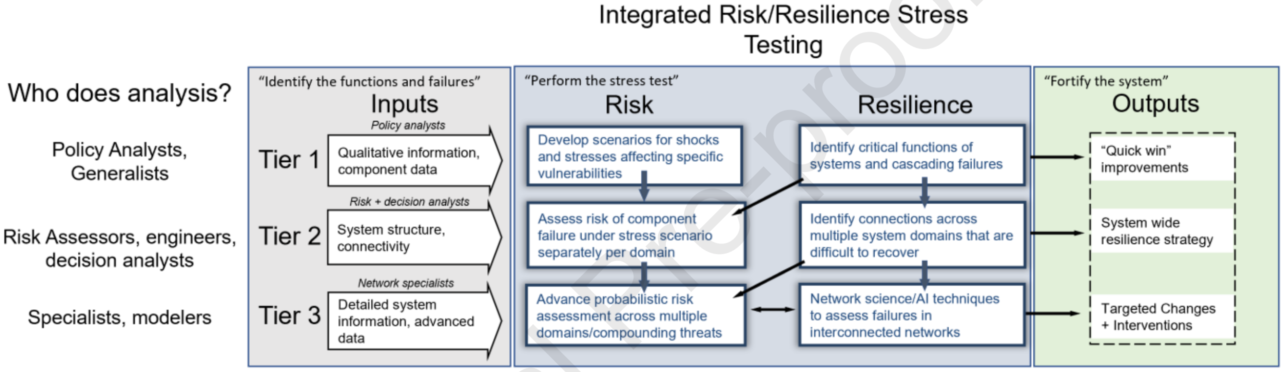
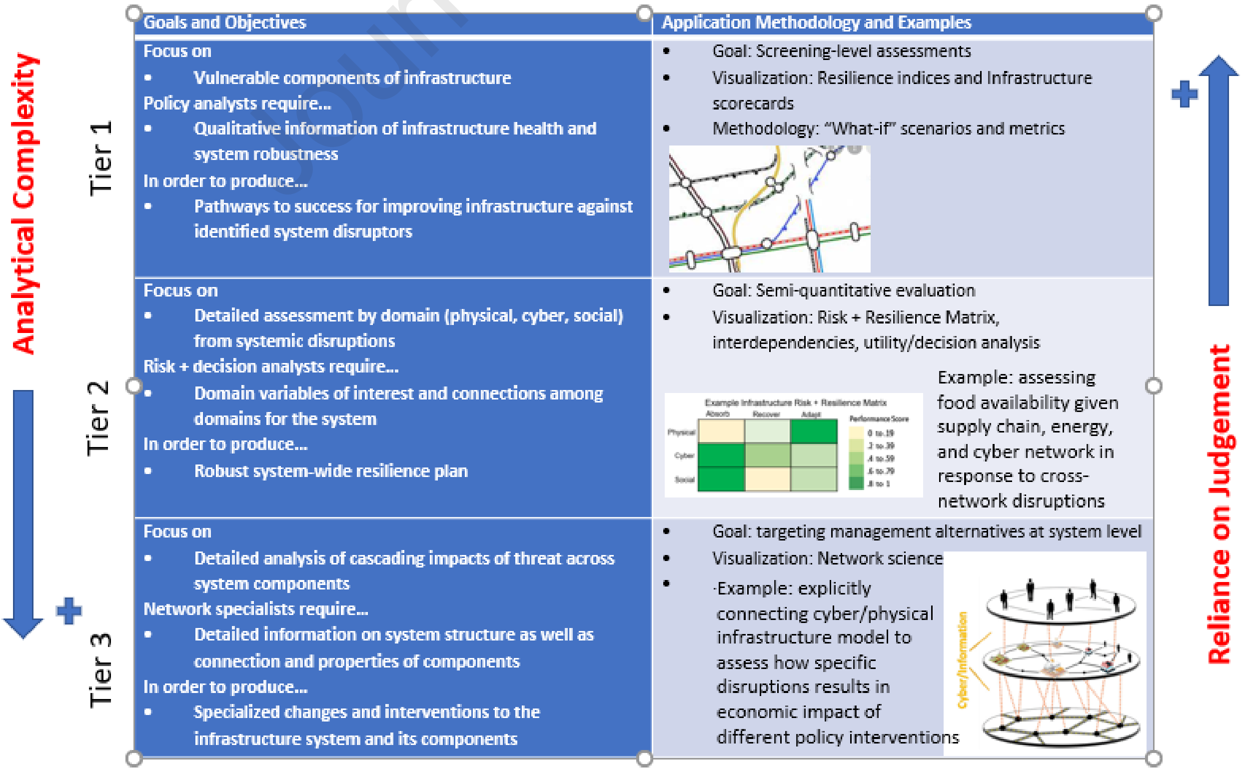


Figure 1. Tiered approach to integrated risk and resilience stress testing for critical infrastructure



| | Goals and Objectives | Application Methodology and Examples |
|---|---|---|
| Tier 1 | Focus on<br>• Vulnerable components of infrastructure<br>Policy analysts require…<br>• Qualitative information of infrastructure health and system robustness<br>In order to produce…<br>• Pathways to success for improving infrastructure against identified system disruptors | • Goal: Screening-level assessments<br>• Visualization: Resilience indices and Infrastructure scorecards<br>• Methodology: "What-if" scenarios and metrics |
| Tier 2 | Focus on<br>• Detailed assessment by domain (physical, cyber, social) from systemic disruptions<br>Risk + decision analysts require…<br>• Domain variables of interest and connections among domains for the system<br>In order to produce…<br>• Robust system-wide resilience plan | • Goal: Semi-quantitative evaluation<br>• Visualization: Risk + Resilience Matrix, interdependencies, utility/decision analysis<br>Example: assessing food availability given supply chain, energy, and cyber network in response to cross-network disruptions |
| Tier 3 | Focus on<br>• Detailed analysis of cascading impacts of threat across system components<br>Network specialists require…<br>• Detailed information on system structure as well as connection and properties of components<br>In order to produce…<br>• Specialized changes and interventions to the infrastructure system and its components | • Goal: targeting management alternatives at system level<br>• Visualization: Network science<br>• Example: explicitly connecting cyber/physical infrastructure model to assess how specific disruptions results in economic impact of different policy interventions |

Figure 2. Tiered approach to stress testing critical infrastructure with examples of applications for each tier.

The tiered approach to stress testing critical infrastructure is part of UNDRR's Principles for Resilient Infrastructure (UNDRR 2022) as a key action of the principle for continuously learning. In order to cope with potential hazards, it is important to develop strategies to continually assess resilience and expose system weaknesses through collaboration with relevant stakeholders and the public. The Principles for Resilient Infrastructure have been developed to provide guidelines to create national scale net resilience gain and improve the continuity of critical services. Net resilience gain is an innovative concept and important pillar in achieving "net-zero", requiring that all interventions into infrastructure must demonstrate that they enhance the systemic resilience of infrastructure and not contribute to any damage.

### *3.1 Tier 1 - Screening-level Assessment*

As the first stress test performance of a system, Tier 1 maps the system's critical functions and interdependencies. How does the system function? How are energy sources acquired and utilized to operate infrastructure? What are the social or operational considerations for safe infrastructure operation? And, for the infrastructure's physical assets, what are the various discrete yet interconnected parts? From these and other qualitative inquiries, analysts chart the critical functions of the given infrastructure system – those components that are essential to system operation, and by which disruption would render the most severe, longest lasting, and systemic harms.

The methods of attaining a system's critical functions and interdependencies in Tier 1 are qualitative and semi-qualitative. The toolbox for Tier 1 may include existing data, table-top exercises, or simple data analytics focused on identifying whether and where a problem exists. Process diagrams or flowcharts can be useful components of Tier 1, visualizing directed policy intervention to either deflect the harm of a disruption or strengthen the system's ability to recover. This type of methodology is already used by the Cybersecurity and Infrastructure Security Agency's (CISA) to assess cyber resilience for infrastructure systems [98]. CISA's methodology relies on interviews, plan reviews, and structured surveys to gather information about critical infrastructure to recommend areas for improvement.

The outcomes of a Tier 1 assessment point to a broad understanding of the system, and the definition of common point of failures that could compromise operational capacity. For example, a Tier 1 assessment is the American Society of Civil Engineers' Infrastructure Report Card, which uses expert-level judgment and data, subjectively scores the nation's infrastructure. With this output, policymakers and subject-matter experts (SMEs) can combine forces to explain where improvements are needed at the subsystem level.

The intended users, creators, and owners of a Tier 1 analysis are subject-matter experts and regional policymakers. Tier 1 is intended for subjectivity in its analysis; employing users that are well-versed in a country or region's critical infrastructure systems and its vulnerabilities benefits the reliability of the assessment. Furthermore, this entry-level tier is meant to be attainable at low resource expenditure, providing stakeholders with a screening-level assessment of the broad system of critical infrastructure.

### *3.2 Tier 2 – Semi-Quantitative Modeling*

The goal of a Tier 2 analysis is to identify interdependencies in a system to assess how the system's risk of cascading failures and resilience is affected at different stress levels. Interdependencies can be assessed across critical functions) as well as system domains. In-depth flowcharts and models may be useful aids in mapping the complexity of the system to explain the system, its subsystems, its critical functions, its risks, and its interdependencies

In order to attain this goal, semi-quantitative methods may be required. Notably, metrics-based approaches in Tier 2 may include matrices of resilience performance that utilize data from Tier 1 approaches but disaggregate them into sub-domains and time stages such as the Functional Resonance Analysis Method (FRAM) [105] or the Resilience Matrix [106]. Decision analysis methods, such as multi-criteria decision analysis and other structured decision approaches, provide an appropriate set of tools to evaluate scenarios, allowing an understanding of how change leads to gains or losses in the system and the impact (or lack thereof) from a particular investment [107]. By applying stress testing through resilience analysis matrices, policymakers can witness where problems arise and *when* they arise based on the timing of a disruption.

The primary outcome of Tier 2 is a semi-quantitative model that reveals how a system and its interrelated components respond to threats to improve the system’s resilience. System-wide resilience strategies can be created to resolve disharmony among multiple critical functions. Policymakers can use these resilience strategies as part of master plans that risk-based analysis alone cannot produce.

The intended users, creators, and owners of a Tier 2 analysis are risk/decision analysts and national policymakers. Consultants for risk and decision analysis may be required beyond SMEs at the government level for more rigor in quantitative analysis. These consultants are meant to simplify the findings of a Tier 2 analysis in a tangible report for national policymakers to construct a priority list for their resilience strategy. While Tier 2 requires more resources, it moves beyond a Tier 1 assessment to highlight how cascading interdependencies impact the system.

### *3.3 Tier 3 – Advanced Modeling to Assess Infrastructure Networks Against Random and Targeted Perturbation*

The goal of a Tier 3 assessment is to reveal the impact of any disruption to critical functions to the level that effective risk and resilience management plans can be developed. Ideally, this process also includes modeling of the post-disruption recovery process in order to identify intervention opportunities that reduce downtime and the potential for spillover impacts to other sections. Either sensitivity analysis or scenario analysis can provide a range of potential performance results so that resilience interventions that are robust to a range of possible futures can be developed.

The methods of Tier 3 build a detailed model of important functions and related sub-systems where each process and each component of the system is parameterized. Possible approaches include system dynamics, graph theory, Bayesian networks, and agent-based models that allow scenario analysis as well as Monte Carlo simulation to support sensitivity analysis [108]. Furthermore, network science and artificial intelligence algorithms likely will provide the most robust understanding of the system at the node-and-link level.

The outcome of a Tier 3 analysis is a detailed list of necessary interventions. These interventions exist at the system level (i. e., Tier 1 and Tier 2 outcomes), as well as at the most granular asset level. While this may encompass an exorbitant amount of feedback, this is the intention of Tier 3 since its owners must require a deep understanding of system and process dynamics. While the initial feedback will be a collection of computationally complex data, the creator will be tasked with summarizing this data into a priority list of actions.

The creators and owners of a Tier 3 analysis are network scientists and national policymakers that require a substantial grasp of the system’s dynamics. Likely, a Tier 3 analysis will not be able to be done in-house at the government level and may even require several private teams to divide and conquer the analysis phase. The owners of this analysis will likely require a high budget, ample time for a period of performance, mountainous pre-existing data, a team of SMEs, and most importantly, an inherent need or reason to have an understanding of the system that is whittled down to the most basic fibers of operation.

## 4. Application Examples and recommendations

### *5.1 Tier 1 – Infrastructure Report Card and CISA Tabletop Exercises*

A highly visible example of a Tier 1 outcome that connects to stress testing is the American Society of Engineers' Infrastructure Report Card [109]. This example follows the qualitative suggestions of this tiered framework for a Tier 1 analysis: a host of SME (civil engineers across America) group together to rank critical infrastructure based on eight principles: capacity, condition, funding, future need, operation and maintenance, public safety, resilience, and innovation. This example subjectively deduces an overall "grade" for American infrastructure, which is commonly used as a talking point in American politics. Other scorecard-based examples also represent Tier 1 effectively and should be used with stress testing in mind by applying a host of different scenarios to forecast potential responses.

The Infrastructure Report Card is meant for policymakers to more easily assess the state of infrastructure systems. While SMEs are involved in this process to boost the fidelity of the report card, the scope of the deliverable is coarse, allowing for subjectivity. Furthermore, the Infrastructure Report Card exemplifies Tier 1 work by considering the critical infrastructure elements without an overt analysis of cascading dependencies. In other words, the overall vitality of individual pieces of infrastructure are primarily assessed as opposed to the connections within different critical infrastructure components.

An example of a Tier 1 philosophy of stress testing is tabletop exercises. Tabletop exercises present a broad view of the critical infrastructure system without complex assessment. Instead, these tabletop exercises establish problem areas within critical functions, such as the National Critical Functions set developed by CISA [110]. Some assessment is done with interdependencies within the tabletop exercises, but cascading interconnections are not qualified or quantified. Similar to the Infrastructure Report Card, the fidelity of tabletop exercises, especially for stress testing, are benefitted by active participation of SMEs and key decision-makers.

### *5.2 Tier 2 – Resilience Matrix for Stress Testing*

A Tier 2 stress test quantifies interconnectedness in the system assessed in Tier 1 through simplified analytical tools at domain/element levels. Domains constitute the physical, cyber, and social elements of any system; elements include the stages of resilience, which can be simplified to the absorption, recovery, and adaptation to disruption [107, 111-112]. In other words, domains are the constructs that *form* the system (e. g., the physical infrastructure, the network functionality, and how people interact with the system), and elements of resilience are temporal indicators of how a system *responds* to disruption.

The resilience matrix [111] quantifies resilient based on metrics associated with domains and elements of resilience. Weights are applied to the individual domains and elements to indicate their importance for specific stakeholder or mission. To populate scores, metrics are used that align the domain/element relationship. For example, Fox-Lent et al. [111] populated a Physical-Absorb metric for a case study of the Rockaway Peninsula's housing through the measurement of highway miles that have a form of hardening to flooding. The physical domain is represented by highway infrastructure, and the absorb element is characterized by the measures that the Rockaway Peninsula uses for protection against coastal storms. Weights were solicited from the municipal authorities. As the result, Fox-Lent et al. [111] uncovered the gap in performance for recovery and adaptation for Rockaway Peninsula. The authors discovered that a disparity existed between the former and latter functions of resilience: preparation and absorption v. recovery and adaptation. The Rockaway Peninsula housing system was able to prepare and absorb coastal storms, but lacked the ability to recover and adapt across multiple domains.

The resilience matrix can be used in Tier 2 stress testing by factoring in various disruptions to measure a system's resilience. Taking the Rockaway Peninsula case study as an example, stress testing can be included through multiple matrices corresponding to different critical functions, which may include interconnections between the domains and extra disruptions beyond coastal storms.

### *5.3– Tier 3 Stress testing in Network Resilience Models*

A Tier 3 stress test serves as the most granular assessment of a critical infrastructure system's response to disruption from cascading failures. It provides a mapping of the system, identifying individual improvements to components of the system in the event of a certain disruption. Tier 3 is reserved for applications that require detailed analysis through network science, agent-based models, artificial intelligence, or advanced mathematics. Examples of Tier 3 risk stress testing applications exist in the financial sector through advanced mathematics with Basel stress testing [22, 63, 113], but are not as widely adopted for systems such as critical infrastructure nor for resilience evaluations.

In the context of Tier 3 resilience stress testing, network science tools can be used. Ganin et al. [114] characterized road networks in 40 major US cities as interconnected roadways (classified as links) which connected to intersections (classified as nodes). Load factors were built for the links based on live data to determine the average annual delay that motorists face from traffic and were cross-referenced to observed data. Resilience was characterized in this analysis by assessing the response in traffic congestion resulting from a random 5% loss of available roadways due to disruption. Some cities, such as Los Angeles, were found to be rather resilient by having less than a 10% increase in average traffic time for motorists, whereas cities such as San Francisco were found to not be resilient in this study with increases over 50%.

While Ganin et al.'s [114] work does not incorporate formal stress testing directly, they varied stress level across all nodes and links and this methodology can be further adapted to incorporate other elements of critical infrastructure. As the authors of this research utilized a 5% randomized loss in roadway function, stress testing analyses could operate at varying percentages of loss. Therefore, worst- and best-case scenarios can be generated to inform analysts and policymakers individual links and nodes are over or underutilized and the overall resilience of the system.

Outside of transportation, this approach was discussed in the context of supply chains, inclusive of the vital infrastructure to process, manufacture, and deliver invaluable goods and services [46-47, 115]. This form of a Tier 3 analysis provides detailed insight at the link-and-node level for systems, providing experts with the tools to inform policymakers with lists of necessary modifications to the critical infrastructure systems of interest. However, these analyses require more resources, time, and manpower than Tier 1 or Tier 2, presenting the value of information for receptive clients.

## Discussion and Conclusion

As policymakers consider extensive investments to help society 'bounce forward' from COVID disruptions, stress testing is a benchmark that must be satisfied to ensure system improvements will be able to withstand and recover from future crises. Abrupt disruptions and chaotic transitions for critical infrastructure systems are both dangerous and societally unacceptable, and can quickly cascade into various other facets of life. Both COVID-19 as well as the economic fallout from the war in Ukraine demonstrate the importance of planning for disruption, as well as the need for expeditious recovery and adaptation when disaster strikes. Instead, policymakers and infrastructure planners must consider how to best extend the useful lifespan and service delivery capabilities of both new and existing infrastructure against a wide universe of threats in a manner that minimizes loss before, during, and after an event strikes 116]. The fundamental transformation in the society requires extending and enhancing the role of stress testing and make it a universal requirement for infrastructure investment consideration worldwide.

Current approaches for stress testing are based on risk assessment that emphasizes analyzing gaps or weaknesses by which a specific threat may gain access to a given system vulnerability, and cause a degree of harms [117]. For example, in the aftermath of the 2008 Financial Crisis, the financial sector adapted a risk-based stress testing approach to evaluate how the large, interconnected networks in finance would respond to range of potentially catastrophic economic conditions. The assessment of systemic performance under variety of threat scenarios in risk stress testing resulted in hardening financial system vulnerabilities.

However, a unified stress testing methodology has not been developed in literature and the methodological approaches to stress testing are fragmented. The lack of methodological data for stress testing infrastructure makes it difficult for engineers and policymakers to evaluate proposed and existing assets. This is exacerbated by a paucity of information regarding how changes in local socioeconomic and environmental conditions contribute to a shift in infrastructure utility and performance under stress.

A streamlined stress testing tool is needed to plan for and overcome uncertainty to infrastructure systems. This tool's focus should be centered around the mitigation of future crises, taking into consideration the increased occurrence of complex scenarios where hazards can combine within interconnected networks, causing cascading effects to infrastructure systems [101]. With cascading disruption in mind, this tool must also incorporate elements of resilience at the forefront through characterizing the infrastructure system's ability to prepare, absorb, recover, and adapt to adverse events [106]. As Linkov & Trump [106] discuss, the inclusion of resilience as a central tenet for these infrastructure systems holds a "risk agnostic" point-of-view, taking into consideration any combination and duration of a hazard. As such, this stress testing tool that needs to be better explored in its application for mitigating disruption to infrastructure systems is represented by stress testing [19].

Methodologically, stress testing for critical infrastructure must accommodate both a complex system's view and navigate uncertainties in data (e.g., a limited characterization of infrastructural hazard, uncertain changes in socioeconomic habits post-shock that may alter the utility of infrastructure, etc). Fundamentally, this is an acknowledgment of the unique characteristics, challenges, and needs of each individual case and infrastructure system. To accommodate such differences, any infrastructural stress testing methodology must be both malleable and expansive, incorporating a mixture of quantitative and qualitative data. The outputs of such adjustable infrastructure assessment must further comment upon considerations of risk (evaluating potential magnitude of loss, given the introduction of one or more stressors) and resilience (evaluating the capacity for infrastructural system recovery and adaptation in the aftermath of perturbation).

Attempts to standardized infrastructural stress testing must accommodate three core challenge beyond cost and time. The stress testing methodology must: (a) delineate infrastructure systems that are placed at greater risk of disruption from a potential hazard, (b) the methodology must incorporate a systems-view of critical infrastructure that evaluates the conditions when infrastructural collapse (and a subsequent inability for recovery) becomes likely, and (c) the methodology must accommodate varying availability of risk-based data, including material properties, use-rates, future environmental and atmospheric conditions, management and data integration/analysis capabilities, and others.

A tiered approach to infrastructural testing was outlined that accommodates both an evaluation of complex systems, as well as a scalable methodology based upon the availability of data and/or the institutional resources available to conduct a basic or advanced assessment. The approach mimics conventional risk assessment practices – characterizing and evaluating risk at differing levels of scrutiny and granularity. In turn, we add an additional component – the tiering of infrastructural resilience analysis – to frame an infrastructure system's capacity to recover from and adapt to perturbation. Collectively, the risk and resilience-driven analysis informs infrastructural stress testing.

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# Resilience Stress Testing for Critical Infrastructure

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