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# ASSESSMENT OF STRAIN CAPACITIES OF POST-DISASTER CRITICAL INFRASTRUCTURE WITH RESPECT TO FUNCTIONAL AND STRUCTURAL STRESS

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**Abstract:** Critical infrastructures are essential to the effective recovery of disaster-affected communities. Adequate infrastructure services enable the communities to sustain and restore their livelihoods. However, disasters are likely to impact critical infrastructure so the infrastructure cannot maintain design capacities to support post-disaster communities. On the other hand, communities' recovery demands often increase exponentially as a consequence of disaster impacts. Therefore, critical infrastructure become susceptible to excessive stress and cannot fulfill the required function during post-disaster recovery. To successfully operate infrastructure services, critical infrastructure should have sufficient capacities to not only serve communities as designed, but also as expected. For example, in a post-disaster situation, a hospital requires certain amount of electricity, water and stream to operate building facilities and medical equipment so that it can treat as many patients as they can. But, it also needs to have redundant resources to expand its capacities so as to accommodate ex-post demand surge in the case of mass casualty events. This research utilizes a stress-strain capacity analysis to evaluate strain capacities of critical infrastructure with respect to post-disaster stress. This research evaluates strain capacities of an infrastructure with respect to both structural and functional stress and proposes a framework to develop capacity building strategies to address them. With simulation capability, we investigate the post-disaster operation of a hypothetical hospital to demonstrate how to develop capacity building strategies to mitigate functional and structural stress.

## 1 INTRODUCTION

Critical infrastructure plays an important role in the social and economic development of communities. A reliable and adequate supply of infrastructure services enables communities to sustain economic and social activities, thereby promoting their well-being (Deshmukh et al. 2011; Oh et al. 2013). In a post-disaster situation, critical infrastructure minimizes the severity of disaster impacts on communities by providing adequate infrastructure services and the requisite services needed to expedite the recovery process (Deshmukh et al. 2011). However, the capacity of infrastructure is often compromised by either direct or indirect disaster impacts. Moreover, an enormous demand for infrastructure services is likely to emerge as post-disaster recovery proceeds (Shultz et al. 2006). As a result, post-disaster infrastructures often fail to meet affected communities' demands, thus exacerbating social and economic losses (Deshmukh et al. 2011). Even when post-disaster infrastructures are overwhelmed by excessive demand, they can remain operational by relying on their limited resources; yet, they cannot accommodate communities' needs in a timely and effective manner (Choi et al. 2016). For example, in the wake of the 1999 Chi-Chi Earthquake in Taiwan, the Puli Christian Hospital could not provide advanced, timely treatment for critical patients because the hospital could only maintain limited operations (Cole 2006). Also, the limited availability of power utility in Taiwan was not sufficient to continue the production and sale of computers and semiconductors, thereby incurring substantial economic losses (Weinni 2000).

Current infrastructure planning and design practices use historical data to predict the most likely future demand trends and determine the capacity of infrastructures to serve communities by applying a certain level of safety factor (Ullman 1992). However, the projection derived from the historical data no longer serves as an appropriate guide due to the frequent occurrence of natural disasters resulting from extreme climate events (Oh 2010; Pryor et al. 2014). Specifically, during post-disaster recovery, the margin of safety of critical infrastructure is not likely to be enough to service post-disaster communities. Infrastructure facilities often utilize auxiliary capacities in addition to their designed capacity to further accommodate an excess of service demands (Choi et al. 2016). For instance, medical facilities utilize auxiliary capacities (e.g., bottled water for water utility and backup generators for electricity) in the event municipal utilities are unable to expand their operational capacities to accommodate excessive demands from communities during post-disaster recovery (Auerbach et al. 2010). As another example, when floodwater is expected to exceed the designed strength or height of a levee, the levee can be fortified with temporary flood protections or structural reinforcing systems (Oh 2010). In both cases, the infrastructure manages to support communities with at least an acceptable quality of infrastructure service (i.e., the quality of medical service for medical facilities and the protection of communities from floodwater via levees) within their capacity constraints (Choi et al. 2016; Deshmukh and Hastak 2014).

The intensity of the impact of infrastructure failures on communities often varies depending on the most limiting capacity of the critical infrastructure in question (Choi et al. 2016; Deshmukh et al. 2011). If an infrastructure does not possess the requisite infrastructure services needed to operate, it cannot function as designed (Deshmukh and Hastak 2014). By contrast, if an infrastructure faces excessive demands but remains functional, it will nonetheless be unable to provide an acceptable level of services for communities (i.e., functional failure) (Oh 2010) due to limited available resources (both auxiliary and planned capacity). For example, hospitals require a certain amount of water to operate normal medical services as designed (Welter 2010). If critical demand exceeds the amount of available water, then the hospital cannot maintain its HVAC system and risks compromising its hygiene requirements, which often results in the shutdown of the facility. On the other hand, in the event the hospital encounters an excessive number of patients during post-disaster recovery, it may provide medical services for some patients at the expense of others, who must wait longer than their critical time (Cimellaro et al. 2010). It is important to note that the degree of service disruption due to the failure of designed capacity is more substantial than that caused by the failure of the capacity to meet the surge in demand, even though communities are vulnerable to disasters in both cases. Also, the two failure modes of critical infrastructure may stem from different sets of risk factors or different types of vulnerable infrastructures (Hastak and Baim 2001). That is, in the former case, the lack of required utility services may be the primary reason for the shutdown of the healthcare facility; while in the latter, excessive medical demand may be the cause. Regardless of the mode of infrastructure failure, the failure of critical infrastructure to maintain required serviceability for post-disaster recovery could incur substantial social and economic losses (Oh 2010).

During post-disaster recovery, critical infrastructure should have sufficient capacities in place to make communities resilient to disasters. Many researchers have investigated the vulnerability of critical infrastructure through ex-ante analysis (Arboleda et al. 2009; Ezell 2007; Nateghi et al. 2014; Oh 2010). Arboleda et al. (2009) analyzed the operational vulnerability of a healthcare facility, induced by insufficient capacities of both internal and external infrastructure systems, in post-earthquake situations. Using mathematical models, the authors evaluated the capacity of external infrastructure systems (e.g., electricity, water, and road networks) with respect to the resource needs of the healthcare facility to meet medical demands in a post-earthquake scenario. Ezell (2007) presented a model to quantify the vulnerability of an infrastructure system by relying on subject matter experts' (SMEs) opinions. In the model, SMEs evaluate the protection measures of infrastructure components against specific post-disaster scenarios in terms of deterrence, detection, delay, and response, all of which are then aggregated to represent the vulnerability of the infrastructure system. Infrastructure components for capacity building are prioritized by comparing their protection score to the system's ideal score. Nateghi et al. (2014) utilized a data-mining technique (i.e., random forest approach) to estimate hurricane-induced outages prior to landfall while minimizing the data collection requirement. The model can identify the part of a power distribution system likely to be the cause of a disruption, which strengthens utility companies' efforts to coordinate restoration plans before a hurricane occurs. Oh (2010) utilized Bayesian network theory to measure the vulnerability of critical infrastructure and its consequent impacts on communities during flood event scenarios. These studies evaluated the ex-ante capacity needs of critical infrastructure from service providers' point of view, enabling them to take preventive measures for vulnerable infrastructures. However, the researchers did not consider the quality of service resulting from the vulnerable condition of critical infrastructure (e.g., patients' waiting times for a healthcare facility and utility disruption times for lifeline infrastructure). In other words, the existing studies evaluated the designed capacity of critical infrastructure, not including auxiliary capacity, to determine their vulnerability.

Capacity strategy analysis should consider both the quality of operating services and the auxiliary capacity options available to infrastructure to prevent its structural and/or functional failure. To reflect the quality of infrastructure service, Choi et al. (2017) proposed a stress–strain capacity analysis for post-disaster infrastructure that interprets the variable quality of operating services based on the relation between stress (i.e., demand) and strain capacity (i.e., coping capacity). However, Choi et al. (2017) also did not consider different failure modes of critical infrastructure when evaluating its strain capacities. Furthermore, as infrastructure networks become more interdependent and the complexity of the networks increases, identifying which vulnerable critical infrastructure causes each failure mode becomes more challenging (Deshmukh et al. 2011; Oh 2010; Oh et al. 2013).

To address the gap in existing studies, this research proposes a framework to evaluate the functional and structural stress of post-disaster infrastructures with respect to their required serviceability for post-disaster communities. It is important to note that the proposed framework builds upon the stress–strain capacity analysis proposed by Choi et al. (2017) while further categorizing infrastructure stress into two types, i.e., functional and structural stress, for capacity assessment. This is followed by the development of a framework for capacity-building strategies. The next section presents the concept of the analysis of structural and functional infrastructure stress, followed by the development of a framework for the capacity-building strategy. The implementation of the proposed framework will be demonstrated with a case study of the post-disaster operation of a healthcare infrastructure.

## 2 A NEW APPROACH TO EVALUATE FUNCTIONAL AND STRUCTURAL STRESS OF POST-DISASTER INFRASTRUCTURE

### 2.1 Stress–Strain Capacity Analysis for Post-Disaster Infrastructure

To ensure the desired infrastructure service during post-disaster recovery, Choi et al. (2017) proposed a functional stress–strain principle for evaluating the capacity of post-disaster infrastructures. In this principle, functional stress is defined as the demand placed on an infrastructure during unit time, while strain is presented as the rate at which potential capacities are used in response to the stress. Infrastructure engineers plan a certain amount of capacity to handle the stress applied by a normal operating service. However, due to the uncertainty of applied stress, infrastructure engineers also plan a certain amount of redundant (or reserve) capacity in the system to cope with additional stress. For example, a hospital is designed to use municipal supplies (i.e., planned capacity) from utility services in a normal situation. However, if municipal suppliers are no longer able to provide sufficient service due to disruptive events (e.g., disasters), the hospital could use backup generators or bottled water (i.e., reserve capacity) to meet the utility demands. The maximum stress an infrastructure can accommodate by using its planned capacity is defined as the allowable stress (*A*, *A'*, *A"*, Figure 1), while the maximum stress level an infrastructure can handle by utilizing all the available resources, including planned capacity and reserve capacity, is defined as the limit stress (*B, B', B"*, Figure 1). When the stress level is below the limit stress, an infrastructure can successfully meet demand during unit time by fully stretching its strain capacity. This state of stress of an infrastructure is represented as the elastic region. However, once the stress level exceeds the limit stress (i.e., the infrastructure is overloaded above its limit stress), the strain capacity of an infrastructure cannot handle the stress, thereby generating a backlog of service. This state is represented as the plastic region. In a pre-disaster situation, an infrastructure can use the full capacity of a resource to accommodate functional stress ($P_{std}$, Figure 1). However, in a post-disaster situation, due to disaster impacts, the capacity of an infrastructure to carry strain might be lower (①, Figure 1), thereby reducing both its allowable and limit stress ($P_{std}$, $P_{std\_post}$, Figure 1). If the stress level of an infrastructure approaches the limit stress, the infrastructure often can reduce the service performance expectation (within allowable limits) so it can accommodate more demand using the same resources, thereby enhancing its strain capacity (②, Figure 1).

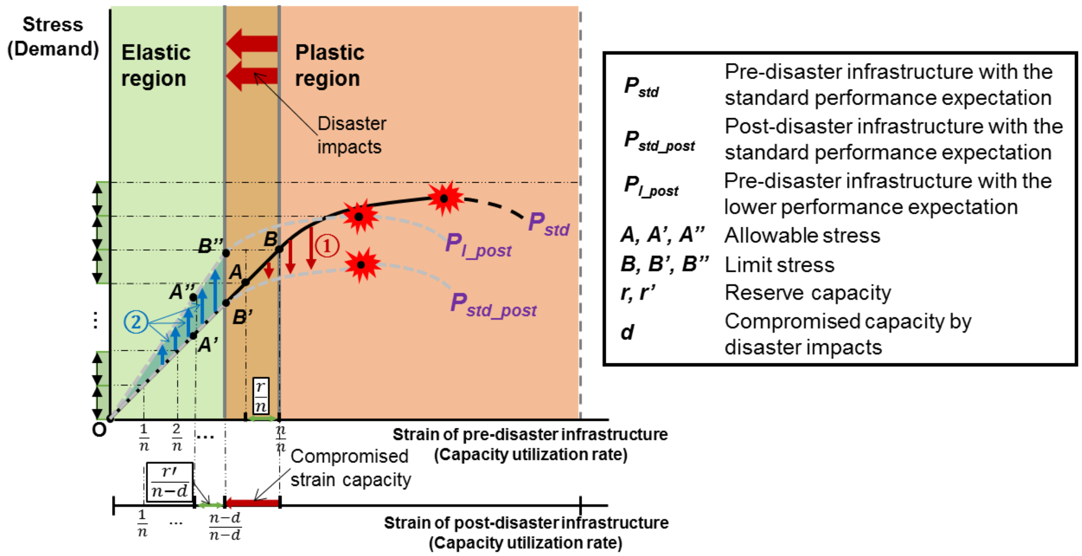


Figure 1: Stress–strain diagram for post-disaster infrastructure

Through the stress–strain principle, Choi et al. (2017) evaluated the ex-post strain capacities of an infrastructure system with respect to a desired service at an operational level and identified the set of vulnerable critical infrastructures that most restrict the operation of the system as a whole.

## 2.2 Functional and Structural Stress of Critical Infrastructure

This study categorizes critical infrastructure failures into two types: functional failure and structural failure. *Structural failure* represents the inability of a system to sustain the purpose for which it is designed because of design limitations and/or the deteriorated condition of design capacity. *Functional failure* indicates the inability of a system to provide services to meet demands in excess of its design limitations and available ex-post serviceability level. The major difference between the two failure modes is that infrastructures that structurally fail cannot function as designed even in response to normal demands. By contrast, infrastructures that functionally fail cannot provide services to meet demands above their design capacities, yet they can still handle normal demands. The two modes have different root causes for the failures and different impacts on the vulnerability of relevant infrastructures, which thus requires the categorization of infrastructure failures and proper actions corresponding to each mode (Hastak and Baim 2001). It is important to note that an infrastructure system or its components fails because of excessive demands above its limit stress (Choi et al. 2017). For example, in a water supply system, raw water is collected from each water source, then sent to a water treatment plant for disinfection and purification; the clean water is then delivered through pump stations to communities. To operate this service in a pre-disaster situation, each component (i.e., water source, water treatment plant, water pump stations) is designed to have sufficient strain capacity to provide the service as expected. But, in a post-earthquake situation, the failure of any component to accommodate stress results in the disruption of the entire water supply system (i.e., structural failure). At the same time, significant water demands may emerge due to accidental fires caused by the earthquake. If a sufficient amount of water is not available as the result of an earthquake event to handle the corresponding stress, the water supply system cannot supply enough water for firefighters in time (i.e., functional failure), thereby incurring substantial economic and social losses. More examples of each failure mode are given in Table 1.

Table 1: Examples of functional and structural failures of critical infrastructure

| Infrastructure | Infrastructure component | Functional failure | Structural failure |
|---|---|---|---|
| Healthcare infrastructure | - Resources (medical staff, medical supplies)<br>- Utility services for medical operations (electricity, water, steamed and chilled water, gas) | - Due to an excessive number of patients, medical teams cannot provide appropriate medical care for patients within their critical time.<br>- As patients need to wait longer than their critical time, some critical patients' health condition may be significantly compromised unless they are transferred. | - Insufficient utility services to operate building facilities (e.g., HVAC) or essential medical equipment cause the shutdown of a hospital.<br>- Reserve capacities (i.e., backup generators or bottled water) enable a hospital to operate medical services at a critical level, but the hospital's resulting operation is very limited compared to its designed function. |
| Levee | Levee section | - Due to heavy rainfall during flood events, the floodwater may flow over the top of the levee without any structural collapse; thus, the levee fails in its function to hold the water back from its adjacent communities.<br>- The flood level (i.e., stress for the levee section) exceeds the height of the levee (i.e., strain capacity of the levee section) | - The structure of the levee section can be broken because of rodent holes, for example, which amplifies the likelihood of structural collapse of the levee section.<br>- The structural strength of the levee is not enough to withstand the water pressure resulting from the flood event. |
| Power supply system | - Power station<br>- Transmission line and tower<br>- Substation | - In a post-disaster scenario, the shutdown of power stations by disaster events may impose excessive demands on the local power stations that remain functional.<br>- Insufficient strain capacity of the power supply system may cause frequent load shedding, which is not enough for local industries to continue their business. | - Disruption of any component in the power supply system can block the supply of power to communities.<br>- For example, if a power station does not produce enough electricity, its downstream infrastructure components (e.g., substations and transmission lines) cannot serve communities as designed. |

This study defines functional and structural stress as demand on an infrastructure during unit time that is associated with functional and structural failure, respectively. After categorizing the stress types of an infrastructure, we utilized stress–strain capacity analysis as proposed by Choi et al. (2017) to evaluate its strain capacity with respect to stress.

## 3 DEVELOPMENT OF A FRAMEWORK FOR INFRASTRUCTURE CAPACITY BUILDING STRATEGIES

This research proposes a framework for applying stress–strain capacity analysis to evaluate the strain capacities of critical infrastructure with respect to its functional and structural stress during post-disaster recovery. This study used a healthcare infrastructure as a case study to first facilitate the development of the framework and then validate its implementation through a simulation model. The framework consists of five steps, as presented in Figure 2.

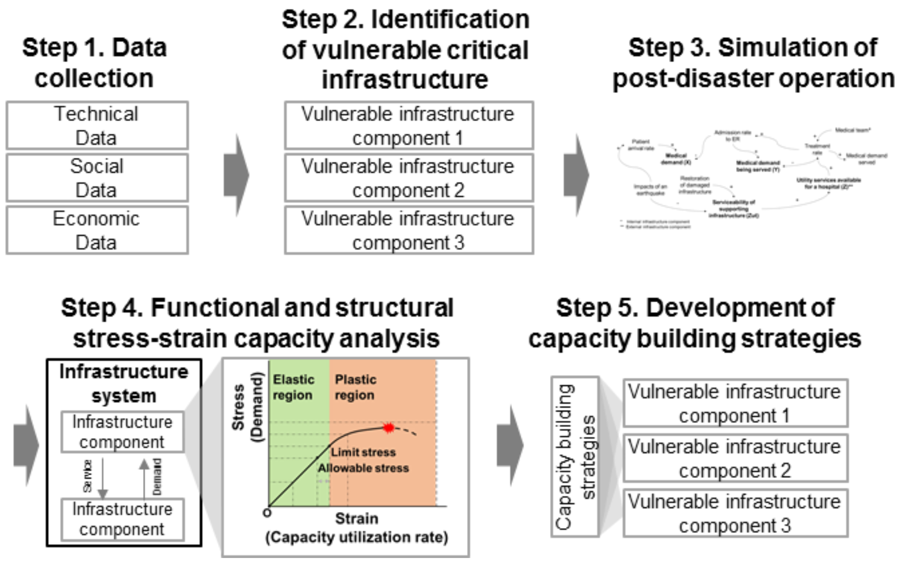


Figure 2: Framework for infrastructure strain capacity building strategies

### 3.1 Data Collection – Step 1

Technical, social, and economic data are required to understand the operation of infrastructure services in a post-disaster scenario (Oh et al. 2013). Technical data include information about the interrelationship between infrastructures, physical and geographical information, and other data needed to perceive the technical operation of an infrastructure system. Economic and social data are related to the demands placed on infrastructure services. These data include sociodemographic information, the economic and social significance of an infrastructure (i.e., the availability of alternative infrastructures to communities), and daily demands on infrastructure services.

In the case of a healthcare infrastructure, the following data would be needed to analyze its operational condition.

**Technical data**

- Data related to the healthcare system (e.g., the number of patients the hospital can treat per hour or per day), reserve capacity (e.g., backup generators, bottled water), infrastructure components, requirements for infrastructure components to operate medical services as designed, and supporting infrastructure networks.

- Data related to supporting infrastructure (capacities of utility services – maximum amount of available utility service per hour or per day; average hourly or daily utility consumption by a hospital; physical condition, emergency plan, and relevant required services of multiple infrastructures).

**Social and economic data**

- Average demands on a hospital/healthcare system in a normal situation.

- Sociodemographic information of communities served by a healthcare system (population, per capita potential patients).

- Budget constraints for capacity building strategies.

### 3.2 Identification of Vulnerable Critical Infrastructure – Step 2

In this step, two types of assessments – i.e., criticality and vulnerability assessments – are conducted, in that order, to minimize the complexity of a relevant, interdependent infrastructure network in potential post-disaster scenarios, considering its technical, social, and economic aspects (Oh 2010; Oh et al. 2013).

**Criticality assessment** measures the level of criticality (interrelationship) between critical infrastructures as they relate to the operation of a healthcare system (or a hospital). The level of criticality for an infrastructure is calculated by considering the contribution of activities of a hospital (e.g., triage, transfer, surgery, hospitalization, etc.) toward operating medical services that its infrastructure components support and the assistance level of the infrastructure (Oh et al. 2013). The criticality of an infrastructure to the functioning of a hospital will determine its prioritization as critical infrastructure for the vulnerability assessment.

**Vulnerability assessment** evaluates the threats or real hazards to a hospital in disaster situations by considering the vulnerability (or conditions) of critical infrastructure to the hazard (Oh 2010). This methodology helps measure the vulnerability of a hospital and related critical infrastructure by calculating the conditional probability of failure based on prior events and the extent of damage using Bayesian network analysis.

Regarding the outputs of this step, we can reduce the complexity of the interdependent infrastructure network (e.g., water supply network, power supply network, etc.) as related to the post-disaster operation of a hospital by focusing on the most likely vulnerable critical infrastructure components (e.g., if water treatment plant 2 and road 1 are vulnerable within their network, then water treatment plant 2 and road 1 are considered). The strain capacity of the identified components is then evaluated with respect to their functional and structural stress in Step 4.

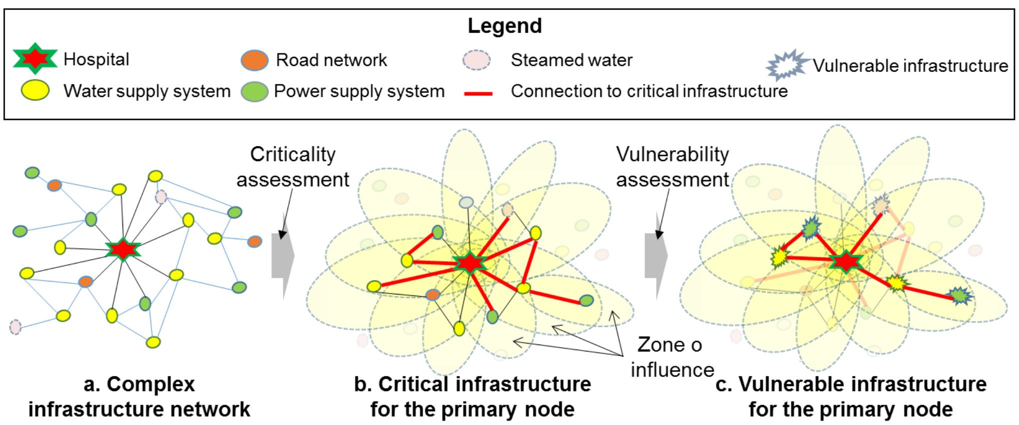


Figure 3: Identification of vulnerable critical infrastructure components

### 3.3 Simulation of Post-Disaster Operation – Step 3

In this step, the post-disaster operation of an infrastructure system is simulated while reflecting disaster impacts on the system. The vulnerable critical infrastructures identified in Step 2 are integrated into the simulation model as the infrastructure components of the system. Figure 4 portrays the schematic operation of a hypothetical hospital in a post-earthquake scenario. In the hypothetical case, the earthquake event affects the operation of the hospital in two ways: by increasing patients' arrival rate and by reducing the serviceability of both the water supply system and the electricity supply system. The water supply system and the electricity supply system are the vulnerable infrastructures identified in Step 2 in this case study. In this simulation model, the required amount of utility services is determined based on the designed operational capacity of a hospital; all the resources of the hospital (i.e., water, electricity, and medical staff) are designed to treat 15 patients per hour. This results in 15 medical teams, 133 gallons of water, and 31 kilowatts of power per hour as the requirement for medical teams, water, and electricity, respectively. Particularly, we can assume that the hospital will shut down (i.e., treatment rate is 0 patients/hour) if the availability of both electricity and water is less than 50% of its required service. The hospital then starts using its reserve capacities to compensate for the gap in the utility services when municipal utility services are not fully available. It is worth noting that the function of utility services is to keep the hospital facilities available for use. As such, the utilities are constantly consumed regardless of medical demands. By contrast, if the required amount of utility services is not available, the effectiveness of medical teams' treatment rate will decline. Finally, the treatment rate of the hospital can be calculated as the function of medical teams and the availability of water and electricity.

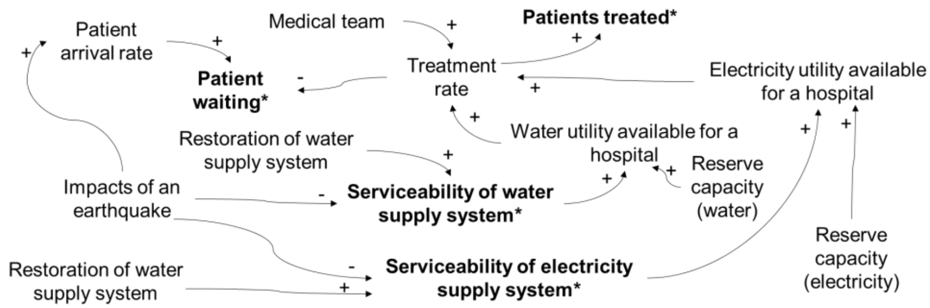


Figure 4: Schematic operation of a hypothetical hospital in a post-earthquake scenario

### 3.4 Functional and Structural Stress–Strain Capacity Analysis – Step 4

Based on the definition of the failure modes, the stress of infrastructure components that triggers the functional and structural failure of the system can be defined. Through a simulation model, we can measure and evaluate the functional and structural stress of a post-disaster infrastructure system. In the case of a healthcare system, a hospital is assumed to design its relevant medical resources and facilities to function as a healthcare system, whereas its expected function might be to treat patients waiting in the hospital within their critical time without compromising their health condition. *Structural failure* of the hospital can be defined as its inability to sustain the designed operational capacity of treating 15 patients per hour because of compromised prerequisite infrastructure components (i.e., electricity and water). By contrast, *functional failure* of the hospital represents its inability to provide acceptable medical services for the excess of patients due to insufficient resources (i.e., medical staff). As a result, some patients need to wait longer than their critical time for medical care. The definition of stress and strain of each infrastructure component is given in Table 2.

Table 2: Stress–strain of a hypothetical hospital in a post-earthquake scenario

| Infrastructure component | Related failure mode | Definition | |
|---|---|---|---|
| Medical team | Functional failure | Stress | Number of patients waiting for medical treatment during unit time (i.e., hour) |
| | | Strain | Ratio of medical team working to the total number of medical teams |
| Electricity | Functional failure /Structural failure | Stress | Required electricity for effectively operating medical services as designed during unit time (i.e., hour) |
| | | Strain | Ratio of consumed electricity to total available electricity (i.e., municipal supply + auxiliary electricity resources, such as backup generators) |
| Water | Functional failure /Structural failure | Stress | Required water for effectively operating medical services as designed during unit time (i.e., hour) |
| | | Strain | Ratio of consumed electricity to total available water (i.e., municipal supply + auxiliary water resources, such as bottled water) |

Figure 5 illustrates the results of the functional and structural stress–strain capacity analysis. In the given scenario, the hospital experiences both functional and structural failure as the stress of its components exceeds their limit stress: The hospital cannot maintain its designed medical function (i.e., treating 15 patients per hour) until 81 hours (Figure 5b) have passed, after which the required amount of water (133 gallons) becomes available (i.e., structural failure) (Figure 5d); meanwhile, the hospital is overwhelmed by an excessive number of patients until 136 hours have passed, after which the functional stress of the hospital falls below the functional limit stress (Figure 5a). Medical teams and water and electricity components all contribute to the functional failure of the healthcare facility (Figure 5c ~ e), while water and electricity components cause its structural failure (Figure 5d, e). During the first 63 hours (Figure 5d), the hospital completely loses its medical function as the available amount of water does not meet the critical demand required for operating as a healthcare facility.

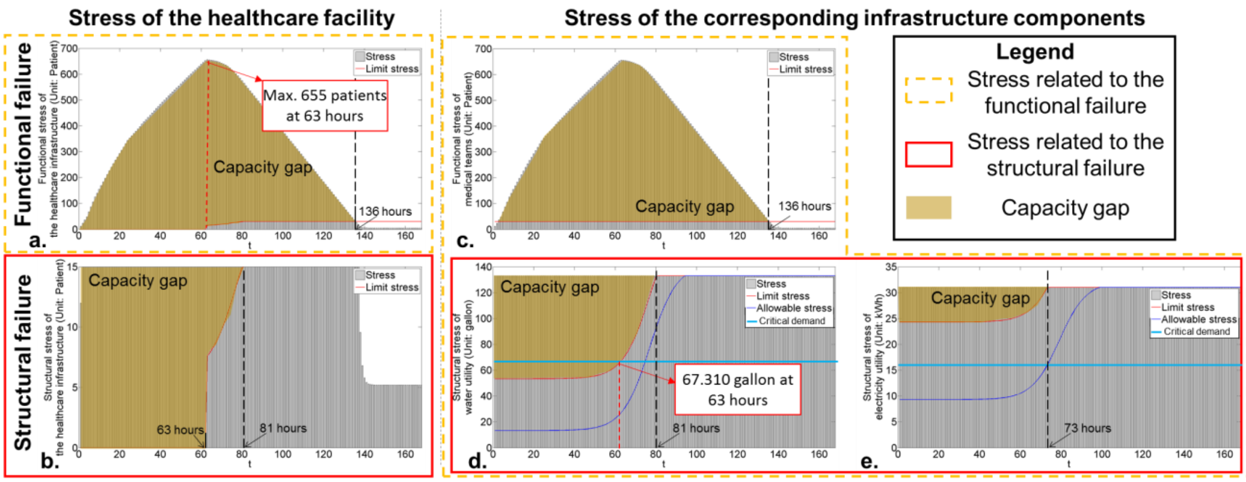


Figure 5: Results of the functional stress–strain analysis

### 3.5 Development of Capacity Building Strategies – Step 5

The functional and structural failure of an infrastructure system occurs as the result of the inadequate strain capacity of its infrastructure components to accommodate stress. The results of the stress–strain capacity analysis show which infrastructure components primarily cause the failure as well as when; additionally, the results show how much capacity is needed to avoid the failure. For example, if emergency managers fill in the capacity gap in both water and electricity (Figure 5d, e) so as to meet the required demand, the hospital can avoid structural failure. On the contrary, staffing more medical teams is necessary to prevent functional failure (Figure 5c).

## 4 DISCUSSION AND CONCLUSION

This paper presented a framework that can help (i) understand the functional and structural failure of post-disaster critical infrastructure; (ii) evaluate strain capacities of infrastructure with respect to functional and structural stress; and (iii) help develop capacity building strategies to prevent infrastructure failures. To both facilitate and demonstrate the implementation of the framework, this study considered the operation of a hypothetical hospital during post-earthquake recovery. The results illustrate how the functional and structural failure of the hospital system occurs in terms of stress placed on its infrastructure components. It is important to note that ensuring sufficient capacity for infrastructure components, of which the service is a prerequisite for the operation of the larger system, is vital in preventing functional as well as structural failure. As a guide for mitigation strategies, the case study illustrates how to prioritize vulnerable infrastructure components for capacity building strategies based on the gap in strain capacity. This may also facilitate effective capacity planning for critical infrastructures. Lastly, the proposed framework does not consider financial constraints for mitigation plans. If the framework comes hand-in-hand with economic analyses, the selected capacity-building strategy will become more economically feasible.

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