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STRESS-STRAIN CAPACITY ANALYSIS FOR THE IMPACT OF NATURAL DISASTERS ON COUPLED INFRASTRUCTURE FACILITIES

For the degree of ___Master of Science in Engineering___

Is approved by the final examining committee:

Makarand Hastak
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Chair

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STRESS-STRAIN CAPACITY ANALYSIS FOR THE IMPACT OF NATURAL

DISASTERS ON COUPLED INFRASTRUCTURE FACILITIES

A Thesis

Submitted to the Faculty

of

Purdue University

by

Juyeong Choi

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Engineering

August 2015

Purdue University

West Lafayette, Indiana

To my father and mother, Seongeun Choi and Ocksoon Yoo,

and

my sister, Choah Choi, and her husband, Myeonghan Yu

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ABSTRACT

Choi, Juyeong. M.S.E., Purdue University, August 2015. Stress-Strain Capacity Analysis for the Impact of Natural Disasters on Coupled Infrastructure Facilities. Major Professor: Makarand Hastak.

Infrastructure facilities serve as the backbone of the communities and industries by sustaining social and economic activities through their services. However, the physical impact of a disaster can have an adverse effect on the functioning of the infrastructure. In addition, the affected infrastructure facilities are unable to adequately meet the needs of the community immediately after the disaster. Thus, to compensate for gaps in services, infrastructure facilities are likely to run their systems, such that it puts additional stress on their resources that exceeds their designed capacities at the expense of level of service. For example, after the devastating earthquake in Haiti in 2010, disrupted utility services, limited available road networks, and the lack of civic governance influenced the capacity of all essential service providers such as hospitals. Furthermore, the hospitals that were impacted by the earthquake had limited resources, such as water and power utility for operating the hospitals, beds for patients, medical staff, and medical supplies, to meet the increased health needs of the community. As a result, the hospitals in Haiti had to put excessive stress on their available resources, as their remaining capacities were not enough to accommodate the increased number of patients without assistance from NGOs or other external entities. If the emergency managers of the hospitals were able to evaluate their remaining capacities based on the excessive stress so that they could make appropriate strategies for mitigating the excessive stress ahead of time, the infrastructure facility would have serviced the affected communities more efficiently.

This research proposes a framework that can be used to understand and evaluate the strain capacities based on the stress imposed on an infrastructure facility under varying post-disaster conditions. A new principle to assess the stress level in a post-disaster infrastructure facility was developed using the analogy of the stress-strain concept in the mechanics of materials. In this research, the definitions of the stress and strain in an infrastructure facility are adapted in order to reflect the ability of a post-disaster infrastructure to provide essential service. Since an infrastructure facility is composed of various infrastructure units that are either tightly or loosely coupled through their exchange of services for the facility, the analysis of stress and strain of an infrastructure facility requires understanding of complex interdependent systems. As such, using the system-of-systems approach, a stress and strain assessment tool (SSAT) for a post-disaster infrastructure was developed based on the proposed stress-strain principle.

Using the discrete event simulation method, the developed SSAT was applied to a case of healthcare facility under an earthquake scenario to demonstrate its implementation to post-disaster infrastructure systems. As a coupled system, water and electricity resources of the healthcare facility were considered besides its medical resources. While running the simulation, the dynamic strain capacities of the hospital, caused by the disruption of the linked external infrastructure, i.e., water and power units, are measured with respect to the applied stress. This enables emergency managers to evaluate the available strain capacities of the infrastructure units based on the imposed stress. Eventually, the SSAT would assist in developing appropriate strategies for mitigating excessive stress on infrastructure units in natural disaster situations.

CHAPTER 1. INTRODUCTION

1.1   Background and Needs

Both natural and manmade disasters affect the functioning of critical infrastructure, which, in turn, adversely affects the communities that rely on them. Consequently, the capacities of infrastructure are likely to be reduced, which results in the failure to accommodate the demands of communities for infrastructure services. According to the U.S. government, the term 'critical infrastructure' is defined as "telecommunications, energy, banking and finance, transportation, water systems, and emergency services, both governmental and private," the disruption of which would have detriment on the national defense or economic security. For instance, the 1999 Chi-Chi earthquake in Taiwan caused significant damage to both the physical infrastructure and communities (Dong et al. 2000). Because of the destruction of dams (Figure 1-1) and damage to the water supply system, there was insufficient water to meet the demand, and more than 80% of the five million residents were unable to get an adequate supply of water as full recovery of the water network took several months. Moreover, the damaged components of Taiwan's electric power system, e.g., transmission towers, substations, and power plants, interrupted the supply of electricity in all the areas except the southern part of Taiwan (Figure 1-1). In the U.S., in the aftermath of the midwest floods in 2008, the flooded area of Cedar Rapids, Iowa exceeded the 500-year flood plains due to the unexpected level of flooding (Oh 2010). The flobod waters inundated the area and restricted the supply of water and electricity for communities and industries. Twenty-seven companies and most of the residents of Cedar Rapids were affected by the disrupted municipal service or by the direct impact of the flooding caused by the Cedar River (Oh 2010).

Failure of a dam in Shihkang   **Failure of a transmission tower in Mingchien**

Figure 1-1 Structural Failures of Lifeline Infrastructure in Taiwan after the Chi-Chi earthquake (EQE International 1999)

Disasters often cause excessive demand for essential infrastructure services, such as medical service, security, and firefighting. For instance, after the terrorist attacks in New York City on September 11, 2001, there was increased demand for firefighting personnel and equipment due to the fires caused by the collapse of the two towers of the World Trade Center (O'Rourke et al. 2003). Thus, the demand for water increased exponentially to support the firefighters in their efforts to suppress the fires. In 2013, Typhoon Haiyan struck the Philippines with devastating impacts, with more than one million houses damaged, which resulted in a huge number of people seeking alternative shelters (OCHA Philippines 2013).

In the infrastructure management, the stress refers to the demand which infrastructure facilities have to meet while the strain is associated with their coping capacities. Having enough strain capacities of infrastructure is pivotal for properly servicing the affected communities. However, in a post-disaster situation, because of the failure of its coupled infrastructure systems and the increase in the demands, it is likely that most of the affected infrastructure facilities are overwhelmed by the enormity of the stress. For instance, in 2005, Hurricane Katrina struck the southeast coast of the U.S., producing a devastating impact on the health facilities in New Orleans. Before the floods occurred, most critical facilities, including hospitals, were thus able to sustain their service by relying on backup

generators and emergency supplies (Rodríguez and Aguirre 2006). Unfortunately however, the hurricane destroyed the levee system in New Orleans, which caused extensive flooding. In most of the hospitals in New Orleans, backup generators and emergency supplies, e.g., food and fuel, had been placed in the basement, making them unavailable when the basements were flooded. As a result, the capacities of the city's medical facilities were compromised even as the number of patients needing medical care increased. Hospitals with very few resources were unable to properly treat patients, and they experienced excessive stress above their strain capacities, placing them in imminent danger (Rodríguez and Aguirre 2006).

Similarly, in the aftermath of 1999 Chi-Chi earthquake in Taiwan, most hospitals lacked adequate electric power and water. One of the major hospitals in Taiwan, the Christian Hospital in Puli, managed to provide medical services at 10% of its normal operational level due to the physical damage and insufficient utility service during the first 72 hours after the earthquake (Cole 2006). However, at the same time, an excessive number of patients visited the hospital, putting high stress on the hospital's resources as it sought to manage the increasing medical demand.

In addition to natural disasters, manmade disasters also are likely to cause the issue of excessive stress on infrastructure facilities. The terrorist attack on the World Trade Center (WTC) in New York City in 2001 caused significant damage to neighboring communities and civil infrastructure (O'Rourke et al. 2003). Even though the attack targeted one regional area, the disruption of the World Trade Center affected the infrastructure systems throughout New York City as the impact on the Center was transferred to other interdependent and interconnected systems (Mendonça and Wallace 2006; O'Rourke et al. 2003). In particular, the collapse and debris of WTC 1 and WTC 2 damaged the water mains below them (Zimmerman 2003). Thus, the damaged water supply infrastructure could not adequately support the efforts to fight the fires (O'Rourke et al. 2003). As WTC 7's demand for firefighting service increased with time, the demand was not met effectively by either the internal fire protection system, i.e., the sprinkler system, or the various fire departments (NIST NCSTAR 1A 2008). The supply of water was inadequate to meet the

growing demand of WTC 7; therefore, the collapse of WTC 7 was due primarily to fire damage (NIST NCSTAR 1A 2008).
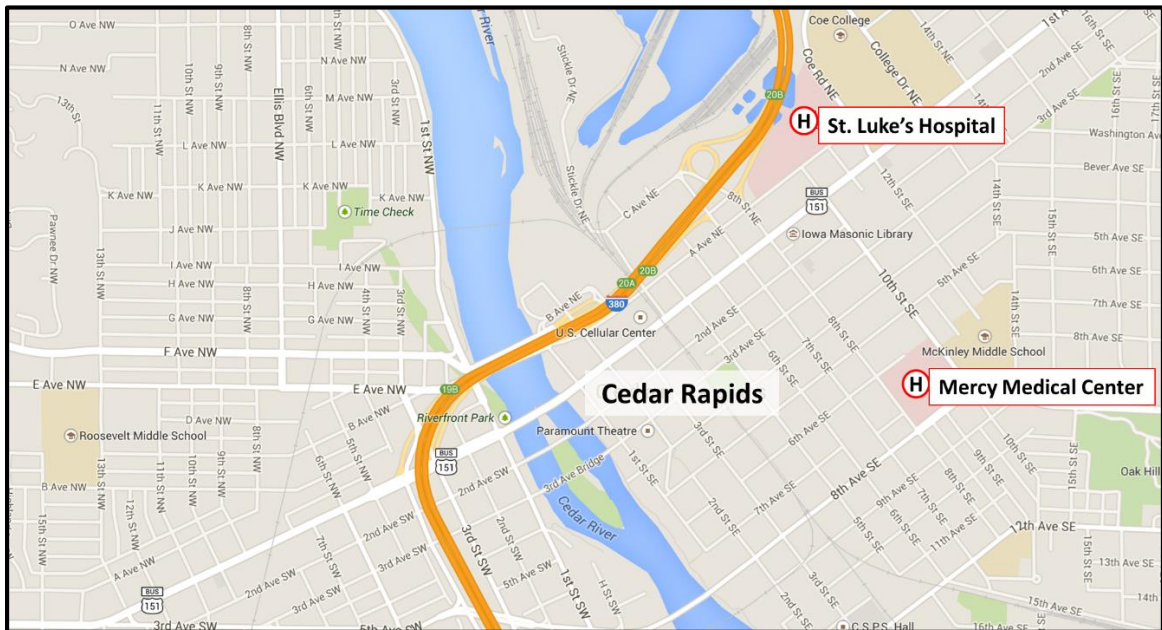
Figure 1-2 Major Medical Facilities in Cedar Rapids, Iowa (Source: Google Maps)

As shown in the examples of disasters presented above, infrastructure facilities are likely to experience excessive stress during a disaster. As a result of high stress, they are unable to provide the required service. However, if the relevant emergency managers have good insight concerning the probable stress on post-disaster facilities, they could take appropriate measures before a disaster happens to ensure proper functioning even in devastating disaster conditions. For example, Figure 1-2 shows that, during the floods in the Midwestern region of the U.S. in 2008, Mercy Medical Center in Cedar Rapids, Iowa, was one of only two primary medical facilities in the area, and Figure 1-3 shows that Mercy Hospital was inundated by flood water. Despite the efforts by staffs and volunteers to prevent the influx of the flood water into the hospital, it poured into the basement of the Hospital where the power generators were located (FEMA 2009). The backup generators were inoperable, so all of the patients at Mercy Hospital had to be evacuated to neighboring hospitals (FEMA 2009). Before the evacuation of Mercy Hospital, the staff at St. Luke's Hospital, another major medical facility in Cedar Rapids, became aware of the impending

evacuation of patients from Mercy Hospital. The manager at St. Luke's perceived the probability of experiencing high stress on the operation of the emergency departments due to their insufficient capacity to accommodate the additional demand (Iowa Public Television 2008). The strategy implemented at St. Luke's was to open additional medical units, to add an extra triage area on the third floor, and to operate six additional exam rooms that were being renovated. In spite of receiving 52 additional patients from Mercy Hospital, St. Luke's was able to provide satisfactory medical services for all of its patients by taking actions in advance to relieve the probable stress level.

Figure 1-3 Mercy Medical Center inundated by water in the 2008 Midwest Flood (FEMA 2009)

As shown in the previous cases, it is obvious that understanding the stress level that will be imposed on a post-disaster infrastructure facility is critical for minimizing the adverse impacts of disasters on the community. Even though infrastructure facilities may still be functional after a disaster, they can experience unexpected stress that prevents them from providing essential service for the affected communities at an acceptable performance level. As a result, inadequate support by essential infrastructure may hamper communities from being resilient against disasters. Therefore, emergency managers who are in charge of the supply of essential infrastructure service should recognize the needs of communities and

the capabilities of providing services ahead of time. Then, when needed, they can implement appropriate strategies to keep acceptable serviceability level for accommodating communities' demands in a post-disaster situation, as St. Luke's Hospital did when 52 extra patients arrived from the Mercy Medical Center. Therefore, it is of great help for emergency managers to i) understand the stress level that their infrastructure facilities are likely to experience following a disaster; ii) observe the varying stress levels during the recovery phase; iii) evaluate the stress imposed on their resources; and iv) develop and implement strategies to relieve the high stress on their resources.

1.2   Research Thesis and Objectives

The thesis of this research is that understanding the stress level in an infrastructure under varying disaster conditions will help emergency-related facilities to be properly prepared and have mitigation strategies in place to relieve excessive stress, thereby sustaining their provision of service for communities at an acceptable level during the recovery phase. To support and advance the thesis, the general objectives of this research are i) to establish the stress-strain principle for a post-disaster infrastructure and ii) to develop a stress and strain assessment tool for infrastructure facilities under disaster conditions. There are the specific objectives which lead to the achievements of the general objectives as shown below:

- To understand the stress placed on post-disaster infrastructure and evaluate its impacts on the provision of the infrastructure services;
- To develop a stress-strain principle for post-disaster infrastructure using the analogy of the stress-strain principle from mechanics of materials;
- To understand the interdependencies of supporting infrastructure and identify the infrastructure which limit the capacities of the coupled infrastructure facility for providing services for the communities;
- To develop a stress and strain assessment tool based on the proposed stress-strain principle using simulation methods;
- To develop guidelines of strategies to relieve excessive stress imposed on the post-disaster infrastructure facilities.

1.3 Research Scope

The focus of this research was on the functioning of infrastructure facilities, such as medical facilities, fire departments, and lifeline infrastructures and their interlinked supporting civil infrastructure, such as electricity, water, and transportation, during disaster conditions. To investigate and define the mechanisms by which stress increases on the infrastructure, a literature review was conducted on stress on the infrastructure under normal conditions; then, the mechanism was further applied to the stress on the post-disaster infrastructure. Also, a new stress-strain principle was proposed based on the analogy from mechanics of materials to analyze how post-disaster infrastructure behave in response to increasing stress with respect to their available strain capacities.

In order to validate the implementation of the developed stress and strain assessment tool (SSAT), the SSAT was applied to the case of a health care facility under simulated earthquake conditions. In the case study, the stress and strain analysis is focused on the influence of utility units, i.e., water and power, on the operation of the case hospital.

1.4 Methodology

Task 1. Literature Review

The literature review in this research can be categorized into two sections, i.e., the literature review for the development of the stress-strain principle for a post-disaster infrastructure and for the establishment of a stress and strain assessment tool for post-disaster infrastructure. The intent of the former literature review was i) to understand how disasters affect communities and industries in terms of demand and supply of infrastructure service, which may pose enormous service-related stress in a post-disaster infrastructure; ii) to study past research results on disaster impact analysis; iii) to understand the nature of infrastructure interdependencies; iv) to identify the stress issue in the provision of infrastructure services; and v) to understand the stress in other areas of study, e.g., psychology, engineering, and organizational resilience, as input to the development of a new principle for understanding the stress on post-disaster infrastructure. The latter literature review was conducted in order i) to study the simulation approach to

infrastructure interdependency issues; ii) to find appropriate operational simulation techniques for the stress and strain analysis;

Task 2. Development of Stress-Strain Principle for a Post-Disaster infrastructure

In order to understand the stress on post-disaster infrastructure facilities, in this study, a novel approach was developed and evaluated by using the analogy of the stress-strain principle in mechanics of materials. The developed principle needs to be able to explain i) the stress and strain of infrastructure facilities with respect to their design parameters (i.e., allowable stress and limit stress); ii) the importance of relieving the excessive stress when the condition of the infrastructure is in the plastic region; iii) the change in infrastructure' performance level in an effort to meet all the demands within their available capacities.

Task 3. Case Analysis

Two cases were selected and analyzed based on the developed stress-strain principle, i.e., 1) a medical facility in the 1999 Chi-Chi earthquake and 2) a power facility in the 1999 Chi-Chi earthquake. These two cases illustrate the need for both stress and strain analysis in order to ensure the proper functioning of infrastructure facilities during recovery phases. In addition, the cases identify the issues concerning various types of stress in supporting infrastructure units, which caused the need for the system-of-system approach in evaluating stress on post-disaster infrastructure.

Task 4. Discrete Event Simulation

In order to understand the complex relationships of stress assessment for an infrastructure facility in the aftermath of a disaster, this study utilized the discrete event simulation to develop a stress and strain assessment tool using Anylogic© simulation software, a Java-based simulation tool. As a case study to validate the applicability of the tool, the discrete event simulation was designed to target the emergency operation of a health care facility under simulated earthquake conditions. The simulation showed dynamic stress and the strain levels in four medical service facilities, i.e., triage, acute care, emergency care, and hospitalization under the influences of compromised power and water infrastructure.

Task 5. Assessment and Recommendation

Based on the stress and strain analysis for a post-disaster facility, an assessment was made to determine strategies that could relieve the excessive stress on the infrastructure so that emergency managers manage to provide service for affected communities at an acceptable level. In this research, the strategies for relieving stress were selected assuming that all the resources are available. That is, the financial feasibility of the alternative options was not investigated.

1.5   Thesis Organization

This thesis is organized into five chapters. Chapter 1 introduces the research background and needs, the research thesis, and the corresponding objectives, scope, and methodology. In Chapter 2, a general literature review is conducted on disaster contexts which may cause the issues related to excessive stress on critical infrastructure; disaster impact analysis on communities with respect to the technical, social, and economic aspects; interdependent nature of critical infrastructure. In addition, the discussion on the application of system-of-systems approach to interdependent infrastructure systems is followed. And then, the simulation approach in disaster management is reviewed.

Chapter 3 develops the stress-strain principle for a post-disaster infrastructure facility by using the analogy between mechanics of material and the infrastructure management. The terms used in the proposed principle are redefined in order to reflect the contexts of infrastructure management. Furthermore, two case studies of post-disaster infrastructure, i.e., a health care facility and power facility, are analyzed based on the developed stress-strain principle, which shows the benefit of using the new principle in understanding disaster impacts.

In order to implement the proposed stress and strain principle for post-disaster infrastructure, Chapter 4 develops a stress and strain assessment tool for infrastructure facilities during disaster conditions using the system-of-systems approach. Considering an appropriate level of complexity, the operation of a post-disaster infrastructure with its supporting infrastructure units is simulated using the discrete event simulation (DES) method. This model has the capabilities for measuring stress and strain of the post-disaster

facility during the simulation time. The SSAT is applied to the case of a health care facility under simulated disaster conditions in order to validate its applicability to the real world.

In this thesis, chapters 3 and 4 are written as two separate research papers. That is, as separate research papers, each chapter includes both an introduction, a literature review, a technical content and a conclusion.

Chapter 5 provides a summary of the findings and the conclusions that resulted from this research. Also, the limitations of this study and guidance for future studies are also presented in this chapter.

CHAPTER 2. LITERATURE REVIEW

2.1   Critical Infrastructure and Natural Disasters

The critical infrastructure serves a critical role for sustaining the daily activities of a community by providing relevant services. In a post-disaster situation, the continuity of the provision of services by the infrastructure becomes more important for the following reasons.

1. The critical infrastructure facilities provide essential services for communities and industries so they can sustain their social and economic activities even during the disaster (Oh et al. 2009). As such, communities and industries are able to prevent the secondary losses that are caused by the disruption in performing daily social/economy activities due to insufficient support from infrastructure.

2. The critical infrastructure facilities also assist civic governments or communities in conducting recovery activities by providing essential services. In the aftermath of a disaster, the demands for certain recovery activities, such as medical demands, debris removal, and other kinds of civic services, are unlikely to be met adequately due to the reduced services from the critical infrastructure, and this may put the affected communities at risk.

In order to ensure the security of the critical infrastructure, the U.S. government defined the term 'critical infrastructure' as "telecommunications, energy, banking and finance, transportation, water systems, and emergency services, both governmental and private," and, then, Presidential directive PDD-63 declared the need for actions to protect certain components of the infrastructure that are susceptible to hazards. According to this definition, the critical infrastructure is focused on the infrastructure that, when damaged, could affect national defense or economic security. In addition to the defined infrastructure, Rinaldi et al. (2003) added five additional components to the infrastructure,

thereby broadening the scope of the national infrastructure to include industries that contribute to sustaining other industries and communities, e.g., food and agriculture, space, numerous commodities, the health care industry, and the educational system. Based on the defined critical infrastructure, Oh (2008) further analyzed these components and their relationships to the relevant industries (Figure 2-1). According to Oh (2008), the 12 main industries are identified and linked to 13 defined critical infrastructure facilities.
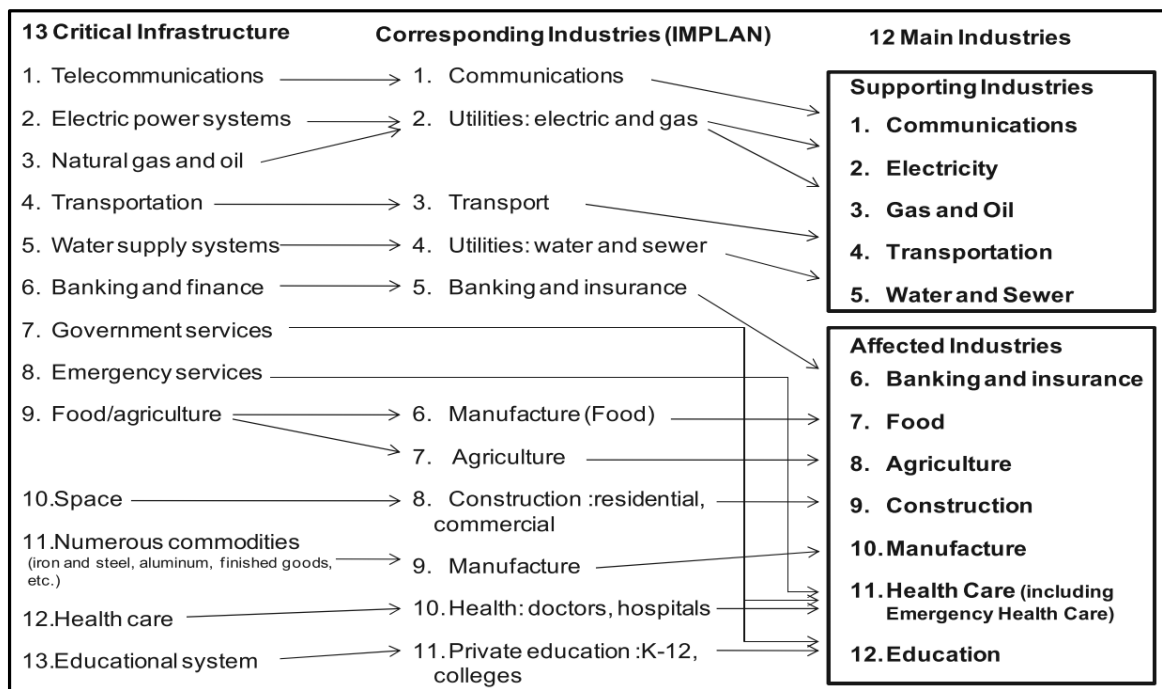
Figure 2-1 Association of Critical Infrastructure and Main Industries (Oh 2008)

Even though a reliable supply of infrastructure services is critical for the security and national economy, some infrastructure services are often vulnerable to natural disasters, epidemics, and terrorist attacks which target specific geographical areas (Parfomak 2005). According to the disaster impact mechanism proposed by Oh and Hastak (2008), disasters can hamper the functioning of the critical infrastructure, related industries, and communities as follows (Figure 2-2).

- **Primary impact:** Disasters primarily affect the physical infrastructure. Depending on the maintenance condition or topographical condition, the direct damage by natural disasters can vary (Oh 2010). Also, depending on the presence of physical

damage to infrastructure, the types of failure are categorized into two modes, i.e., structural failure and functional failure.

- **Secondary impact:** The damaged infrastructure transfer their impacts through their interdependence on other connected infrastructure and on dependent entities. Due to the reduced serviceability of the damaged infrastructure, industries and communities cannot sustain their ordinary activities, and this means that indirect losses will be incurred. In order to perceive the resulting impacts on the critical infrastructure, communities, and industries, the technical, economic, and social aspects of disaster impacts must be considered.
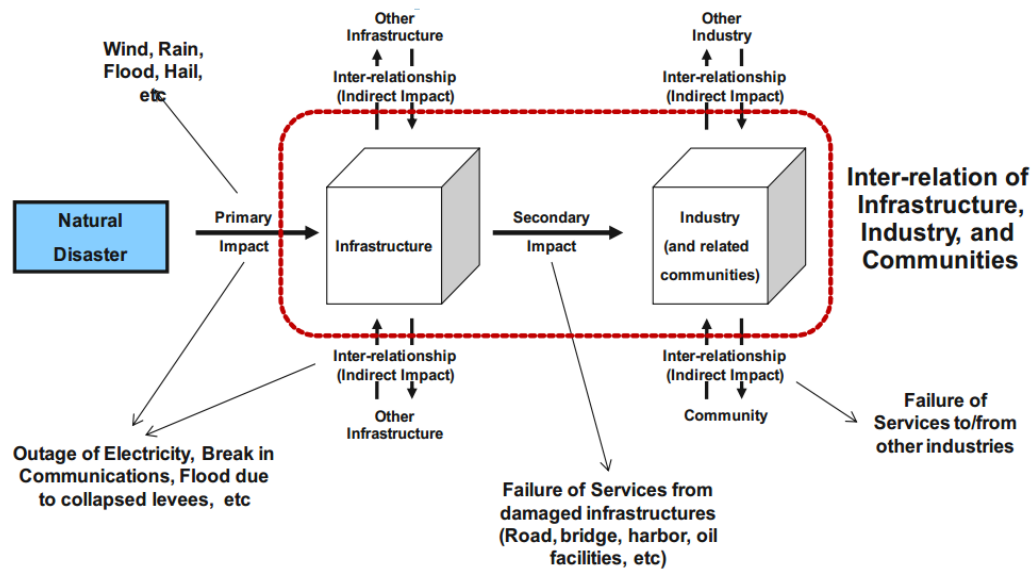
Figure 2-2 Disaster Impact Mechanism (Basic Cell Model) (Oh and Hastak 2008)

In addition to the deterioration of the capacities of the infrastructure, they can incur demands that exceed the capacities of the disaster-damaged infrastructure. Many studies have defined and illustrated the impact of disaster events as the imbalance between the demand and the infrastructure's capacity required to cope with the demand (WHO 1992; Shultz et al. 2006). Lindell and Prater (2003) also defined natural disasters as the condition in which an extreme geological, meteorological, or hydrological event exceeds the ability of a community to handle the ensuing effects.

By investigating the operation of infrastructure facilities in a past disaster, i.e., Hurricane Katrina, the demand could surpass the coping capacities of the infrastructure for the following reasons (Quarantelli 2006)

1. **Increase in demand**: Due to the extreme impact of disasters, demands of affected communities are generated beyond the design capacity of the infrastructure. In the case of Hurricane Katrina, the hurricane caused the destruction of two major levees. The destruction of the levees resulted in approximately 25,000 evacuees seeking shelter in the New Orleans Superdome, which exceeded its capacities.

2. **Compromised coping capacities**: The capacities are compromised by the disaster's physical impact, so they are not enough for accommodating the community demand. Following Hurricane Katrina, essential infrastructure facilities were inoperable; food, water, gas, electrical power, and civic governance (i.e., police, emergency agents) were unavailable. The weakened functioning of the essential infrastructure was unable to meet the demands of the community.

Therefore, the infrastructure facilities are likely to fail in successfully meeting the community demands, ultimately having an adverse impact both on the social/economic activities and on the community's recovery (Deshmukh et al. 2011). Considering the aforementioned effects of a disaster on the infrastructure, plausible disaster contexts around the functioning of infrastructure system were assumed to include three scenarios (Figure 2-3), i.e., i) the case of compromised capacities of the infrastructure, ii) the case of increased demands for infrastructure services, and iii) consideration of both cases (i.e., demand increasing while the coping capacities of the infrastructure are decreasing).
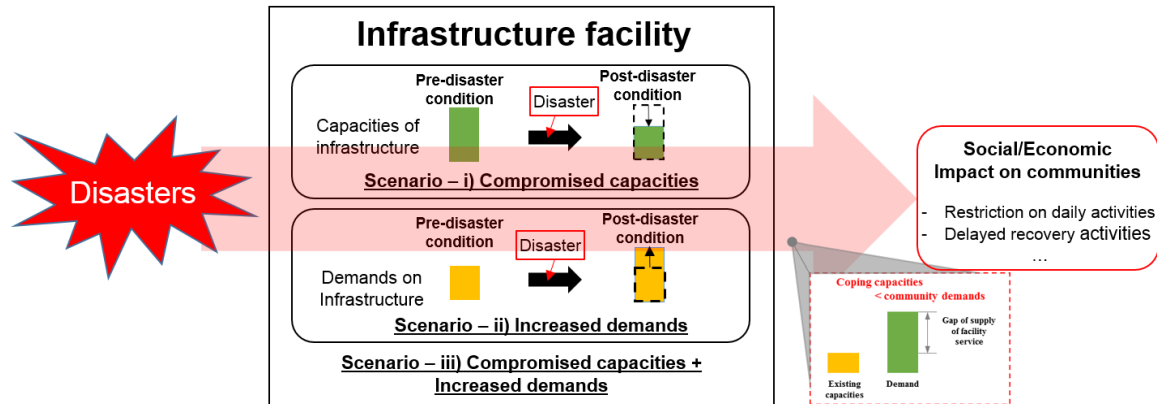
Figure 2-3 Impact of Disasters on the Functioning of Infrastructure Facilities

Just as the identification of the components of the infrastructure that are vulnerable to disasters will help infrastructure organizations or emergency managers in better preparing and developing a mitigation plan (Oh 2010), understanding the scenarios in which components of the infrastructure are likely to fail is a very important aspect of risk management (Zagst 2002). However, estimating the future demand and capacities are not an easy task for infrastructure engineers (Babu et al. 2011). If engineers or infrastructure planners can consider the effects of various disasters in terms of service demand and supply aspects ahead of time, it helps them to ensure an adequate supply of infrastructure services even during disasters.

2.2   Impact Analysis of Natural Disasters

The impacts of disasters are not limited to the affected infrastructure or communities; the impact is likely to be transferred to other linked infrastructure and communities through the supply-chain relationship. In addition to the technical interrelationship between the components of the infrastructure and their dependent entities (e.g., communities and industries), Daniell (2014) and Oh (2010) also emphasize the importance of considering its social and economic aspects in understanding the interrelationship and impact of natural disasters on communities.

As discussed in the previous subchapter, disasters affect communities and industries due to the reduced services from the damaged infrastructure and influence the affected

communities' and industries' demands for infrastructure service. Therefore, a large gap in the provision of essential services may be generated, and this could have debilitating impacts on communities and industries in disaster situations. As such, when investigating the technical, social, and economic effects of disasters, it is necessary to take into account the interplay of the intermediate coping capacities of the infrastructure and the demands that will be imposed on it.

<u>- Economic impact</u>

From the economic perspective, disasters often cause the destruction of the built environment and direct losses to communities, which, in turn, stops the production of industries and interrupts businesses of affected industries, ultimately resulting in economic losses (Okuyama and Santos 2014; Deshumkh et al. 2011). The impact on one local business will spread out throughout the supply chain to other businesses. Okuyama and Santos (2014) used structural decomposition methods in an attempt to measure how the economic structure of Kobe was affected and changed by the 1995 earthquake. The devastating event, which caused approximately 10 trillion yen in losses, devastated the regional economy, and its destruction of the ongoing transactions with other associated industries had ripple effects on other regional economies. In addition, the recovery and reconstruction activities influenced the continuity of the businesses. The overall impact of the earthquake ultimately resulted in considerable economic changes of Kobe's economy. One of the major factors that contributed to these changes was changes in the regional market demand. Lian et al. (2007) proposed an input-output model to understand the changes in consumption patterns and the adaptation of production of associated industries to meet the prevalent demand after disasters. According to Lian et al. (2007), market demands will be changed because of the security concern of the public as well as the limited supply of business services after disasters.

Unlike other studies on the economic impact of disasters that measured the impact based on comprehensive cost criteria across the national economy, Rose et al. (2007) focused on regional economies that are highly dependent on electricity. Even though power outages result in economic losses from various perspectives, such as the value of lost lives,

increased crime rates, medical trauma, and damage to the public and private physical infrastructure, the authors only measured the regional economic loss associated with the interruption of business activities caused by the power outage. The previous studies have focused on ordinary outages caused by natural disasters, and they calculated the economic loss by considering the proxy of the damage and its cost and cost of reserve capacities, e.g., backup generators (Caves et al., 1992; Beenstock et al., 1997). Unlike previous studies in which directly-related costs were considered, Rose et al. (2007) considered indirect economic impacts – often referred to as multiplier or general equilibrium effects – and economic resilience, i.e., the ability to minimize the maximum impacts through adaptive responses at the level of the firm, industry or regional economy. In particular, the authors emphasized the importance of maintaining an equilibrium condition that balances supply and demand in goods and services when considering disruptive events, e.g., terrorist attacks. This kind of disruptive event often produces a disequilibrium condition between supply and demand, which makes it difficult to reduce the economic impact. Furthermore, Rose et al. (2007) suggested a way to increase the supply of electricity for communities to meet the high demand in order to reduce the regional economic loss. Rose and Liao (2005) also measured the regional economic losses caused by the disruption of the water supply for various earthquake scenarios by varying water prices to manage the supply of water and the demand for it.

Most researchers use economic impact as a measure of the impact of a disaster. In order to calculate the economic losses, they consider various factors, such as business interruptions, physical damage, and reconstruction and recovery efforts. It is worth noting that economic losses are influenced by the available capability of industries to continue their businesses as well as by the resulting change in market demand. As a result of natural or man-made disasters, gaps will occur between supply and demand, and this will have detrimental effects on the regional (or national) economy. In order to calculate economic impacts, researchers use various computational approaches, such as input-output models or computational general equilibrium simulation methods, to consider the interdependencies among industries (i.e., technical aspect).

- Social impact

Disasters cause physical damage to communities, such as casualties and property damage, as well as social impacts, including psychosocial, socio demographic, socioeconomic, and sociopolitical impacts (Lindell and Prater 2003). Figure 2-4 describes that physical impacts are caused by hazard agents, i.e., disasters, and the magnitude of these impacts depends on the affected communities' mitigation and preparation strategies. The physical impacts, in turn, incur social impacts on communities, which can be minimized by the communities' recovery resources and the assistance of extra-communities, i.e., outside resources (Lindell and Prater 2003). Understanding the social impacts of disasters is a significant challenge because these impacts can be affected by multiple factors (i.e., mitigation and preparation practices and extra- and inner-communities' resources). Even so, monitoring and assessing social impacts are pivotally important because these activities are likely to affect the ability of communities and industries to return to their pre-disaster conditions during the long-term recovery stage. Also, Lindell and Prater (2003) emphasized the local governments' reliable supply of disaster-related services for communities, even if they undergo significant damage to their resources in order to protect communities.
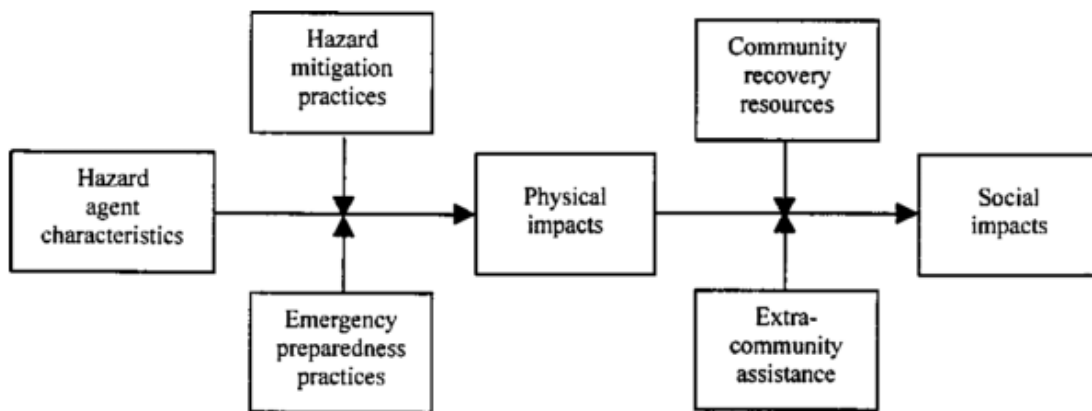
Figure 2-4 Model of the Impacts of a Disaster on a Community (Lindell and Prater (2003))

When disasters strike communities, they are likely to damage communities and built environments, including, for example, the destruction of residential buildings and the lifeline infrastructure. In particular, the reduced supply of utility services, e.g., water, gas, and electricity, hampers the communities' ability to sustain the normal daily activities, and this changes the pattern of social behavior and degrades the quality of life (Picou and Martin 2006). Picou and Martin (2006) emphasized the consideration of the social and psychological impacts of Hurricane Ivan. After Hurricane Ivan struck in Orange Beach, Alabama, the authors conducted a survey of the affected community to evaluate the social impacts and to identify the factors that caused these impacts. Based on five primary social impacts, i.e., community disruption, intrusive psychological stress, depression, recovery satisfaction, and organizational response satisfaction, which were defined via a literature review, the authors conducted a multi-regression analysis to identify the causes of the social impacts. They found that a large number of survivors experienced severe personal distress, psychological distress, and were depressed eight months after Ivan struck the community. Even though the findings were based on regional data and the authors did not identify the mechanisms that caused the social and psychological impacts on the communities, the authors clearly defined the types of social impacts that communities experience after a hurricane and the critical factors that contribute to specific types of psychological and social impacts.

Martinez et al. (2013) tried to understand the mental health effects of the 2010 earthquake in Haiti on the Haitian community living beyond the boundaries of the country. While most studies focus on the health effects on the geographically-affected area, Haitian immigrants living abroad also could suffer psychologically from either the loss of property or of deaths of family members and friends in the affected area. In order to understand the social impact of disasters, the authors stressed the need for recognizing the social networks and the interconnectedness of the population beyond the boundaries of the country. Through a survey of more than 64 Haitians living in Somerville, MA, the authors measured their depression and their perception of stress due to the earthquake. The results of the survey indicated that 58% of the respondents had connections to the victims of the earthquake, and most respondents felt the burden of providing financial support to help them recover,

which causes psychological stress for them. This shows that the unmet demand within one regional area, in this case, Haiti, affects others outside the area who have social connections with the victims, thus causing the ripple impact.

Even though the social impact is essential in assessing the total impact of disasters, the consideration of social impacts is likely to be ignored because of the difficulty in quantifying them (Cutter et al. 2003). In order to address this issue, Cutter et al. (2003) developed 11 composite factors that described the level of social vulnerability of the people in 3,141 U.S. counties in 1990 based on the socioeconomic data from those counties, as shown in Figure 2-5. Since the authors acknowledged that there are disagreements concerning the factors that affect social vulnerabilities, they started with a large number of 250 variables that other researchers identified as standing for social impacts. Using statistical tests, including factor analysis, the authors identified 11 significant factors that explained 76% of the statistical variance in the U.S. counties. To validate the correlation of the developed vulnerability index with their actual vulnerability to disasters, the authors conducted a simple regression model that used the frequency of Presidential disaster declarations by county. Even though the output of the regression model does not show a statistically significant relationship between the social vulnerability index and the frequency of disaster declarations, the authors contributed to the body of knowledge by quantifying social vulnerability, which otherwise is difficult to consider. Fekete (2009) also took a similar approach for creating a social vulnerability index, especially in context of flooding rivers in Germany. He pointed out that, even though the development of vulnerability indices is prevalent, there have been few attempts to validate the indices for three reasons, i.e., 1) difficulty in finding empirical evidence about social vulnerability itself, 2) the various aspects associated with measuring social impacts, i.e., a holistic view or a single-dimensional view, and 3) the difficulty of quantification. In the study, the author used factor analysis to analyze standard census data provided by the Federal Statistical Office in Germany. As a result, three primary factors, i.e., fragility, socio-economic conditions, and region, were identified. The three composite factors were verified further by using a second, independent dataset. Compared with the SoVI developed by Cutter et al (2003), the social vulnerability index focused on specific types of disasters rather than

all of the types of hazards in order to increase the statistical significance of the social vulnerability index (Fekete 2009).
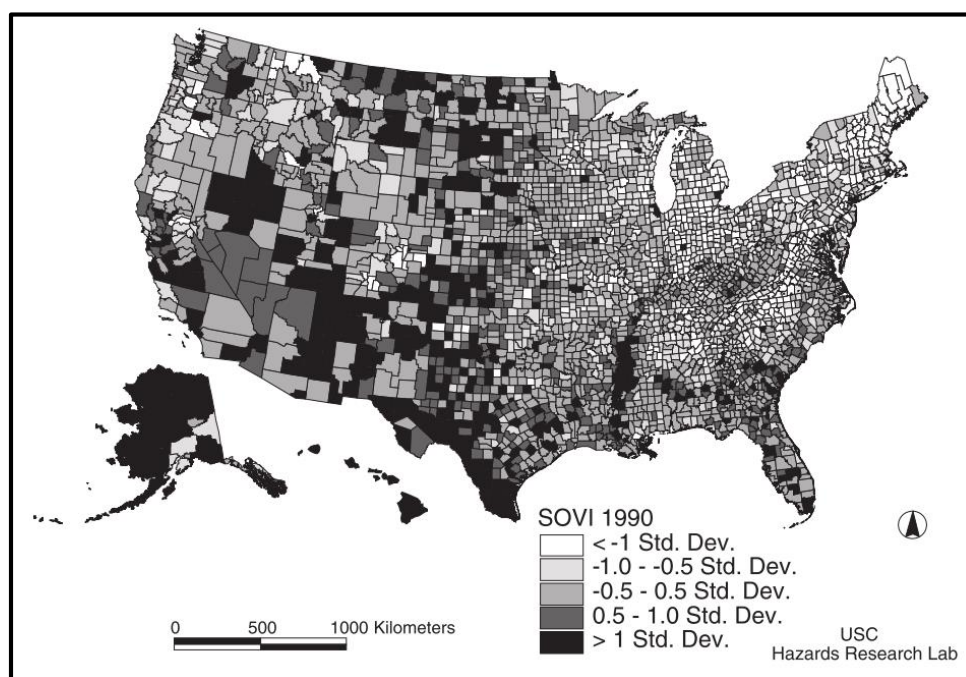
Figure 2-5 Comparative Vulnerability of U.S. Counties based on SoVI (Cutter et al. (2003))

Unlike the researchers who develop vulnerability indices, Deshmukh et al. (2011) quantified the social and economic impact by measuring the social and economic contribution of daily activities and by calculating the serviceability level of relevant infrastructure after disasters. In the study, they measured and assessed the level of severity of the social and economic impacts of the 2008 Midwest Flood on Oakhill Jackson community in Cedar Rapids, Iowa. Through interviews with community leaders, the authors identified the daily activities of the residents of Oakhill Jackson that made social and economic contributions to the wealth of the community. Also, the critical components of the infrastructure that supported the daily activities of the residents of the Oakhill Jackson community were identified. Based on the effect of the flood on the serviceability of critical infrastructure, such as power, water, or roads, and their interdependencies with the community's activities, the authors measured the social and economic impacts on

Oakhill Jackson by configuring the severity levels of various activities. In addition, integrated with the criticality and vulnerability assessment developed by Oh (2010), the dynamic level of severity on communities in terms of social and economic aspects can be measured depending on other parameters, such as the increasing flood level, topographical characteristics, physical condition of the infrastructure, and interdependencies of the components of the infrastructure.

Many researchers have acknowledged the importance of social impacts in understanding impacts of disasters on communities. In particular, the social impacts themselves naturally are difficult to measure in numerical terms, so many researchers try to overcome this issue by developing vulnerabiltiy indices or by identifying the contribution of activities and measuring the reduced serviceability of the infrastructure that supports the activities. However, most studies simply try to measure the inherent characteristics that make communities soically vulnerable or to account for the supply of infrastructure facilities, rather than taking into consideration both the changes in the demands of communities and the coping capacities of infrastructure facilties.

- Technical impact

Understanding the technical aspects of the impacts of disasters enables the measurement of the economic and social impacts on communities and industries. In particular, the lifeline infrastructure, such as electricity, gas, water, and transportation, provide essential services that are necessary for sustaining the social and economic contributions of communities or industries (Chang 2003). Therefore, the failure of these lifeline infrastructure due to the occurrence of natural disasters, especially earthquakes that are most likely to threaten the lifeline infrastructure, could result in regional economic losses to communities that are greater than direct losses to the lifeline agency itself (Chang 2003). Moreover, since infrastructures are highly interlinked and complex systems, understanding the interdependencies of infrastructures with the effects of their disruption on communities is a base for evaluating the social and economic impacts of disasters (Deshmukh et al. 2011; Oh et al. 2012). For example, Shi et al. (2015) used a regional general equilibrium model to simulate the economic impact of the 2008 Wenchuan earthquake by focusing on the

ripple effect caused by interruption of a highway network. In addition to the direct cost to repair the damaged highway in Shifang Province, the reduced ability to maintain transportation service resulted in the interruption of the business in the highway transportation sector. The reduced performance of the damaged highway also decreased the transport of products from suppliers to customers who rely on the highway to supply products to consumers. Reed et al. (2010) placed emphasis on securing the electric power delivery systems considering the regional impact on the economy of disruptions in the energy supply caused by Hurricane Katrina. The failure of the power supply system causes other significant impacts on related energy supply systems, such as oil refineries, which rely on the power supply system to run their operation. The reduction in goods produced at the refineries in turn incurs economic losses in the U.S. economy (Reed et al. 2010). The authors evaluated the power delivery system in Louisiana in terms of the system performance (i.e., outage rate) and the restoration process by varying specific climate variables, such as wind speed, the storm surge, and rainfall.

In order to understand interlinked infrastructure systems, Rinaldi et al. (2001) proposed a conceptual framework (Figure 2-6). Infrastructure systems are very complicated, and they can be influenced by various factors. In this framework, the authors illustrated the interdependencies by using six dimensions, i.e., i) the environment for considering contexts that affect system operation; ii) coupling and response behavior for measuring the level of flexibility against disruptions; iii) type of failure augmented by interdependencies; iv) infrastructure characteristics that affect systems' abilities to adapt to disruptions; v) state of operation of the infrastructure; and vi) the types of interdependencies within the infrastructure. The authors used the example of the energy crisis in California to show the environmental factors that can contribute to an energy crisis and to show how this impact can be transferred to other linked infrastructure via n-order interdependencies.
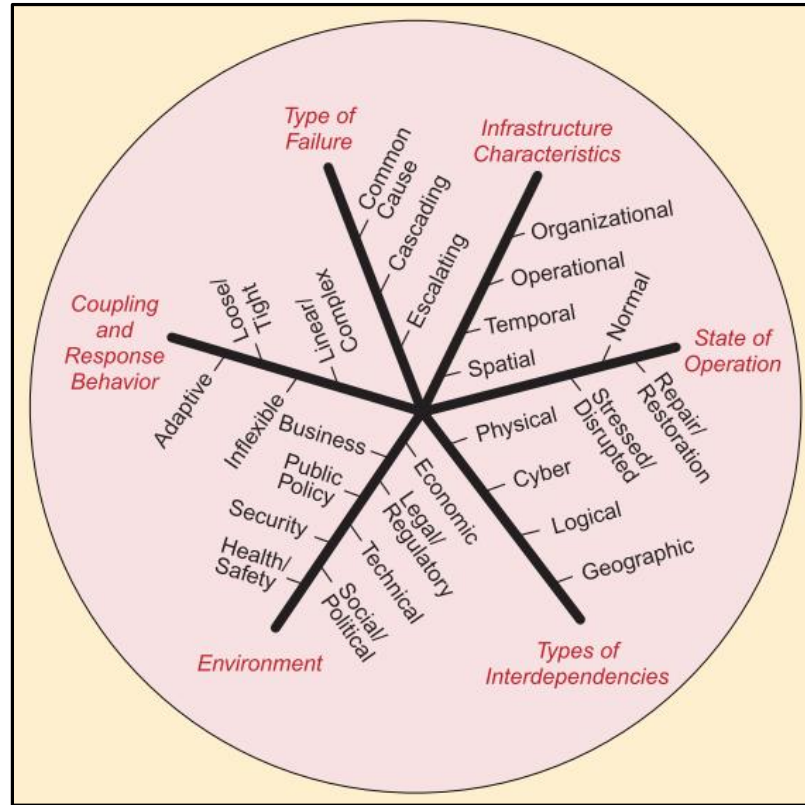
Figure 2-6 Dimensions of Infrastructure Interdependencies (Rinaldi et al. 2001)

Oh et al. (2010a) acknowledged the importance of understanding the interrelationships between critical infrastructure and relevant industries in evaluating the impacts of disasters. In this research, the authors defined the interdependencies in the infrastructure based on the main functions of the associated industries (Figure 2-7). Industries can function with the provision of services from the relevant critical infrastructure. Industries were divided further into two types of industries, i.e., supporting industries and affected industries. Supporting industries, which consist mainly of the lifeline infrastructure, are in charge of operating, maintaining, and providing essential services for dependent entities. Affected industries are industries that are very dependent upon both the supporting industries and the critical infrastructure. The authors also measured the impact of disasters on communities and industries in terms of reduced serviceability of the damaged infrastructure for them. Coupled with the reduced services provided by the infrastructure, the dependency of communities and industries on the damaged infrastructure for conducting their daily

activities was used to measure the impacts of disasters on communities. Based on this analysis, Deshmukh (2010) and Oh (2010) developed a framework they called a Disaster Impact Mitigation Support System (DIMSuS), which is comprised of three modules, i.e., criticality, vulnerability, and severity. Criticality measures the importance of the infrastructure to communities or industries in performing their daily activities. Vulnerability determines the threats of disasters to communities or industries. Reduced serviceability of infrastructure is calculated as the output of the vulnerability module with respect to the activities it supported. Severity measures the extent of impact on communities due to reduced serviceability. The authors measured the impacts of disasters on communities by considering the interdependencies of the critical infrastructure and their dependent activities and calculating reduced serviceability associated with the social and economic activities of communities.
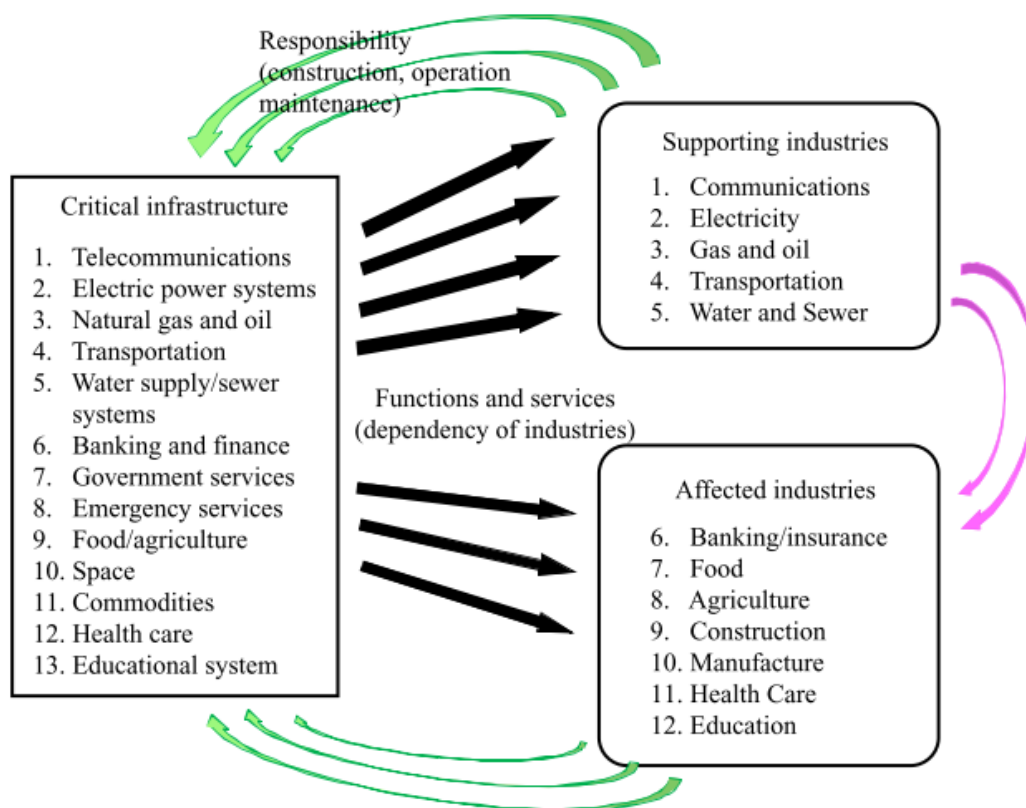
Figure 2-7 Inter-relationship between critical infrastructure, supporting industries, and affected industries (Oh et al. 2010a)

Sultana and Chen (2007) proposed a vulnerability assessment based on the flood-related interdependencies in the critical infrastructure. The infrastructure system in this study was comprised of a dam, water supply infrastructures, water and power distribution pipes, and a highway. In this analysis, the chain failure of the system by floods was assumed to have been initiated by the structural disruption of the dam. As a way of representing the interactions among the components of the infrastructure system, the authors uses the Petri-Net method in which a basic structure consists of a four-tuple, i.e., P, T, I, O, where P stands for places, T stands for transitions, I stands for input functions, and O stands for output functions. Another element of the Petri-Net method is a token that can be moved through the network to serve as a trigger for a transition of the input place. Even though, by considering interdependencies, this study determined that there were vulnerable water infrastructure components, it cannot be used to measure the specific levels of their vulnerability.

In addition to lifeline infrastructure, other researchers have tried to understand the impacts of disasters on emergency-related facilities. For instance, health care systems play a critical role in emergency situations; their ineffective operation could aggravate communities' responses to devastating events (Arboleda et al. 2007). Since hospital operations can be affected either by direct damage to the hospitals, such as the destruction of buildings, or by indirect impacts, such as the disruption of the utility services required to operate, hospital administrators should evaluate their hospital's internal resources and their interdependencies with other external systems, such as gas, water, and transportation (Arboleda et al. 2007; Cimellaro et al. 2009). Arboleda et al. (2007) suggested a simulation tool to assess the operation of a hospital during and immediately after an earthquake event using the System Dynamic (SD) simulation method. The authors used SD to address the complex interactions of external systems, i.e., water, electricity, and transportation, and of internal systems, i.e., emergency rooms, wards, and operating rooms. In this study, the authors assumed that the earthquake disrupted the supply of municipal utility service. As a result of the earthquake, the level of occupancy in each service area, i.e., emergency room, intensive care unit, and operation room, was observed to increase due to the insufficient resources of hospitals and the increased numbers of patients waiting for treatments. In order

to suggest preparation strategies, the authors conducted a sensitivity analysis by varying the hospital's resources and assessing different occupation levels in each service area.

In order to measure the resilience of a health care facility against disruptive events, Cimellaro et al. (2009) use simplified recovery functions that considered the direct and indirect losses in physical systems. In order to account for the physical losses, the authors defined the fragility of the hospital systems by using a multi-dimensional structural performance threshold, which enabled the consideration of the how the components of buildings, with their different physical characteristics, could withstand the impacts of disasters. Furthermore, in the second part of the paper, the authors estimated the functionality of a hospital during an earthquake by considering the structural and non-structural damage to the hospital. The disruption of lifeline infrastructure systems was regarded as a penalty factor in the hospital's functional capacity. Using a metamodel, the authors took into account the dynamic behaviors of a hospital system that was undergoing changes in the availability of resources, organizational policy (i.e., emergency plan), and maximum capacity. However, in the studies, the authors focused more on the structural and organizational performance of an individual hospital than on considering the benefits from sharing medical capabilities within the hospital's regional network. In other words, the authors did not consider interactions between local medical facilities.

In addition to medical facilities, Bristow et al. (2007) considered firefighting operations when the water supply systems were damaged. Generally, disruptive events, such as natural or manmade disasters, impact one or more components of the infrastructure that support fire protection systems. In order to consider the complex types of vulnerabilities inherent in fire protection systems, the authors started by analyzing a small set of failures of water supply systems, such as the destruction of the water pump and the loss of power for the pump system. The scenario they developed was made more complicated by including the consideration of a variety of urban fire ignition points. Considering damaged urban water supply systems and the urban fire scenarios, the authors perceived a range of vulnerabilities of the fire protection system with various fire ignition points.

Bristow and Brumbelow (2012) proposed a simulation approach to assess the vulnerability of urban water distribution systems with respect to their capability to support fire protection

activities. Using the EPANet to simulate a complicated water distribution system and the Fire Following Earthquake module of HAZUS-MH to generate fire-spread areas, the authors estimated the effects of the disruption of water distribution systems on firefighting. The authors also conducted a cost-benefit analysis for use identifying the best mitigation strategy based on the societal benefits derived from applying various mitigation options, i.e., reduction in the total number of people displaced due to the fire and increased time for occupants to structures that were on fire.

As discussed in previous research, understanding the technical aspects of infrastructure systems is pivotal for identifying the social and economic impacts of disasters. The efforts of previous researchers in this area can be largely divided into two categories. First, most researchers agree that understanding the interdependencies of infrastructure is necessary to understand the impacts of disasters. Thus, they attempt to identify and understand the interdependencies of the components of the infrastructure and to determine the impacts that result from these interdependencies. Also, most researchers strive to suggest mitigation strategies for possibly vulnerable infrastructure systems to prevent system failures. However, previous research did not address the possibility that post-disaster infrastructure are likely to suffer from high stress. Even though the components of the infrastructure that are under high stress may still be functional, they cannot adequately service communities and industries because the demand exceeds the coping capacities of the infrastructure. In order to consider the stress-related issues of the post-disaster infrastructure, an impact analysis is required that considers the demand for and the supply of infrastructure services.

2.3   Interdependencies among Infrastructure

The critical infrastructure are interconnected significantly with other infrastructure. In 1998, when the disruption of the communication infrastructure occurred due to the failure of the *Galaxy 4* telecommunication satellite, various financial and banking services were adversely impacted because they could no longer process real-time transactions, such as credit purchases and transactions at automated teller machines (Rinaldi et al. 2001). Also in 1998, the ice storm in Canada struck the northeastern region of the country, creating power outages, which, in turn, disrupted the water supply (insufficient water pressure due

to the unavailability of electricity), required the closure of schools, and restricted hospitals' medical services (Chang et al. 2007). The attack on the World Trade Center in 2001 resulted in the disruption of multiple involved infrastructure components. Disruption of the power supply to train lines caused the closure of all the stations in lower Manhattan, and people could not access the financial district near the Trade Center because of damaged roads, causing congestion in other financial areas (Mendonça and Wallace 2006). The critical infrastructure has become more interconnected because of the advances in communication technology (Chang et al. 2007) and the benefits of geographic concentration (Parfomak 2005).

  To further analyze the dependencies of infrastructure, many researchers have attempted to define and characterize the different types of interdependencies. According to Rinaldi et al.'s (2001) definition, the interdependencies of infrastructure can be categorized into four classes, i.e., physical, cyber, geographic, and logical. Physical interdependencies exist if one infrastructure system is dependent on the material output of another infrastructure system. Cyber interdependencies occur when the state of one infrastructure system depends on information transmitted from another infrastructure system. Geographic interdependencies indicates the situation in which infrastructure systems are concentrated geographically, meaning that they can be affected by local environmental changes. Logical interdependencies exist when one infrastructure system depends on the state of other infrastructure system via a mechanism that does not belong to aforementioned classes. Unlike Rinaldi et al (2001), Zimmerman (2001) defined the interdependencies of infrastructure into two types, i.e., functional interconnectedness and spatial interconnectedness. If the operation of one infrastructure is required to operate another infrastructure, the interdependency between two infrastructure systems is called functional interconnectedness. Also, if two infrastructure systems are geographically close to each other, the relationship is referred to as spatial interconnectedness. To simulate the interdependencies of infrastructures, Dudenhoeffer et al. (2006) suggested four types of interdependencies, i.e., physical, geospatial, policy, and informational. Physical interdependencies refer to a direct linkage between infrastructures from supply/consumption/ production perspectives. Geospatial interdependencies refer to the

relationships between co-located components of the infrastructure. Policy interdependencies exist when there is a bonding of infrastructure components due to policy. Informational interdependencies indicate the relationships between infrastructures that rely on sharing information.

In addition to the study of the types of interdependencies of infrastructures, Oh and Hastak (2008) suggested that the interdependencies of infrastructures could be identified by understanding the roles of infrastructure that contribute to the key function of the dependent infrastructure of interest. For example, in order to provide a medical service for communities (i.e., the key function of a hospital), several key components are required, including a system (e.g., civic infrastructure, communication, emergency medical service), a space (e.g., clinic building, wards, emergency rooms), staff (e.g., medical staff, accessibility of medical staff to the hospital), and supplies (e.g., food, electricity, and water) (Kelen and McCarthy 2006). Oh et al. (2010b) highlighted the interdependencies of infrastructure and reflect them to disaster impact analysis for communities by calculating the criticality of the infrastructure. According to Oh et al. (2010b), the criticality of infrastructure is calculated as the degree of interdependencies of the components of the infrastructure with daily activities or functions of communities.

Because of coupled infrastructure systems, in order to evaluate the vulnerabilities of infrastructure systems, the interdependencies of the systems must be considered carefully. However, identifying the behavior of systems when complex interdependencies exist is a significant challenge (Rinaldi et al. 2001).

2.4   Infrastructure System-of-Systems

With the advances in communication technology, the different systems, each of which is complex, become aggregated and interrelated into one large system (Egan 2007). As such, complex systems that have been developed and designed to be isolated to address a single problem can no longer be considered to be solitary systems now that they are part of one integrated system (Keating et al. 2008). In addressing a complex, integrated system, the concept of the system-of-systems approach has attracted the attention of many systems engineers and researchers (Carlock and Fenton 2001; Pei 2000; Sage and Cuppan 2001;

Tolone et al. 2008). According to Keating et al. (2008), the system-of-systems approach is defined as "the design, deployment, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results." In the definition, the "metasystem" refers to "one large system that is comprised of multiple, autonomous, embedded, complex systems that can be diverse in technology, context, operation, geography, and conceptual frame." The system-of-systems is distinguished from one large complex, but monolithic, conventional system in that the components of the systems-of-systems are independent of others and are systems themselves in that they are composed of multiple system components (Maier 1998). To differentiate between a conventional system and a system-of-systems, Maier (1998) proposed five characteristics that distinguish a system-of-systems:

- Operational independence: The component systems can operate independently to achieve their missions;

- Managerial independence: The component systems are managed independently. The component systems are separately acquired and operated, but integrated for the purpose of accomplishing the aggregate goal of the system-of-systems;

- Evolutionary development: The system-of-systems is not stationary and fully developed. Rather, the system-of-systems changes and develops with purposes and functions added, changed, and removed;

- Emergent behavior: The system shows the emerging behaviors that are not observed in its component systems individually;

- Geographic distribution: The geographic realm of systems in which a component system can readily exchange information without a significant amount of energy or mass.

Critical infrastructures are composed of managerially- and operationally-independent subsystems (Mostafavi and Abraham 2014). Approximately 85% of the U.S. critical infrastructure is owned by the private sector (Government Accountability Office 2009). Since critical infrastructures are interrelated and interdependent, protecting and securing their functioning require a close partnership among different infrastructure systems (NIPP 2013). For instance, in the 1998 ice storm in Canada and in the 2001 attack on the World

Trade Center, localized impacts have significant potential for becoming catastrophic impacts as the disruption of one infrastructure influences the other connected infrastructures. While it is impossible to prevent disruptions with certainty, the impact of disruptive events, i.e., natural or man-made disasters, can be lessened and mitigated in an efficient manner if their impacts on infrastructure systems are evaluated and mitigated in an integrated way (Cavallo and Ireland 2014; Tolone et al. 2008).

In response to the need for an integrated approach, there have been several studies of infrastructure systems. Mostafavi and Abraham (2014) defined the civil infrastructure as a system-of-systems by focusing on two primary characteristics of a system-of-systems, i.e., operational independence and managerial independence, which were proposed by Maier (1998). Different independent infrastructure systems exist and interact with one another. Cavallo and Ireland (2014) pointed out that the impact of disasters on infrastructure systems is not simply the sum of the partial impacts on the components of the infrastructure. Since disasters affect different independent and heterogeneous infrastructures, all of which are dependent on each other, an infrastructure system should be considered as a system-of-systems. Tolone et al. (2008) posited that critical infrastructure systems are highly interdependent systems, thus they are complex phenomena. Therefore, a system-of-systems analysis is appropriate for critical infrastructure systems. In addition, the analysis of critical infrastructure systems should account for both the engineering and behavioral properties; the engineering properties are the physical properties that indicate the physical constraints on the operation of the infrastructure, while behavioral properties are the properties that emerge via the business processes, stakeholders' decisions, and interactions among infrastructure systems. These two properties result in complicated, non-linear problems. Combined with the interdependent nature of infrastructure systems, these two properties justify the application of the system-of-systems approach for the analysis of critical infrastructures in order to understand large-scale, complex phenomena (Tolone et al. 2008). In addition to the reliability analysis of critical infrastructure systems, Mostafavi et al. (2012) utilized the system-of-systems approach to investigate innovation policies, e.g., intelligent transportation systems and alternative fuels, in interdependent infrastructure systems. The

system-of-systems approach allows the consideration of the adaptive behaviors of the sub-systems within and across the different levels of analysis. Faust et al. (2013) used the system-of-systems approach to assess stakeholders' perceptions in water infrastructure projects and to identify the key stakeholders who must be considered in the decision-making process and in categorizing the stakeholders into different hierarchical levels. This enables concentration on the relevant stakeholders and the components of interest. Thissen and Herder (2008) found that the researchers' preferred system-of-systems model can vary depending on whether they focus more on technical engineering issues or the non-engineering aspects, such as political science, economics, and public management. In engineering, researchers prefer layer modeling (DeLaurentis and Callaway 2004), and others prefer models that are comprised of stakeholders who have relevance to the phenomena of interest (Thissen and Herder 2008). Thissen and Herder (2008) developed a reference model (Figure 2-8) to illustrate an infrastructure system-of-systems with the relevant stakeholders. As shown in Figure 2-8, the model is comprised of three layers. The lower layer of the infrastructure supports the functioning of the upper layers. The lowest layer in Figure 2-8 corresponds to the physical infrastructure, which is made up of a system of links (e.g., roads and pipelines) and nodes (e.g., power plant and water treatment facility) The second layer covers the infrastructure's network in which capacity management and network control are performed by the coordinated actions of the other physical infrastructure systems (e.g., transportation, water, and electricity). The third layer is related to the provision of facility service for communities and industries. Based on the support of the second layer (operation and management of infrastructures), the infrastructure-based products or the service from the dependent infrastructure is provided for communities and industries.
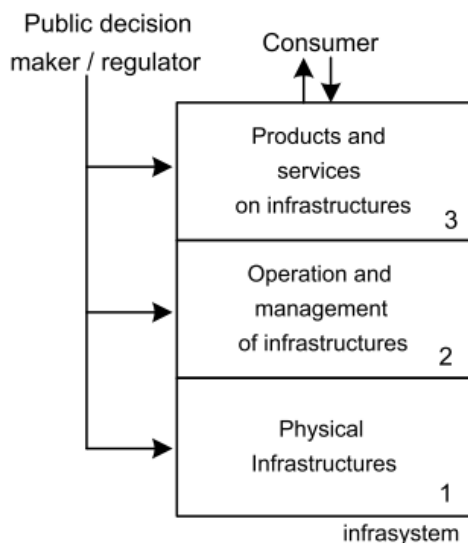
Figure 2-8 Infrastructure System Layer Model (Thissen and Herder 2008)

Even though the complex interactions of a variety of systems are considered, either within the same layer or across the layers, it is important to manage the infrastructure's system-of-systems in an efficient manner. It is too large and complex to conduct only one integrated system analysis considering all the complexity (Thissen and Herder 2008). In order to address the problems associated with the system-of-systems, DeLaurentis (2005) defined the flow of the system-of-systems approach called "Proto-Method," which is comprised of three phases, i.e., a definition phase, an abstraction phase, and an implementation phase (Figure 2-9). The primary purpose of the definition phase is to understand the SoS problems; major activities are to identify and characterize complicated systems, which have potential for causing evolutionary and emergency behaviors of the systems, and to understand the appropriate level of complexity for solving the defined problems. In the abstraction phase, it is important to identify all of the main actors, effectors, disturbances, and networks and their corresponding interactions with other factors. By abstracting main entities and interactions, which later guides the implementation phase, the complicated real-world problems are decomposed to a more simplified level in which there are entities connected with the link. In the implementation phase, all or part of the abstraction phase is represented and tested using simulation technologies.

Definition Phase	Abstraction Phase	Implementation Phase
Categories	Resources	Classes
Levels	Stakeholders	Objects
Status Quo	Disruptors/ Drivers	Methods/Data
Barriers	Networks	Measures
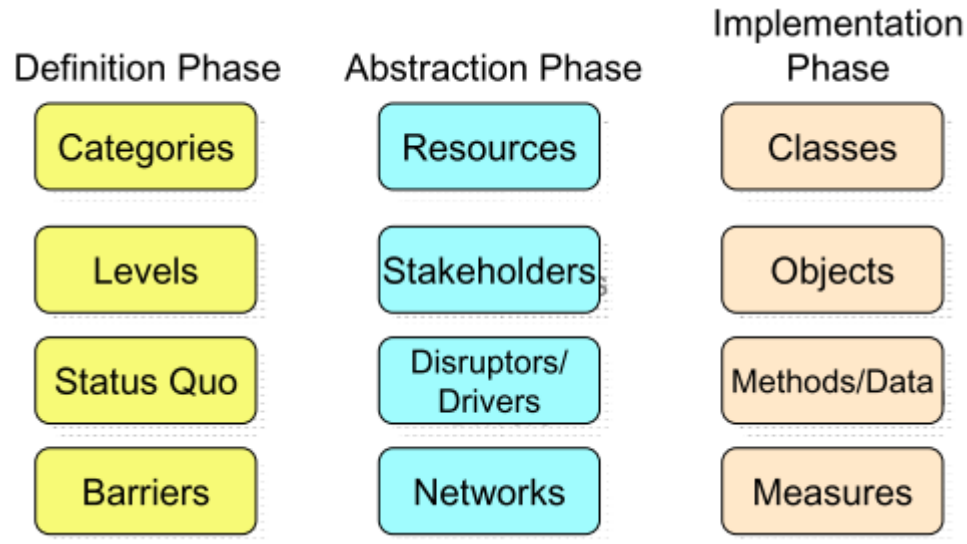
Figure 2-9 "Proto-Method" for SoS Problems (DeLaurentis 2005)

2.5 Simulation Methods

In order to measure the impact of a disaster on the infrastructure, communities, and industries, it is indispensable to address the system-of-systems problems. In particular, a stress assessment tool was developed in this research that targets the functioning of individual essential infrastructure facilities, such as health facilities, fire departments, and utility services. In operating one-infrastructure facility, there are multiple infrastructure units that may experience high stress in supporting the facility, which ultimately limits the performance of the facility as a system. Therefore, a simulation candidate must have the capabilities of reflecting the stress levels in various supporting infrastructure units. This research explains how the impacts of a disaster generate excessive stress on the functioning of an essential facility assuming that the disaster impacts on the external infrastructure systems that support it, such as water, electricity, and transportation systems, and the demands of communities for the infrastructure service. In a post-disaster situation, since the demands and capabilities of the facility vary as the supporting infrastructure is restored over time, stress levels in the facilities are required to measure their effects in terms of the provision of infrastructure service. Consequently, the simulation model developed in this research was intended to i) consider the impacts of disasters on the functioning of an infrastructure facility in terms of changes in demand and supply of services; ii) demonstrate

varying stress levels in an infrastructure facility and their impacts on the serviceability for communities; and iii) identify bottleneck resources in providing infrastructure services with communities; and iv) enable the development of strategies for relieving excessive stress.

The design of the model is comprised of two parts, i.e., the internal operation system of an infrastructure facility (e.g., in the case of medical facilities, medical supplies and medical staff) and the interaction with external systems (e.g., in the case of medical facilities, electricity and water for operating hospitals). It is worth noting that resources that cause bottlenecks in the facility's operation will be changed as the communities and the supporting infrastructure recover from the effects of the disaster. That is, the limiting resources will vary with time. Thus, in order to appropriately understand and relieve the stress imposed on a post-disaster infrastructure facility, the model should be capable of identifying the limiting resources as time passes. Moreover, the criterion for evaluating the stress on the facility is to measure the quality of service provided for communities. So, the model must track the overall quality of service offered to individuals. The required characteristics of the simulation method are as follows:

- The model is structured to reflect the process of operating an infrastructure facility;
- The model is associated with the operational strategies used to relieve the excessive stress on the functioning of an infrastructure facility;
- The model must be capable of tracking individuals who receive infrastructure service.
- The model must be capable of predicting the performance of an infrastructure facility and of identifying resources that cause bottlenecks.

2.5.1   Current Simulation Approach

The main purpose of using the simulation approach was to develop the stress assessment tool for a post-disaster infrastructure facility. Due to the nature of a highly-interrelated infrastructure, excessive stress can be generated on infrastructure facilities due to various factors. The current operational simulation methods that are used extensively for designing

complex systems include Discrete Event Simulation (DES), System Dynamics (SD), and Agent Based Model (ABM) (Borshchev and Filippov 2004; Siebers et al. 2010). DES and SD have been used extensively since they were developed, while ABM, which is relatively new, is gaining in popularity as an operational simulation tool (Siebers et al. 2010). Even though all of them give the same benefits to modelers by solving real problems in the systems without experimenting with real systems, the selection of the simulation method depends on the characteristics of each method (Table 2-1).

Table 2-1 Comparison of Simulation Methods: Discrete Event Simulation, System Dynamics, and Agent Based Model (Brailsford and Hilton 2001; Borshchev and Filippov 2004; Siebers et al. 2010)

Features	DES	SD	ABM
Structure	- Top down modelling approach; - Focus on the system in detail	- Top down modelling approach; - Focus on dynamic complexity	- Bottom up modelling approach - Focus on individual entities and interactions between them
Abstraction	- Low and middle abstraction	- High abstraction	- Low, middle, and high abstraction
Behavior of entities	- Passive - Intelligence is modelled as part in the system	- Continuous quantity - intelligence is affected by policy pressures	- Active - Intelligence is represented within each individual entity
Control	- Holding (Queues) - Centralized	- Rates (flows) - Centralized	- Rules governing the individual entities - Decentralized
Data sources	- Collected/measured (objective) data	- Broadly drawn from the observation of a real world (Subjective)	- Often based on theories or subjective data
Purpose	- Operational and tactical level	- Strategic level	- Operational, tactical, and strategic level
Capability of tracking individuals	- Capable	- Incapable	- Capable
Number of entities	- Small	- Large	- Small to large

Discrete Event Simulation (DES) focuses on the process and represents the operation of the system as a chronological sequence of discrete events. The components of this model are comprised of entities, interlinked queues, and activities. State changes in discrete times and entities go through the systems following the pre-defined system process. The duration of each of the activities often is sampled from probability distribution functions. It is worth noting that, since DES is capable of tracking the delay of entities' procedures in queues, modelers can compare different operational strategies and predict or optimize specified performance criteria (Brailsford and Hilton 2001). Compared to other simulation methods, i.e., SD and ABM, the complexity lies in the detail of the design of processes (Brailsford and Hilton 2001). Also, DES enables modelers to map relatively small and middle-sized problems from the real world to the system compared to SD. That is, DES has less abstraction in representing the real world to the simulation model.

The **System Dynamic model (SD)** usually is used by policymakers in order to improve public policies or organizational systems by identifying weaknesses and problems (Sumari and Ibrahim 2013). Rather than handling the individual behaviors of entities, SD focuses on the flow of networks around the system (Maidstone 2012). By adjusting the rates of the individual flows, the overall flow can be controlled. There are qualitative analyses and quantitative analyses within SD (Brailsford and Hilton 2001). Qualitative analysis precedes quantitative analysis. Qualitative analysis involves conducting the initial discussion about the causes of the problems, which the modeler wishes to determine with the SD. In this stage, modelers identify the factors that can influence the problem. In quantitative analysis, based on the findings of the qualitative analysis, a flow diagram is drawn that represents the effect of the loops using differential equations with time. Compared to other simulation approaches, SD handles systemic problems at an aggregate level over time based on the feedback loops (Scholl 2001). Rather than providing a deterministic solution to problems, SD attempts to conceptually understand a large, complex system (Brailsford and Hilton 2001).

The **Agent Based Model (ABM)** models the systems as a set of autonomous agents that have their own objectives and predefined rules and as their interaction with other agents and their environment (Maidstone 2012). Instead of determining the global behavior of the

system, modelers define simple rules for individual agents. As such, complex systems are represented to the model as the emerging behaviors of agents (Borshchev and Filippov 2004). In particular, ABM can reap benefits if the problems that the modelers want to resolve via the simulation approach require consideration of the individual properties of agents (Siebers et al. 2010). Moreover, if systems can be scaled up to an arbitrary level and their overall processes are difficult to define at the simulation design stage, ABM is appropriate because it designs systems without the pre-defined rules for the overall system, as emerging behaviors of agents over time.

- Comparison of each simulation approach

As discussed so far, each simulation approach has its own distinctive benefits in addressing real-world problems. However, based on the purpose of using a simulation approach, the simulations must be compared carefully.

Discrete event simulation (DES) models a defined series of processes as discrete events (Maidstone 2012). So, entities pass through the processes in sequence as time passes. In particular, entities in queues can be tracked and their delay time for moving to the next process can be extracted. In that way, the bottleneck process and resources used in the process can be identified. By deriving input data from probability distributions, the DES can predict the performance of the system. In addition to the information about the performance, the DES gives information about the utilization of resources (Brailsford and Hilton 2001).

System Dynamics (SD) model can reflect the defined conceptual structure of the system by using feedback loops. However, SD does not model the system by using both the specific resources and entities; rather, it focuses on the flow of entities. As such, SD controls the flow by adjusting the rate of flow into the system. So, SD cannot be used to calculate the specific performance of the system, but it does allow modelers to acquire an overview of large complex systems through the feedback loops.

Agent Based Model (ABM) does not model the system through the defined structure or overall rules, i.e., a top-down approach. Instead, ABM incorporates complex systems by allowing individual autonomous entities to behave and interact with each other and their

environment, i.e., a bottom-up approach. Under the defined environment and the simple rules for agents' behaviors, system properties or phenomenon emerge from its constituent agents (Siebers et al. 2010). So, instead of predicting and optimizing the deterministic performance of the system, ABM is more appropriate for identifying the properties of emerging systems caused by the interaction of agents.

Table 2-2 shows the characteristics of research problems that the candidate simulation methods should be qualified for. Based on Table 2-2, the DES is the most appropriate choice for this research. In particular, the stress assessment tool is capable of evaluating the resultant performance of an infrastructure facility after applying disaster-driven stresses to the facility, and it also suggests strategies for relieving stresses. In addition to the benefits of DES in designing the complex operational system, DES has advantages for making operational strategies in order to improve the performance.

Table 2-2 Comparison of the Features of Simulation Approaches

Characteristics of the research problem	Discrete Event Simulation	System Dynamics	Agent Based Model
Reflecting the pre-defined operation process	Yes	Yes	No
Identifying the bottleneck of resources in the system	Yes	No	No
Tracking entities	Yes	No	Yes
Predicting and optimizing the performance of the system	Yes	No	No

2.5.2   Discrete Event Simulation

Discrete Event Simulation (DES) has been used extensively for the past 40 years (Sumari and Ibrahim 2013) in operational research, including construction projects (Lee et al. 2007),

operation of emergency departments (Cimellaro et al. 2009; Sumari and Ibrahim 2013), disaster restoration operations for utility systems (Luna et al. 2011), and housing projects after a disaster (Patel and Hastak 2013). The DES approach focuses on the organizational processes that occur in discrete events. In the DES, there are four basic elements, i.e., entity, resource, control elements, and operations (Schriber and Brunner 2006). Entity is a unit that goes through each process before exiting the system. When discrete events occur, entities respond to the events either by moving to the next process or by remaining in the queue until the next process is ready to admit them. Resource is a system element that provides service for the admitted entities. Resources are usually limited, so the entering entities compete for their use. Some entities that are not assigned to resources must wait to utilize them, which causes delays. Control element is a construct that supports other types of delay and enables the maneuver of resource usages. Operation is a step or process conducted by an arriving entity while it proceeds through a system.

To better understand the application of DES to disaster management, two case studies were investigated in which the DES model was used in disaster management. The applications illustrate how essential facilities sustain their operations in a post-disaster situation and how they can improve their performance in response to demands for services.

- Application of DES to the development of a plan for providing post-disaster housing

After disasters strike communities, infrastructure facilities and residential buildings are likely to be damaged. The lack of availability of utility services and the destruction of residential buildings cause large numbers of people to live in shelters until their houses can be rebuilt. However, private homes provide people with favorable and relaxing environments, so living in temporary shelters sometimes causes them to incur adverse health effects and hinders them from getting back to their normal lifestyle(Patel 2010). However, the lack of a solid framework for helping emergency agencies distribute emergency housing units makes it difficult to provide housing for all victims in a timely manner. Patel (2010) proposed a framework for developing pre-disaster strategies to expedite the construction and distribution of housing units to victims of disasters using a Discrete Event Simulation method.

Due to the physical impacts of disasters on existing assets and limited resources, it is a huge challenge to construct and provide housing units for the large numbers of people who have been displaced from their homes. Considering the limited resources, Patel (2010) offered a strategy for providing 200 manufactured homes within 30 days after disasters. In order to optimize strategies for providing post-disaster housing, the following constraints must be considered (Patel 2010).

- Cost constraint;
- Time constraint;
- Resource constraint (labor and equipment).

Depending on the strategy, tradeoffs can occur among the three constraints. For instance, if local government adds more resources to expedite the completion of the housing project, the cost of the project will increase. Patel (2010) used the Discrete Event Simulation method to deal with the tradeoff problem and optimize the strategy. The developed simulation model enabled i) the assessment of the initial planning strategy compared to the goal (i.e., providing 200 houses within 30 days); ii) the evaluation of alternative strategies; iii) the identification of backlogs of resources in expediting the project; and iv) the provision of a guide for participating agencies so they could understand the proposed strategies.

The operation of constructing housing units follows the pre-defined flow of the process, as shown in Figure 2-10. As a preliminary stage, the author developed a pre-disaster strategy that included 1) site selection to build housing units considering accessibility to essential facility services (e.g., water, electricity, and education); 2) selection of the design of the houses and the layout of the site, considering the size of the houses, the duration of construction, and cost; 3) consideration of routes for home delivery; and 4) estimation of the time required to build the houses. After defining the sequence of each task (operation) and its required resources (resource), as shown in Figure 2-10, the authors ran the DES model. The model went through all of the defined tasks following its logical sequence (entity), i.e., a task will start after all of its preceding tasks are completed. In order to reflect a real construction sequence, DES includes logics (control), i.e., all pipe-laying activities are not conducted simultaneously.

This model shows the ability of the DES model to optimize a post-disaster housing strategy. The model evaluates the current post-disaster housing strategy and demonstrates how much the strategy could be expedited by adding different amounts of resources.
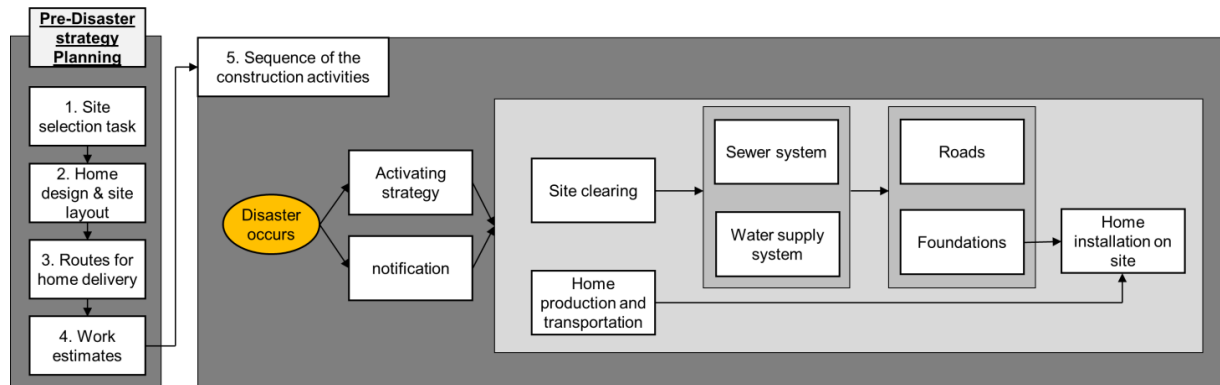
Figure 2-10 Flow of the Operation of a Post-Disaster Housing Project (Patel 2010)

- Application of DES to the development of emergency planning for a hospital

The role of medical facilities is critical since disasters sometimes cause a large number of casualties and injuries (Paul and Hariharan 2007). However, due to the limited budget for operating hospitals, most medical facilities, especially their emergency departments, fall short of accommodating the increased demands when disasters occur. Most existing studies have focused how more resources can be added to avoid bottlenecks and to improve the rate at which patients can be treated during a disaster situation. But, a few studies have focused on ways to improve the rate at which patients can be treated without allocating more resources, e.g., rearrangement of the treatment procedures even though accelerated processes might increase the capacities of an emergency department (Xiao et al. 2009). To fill this gap, Xiao et al. (2009) proposed a framework to reconfigure the workflow of treating patients in order to improve the performance of an emergency department. Given the limited budget and resources, the authors rearranged the procedure of treating patients by removing non-critical processes, i.e., collecting patients' insurance information or other activities not related to medical treatment, without compromising the quality of the medical treatments. To understand the effects of the reconfiguration on the rate at which patients could be treated, the authors used the DES method to simulate the operation of an

emergency room during a simulated disaster situation. In order to understand the effect of reconfiguration of patients on the rate at which they could be treated the authors had to understand the processes of an emergency department during a disaster situation as well as the priorities of the tasks within the operation. Also, in order to evaluate the performance of an emergency room, the authors used the number of high-priority processes and patients' waiting times as criteria for determining the optimal solution. The DES model is capable of considering the following properties:

- Designing of the patient treatment procedure;
- Reconfiguring the procedure of patients;
- Calculating the patients' average waiting time.

Figure 2-11 shows the processes of patients' treatment within an emergency department. When patients (entity) enter the emergency room, they are registered by the receptionist in the patient check-in process (operation). Then, the patients move to the next process, called the triage station process, where they are rated with an emergency severity index depending on the severity of their injuries. After triage, all of the patients go through different processes, depending on their severity levels. Finally, they are either discharged or admitted to hospitals depending on the results of the examinations (Control) or on the condition of their health. Each process requires staff with different specialties, e.g., a triage nurse or technicians (resource) are needed for the triage process.

This DES model demonstrates the different reconfiguration results on the different waiting time of the patients. In the course of searching for the best reconfiguration strategy, the DES model updates the modified processes of patient care in response to the increased number of patients. The capability of DES to track patients' waiting time as times passes enables the evaluation of alternative configuration strategies and determines the optimal strategy based on the predefined criteria, i.e., retaining a high number of treatment processes and reducing the time that patients have to wait.
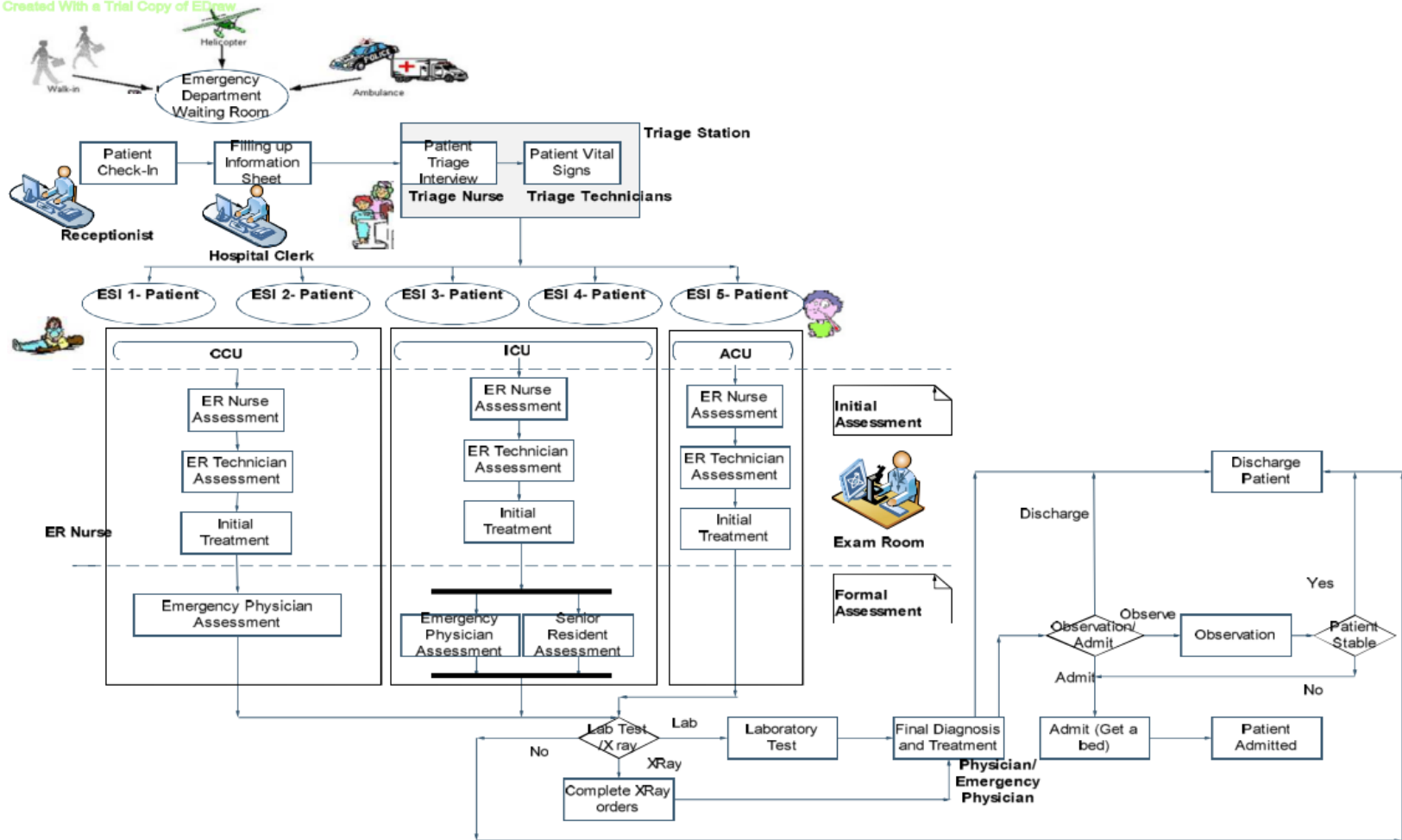
Figure 2-11 Process of Treating Patients in an Emergency Department (Xiao et al. 2009)

2.6   Summary

Natural disasters often affect the functioning of critical infrastructure, which compromises the capacities of the infrastructure to provide essential services for the affected communities. However, the impacts of disasters also are likely to boost the demand for services exponentially. The post-disaster conditions cause the essential infrastructure facilities to be overwhelmed by excessive stress, which ultimately disturbs the provision of adequate service for affected communities. Even though essential facilities still function, their services, which substantially fall short of victims' demands, may put the victims in great danger. Therefore, understanding the stress level is indispensable for making disaster plans.

However, due to the nature of the interdependencies of the infrastructure, the proper assessment of the stress imposed in the infrastructure facilities requires the system-of-systems (SoS) approach. Based on the required level of complexity and the required properties of simulation methods (i.e., identifying stress levels in the infrastructure and developing strategies to relieve stress), the Discrete Event Simulation (DES) model was selected as the most proper method because it can identify bottleneck resources as well as facilitate the development of the strategies for fortifying the limiting resources. The two examples of applying DES to disaster management discussed proved the benefits of its use in optimizing disaster management.

CHAPTER 3. STRESS LEVEL IN INFRASTRUCTURE AND ITS EFFECTS ON AN INFRASTRUCTURE FACILITY SYSTEM

3.1   Introduction

Due to the major impact of disasters, the capacities of infrastructure are likely to be compromised, while the demands of affected communities frequently increase significantly above their pre-disaster demand. Consequently, such reduced infrastructure services are unable to adequately meet post-disaster community needs. In order to support supporting a nation's wealth, economy, and security (Ben-Akiva et al.1993), infrastructure facilities undertake excessive stress on all available resources, as they try to provide the best service for as many communities as possible. In other words, the stress level in infrastructure facilities is likely to exceed their capacities, and ultimately driving down the service to an unacceptable level in a post-disaster environment. In such a situation, deteriorated essential services often place even greater hardship on the affected communities; more deteriorated service the public has to use, more quickly the public reaches its hardship limits (Maguire Group 2008).

In addition to the impact on communities, the deteriorated service of even a single infrastructure can influence the functioning of other dependent infrastructure ultimately making the entire system and its performance unsustainable. For example to operate only one infrastructure facility (e.g., a hospital), other supporting infrastructure units (e.g., electricity, water, etc.) are needed for the facility to be able to provide the required service (e.g., medical treatment) for that facility. A single infrastructure unit (e.g., a water facility) under stress, which exceeds its capacities, is unable to provide its required service (e.g., water supply) for the facility system (e.g., a hospital) at the expected performance level. That scenario causes the facility (e.g., the hospital) to deliver unacceptable service (i.e., delayed patient wait time due to deteriorated medical treatment) to communities during the disaster recovery phase without external assistance (e.g., bottled water from non-

governmental organizations, other civic organizations, etc.).Therefore, assessing the stress level of each supporting infrastructure unit is important in order to keep its essential services at an acceptable level.

This chapter discusses the need for understanding the nature of the stress placed on post-disaster infrastructure facilities in terms of their required services provided to their communities. Through a literature review, the nature of critical infrastructure is identified as well as the features of natural disasters that can produce the conditions that place stress on infrastructure which exceeds their strain capacities.

Through a literature review, the effect of high stress on infrastructure is investigated in terms of the resulting serviceability for communities and thus the need for understanding the nature of any stress is highlighted especially for a post-disaster infrastructure. And then, the stress is reviewed throughout various disciplines. After that, the stress-strain principle for post-disaster infrastructure is developed using the analogy between mechanics of materials and infrastructure management, which is capable of interpreting the stress with respect to its strain capacities.

The applicability of such a proposed stress-strain analysis to post-disaster infrastructure management is discussed using two case studies of essential infrastructure, namely, a medical facility and a power facility. By discussing the emergency response of essential facilities in terms of their stress and strain, the benefits obtained from such an analysis are offered. In conclusion, due to the interconnection with other infrastructure systems, the difficulty of capturing the stress and strain of an overall infrastructure is examined in two case studies. As a candidate solution for addressing interdependency issue, the potential of using the system-of-systems is briefly discussed.

3.2   Literature Review

In a post-disaster situation, the role of critical infrastructure becomes even more crucial, as it must sustain the daily activities of communities as well as support and facilitate recovery activities. In this chapter the critical infrastructure and its overall missions are presented, and the features of disaster events that put an infrastructure facility under excessive high

stress are discussed, followed by the effects of high stress on infrastructure facilities, and the investigation of existing studies on stress in various disciplines.

3.2.1   Infrastructure Facilities in a Post-Disaster Situation

The critical infrastructure serves a critical role for sustaining the daily activities of a community by providing relevant services. In a post-disaster situation, the continuity of the provision of services by the infrastructure becomes more important for the following reasons.

1. The critical infrastructure facilities provide essential services for communities and industries so they can sustain their social and economic activities even during the disaster (Oh et al. 2009). As such, communities and industries are able to prevent the secondary losses that are caused by the disruption of undertaking social/economic mundane activities due to insufficient support from infrastructure.

2. The critical infrastructure facilities also assist civic governments or communities in conducting recovery activities by providing essential services. In the aftermath of a disaster, the demands for certain recovery activities, such as medical demands, debris removal, and other kinds of civic services, are unlikely to be met adequately due to the reduced services from the critical infrastructure, and this may put the affected communities at risk.

In order to ensure the security of the critical infrastructure, the U.S. government defined the term 'critical infrastructure' as "telecommunications, energy, banking and finance, transportation, water systems, and emergency services, both governmental and private." The presidential directive PDD-63 declared the need for actions to protect certain components of the infrastructure that are susceptible to hazards (Clinton 1998). According to this definition, the critical infrastructure is focused on the infrastructure that, when damaged, could affect national defense or economic security. In addition to the defined infrastructure, Rinaldi et al. (2003) added five additional components to the infrastructure, thereby broadening the scope of the national infrastructure to include industries that contribute to sustaining other industries and communities, e.g., food and agriculture, space, numerous commodities, the health care industry, and the educational system. Based on the

defined critical infrastructure, Oh (2008) further analyzed these components and their relationships to the relevant industries (Figure 3-1). According to Oh (2008), the 12 main industries are identified and linked to 13 defined critical infrastructure facilities.
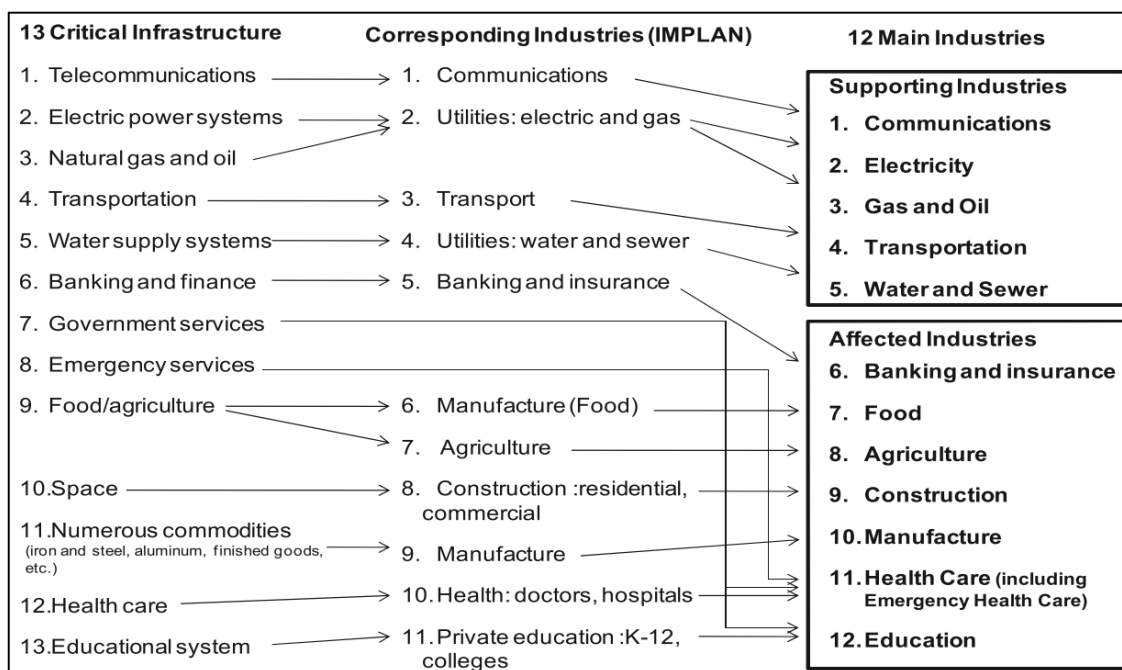
Figure 3-1 Association of Critical Infrastructure and Main Industries (Oh 2008)

Even though a reliable supply of infrastructure services is critical for the security and national economy, some infrastructure services are often vulnerable to natural disasters, epidemics, and certain kinds of terrorist attacks (Parfomak 2005). According to the disaster impact mechanism proposed by Oh and Hastak (2008), disasters can hamper the functioning of the critical infrastructure, related industries, and communities as follows (Figure 3-2).

- Primary impact: Disasters primarily affect the physical infrastructure. Depending on the maintenance condition or topographical condition, the direct damage by natural disasters can vary (Oh 2010). Also, depending on the presence of physical damage to infrastructure, the types of failure are categorized into two modes, i.e., structural failure and functional failure.

- Secondary impact: The damaged infrastructure transfer their impacts through their interdependence on other connected infrastructure and on dependent entities. Due to the reduced serviceability of the damaged infrastructure, industries and communities cannot sustain their ordinary activities, and this means that indirect losses will be incurred. In order to perceive the resulting impacts on the critical infrastructure, communities, and industries, the technical, economic, and social aspects to disaster impacts must be considered.
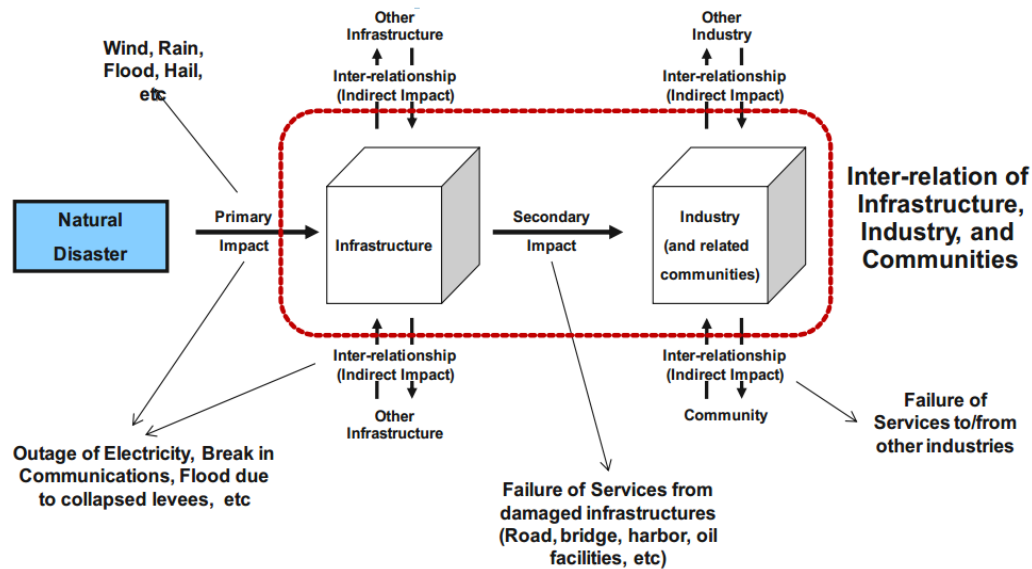
Figure 3-2 Disaster Impact Mechanism (Basic Cell Model) (Oh and Hastak 2008)

In addition to the deterioration of the capacities of the infrastructure, they can incur demands that exceed the capacities of the disaster-damaged infrastructure. Many studies have defined and illustrated the impact of disaster events as the imbalance between the demand and the infrastructure's capacity required to cope with the demand (WHO 1992; Shultz et al. 2006). Lindell and Prater (2003) also defined natural disasters as the condition in which an extreme geological, meteorological, or hydrological event exceeds the ability of a community to handle the ensuing effects.

By investigating the operation of infrastructure facilities in a past disaster, e.g., Hurricane Katrina, the demand could surpass the coping capacities of the infrastructure for the following reasons (Quarantelli 2006)

1) **Increase in demand:** Due to the extreme impact of disasters, demands of affected communities are generated beyond the design capacity of the infrastructure. In the case of the devastating Hurricane Katrina, the hurricane caused landfall, which destroyed two major levees. The destruction of the levees resulted in approximately 25,000 evacuees seeking shelter in the New Orleans Superdome, which exceeded its capacity;

2) **Compromised coping capacities:** The infrastructure capacities are compromised by the disaster's physical impact, so they are not enough for accommodating the community demand. Following Hurricane Katrina, essential infrastructure facilities were inoperable; food, water, gas, electrical power, and civic governance (i.e., police, emergency agents) were unavailable. The weakened functioning of the essential infrastructure was unable to meet the demands of the community.

Therefore, the affected infrastructure facilities may not be able to successfully meet the community demands, resulting in an adverse impact both on the social/economic activities and on the community's recovery (Deshmukh et al. 2011). Considering the aforementioned effects of a disaster on the infrastructure, three plausible scenarios were considered (Figure 3-3), i.e., i) the case of compromised capacities of the infrastructure, ii) the case of increased demands for infrastructure services, and iii) consideration of both cases (i.e., demands increasing while the coping capacities of the infrastructure are decreasing).
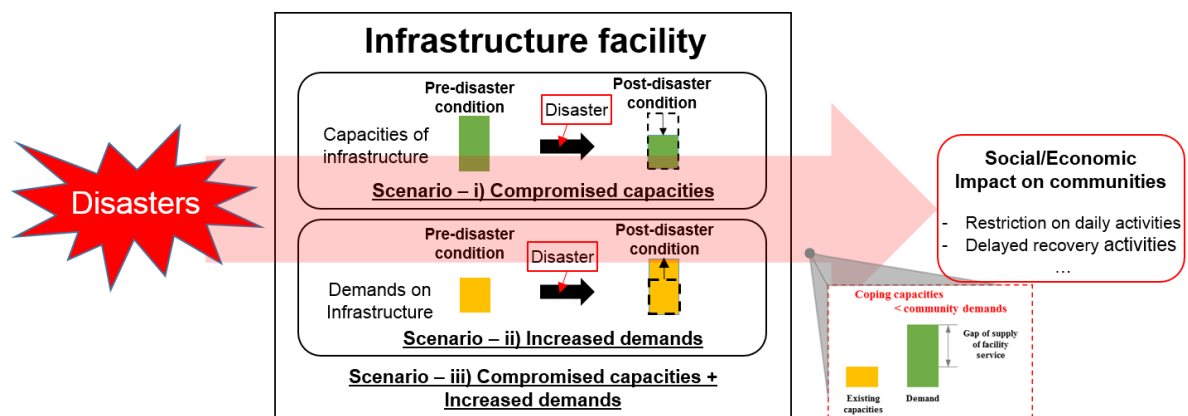
Figure 3-3 Impact of Disasters on the Functioning of Infrastructure Facilities

Just as the identification of the components of the infrastructure that are vulnerable to disasters will help infrastructure organizations or emergency managers in better preparing and developing a mitigation plan (Oh 2010), understanding the scenarios in which components of the infrastructure are likely to fail is a very important aspect of risk management (Zagst 2002). However, estimating the future demand and capacities are not an easy task for infrastructure engineers (Babu et al. 2011). If engineers or infrastructure planners can consider ahead of time the effects of various disasters in terms of service demand and supply, it would help ensure an adequate supply of infrastructure services even during disasters.

3.2.2   Stress on Infrastructure Facilities

The wealth of modern societies depends on the functioning of their infrastructure facilities. Communities and industries can sustain social and economic activities based on the reliable supply of essential facility services, such as transportation, water and wastewater, the provision of energy, and other civic governance activities (Deshmukh 2010; Thissen and Herder 2008). Infrastructure engineers strive to provide the best possible service within the constraints of the available resources (Ben-Akiva et al. 1993). Given this goal, infrastructure engineers try to predict future demands for infrastructure service and ensure that the infrastructure can always provide adequate service for communities by either developing a new infrastructure project or making maintenance and rehabilitation decisions for the existing infrastructure (Ben-Akiva et al. 1993).

However, due to the issue of uncertainty, such as the uncertainties of supply and demand, infrastructure facilities sometimes fail to meet the expectation of communities in providing the required services. When the demands for infrastructure or organizational services exceeds the relevant infrastructure's capabilities of dealing with them, the infrastructure is subjected to increased stress due to the excessive demands (DRC 1967). As the degree of stress on the infrastructure or on organizations increases beyond their capacities, the quality of their services becomes compromised, and infrastructure under high stress are unable to sustain its normal level of performance. For example, because of the unpredictable increase in the demand for electricity that resulted in overloads that exceeded typical demand, the

power infrastructure in Coimbatore, India, was subjected to high stress, which caused frequent load shedding (Preetha 2012). Due to the inadequate supply of coal for power generation, the natural gas and oil infrastructure was stressed, and the power infrastructure in India has been unable to meet the increasing demand for electricity as the national economy has prospered, resulting in frequent blackouts (Hamilton Spectator 2012). The poor condition of the sewer systems in Columbia significantly impaired its wastewater treatment capabilities. The sewage systems underwent high stress in order to treat the wastewater, but the deteriorated sewage system failed to process required amount of wastewater, and the untreated wastewater spilled out from the manholes (Wilkinson 2010). Also, climate change has caused increase in the sea level, which threatens coastal agricultural land and water resources in Bangladesh. The reduced agricultural land and water resources put high stress on the food/agricultural infrastructure in Bangladesh, which is struggling with food shortages caused by population growth and the lack of productivity (Fagan 2013). Due to the trend of increasing numbers of patients visiting emergency departments while the capacities of hospitals are declining, the emergency departments of hospitals in the United States are under high stress. As a result, ambulances are frequently diverted from overcrowded hospitals, meaning that it takes excessive amounts of time to get critically ill or injured people the medical attention they need (O'Shea 2007).

3.2.3   Stress within Various Disciplines

- Stress in the area of psychology

In the area of psychology, the term "stress" can be defined as an agent, circumstance, or other factors that disturb the functioning of the individual (Tepas and Price 2001). The generation of stress in individuals is categorized into two types, i.e., stimulus-based stress and response-based stress (Staal 2004). Stimulus-based stress is caused by external factors, e.g., temperature and workload, irrespective of the response of individuals; this is similar to "physical stress." Response-based stress is stress that is generated by the pattern of response or internal factors, e.g., behavioral and cognitive factors. Considering the dynamic properties of people's stress, stimulus-based stress and response-based stress have been regarded as too simplistic, because a single consideration, i.e., either external or

internal factors, is inadequate for understanding people's stress (Stokes and Kite 2001). Stokes and Kite (2001) posited that stress occurs in a transactional approach between internal and external factors, and they defined stress as "… the result of a mismatch between individuals' perceptions of the demands of the task or situation and their perceptions of the resources for coping with them." In addition to the two factors of demand and resources for coping, McGrath (1976) claimed that stress is the consequence of the interaction between three elements, i.e., perceived demand, perceived ability to cope, and the perception of the importance of being able to satisfy the demand. While there are various definitions of stress in the field of psychology, all of them define the effect of stress on people in essentially the same way, i.e., stress disturbs the individual's normal performance (Staal 2004). To understand the effect of stress on people's performance, Yerkes and Dodson (1908) suggested the symbolism of an inverted U-shaped curve, which shows the curvilinear relationship between arousal, i.e., level of stress, and performance; in an experiment in which mice were required to choose the white box among other different boxes with different stress conditions, i.e., electric shocks, the authors showed a definitive relationship between the performance of the mice and their levels of stress.
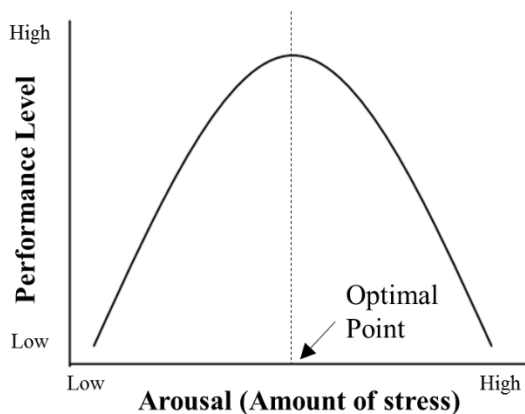
Figure 3-4 Human Performance and Stress Curve (Yerkes and Dodson 1908)

Figure 3-14 shows that, as stress increases, performance improves until it reaches a maximum level, after which performance decreases as the stress continues to increase. In

other words, initial levels of stress help to improve performance until the optimal level is reached, after which the continued increase in stress degrades performance (Staal 2004).

-Stress in the area of engineering

Unlike the various definitions for the psychological stress, physiological stress, or engineering stress, has a meaning that is commonly accepted among researchers even though the definition of stress varies on an area-by-area basis within the engineering discipline. For instance, in continuum mechanics, stress is defined as "a physical quantity that expresses the internal forces that neighboring particles of a continuous material exert on each other" (Eisenberg et al. 2014). However, in mechanics of materials, stress is defined as the force per unit area (Gere 2003). Even though there are differences, both definitions have one aspect in common, i.e., they refer to the responsive forces of the material against the load that is applied to it.

In addition to stress, strain is also an important characteristic in mechanics of materials (Gere 2003). Stresses over the cross section increase in response to increasing loads, and changes in the length of materials depend on the type of load, i.e., length increases in tension and decreases in compression. In materials science, the change in the length is measured by the term 'strain,' which is elongation per unit length, which represents the responsive behavior of materials as the stress increases.

In mechanics of materials, the behavior of materials can be observed and evaluated by plotting stress and strain together. For example, in the stress-strain curve of a typical structural steel (Figure 3-5), the various states the steel goes through as the applied load increases can be observed until the steel reaches the fracture point. In sequence, these states are referred to as the linear region, perfect plasticity or yielding, strain hardening, and necking (Gere 2003).
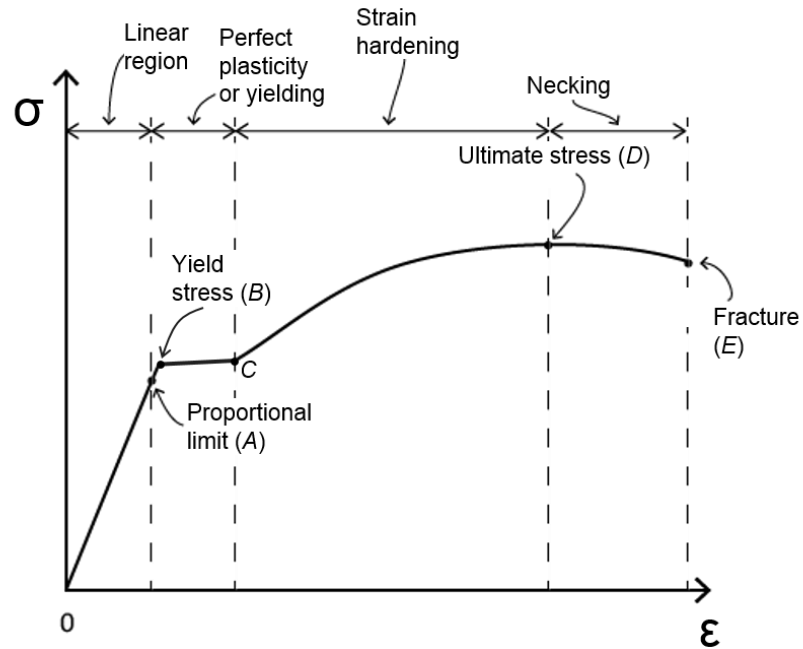
Figure 3-5 Stress-Strain Diagram for a Typical Structural Steel in Tension (Gere 2003)

Initially when the load is applied to the material, it stretches proportionally to the applied load until point A, i.e., the proportional limit, is reached. Until point A is reached, the material can return to its initial, unloaded condition if the load is removed. So, this region is called the 'elastic region.' In the region from A to E, the material cannot return to its original shape even when the load is removed, and this is called the 'plastic region.' As stress increases beyond the proportional limit, the curve has a smaller slope at point B, and the stress at this point is called the 'yield stress.' After point B, the curve levels off, indicating no further increase in stress. In other words, significant elongation occurs from point B to point C. After the perfect plasticity where the materials undergo large strains, the materials enter the strain-hardening region in which changes in the crystalline structure of the materials occur. These changes result in the material's resisting further stress until it reaches point D, the ultimate stress. The material undergoes structural failure at point E. Even though materials can continue to resist above the proportional limit up to the ultimate stress, in reality, materials are expected to resist below the proportional limit (or yield stress, since both the proportional limit and yield stress are regarded as the same in structural design) to avoid permanent deformation (Gere 2003). Considering the margin of safety,

the allowable stress of structural materials is calculated below the yield stress of the material unless the structural materials do not have either a low value of strain before the failure (i.e., they are brittle) or unclear yield stress. In these cases, a safety factor is applied with respect to the ultimate stress for setting the allowable stress as shown in Equation 3.1.

$$Allowable\ stress = \frac{Yield\ stress\ (or\ Ultimate\ stress)}{Factor\ of\ safety} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3.1)$$

In addition to the allowable stress of materials, adjustment factors are further applied to the allowable stress in order to define the design stress depending on the design principle (Gere 2003). For instance, in the design of wood columns, following the design codes of the American Forest and Paper Association, the design stress is determined by considering various service conditions (C^*), including duration of loading, exposure to moisture, excessive temperatures, and column stability factors (C^p), including concerns about buckling based on the allowable stress as shown in Equation 3.2.

$$Allowable\ stress = Design\ stress \times C^* \times C^p \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3.2)$$

- Effects of stress on the resilience of an organization

In order to understand the behaviors of organizations under stress, DRC (1967) defined organizational stress as the state of organizations when the demands on organizations exceed their capabilities. In normal conditions in which a stable relationship exists between demands and capabilities, i.e., demands do not exceed their coping capabilities, organizations can interact with communities with their regular performance structure. But, when disruptive events occur, such as disasters, organizations' capabilities are likely to be compromised as demands on the organization increase, and their performance structure must change to cope with the sudden change in demands. According to DRC (1967), the changes in the performance structures of organizations are defined as follows:

- Implementation of a list of tasks depending on their priority;
- Frequent unofficial decision making for a prompt response;
- Change in the modes of communication in order to maximize the speed of information sharing.

DRC (1967) also used the term 'organizational strain,' which stands for the inconsistencies of organizational structures. As stress increases, the priority among the tasks of an organization is changed. Thus, even though there are organizational demands for some tasks in communities, organizations allocate their limited resources to performing other tasks with higher priority. For instance, when a fire occurs, there may be conflict between two tasks, i.e., the provision of first-aid service and fire suppression. If there is a danger that a fire will occur, fire officers try to maintain their resources that are used for fire suppression. The more stress that organizations experience, the more strain they have in their operation (DRC 1967).

Based on the analogy of the fundamentals of mechanics of materials, Woods and Wreathall (2008) developed stress-strain plots of organizations in order to understand how an adaptive system can accommodate the varying demands. They regarded organizations and infrastructure as adaptive systems. As analyzed in mechanics of materials, they also tried to understand the adaptive behavior of organizations or infrastructures against disrupting events by plotting both their stress and strain. As shown in Figure 3-6, the ordinate is labeled as demand or stress, which indicates how the system responds to an increase in demand. The abscissa is labeled as the response axis or strain, which represents how the system or organization can stretch in response to varying demands. Just as the stress-strain plots of materials have two different regions, an adaptive system also has two different regions as the demand increases, i.e., the elastic region and the plastic region. Within the elastic region (or competence envelope), organizations or systems can accommodate the increased demand effectively by utilizing their planned and allocated resources (Wood 2006). Also, within this region, organizations can cover the increasing demands from point O to point A by placing the priority on the use of their planned resources, which enables them to respond successfully to changes in the demands. This mechanism of organizations to respond to growing demands is regarded as the first-order adaptive capacity of the organization (Hollnagel et al. 2008). But, once the demands get out of the elastic region, i.e., the stress level exceeds that of point A, organizations cannot uniformly stretch to meet the increasing demand. Thus, they start accumulating gaps in performance since demands

have exceeded the ability of the organization to adapt within the competence envelope (Hollnagel et al. 2006). This region is called the 'plastic region.'
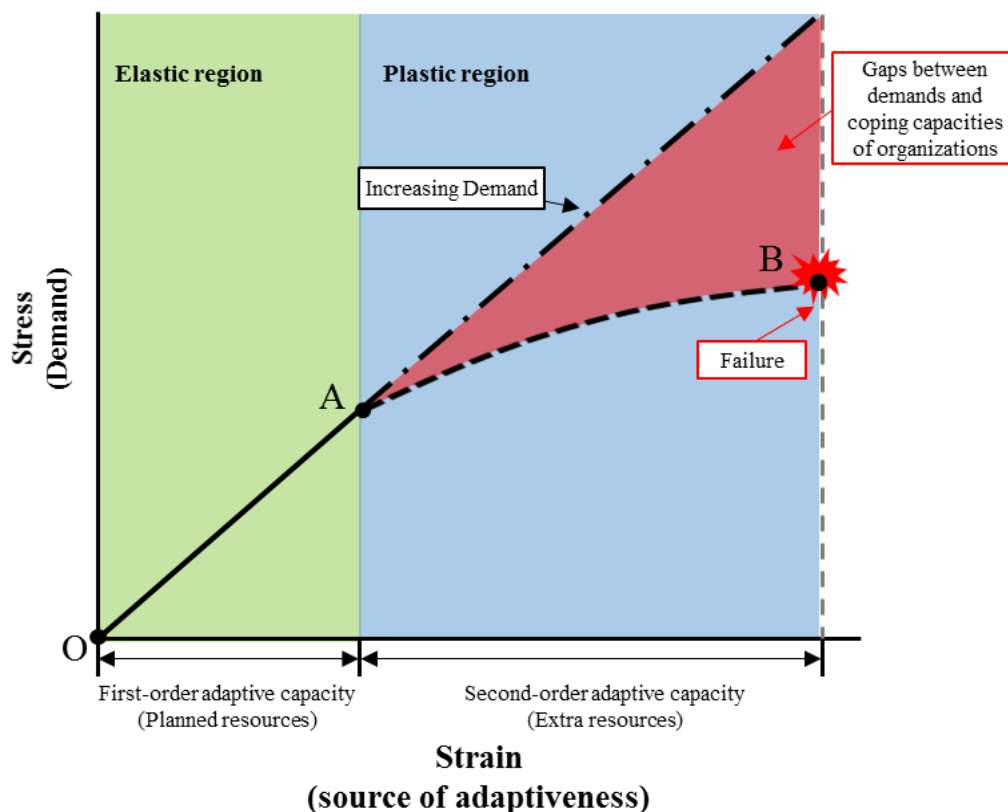
Figure 3-6 Stress-Strain Space for an Organization (Hollnagel et al. (2006))

In order to prevent the failure of the organization due to the accumulation of gaps, i.e., in the plastic region, organizations use the second-order sources of adaptiveness, e.g., extra work and extra resources, to fill in the gaps. If demands continue to increase, the gap of organizations' production remains constant until the second-order sources are exhausted, and they reach the failure point. Otherwise, the structure of organizations is redesigned and improved to adapt to the increasing demand. In the latter case, the organizations have new slopes and lengths of the elastic region.

Various areas of study have their own definitions for stress and ways of dealing with the stress. Even though the ways in which stress is addressed vary from area to area, stress remains manageable until it goes beyond the capabilities of the entities to cope with the

stress. In particular, in the area of engineering and organizational stress, understanding stress is pivotal for gauging the capacities of entities (i.e., material in engineering and organization in organizational resilience), while strain also serves the important role of indicating the capacities of entities.

3.2.4   Summary

In a post-disaster situation, critical infrastructure are likely to experience excessive demand not expected in pre-disaster conditions due to both its compromised capacities and increase in demand due to disaster effects. Therefore, to cover all post-disaster demands, infrastructures often must push themselves to run under high stress conditions. Consequently, the stress exceeding infrastructure's capacities will disable them and prevent them from giving the affected communities adequate needed services at the expected performance level, making it more difficult for communities to resist and recover from the effect of the disaster. As such, for infrastructure to function properly, managing the stress on them is thus vital. By reviewing the stress seen in various areas of study, the properties of stress and strain can be carefully discussed. Since the stress and strain principle in mechanics of material is capable of perceiving the structural performance of materials considering both their structural demand and capacities under working load conditions. Thus, the use of the stress and strain principle in the mechanics of material may have the potential for understanding stress on a post-disaster infrastructure.

3.3   The Conceptual Mechanism for Stress Development in Infrastructure

Like the internal action in mechanics of material, the stress on infrastructure exists whenever there is demands on the infrastructure. In fact, the effects of inherent stresses of infrastructure will vary based on the change in equilibrium between demands for its services and its coping capacities (DRC 1967). In a normal situation where infrastructure experiences manageable levels of stress, the facilities can provide services using planned capacities. However, the effects of high stress arise when demand exceeds the coping capacities of that particular infrastructure. Thus, if either demand for the infrastructure service increases or its coping capacities decline, which ultimately causes a reversed

relationship, the infrastructure will fail to provide the service needed by its dependent entities. Applying that point of view, the mechanism for growing the impact of the stress on infrastructure can be developed as shown in Figure 3-7**.**
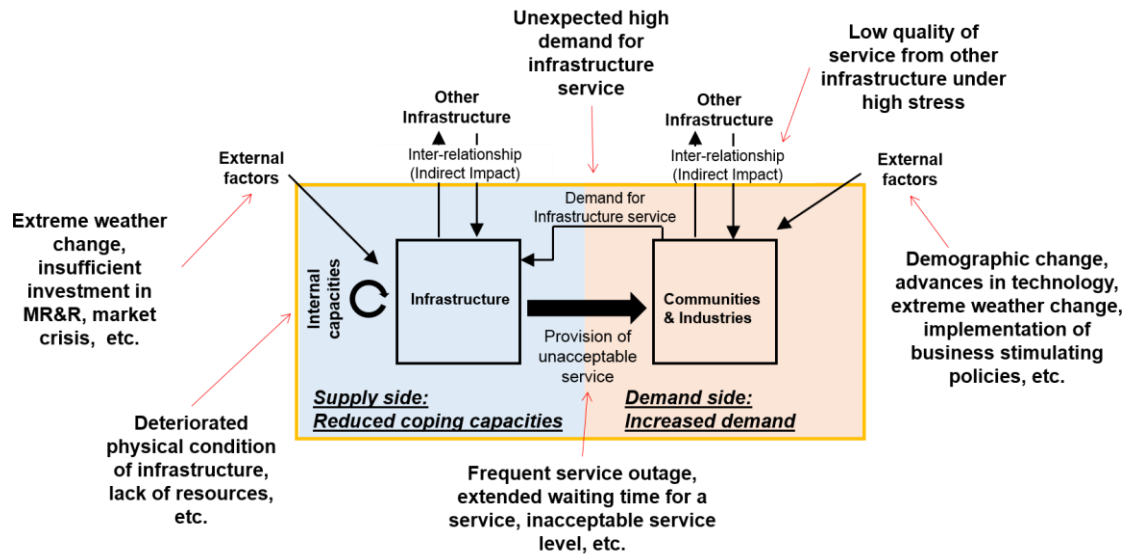
Figure 3-7 The Stress Development Mechanism of Infrastructure

The impact of stress will appear on the service provision as the demand approaches the capacity of the infrastructure due to i) insufficient available coping capacities (compromised capacities on the supply side) or ii) unexpected high demand for the service (increased demand on the demand side). External factors – e.g., unstable supply of fuel for power generation (Hamilton Spectator 2012), insufficient investment in MR&R for a sewage system (Wilkinson 2010), reduced areas for food production due to rise in sea-level (Fagan 2013), and others will impair the coping capacities of an infrastructure. Also, depending on its internal capacities, e.g., degree of deterioration rate or available resources and service from other supporting infrastructures, the coping capacities of the infrastructure will vary.

On the demand side, the demand of communities and industries can significantly increase based on external factors – e.g., for electricity demand, advances in technology, an economy boom (Preetha 2012) and the implementation of business stimulating policies

(Hamilton Spectator 2012), – and the failure of other alternative infrastructure to meet the demand for the service, e.g., an excess of floodwater from fully-filled sewage lines (Wilkinson 2010) and the transport of patients by ambulance from a closed emergency department to other facilities.

The impacts of high stress can be characterized by two service -related issues:

1) **Reduced performance level:** Performance level in this research represents the operating quality of service offered by the infrastructure to the dependent communities and industries. In a saturated and over-capacity condition, i.e., under high stress, infrastructure facilities are likely to cover as much demand as they can by lowering the performance level.

2) **Reduced serviceability:** Serviceability is defined as the ratio of satisfied demand to total demand for the infrastructural service (i.e., satisfied demand / [satisfied demand + unsatisfied demand]) (Adachi and Ellingwood 2008). That is, depending on the performance level the infrastructure is expected to provide, that serviceability level will vary. If an infrastructure must run on restricted resources, then the infrastructure can cover more demand with a lower level of service. However, in any situation where the demand surpasses the capacities of the infrastructure, some demands might not be met even with a lower level of service.

Examples that illustrate these two characteristics of infrastructure in terms of stress-related issues are offered in Table 3-1.

Table 3-1 Characteristics of Infrastructure Facilities Experiencing High Stress

Infrastructure facilities	Cause of high stress	Serviceability	Quality of Service	Reference
Hospital	Substantial increase in demand (Overcrowding)		- Wait time spent by patient in the emergency room increases. - Quality of technical treatment	(Kennedy et al. 2008; Warren 2012)
Water	Compromised capacities of water supply due to (disasters, including earthquake, etc.)	- Supply of water for customers is reduced		(Adachi and Ellingwood 2008)
			- Restriction on amount of water supply available to communities	The Rhode Island Water Resources Board (2008)
		- Supply of water for customers is reduced	- Water flow and water pressure in water delivery system are reduced.	(Hwang et al. 1998)
Electricity	Substantial increase in demand (Growing need for electricity)	- Unavailability of power beyond the allowed time	- Frequent load shedding occurs (Low reliability).	(Preetha 2012; Hamilton Spectator 2012)
Gas & oil	Substantial increase in demand (Growing need for gas & oil)	- Insufficient supply of fuel to generate power		(Hamilton Spectator 2012)
Waste water	Compromised capacity of wastewater system (Deteriorated physical condition with age)	- Amount of wastewater treated reduced	- Extra wastewater spilled out	(Wilkinson 2010)
Firefighting	Substantial increase in demand & compromised capacity (Fire accidents occur, but water mains damaged by 911 attacks)	- Firefighting activities delayed		(O'Rourke et al. 2003)

3.4   The Stress and Strain Principle of Post-Disaster Infrastructure

Based on the literature review and the stress mechanism for infrastructure developed in Section 3.3, these terms can be newly re-defined to understand stress on infrastructure facilities when experiencing a in a better context. Then, using an analogy for the stress-strain principle from mechanics of material, a novel approach is developed to understand the stress on post-disaster infrastructure more clearly.

This developed stress-strain principle is capable of illustrating the behaviors of an infrastructure facility under varying levels of stress and thus understanding its impact on provision of the infrastructure service for communities with respect to their available capacities. Further the strain of a post-disaster infrastructure enables closer observation of the current stress level by comparing the current strain with its full strain level of 1.0. Additionally, the parameters needed for this stress-strain analysis are discussed. The developed stress-strain principle is then applied to a case example, namely, hypothetical medical facility operating in a post-disaster situation to facilitate the understanding the concept further, followed by two case studies for proving the benefits of using the stress and strain analysis.

3.4.1   Definition of Relevant Terms

In this research, the relevant terms are re-defined to reflect the features of infrastructure management, particularly in disaster situations. To facilitate the understanding of each term, the emergency operation of a hospital in a post-disaster situation is utilized here as an example to help explain terms.

- **Stress** is the demand on an infrastructure unit during unit time. For instance, to treat one inpatient per day, the stress, with an amount of electricity at 228~261 kwh per day, is applied to the electricity unit to treat patients as usual.

- **Strain** is the rate at which potential capacities are used in response to the applied stress. For instance, in a disaster situation where the supply of municipal electricity for a hospital is limited, a hospital tries to stretch that supply in response to the stress applied to the electricity unit by using its back-up generator. If the hospital

has to use the whole capacity of that generator and no remaining auxiliary capacities exist, then the strain is 1.0.

- **Allowable Stress** is the maximum amount of demand an infrastructure unit is expected to satisfy at the expected performance level using the planned capacities. For instance, in a post-disaster situation, a limited number of beds within a hospital can be provided with the appropriate amount of electricity by relying on municipal electricity throughout each day. Since the supply of electricity from the power infrastructure is already planned to support the hospital in normal operations, then the maximum number of beds that the hospital operates by relying on municipal electricity is the allowable stress for the electricity unit of that hospital.

- **Limit Stress** is the maximum amount of demand an infrastructure unit is expected to satisfy at the expected performance level, using both the planned capacities and its reserve capacities. For instance, in a post-disaster situation, the beds that are unmet with electricity due to power outage can be provided with that electricity by relying both on the municipal electricity and a back-up generator. The back-up generator is the reserve capacity in this instance. The maximum number of beds the hospital can support by relying on both the municipal supply and the generator becomes the limit stress in a power outage situation.

  Note: Allowable stress and limit stress can vary depending on expected performance level. For example, if a hospital can expect only 90 % of its standard electricity consumption instead of the standard electricity daily consumption of 228-261 kwh for inpatients, then the allowable and limit stress will increase because more inpatients are met with a reduced amount of electricity even within the same resource.

- **Serviceability** is defined as the ability of post-disaster infrastructure facilities to meet demands on them compared to their pre-disaster ability to provide service (i.e., satisfied demand / [satisfied demand + unsatisfied demand]) (Adachi and Ellingwood 2008; Deshmukh et al. 2011). That is, depending on the performance level the infrastructure is expected to provide, that serviceability level will vary. For instance, in a pre-disaster situation, municipal power is available 24 hours/day

to a hospital with no power shedding. So, all the demands of hospital for electricity are met by the supply of municipal electricity throughout that day (100% serviceability).

- **Performance level** in this research represents the operating quality of service offered by the infrastructure to the dependent communities and industries. Examples are given in Table 3-2.

- **Standard performance level** is the designed performance level devoted to communities or dependent entities in a pre-disaster condition. For example, in a pre-disaster condition, the 24-hour availability of electricity (i.e., no load shedding) is a standard performance level for a dependent facility.

- **Infrastructure units** are the resources needed to operate an infrastructure facility. These can be infrastructure services from external systems or its own internal resources. For example, in running a hospital, utility services, e.g., gas, electricity, water, and medical resources, e.g., medical staff, beds, medical supplies, become these infrastructure units.

Table 3-2 Levels of Different Infrastructure Services

Infrastructure	Performance level (=quality of service)	Reference
Water	- Timely installation - Prompt responses to customer complaints - Network reliability	(Holt 2005)
	- Continuity - Water quality - Complaints	(Berg and Padowski 2007)
Electricity	- Continuity of supply, voltage quality, loss of electricity	(Çelen and Yalçın 2012; Robert 2001)
Transportation	- Time-based measurement (Access and egress time, service intervals, etc.)	(Paulley et al. 2006)
	- Travel speeds - Traffic volumes	(Highway 1965)
	- Reliability (e.g., predictability of traffic volume and safety)	(McNeil et al. 2014)
Hospital	- Patient wait time before receiving treatment	(Cimellaro et al 2009)
	- Technical quality of health care service associated with accuracy of medical diagnosis and procedures delivered to professional specifications - Functional quality of health care service related to patient perception of the treatment	(Aghamolaei et al. 2014; Lam 1997))
Fire Department	- Response time to reach fires	(Aleisa and Savar 2014)
Police	- Tangibles – appearance of physical facilities or related materials - Reliability – ability to deliver the promised service - Responsiveness – Spontaneous response to help people - Assurance – ability to earn trust and give confidence to people - Empathy – special care given to individual people	(Furstenberg and Wellford 1973; Domnelly et al. 2006; Shin 1977)

As defined in the literature review (see Chapter 3-2), the stress-strain principle is widely used not only in the mechanics of material scenario, but also for organizational resilience. Each discipline defines the terms that reflect the context inherent in them. It is worth noting that how the terms in this research are defined different from other disciplines because the

comparison prevents one from mistakenly using the terms interchangeably. The redefined terms are shown in Table 3-3 and there compared to other disciplines.

Table 3-3 Redefined Terms Used for the Stress-Strain Principle

Terms	Mechanics of material (Gere 2003)	Organizational Resilience (Woods and Wreathall 2008)	Disaster Risk Reduction
Stress	- Force per unit area	- Demands imposed by events and variations in the events	- Demand on an infrastructure unit during unit time
Strain	- Elongation per unit length	- How system stretches to accommodate applied demands	- Rate at which potential capacities are being used in response to the applied stress
Allowable stress	- Working stress not to be exceeded - Stress after applying safety factor to stress yield	- Most expected demand	- Maximum amount of demand an infrastructure unit is expected to satisfy at the expected performance level using the planned capacities.
Limit stress	- Stress yield - Stress above stress limit causing permanent deformation to material	- Demand above designated level not covered without external resources	- Maximum amount of demand an infrastructure unit is expected to satisfy at the expected performance level using both the planned and reserve capacities.

3.4.2   Development of the Stress-Strain Principle

When the demands for infrastructure service are generated, the stresses that correspond to the demands are imposed on the infrastructure facility. As discussed in the literature review, infrastructure facilities are designed to successfully provide services for their communities within the capacities of those facilities. However, once the demands exceed these capacities, the enormous stress has a detrimental impact on the provision of services to these communities. In this research effort, the developed stress-strain analysis evaluates the functioning of the infrastructure in terms of stress and strain of that specific infrastructure.

An analysis of stress enables better understanding of the applied stress with respect to the available strain capacities, while a strain analysis allows for the observation of the current stress level by referring to how much infrastructure additionally can stretch in response to the growing stress. Both stress and strain analyses play a key role in perceiving the functioning of infrastructure facilities in an environment that is likely to cause undue stress issues, i.e., disaster situations.

The stress and strain analysis for infrastructure facilities are based on the unit time within which the stresses on that infrastructure is measured. Since the stress on infrastructure facilities can vary depending on the specific unit time, it is important to determine an appropriate time unit. Figure 3-8 assumes the stress level in a hypothetical infrastructure facility. As time passes, the demand for the infrastructural service will fluctuate, which in turn imposes dynamic stress on that infrastructure. In Figure 3-8, the stress analysis A measures the stress level based on a 1- hour unit. Each hour represents the different stress generated during an hour. The trend of the change in stress level is irregular.

However, as the unit time increases from 1 hour to 3 hours (Stress analysis A→ B→ C), since the range of unit time is larger, the time unit does not include as many stress levels as stress analysis A did. The stress levels within the unit time are then combined into a one value as the representative of other stresses measured, e.g., average value or maximum value, which makes the trend of change in stress level smooth. It is worth noting that the larger the size of a unit time, the bigger the difference will be between the real-time stress and the unit stress. In other words, an inappropriate size of a unit time will fail to reflect the stress imposed on the infrastructure facility. However, a too small unit time presents a challenge to emergency engineers or relevant engineers when designing strategies for managing stresses during very small units of time. Since stress will vary depending on the unit time, the measure for strain in response to the applied stress also will vary.
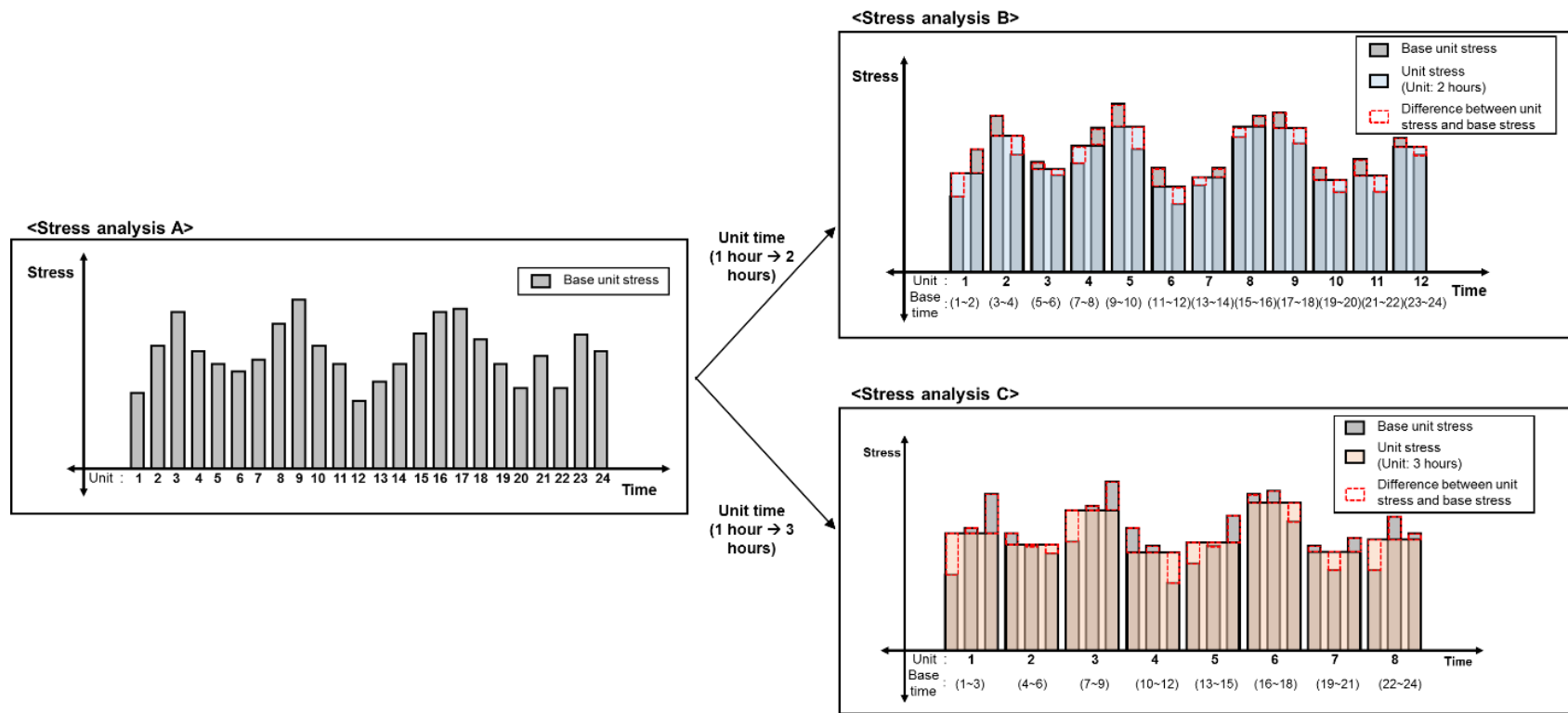
Figure 3-8 Varying of Stress Level depending on Unit Time

In Figure 3-8, The stress level in an infrastructure unit is measured as the average of stresses applied in order to sustain the provision of acceptable service for communities. Based on the amount of stresses on the infrastructure facility and the expected performance level, the stress level for different types of infrastructure units can be calculated, respectively (e.g., for a medical facility, the demands on electricity, water and gas are different). Given that the measured n number of stresses (S) are applied to the infrastructure unit during the unit time, the stress (S_t) at the unit time (t) can be calculated as shown in Equation 3.3.

$$S_t = f(S, n) = \frac{\sum_{i=1}^{n} S_i}{n}$$ ....(3.3)

The strain in an infrastructure unit is defined as the rate at which potential capacities are being used in response to the applied stress. Since the denominator is the maximum capacities which are available to be utilized, a strain greater than 1 is not considered in the planning stage. Given that the potential capacities are p_{tot} and the actual capacities being used in response to the applied stress are p_{app}, then the strain of the infrastructure unit can be defined as

$$strain = f(p) = \frac{p_{app}}{p_{tot}}$$ ....(3.4)

In defining the term strain, the potential capacities include both planned capacities and reserved capacities. For example, for hospital operations, the electricity necessary to operate the hospital is planned so as to be received from the municipal electricity organization in a pre-disaster situation. However, once the hospital recognizes the shortage of electricity coming from the municipal utility to sustain its operation, the hospital starts considering auxiliary capacities, such as back-up generators. In this instance, the supply of electricity for the hospital from the power organization corresponds to the planned capacities and the auxiliary capacities become the reserve capacities.

Nevertheless, if an infrastructure unit cannot successfully stretch even by employing both planned and reserves capacities, then that infrastructure unit will have difficulty in meeting its expected performance level. That is, the strain capacity is required to stretch above its maximum strain level of 1.0 without lowering the performance level. Figure 3-9 illustrates how the strain of an infrastructure unit stretches in response to the applied stress and how

the failure of the infrastructure unit to stretch will affect the performance of the infrastructure facility.
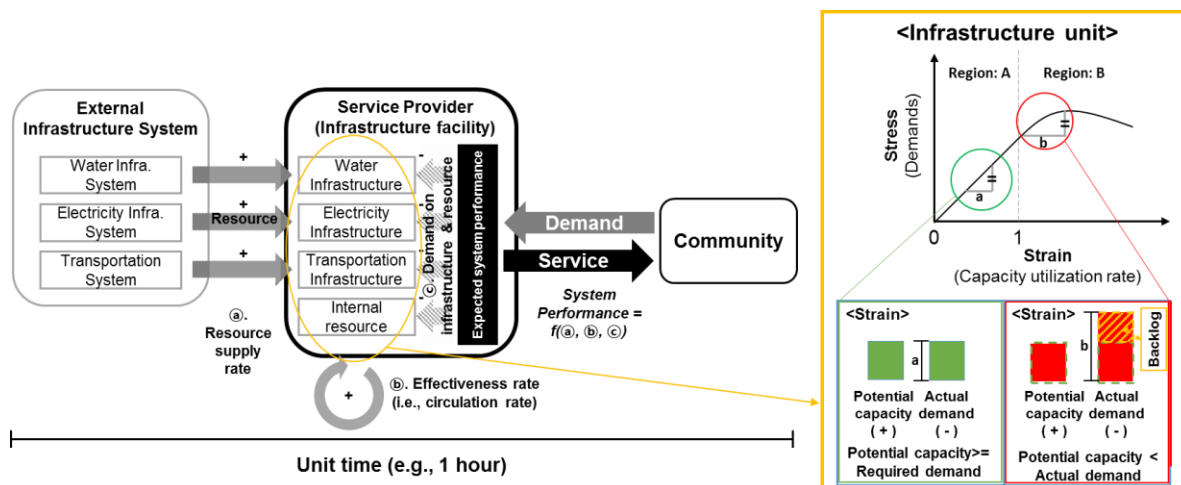
Figure 3-9 Strain of an Infrastructure Facility when Responding to Stress

With the supply of resources from external systems (e.g., water, electricity, or transportation) and its internal systems (e.g., supplies, goods, workers, etc.) an infrastructure facility can provide its service to communities in response to ongoing demands. For each unit of time, a certain amount of resources (e.g., electricity, water, supplies, etc.) are planned to meet the stress throughout the time while infrastructure facilities may have reserve capacities as a margin of safety.

With the stress level being below the limit stress, the infrastructure unit can fully stretch as required to maintain the expected facility performance level (Region A in Figure 3-9). However, once the stress level goes beyond the limit stress, then the infrastructure is unable to fully stretch, incurring backlogs in supplying of the required resource (Region B in Figure 3-9). The backlogs for the service of the infrastructure unit will accumulate the burden of resource shortage to the infrastructure unit throughout the timeframe, which then severely impairs the infrastructure unit's ability to sustain its service for the facility at the desirable level.

To take a post-disaster operations of a hospital as an example, since the supply of electricity from the power companies is reduced because of the damage to their physical components,

the hospital has to operate using the back-up generator. It is assumed that this back-up gives the hospital 50% of its pre-disaster serviceability level. During the first few hours when a few patients reach the hospital, the limited availability of electricity does not affect the hospital in treating them with medical machines that rely on electricity (Region A in Figure 3-9). In other words, the electricity unit can fully stretch in response to the demand. However, as the number of patients increases, the 50 % of reserved electricity does not fully cover the increased demand for electricity; specifically, during a unit time, some patients cannot receive service using the machine because of the reduced availability of electricity to run the machine (Region B in Figure 3-9). In that case, the remaining patients should wait for the next availability of electricity in the successive unit time. However, if there are another patients wanting to use the medical machine during the next unit time, all the patients including the additional patients from the previous unit time will further increase the burden of electricity shortage. The facility, i.e., the hospital, thus cannot provide expected medical treatments to patients in time, which puts those who need prompt medical treatments in grave danger.

Figure 3-10 illustrates the accumulation of resource shortage over time. If the electricity cannot fully stretch within the available capacities (i.e., the strain required to increase is beyond 1), the excess of strain required will accumulate with time, thereby delaying the waiting times of patients due to the unavailability of electronic medical machines. If the shortage of electricity resources reaches a threshold above which the service of the hospital is then not acceptable (e.g., patent need to wait over their critical waiting time since their arrival), the facility, i.e., the hospital, will functionally fail. In other words, the accumulation of a gap in strain above the threshold leads to the unacceptable performance level of the hospital. In Figure 3-10, after unit time 6, the infrastructure will fail because of an accumulation of the backlogs of strain that are above the acceptable threshold. Therefore, it is important to keep the stress level within a range of strain capacities between 0 and 1, i.e., below the limit stress.
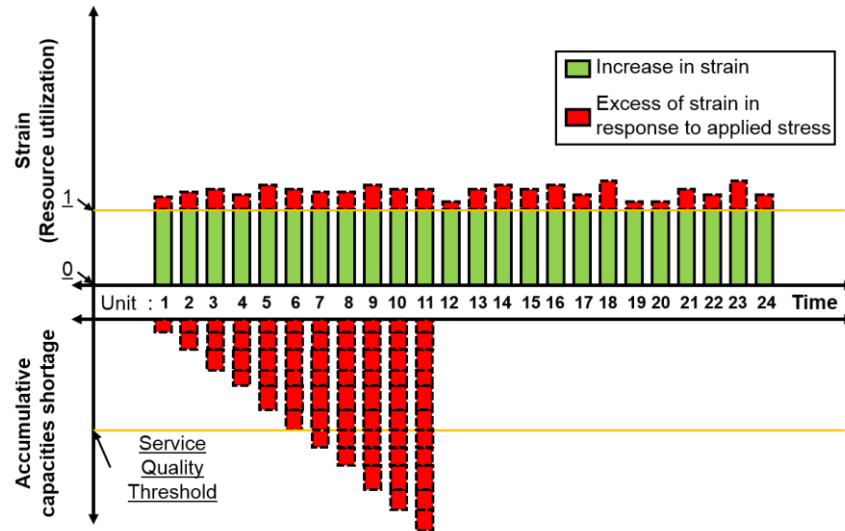
Figure 3-10 Accumulation of the Stress Burden from a Resource Shortage

Assuming that the stress and strain of an infrastructure unit are measured while the demand on it keeps increasing, the stress and its corresponding strain can be plotted into a diagram of stress versus strain (see Figure 3-11). A stress-strain diagram represents the managerial characteristics of a particular infrastructure and conveys the important information about how much stress that infrastructure facility can handle and how it behaves under the condition of growing demand. In order to explain the fundamentals of stress-strain curves, the stress-strain curve for a hypothetical infrastructure as shown in Figure 3-11 is used.
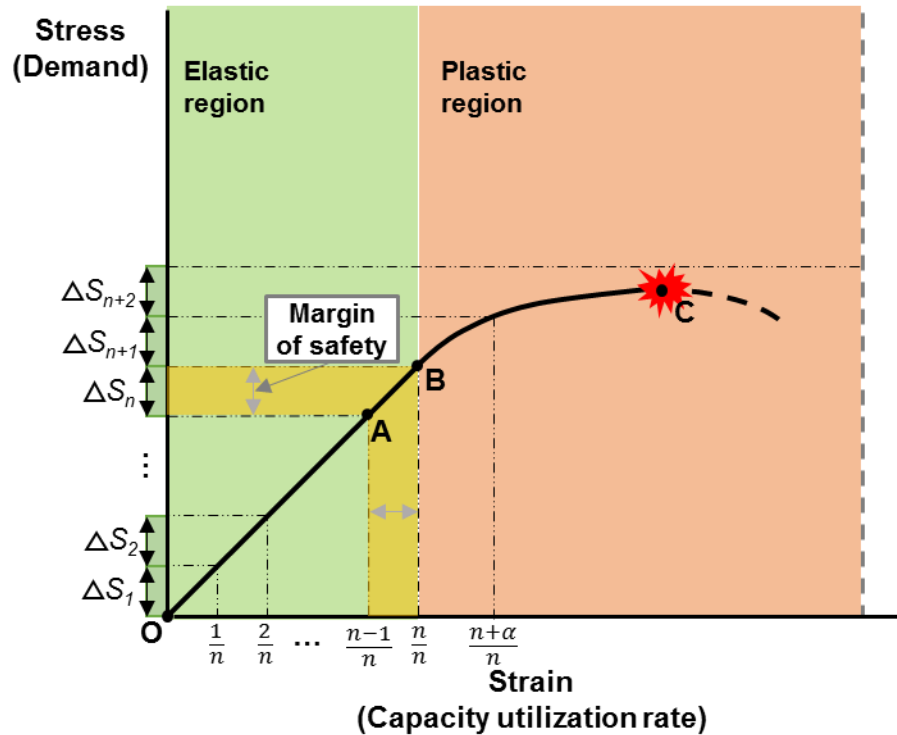
Figure 3-11 A Stress-Strain Diagram for a Hypothetical Infrastructure Facility

The stress-strain curve starts with a straight line from origin O to point B (limit stress), which shows the linear relationship between stress and strain. This region is defined as the linear or elastic region. The linear relationship implies that infrastructure successfully stretches out its capacities with the increment ($\Delta S_1 \sim \Delta S_n$) of stress immediately after the stress occurs. Under the linear relationship, with the increase in stress, the infrastructure gradually increases the rate proportionally at which the capacities are being used in response to the increased stress, i.e., the increase in strain ($\frac{1}{n} \sim \frac{n}{n}$) corresponds to the increment of stress ($\Delta S_1 \sim \Delta S_n$). As structural designers set the expected working stress below the actual limit stress, while still considering the margin of safety, in infrastructure planning, the infrastructure considers its reserve capacities in addition to planned capacities – which are expected to cover most stress in normal conditions – so as to keep a margin of safety when managing resources. In Figure 3-11, point A, **allowable stress**, is the highest stress level that an infrastructure is most expected to encounter in a normal condition.

Under the stress below the allowable stress A, infrastructure can meet all the demands with the standard performance level while still using the planned capacities. Considering the margin of safety, the infrastructure has auxiliary capacities reserved for such a case where the stress is beyond the allowable stress. The stress level that the hypothetical infrastructure additionally can withstand using the reserve capacities is defined as the point B, **limit stress**. Under the stress level that is within the range of the allowable stress to the limit stress, the infrastructure still provides the service for dependent entities and at an expected level. However, in order to leave that region for the margin of safety, the stress between allowable stress and limit stress is not operable for infrastructure management. Since the potential capacities within infrastructure consist of planned capacities and reserve capacities, the strain which corresponds to the limit stress is 1/1.

In the region beyond the limit stress, point B, the linear property between stress and strain no longer exists, as the infrastructure cannot cover the stress with the standard performance level still relying on its own capacities. This region is called the plastic region. Without the influx of external resources, the infrastructure cannot sustain the expected performance level in response to all the demands thus accumulating the backlog of resource shortage in the plastic region. In other words, the infrastructure cannot stretch far enough in response to the applied stress. In the plastic region, even with the same increment of stress (ΔS), the strain is further stretched out, which causes the burden of resource shortage to the infrastructure and harms the ability of infrastructure to sustain the operation through successive unit times. Moreover, in plastic region, the capacity of infrastructure system itself is likely to be further compromised since the demand may approach the ultimate stress which pushes the infrastructure system to place excessive burden to its component thus sometimes causing the malfunction of the component. If the infrastructure no longer stretches out in response to the higher stress (point C), then that infrastructure cannot serve their role, i.e., reaching the functional failure. Because of the issues regarding the reliability of service, the behaviors of the infrastructure in the plastic region are then regarded as a service-related failure.

- Discussion on the linear relationship between stress and strain

Within the elastic region, stress and strain have a linear relationship. The linear relationship between stress and strain for an infrastructure is expressed by Equation 3.5.

$$Stress = D \times Strain \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(3.5)$$

where D is the maximum demand which the infrastructure unit can satisfy using the full strain capacities. The demand that an infrastructure can satisfy can vary depending on i) the performance level or ii) the available strain capacities of infrastructure. Figure 3-12 and Figure 3-13 illustrate the different stress levels that a system can handle varying these two conditions. The performance of the infrastructure is changed under the purpose of accommodating all the demands within the available capacities, i.e., keeping the resulting strain within 1.0. Under the condition where demands are relatively high compared to their available strain capacities, the infrastructure is willing to lower the performance level in order to improve the strain capacities (①️ in Figure 3-12). If the capacities required per unit demand are reduced, then the maximum stress level which an infrastructure unit can withstand increases, thereby increasing the strain capacity to handle demand. As a result, the infrastructure withstands the higher stress than it does with the standard performance level (P_{std}) while keeping the strain within 1.0. That is, all the allowable stress, limit stress, and ultimate stress increase. In contrast, the system capacity to handle demand can be declined (②️ in Figure 3-12) if the infrastructure increases the performance level for the dependent entities. In other words, all allowable stress, limit stress, and ultimate stress will decline.
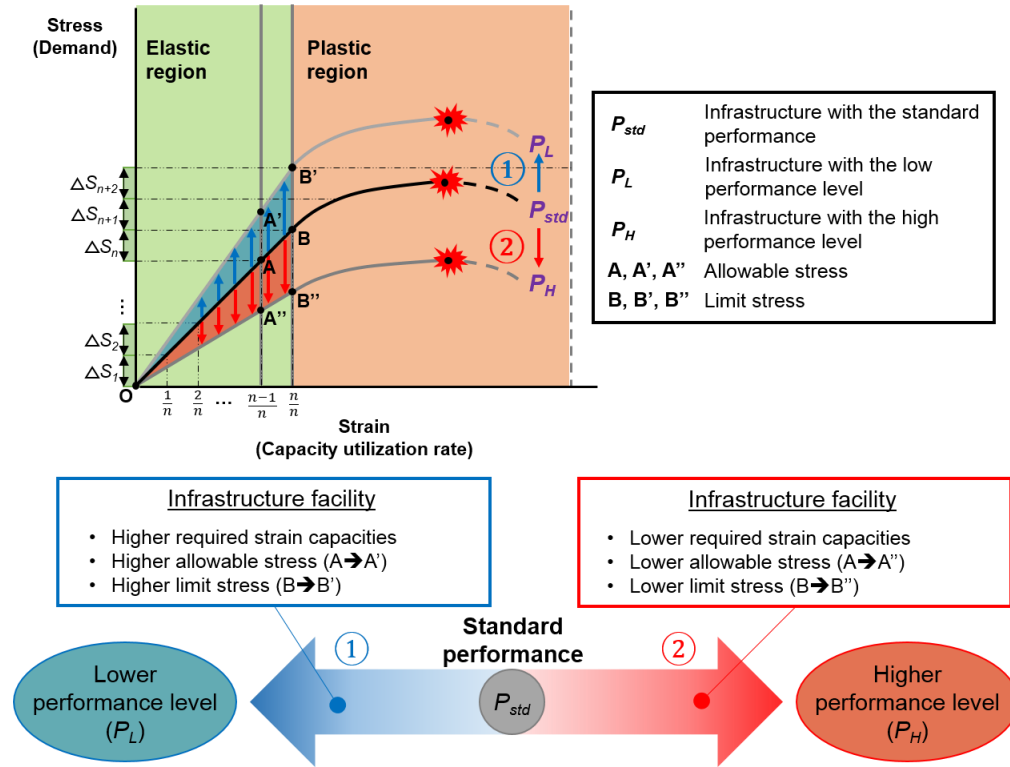
Figure 3-12 Stress-Strain Diagram for an Infrastructure Facility with a Different Performance Level

In post-disaster conditions, the capacities of the supporting infrastructure units are likely to be compromised, which in turn results in the reduction in the strain capacities of the infrastructure facility. Figure 3-13 illustrates varying the stress level which the post-disaster infrastructure facility can satisfy as its supporting infrastructure units are either damaged by disasters or restored. When the strain capacities are reduced immediately after a disaster, the demand which the facility can satisfy is reduced either (② Figure 3-13) since the strain capacities is compromised by disaster impacts by d. It is worth noting that even though post-disaster infrastructure can stretch to the full strain of 1.0, but because of the reduced strain capacities, the allowable stress (A'') and limit stress (B'') are less than the allowable stress (A) and limit stress (B) of the pre-disaster infrastructure. By contrast, as affected infrastructure units are restored, the strain capacities are recovered to the pre-disaster level so that the demand which the infrastructure facility can meet will increase as well (① Figure 3-13).
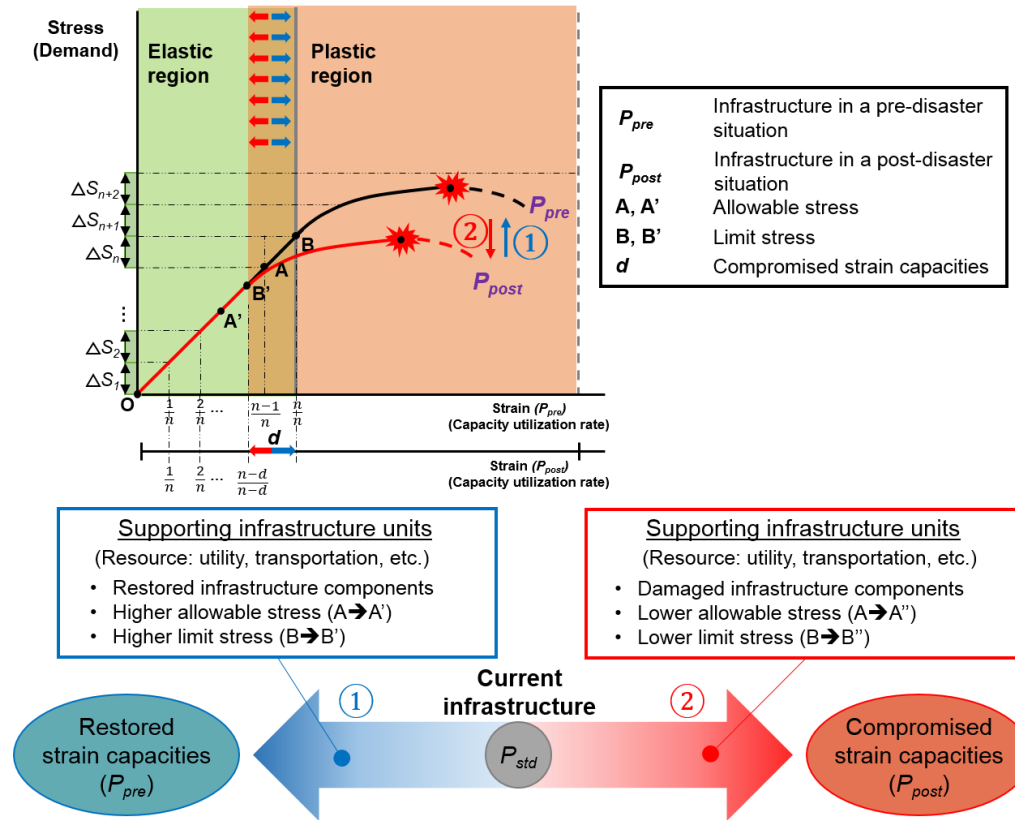
Figure 3-13 Stress-Strain Diagram for an Infrastructure Facility with Varying Strain Capacities

3.4.3   Measurement of Design Parameters

In disaster situations, i.e., where infrastructures are overwhelmed by enormous amounts of demand, infrastructure facilities will strive to cover all the demands without compromising the performance level to their communities. In a post-disaster situation where the stress level is likely to be beyond its planned capacities, i.e., allowable stress, the success in the provision of adequate service for dependent entities depends on how much reserved capacity the infrastructure has in addition to its planned capacities, i.e., when determining an appropriate margin of safety. This reserve capacity is widely used in infrastructure planning, which is also associated with the flexibility of infrastructure against design uncertainty, such as growing demand or growing number of demands and compromised capacities (Lu et al. 2005; Morlok and Chang 2004). According to Morlok and Chang (2004), that flexibility is defined as "the ability of a system to adapt to external changes,

while maintaining satisfactory system performance." The flexibility of an infrastructure accounts for the margin of safety that should be considered in infrastructure planning. The determination of both limit stress and allowable stress is based on the amount of the margin of safety (or factor of safety). Margin of safety is widely used in Engineering to account for the expected uncertainty of the design process (Ullman 2010). Depending on the margin of safety, the material will enter either the plastic region or not enter it. Thus, margin of safety is defined as a ratio of the allowable stress to applied stress as shown in Equation 3.6.

$$Margin\ of\ safety = \frac{Allowable\ stress}{Applied\ stress} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3.6)$$

In infrastructure planning, design stress is calculated based on the projection of future demands and their targeted satisfactory level of service (Babu et al. 2011; Sumalee et al. 2008). In order to have enough flexibility against uncertainty, the selection of an adequate size of safety margin with respect to allowable stress is important (Sumalee et al. 2008). Under those situations that can cause excessive stress to infrastructure, i.e., post-disaster situations, the stress level is likely to reach allowable stress. In this situation, without any degradation of level of service, the supply of infrastructural service counts on how much reserve capacities they have as a margin of safety, i.e., limit stress. Thus, the margin of safety, particularly for a post-disaster infrastructure, is defined in this paper as the ratio of limit stress to allowable stress in this paper (Equation 3.7).

$$Margin\ of\ safety = \frac{Limit\ stress}{Allowable\ stress} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3.7)$$

The size of the margin of safety will vary from infrastructure to infrastructure based on its preference for taking risks, i.e., reliability. Based on the statistical- and reliability-based approach for measuring the margin of safety, as proposed by Ullman (2010), the way to measure margin of safety for infrastructure planning is presented in this research. Figure 3-14 below shows the distribution of both allowable stress and the limit stress of infrastructure. The probabilistic distribution of allowable stress and limit stress reflects the uncertainty on the supply side that is associated with the available capacities of a post-disaster infrastructure.
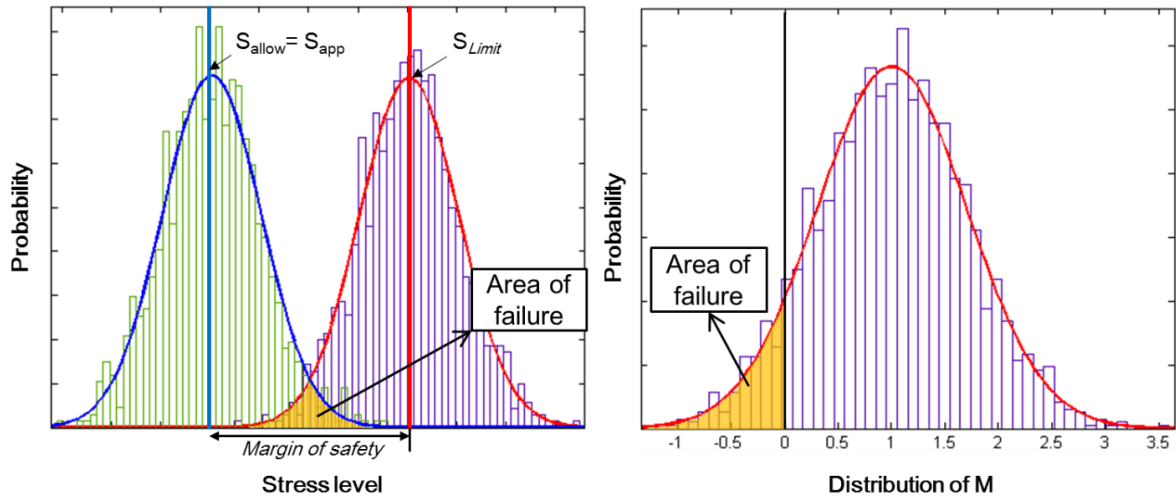
Figure 3-14 Distribution of Allowable Stress (=Applied Stress) and Limit Stress [Left Side], and the Distribution of the Different (Right Side) (Adapted from (Ullman 2010))

Since planned capacities are subjected to being occupied by applied demands during a disaster, the planned capacities would be also considered as required demands. As such, the applied stress is assumed to have the same probabilistic distribution as the allowable stress. In Figure 3-14, the graphs on the left side are the probabilistic distribution of allowable stress (=applied stress) and limit stress. It is worth noting that regardless of the size of the margin of safety, there is always an area of overlap between these two areas (Yellow area in Figure 3-14). This area of overlap is where the applied stress exceeds the limit stress of the infrastructure; therefore, the overlap indicates the probability of an infrastructure entering the plastic region.

On the right side of Figure 3-14, the probabilistic distribution of the difference between the applied stress and the limit stress (= the limit stress − applied stress) is presented. The yellow area in this graph is where the limit stress is less than the applied stress and indicates the plastic condition of the infrastructure. As the size of the margin of safety, i.e., the distance between two stress levels – S_{allow} or S_{app}, and S_{Limit} – increases, the probability of entering the plastic region decreases. Therefore, if infrastructure organizations place more emphasis on the reliable supply of service against future uncertainty, then they will reserve more capacity as a margin of safety and thus have a larger difference between allowable stress and limit stress.

In a pre-disaster situation wherein the stress level is generally met with planned capacities, service provision relates to allowable stress and the standard performance level. That is, having large redundant capacities, i.e., a significant margin of safety, will put a burden on the infrastructure for operating the services in terms of economic aspects (Alvarez et al. 2012; Morlok and Chang 2004). However, if the demands on the infrastructure increase significantly beyond the allowable stress, the reserve capacity starts being utilized to provide that required service, i.e., reaping benefits from having the reserve capacity.
Figure 3-15 below shows the range of profitable demand by having reserve capacities for supplying a required service. If the infrastructure does not have enough of a size of margin of safety (= redundant capacity), the infrastructure will finally enter the plastic region, which impedes the proper functioning of that infrastructure. Figure 3-15 below illustrates this concept. Depending on both supply uncertainty (i.e., the probabilistic values of limit stress and allowable stress) and demand uncertainty (i.e., the probabilistic value of demand for the infrastructure service), the range of benefits for the infrastructure will vary. So, the determination of the size of reserve capacities is based on how the infrastructure manages the demand in terms of its own system goals (Meyer 2008).
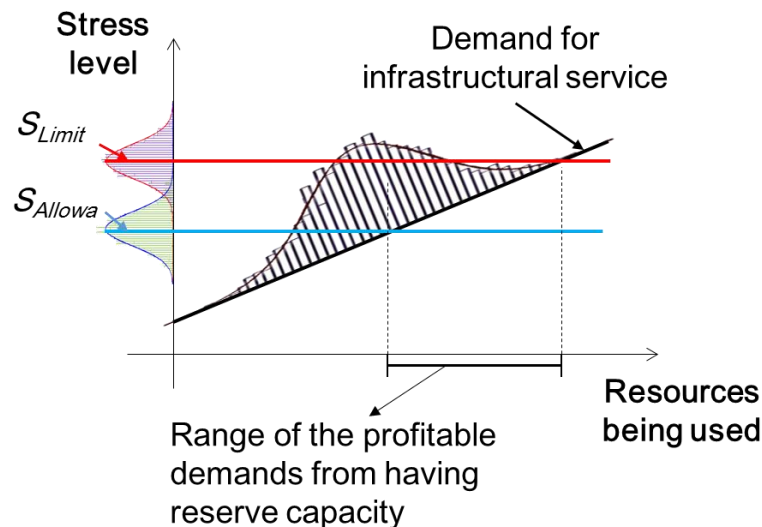
Figure 3-15 Benefits of Allowable Stress and Limit Stress during Uncertainty (Adapted from (Morlok and Chang 2004))

3.4.4 Hypothetical Example: The Emergency Operation of a Hospital during Disaster Conditions

To help understand the stress-strain principle for a post-disaster infrastructure, this chapter illustrates the behavior of a post-disaster facility under the condition of increasing stress by using the hypothetical example of the emergency operations of a post-disaster hospital. The example exhibits how stress and strain analysis assists in understanding the disaster effects on the operations of this hospital in terms of its stress and strain.

- Hypothetical infrastructure

To operate, a hospital needs services from its infrastructure units, i.e., electricity, gas, medical resources and water. Figure 3-16 shows the required resources or services from its infrastructure units for treating one patient or operating one bed per day. The failure to receive the required amount of resources from the infrastructure units will affect the operation of this hospital.
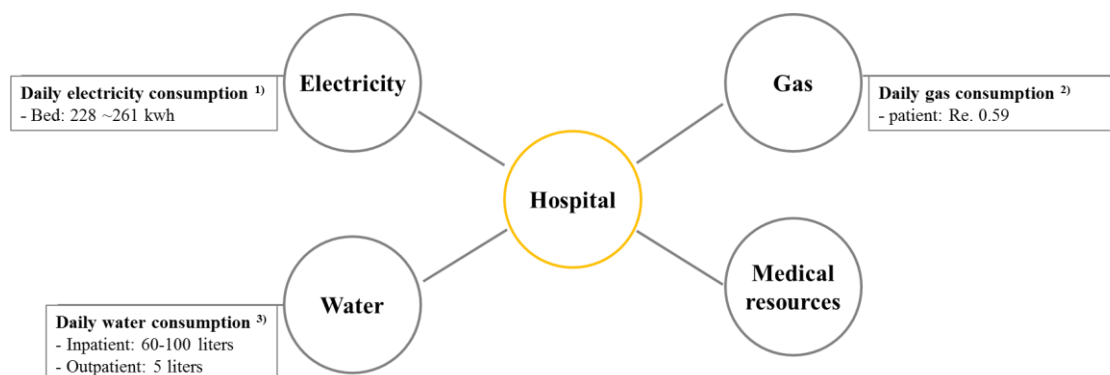
Figure 3-16 Sample Medical Facility and its Infrastructure Units (WHO 2011; Tabish and Qadiri 1994; ESC 2007)

In a post-disaster situation, a medical facility plays an important role in treating the injured and providing a safe environment; thus, the proper functioning of a hospital is critical for the public health. However, especially, in a post-disaster situation, a large number of patients that need urgent care is likely. Since patients have a critical timeframe, depending on their severity, within which they have to receive appropriate treatment to prevent

extremely risky health conditions, it is pivotal to provide that medical treatment within that critical time period.

In this hypothetical hospital, system performance is determined under the system goal of providing care to all patients within 3 hours of their arrival at the maximum. Also, it is assumed that the operation of the hospital depends on three infrastructure units, namely, water, electricity, and medical teams (see Figure 3-17). A disaster will influence the hospital's operation by i) increasing the number of patients and ii) reducing the serviceability of utility providers (i.e., power infrastructure and water infrastructure).
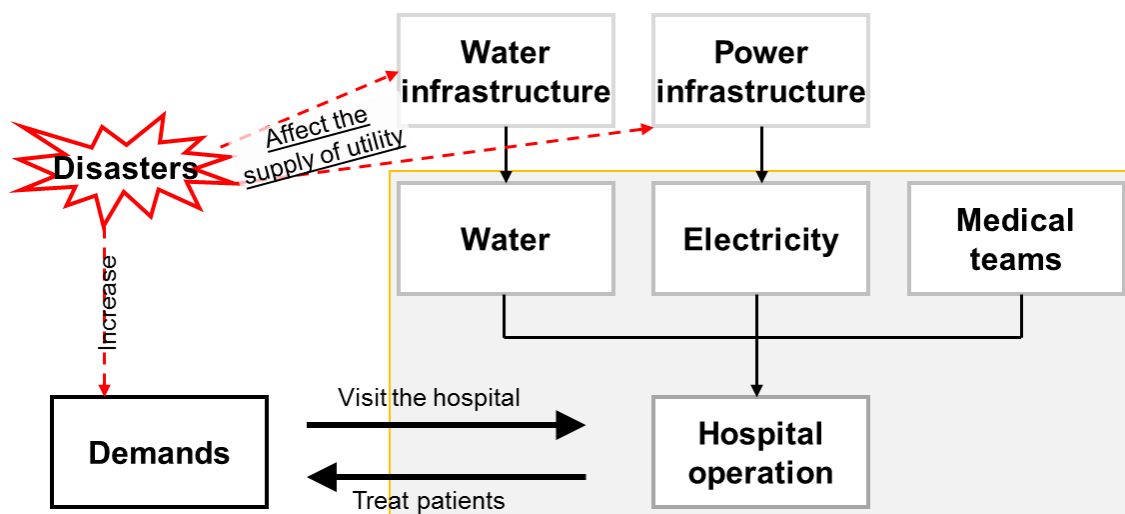
Figure 3-17 Example of a Hypothetical Medical Facility

- Description of stress and strain

Each infrastructure unit has its own stress and strain when supplying required resources or service to the hospital system. Based on the condition of these infrastructure units, the capacities of the hospital operation will also change.

Based on the definition of stress and strain, the stress and strain of infrastructure units are defined in Table 3-4. To achieve the system goal, i.e., providing medical treatment within 3 hours of their arrival at the maximum, the hospital has demands on its infrastructure units.

Table 3-4 Stress and Strain on Infrastructure Units of the Hypothetical Hospital

Medical Teams	Strain	Ratio of medical teams' working to the total medical teams, i.e., working medical teams plus idle medical teams to achieve system goals (treating all patients within 3 hours of arrival)
	Stress	Number of patients in the hospital during the unit time
	Allowable stress	Maximum number of patients the medical team units can cover based on planned work-shift (e.g., 8 hour shift)
	Limit stress	Maximum number of patients the medical team units can cover based on an extended work-shift (e.g., 10 hour shift)
Electricity	Strain	Ratio of consumed electricity to total electricity i.e., planned electricity resources plus auxiliary electricity resources, to achieve system goals (treating all patients within 3 hours of arrival)
	Stress	Required electricity demand [met electricity demands/(met electricity demand + unmet electricity demand)]
	Allowable stress	Maximum demand a hospital can satisfy while relying on a municipal supply of electricity
	Limit stress	Maximum demand a hospital can satisfy while relying on both a municipal supply of electricity and reserve capacities, i.e., back-up generators
Water	Strain	Ratio of consumed water to total water supply, i.e., planned water resources plus auxiliary water resources available for achieving system goals (treating all patients within 3 hours)
	Stress	Required water demand [met water demands/(met water demand + unmet water demand)]
	Allowable stress	Maximum demand a hospital can satisfy while relying on a municipal supply of water
	Limit stress	Maximum demand a hospital can satisfy while relying on both a municipal supply of water and reserve capacities, i.e., bottled water

- Medical team

For the medical team unit, the hospital expects to treat a certain number of patients within the unit time, depending on the number of patients and the target system goal, i.e., patient critical waiting time. Based on the definition for stress and strain, the stress on this unit can be defined as the number of patients in the medical facility while strain measures how many medical teams are working on meeting the expected performance to achieve the goal compared to the total number of medical teams. The allowable stress and limit stress are determined based on medical staff planned shift hours (e.g., 8-hour work day) and the

maximum shift hours (e.g. 10-hour work day) which they can work without impact on their ability of being replenished.

By extending the shift hours of the medical staff, this unit can allows for treating more patients during the unit time if the medical unit experience high stress. In addition, the medical team is likely to reduce treatment time, i.e., lowering performance level for individual patients to accommodate greater demand within maximum shift hours. The reduced treatment time for a patient will increase the number of patients that the medical teams can treat overall. In this hypothetical example, it is assumed that the allowable stress for the medical team unit is considered, i.e., leaving the difference between the allowable stress and limit stress as the margin of safety, and the change in treatment time based on the number of patients.

- Utility service (water and electricity)

In order for the medical facility to treat patients, there are some demands on utility units, i.e., water and electricity, for maintaining desirable operational condition. For example, if the medical teams can use power utility at pre-disaster level, i.e., 100% serviceability, they can treat as many patients as they can without any restriction on the use of medical equipment, which relies on electricity. However, if only 50 % serviceability of the power unit is available, then the staff may not treat as many patients as they do with 100% serviceability during the unit time.

Since medical facilities are required to treat patients in a timely manner to prevent degradation in their health condition, the required utility demands for treating patients can vary depending on the number of patients. For instance, if there is a small number of patients in the hospital, the full capacities of utility, i.e., 100% serviceability, is not necessary based on the system goal. However, if the hospital encounters a large number of patients, any unmet demand for utility service leads to a failure of the hospital to cover that number within the maximum wait time of 3 hours since patients arrive at the hospital. With respect to allowable stress and limit stress, the hospital is able to respond to the stress by relying on the municipal supply of utility in a pre-disaster situation, while the hospital may start using its reserve capacity, i.e., bottled water for water and back-up generator for

electricity, to maintain the required serviceability level in a post-disaster situation when municipal utility services are disrupted. Therefore, in this hypothetical hospital, the allowable stress is the maximum serviceability of utility which the hospital can receive from the utility companies and its limit stress is the maximum serviceability which the hospital can receive by relying on both the utility companies and its own auxiliary capacities.

- Behavior of infrastructure

After a disaster, the stress imposed on the hypothetical hospital varies with time because of i) the change in the number of patients reaching the hospital and ii) the restoration of utility infrastructure. Figure 3-18 shows the result of a stress analysis for this hypothetical hospital. The red line in each graph represents the stress applied to the infrastructure units (Stresses 2, 3 and 4) and the system (Stress 1).There are four types of stress that restrict the hospital in achieving the hospital's system goal. As the number of patients in the hospital increases, the medical staff unit starts lowering the performance level, i.e., treatment time for each patient, so that they can increase their capacities (i.e., increase the Allowable stress (P→P+) in Figure Stress 3, Figure 3-18). Other infrastructure units, i.e., electricity and water, also start using reserve capacities since the municipal supply of utilities is no longer fully available (Stress 2 and Stress 4, Figure 3-18).
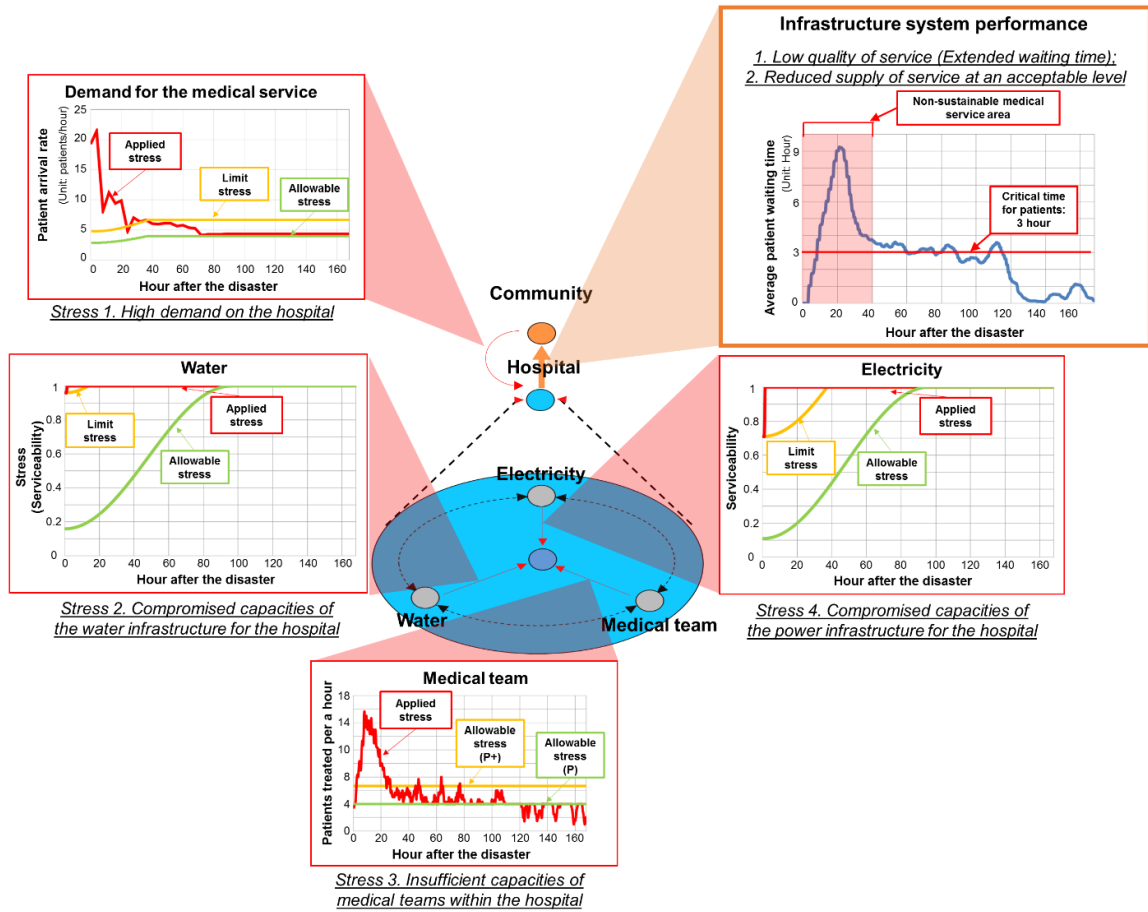
Figure 3-18 Stress Analysis for the Hypothetical Hospital

However, due to these insufficient capacities, the stresses on all the other infrastructure units exceed their allowable stress (i.e., Stress 3) and limit stress (i.e., Stress 2 and 4), which further affects the hospital's capacities (i.e., limit and allowable stress in Stress 1, Figure 3-18). Consequently, the goal of treating all patients within 3 hours is not likely to be achieved the first 40 hours after a disaster (i.e., Non-sustainable medical service area in the Infrastructure system performance, Figure 3-18). It is worth noting that the stress on the medical team unit and the water unit return to below the limit stress and allowable stress, but the capacities of the hospital still remain compromised because of the electricity unit wherein the applied stress is still above the limit stress during the first 30 to 38 hours after the disaster. That is, the resources that suffer from stress that exceeds the limit stress will function as a limiting resource for the entire system.

Also, as shown in the graph of average patient wait time versus hours after the disaster, in Figure 3-18, even though stress on all the infrastructure unit is below their limit and allowable stress, the average waiting time of patients will fluctuate around the system goal, i.e., 3 hours. That is because the medical staff unit can perform at the expected level by using its full capacities. Therefore, the prompt increase in the number of patients may trigger an increase in the patient waiting time above 3 hours. That is, even though applied stress is below limit stress, this stress condition is not operable. The emergency managers may need to add more staff to increase the capacities of the unit. The strain analysis is the capability of explaining such a condition for the medical staff unit.
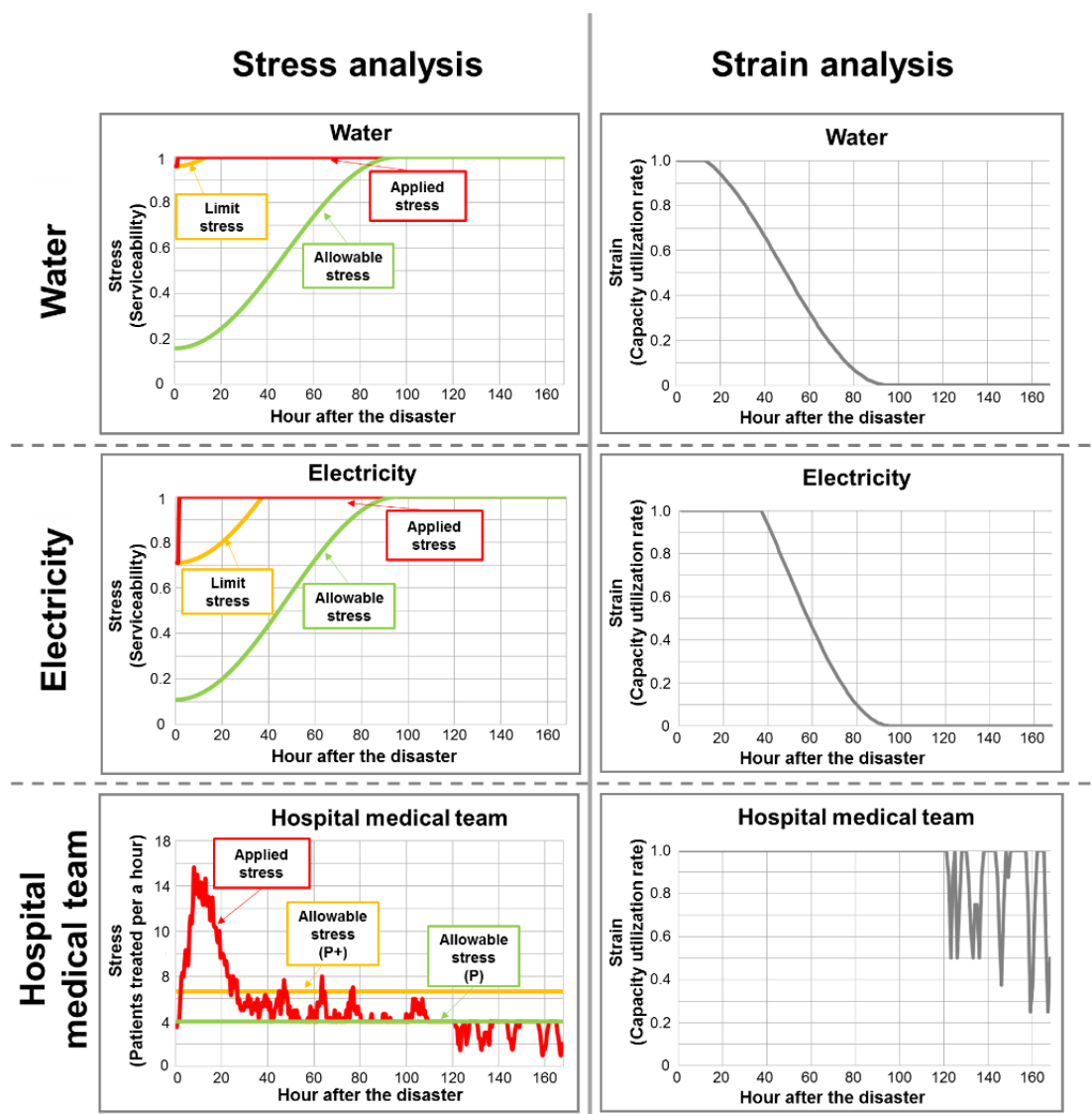
Figure 3-19 Stress and Strain Analysis of the Hypothetical Hospital's Infrastructure Units

Figure 3-19 above explains the results of the stress and stain analyses for each infrastructure unit within the hypothetical hospital. Since it is hard to measure the amount of capacities of a municipal utility service for the hospital, the strain in water and electricity units is configured as the ratio of the auxiliary capacities being used to the total capacities of those auxiliary capacities. While the strain of the water and electricity units gradually declines as the municipal supply of utilities is restored, the hospital medical team still remains at a strain of 1 until 120 hours after the disaster. That is, medical team unit has to

utilize its full medical groups to keep the desired waiting time for patients. From the perspective of developing strategies, managers can gain insight from a strain analysis and add more medical staff to prevent probable extended average waiting time for patients. Without the strain analysis, the stress analysis cannot give emergency managers any hint about the probable unacceptable service, i.e., waiting time longer than 3 hours. Therefore, emergency managers at the hospital might learn from a stress analysis how much stress the hospital can handle and from a strain analysis how to observe the stress level and develop appropriate strategies to confront it.

- A system-of-systems approach

In the operation of the hospital, various infrastructure units are needed to provide adequate service. For instance, in the example here, it is assumed that the hypothetical hospital will perform based on the available capacities of water, electricity, and medical team units. However, through a link of infrastructure units to other external systems, the hospital operation becomes highly coupled with them. Figure 3-20 shows the interaction of the hypothetical hospital (i.e., hospital 1, Figure 3-20) and other external systems. A stress and strain analysis for the hypothetical hospital is carried out for the water, electricity, and medical teams for hospital operation (i.e., infrastructure network layer in Figure 3-20) without any consideration of sub-systems (i.e., the infrastructure component layer in Figure 3-20).
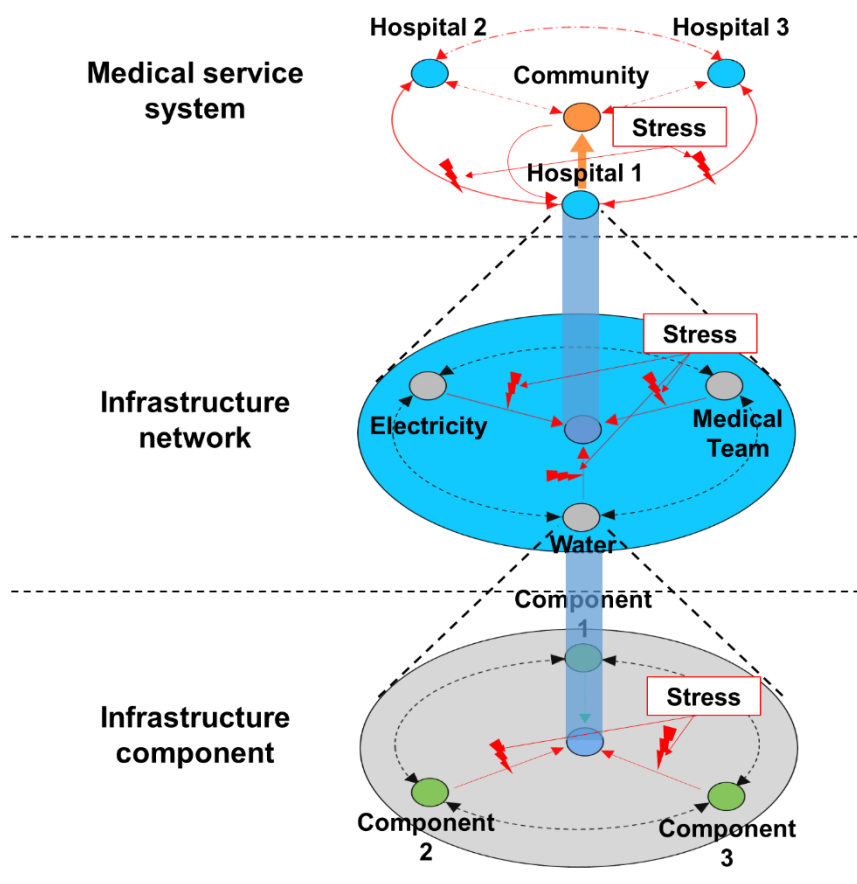
Figure 3-20 Medical Facility System-of-Systems under the Hypothetical Situation

However, stresses on the sub-systems are also likely to affect the availability of service for the hypothetical hospital in its infrastructure network layer, thereby putting excessive stress on the hospital. Moreover, demands on the hospital can vary, depending on the availability of other hospitals (i.e., Hospital 2 and 3, Figure 3-20) for transferring and receiving patients in the medical service system layer (see Figure 3-20). In addition to the interdependencies of infrastructure, since each subsystem in the infrastructure component layer and other hospitals in the medical service system operate their systems independently, the system-of-systems approach may be useful (DeLaurentis 2005).

3.5   Case Study: Analysis of Post-Disaster Infrastructure Operations Applying the
Stress-Strain Principle

In this subchapter, using a case study on the operation of infrastructure facilities in the past post-disaster situations, the applicability of stress and strain analyses are discussed in terms of their benefits and ability to minimize possible disaster impacts. Even though each term is not measured in a quantitative way, this qualitative case study enables an understanding the stress-strain principle in various contexts, i.e., disaster situations, with respect to its benefits and applicability (Baxter and Jack 2008). In this current research, two cases are discussed: 1) Puli Christian Hospital and 2) the power infrastructure in Taiwan after the 1999 Chi-Chi earthquake. The following 3 questions will be answered:

- What are the stress and strain of a post-disaster infrastructure?
- How can the limit stress (or allowable stress) of a post-disaster infrastructure vary?
- Why is it important to understand the stress and strain of a post-disaster infrastructure?

By answering these questions in each case, they can be generalized to other types of infrastructures. In the end, the concern about the high coupled infrastructure system is seen from the two case studies, which refers again to the need for a system-of-systems approach.

3.5.1   Chi-Chi Earthquake: High Stress on the Puli Christian Hospital, Taiwan

 - 1999 Chi-Chi earthquake

On September 21, 1999, an earthquake with a magnitude of (Mw) 7.3 struck central Taiwan as illustrated in Figure 3-21 (Schiff and Tang 2000). Even though the shaking lasted for only around 40 seconds, the impact of the earthquake was extensive around the nation due to its coupled infrastructure system. Long power outages were sustained nationally because of widespread damage to the power system. In addition, the failure of a dam in Shihkang caused drinking water problems to communities and industries (EQE International 1999). The utility outages restricted the operation of essential facilities, including hospitals, and high-tech facilities, e.g., semiconductor and silicon manufacturers. In terms of need for the medical facilities, the earthquake created a large demand for them; a total of 2,405 people

died and 10,718 people were injured (Dong et al. 2000), putting a severe demand for services on all medical facilities. The subsequent curtailed capacities of hospitals and the upsurge in medical demand drove the stress on the hospitals toward approaching their full capacities thus making medical services inoperable in many instances.

Figure 3-21 Epicenter and Surrounding Impacts of the Chi-Chi Earthquake (EQE International 1999)

- High stress on Puli Christian Hospital

The Puli Christian Hospital (PCH) was one of the hospitals that was able to keep providing medical services for victims of the earthquakes even though it suffered from an enormous stress on its resources. As shown in Figure 3-21, Puli Province is located close to the epicenter of the earthquake. The PCH is a medical facility with approximately 400-acute care beds. There are two sections of buildings: One that was 20-years old and one that was only 1-year-old (Cole 2006). Because of its closeness to the epicenter, PCH experienced a strong physical impact that demolished the old building section but and only caused nonstructural damage (e.g., equipment damage, water damage) to the new building.

In addition to the structural damage to PCH, the Chi-Chi earthquake put severe stress on the PCH facility and its available strain capacities for various reasons (see Figure 3-22).

Demand for the medical service

Growing demands for the medical service

- **Impact on the operation of hospital**
  @ Number of patients seeking for the treatment >> coping capacities of hospitals

Cause 1. High stress because of high demand for a medical service

Water supply for the hospital

Disruption of the supply of water during 10 days, but less impact on the hospital operation

@ Supply of water by water tanker trucks
@ No large fire occurs → less demand for water supply

Cause 2. High stress because of compromised capacities of the water infrastructure system for the hospital

Healthcare facility system

Excessive stress on the functioning of the hospital

- **Pre-disaster situation:**
  400-bed acute care available
- **Post-disaster situation:**
  @ During the 72 hours (the peak time of patients after the earthquake), 10 % of its original capacity is available
  @ More than 200 patients required to be transported to other hospitals due to the limited medical service

Electricity supply for the hospital

Disruption of the supply of electricity during 10 days

- **Impact on the operation of hospital**
  @ Inability to operate the acute care
  @ Limited functioning of hospital operation

Cause 5. Compromised capacities of the electricity system for the hospital

Medical resources

Lack of medical staffs and resources

- **Impact on the operation of hospital**
  @ Overworked medical staffs
  @ Insufficient operable rooms
  @ Insufficient medical supplies
→ Limited acute care is implemented 3 days after a disaster

Cause 3. High stress because of insufficient internal capacities of the hospital

Road networks for transferring patients & supplying medical supplies

Loss of transportation connections

- **Impact on the operation of hospital**
  @ Difficulty in resupplying the medical supplies and equipment
  @ Limited number of transferred patient

Cause 4. High stress because of compromised capacities of the transportation network for the hospital

Figure 3-22 Various Causes of Limiting Strain Capacities of the PCH Hospital (Cole 2006)

Due to the disruption in power and the water infrastructure, the hospital had to operate without a supply of water and power for the first 10 days (Cole 2006). Even though PCH received water by water tank trucks, operational capacity of the hospital dropped to 10% of its pre-disaster level (Cause 2) due to a power outage the first 3 days after the earthquake (Cause 5) as noted in Figure 3-22 (Soong et al. 2000). At that time, however, the hospital

encountered the highest number of patients seeking medical service (Cause 1). The road network going to other hospitals was wiped out for any transportation and transfer of excessive patient population to other venues (Cause 4). The Puli Christian Hospital could only rely on helicopters to evacuate patients, which meant that the transfer option was not available to all those patients who needed it. Also, limited access to the hospital produced a concern about the shortage of medical supplies (Cause 4) (Cole 2006). The re-evacuation of all the patients after the 9/27 quake put a physical burden on the medical staff, adding to their burden and fatigue and making it more difficult to provide adequate medical treatments to the victims (Cause 3) (Cole 2006). Evacuated patients were housed in a temporary trailer with significantly reduced capacities (50 beds) (Soong et al. 2000). The demands for transfers to other hospitals also overwhelmed the hospital's capacities for transferring patients.

- What are the stresses and strains of a post-disaster infrastructure?

In the case of the Puli Christian Hospital (PCH), both stress and strain analyses were applied to acute care based on the available data. In a case analysis, PCH defined acute care as the advanced treatment for patients who needed to be admitted to the hospital, while emergency care was defined as medical treatment for the patients who could be discharged after treatment in the emergency room. As shown in Table 3-5, during the first 2 days following the earthquake, the hospital lost its capabilities for providing acute care to patients (Cole 2006). But, as these capacities were restored, the functionality of acute care was also restored and fully re-established, by September 28, 1999, a week after the earthquake.

Table 3-5 Post-Earthquake Health care Demands on PCH (Cole 2006)

Date	Acute Care	Emergency Care	Transferred Patients	Deceased Patients
09/21/1999	-	753	70	58
09/22/1999	-	302	69	14
09/23/1999	83	166	75	10
09/24/1999	439	388	12	6
09/25/1999	192	385	5	4
09/26/1999	283	339	16	3
09/27/1999	723	25	3	1
09/28/1999	1578	88	2	2
09/29/1999	1621	83	2	0
09/30/1999	1653	68	4	0
Total	6572	2598	258	98

Based on the definitions for stress and strain, stress for acute care is defined as the number of patients who need to receive acute case service during a day, i.e., a one day as the unit time, while strain is the rate at which resources are being used to respond to the applied stress. The capacities associated with acute care are required resources, including water, electricity, medical staff, beds, and medical supplies. In order to support the needed acute care at PCH, the hospital also applied some of the demands to its resources. The demands that required supporting the desired acute care became both a stress and strain of the resources. The stress and strain of each resource is defined in table 3-6.

Table 3-6 Stress and Strain on Infrastructure Units for PHC

Resources for Hospitals	Stress	Strain
Medical resources	- Required number of patients treated during single day	- Rate at which medical resources are used
Water	- Required amount of water during single day	- Rate at which available water resources are used to meet the demand
Electricity	- Required amount of water during single day	- Rate at which available electricity resources are used to meet the demand
Transportation of medical supplies	- Required amount of medical supplies transported during single day	- Rate at which available road capacities are used to transport needed medical supplies

- How can the limit stress of a post-disaster infrastructure vary?

As discussed in the previous section, the capabilities of the hospital for performing treatment, including acute care, varied depending on the stress and strain capacities of its resources. In other words, the causes that were limiting strain capacities for acute care were infrastructure units where the stress exceeded the hospital's available capacities. Since the limit stress[1] for acute care can vary depending on available strain capacities, the dynamic limit stress for acute care over time can be described as a combination of stress-strain curves for its infrastructure units (see Figure 3-23). According to Cole (2006), the capacities for Acute Care fully recovered on September 28, 1999. Assuming that the number of patients who received acute care on September 28 were the pre-disaster performance rate, Table 3-7 shows the relative change in the limit stress for acute care as corresponding to the change in the stress-strain curve.

Table 3-7 Capacity for Acute Care

Date	Current capacity for acute care/pre-disaster care	Change in performance of acute care (See Figure 3-23)
9/21/1999	0%	
9/22/1999	0%	-
9/23/1999	5%	①
9/24/1999	28%	①
9/25/1999	12%	②
9/26/1999	18%	①
9/27/1999	46%	①
9/28/1999	100%	①
9/29/1999	100%	-
9/30/1999	100%	-

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[1] Due to the limited information on the margin of safety for PHC's acute care performance, we regarded the number of patients treated as its limit stress.
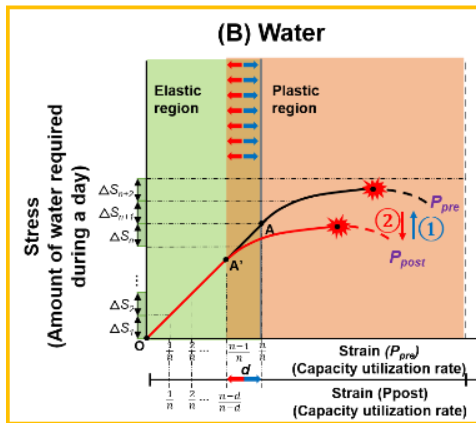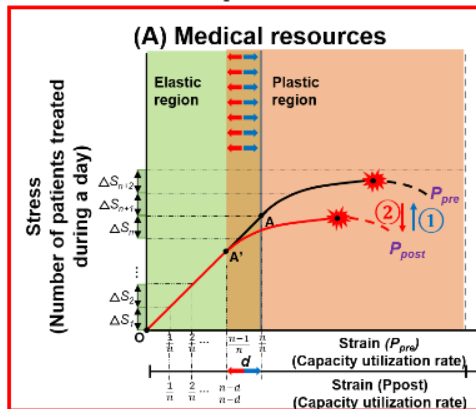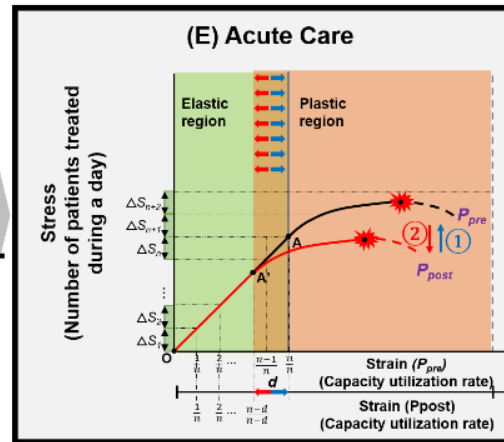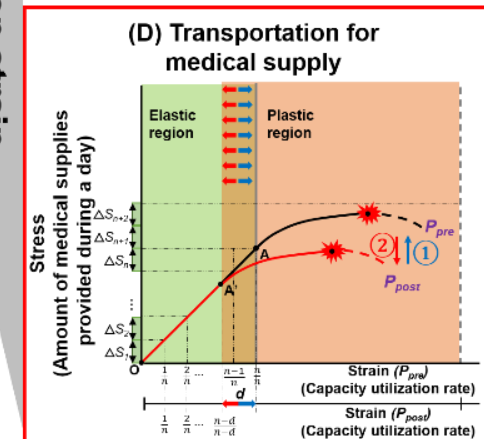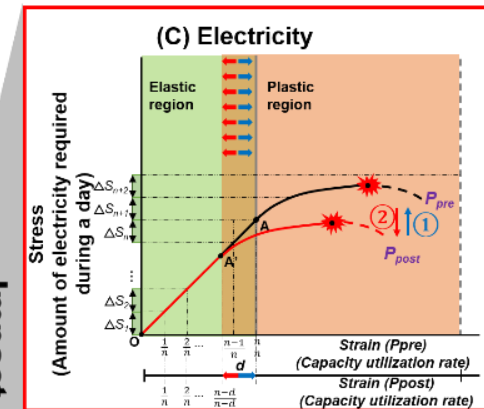
Figure 3-23 The Stress-strain Curve of Acute Care at Puli Christian Hospital

Because of the lack of electricity and the non-structural damage to the hospital, advanced treatment was not offered the first two days (Cole 2006). In other words, the Puli Christian Hospital could not withstand any demand on acute care at all because there were no strain capacities on electricity and non-structural damage (Cause: ② in the graph (C), Figure 3-23). As each infrastructure unit was restored with time, i.e., ① in the graph (A) to (D), Figure 3-23 (Core 2006), the strain capacity of the hospital also recovered thus increasing the limit stress for acute care (① in graph (E), Figure 3-23). As reported in Core (2006), the limited capabilities of acute care created a huge demand for transferring patients (200 patients to other hospitals). From the strain perspective, this overflowing demands for transfer can be explained by the fact that the demands on the hospital are beyond its strain capacities so the hospital tries to transfer patients above their limit capacities to other hospitals to keep the strain below 1. Until the inpatients were re-evacuated because of the aftershock that occurred on September 25, the increase in limit stress for acute care continued (0% → 5% → 28% increase in capacity, Table 3-7). Since the re-evacuation impaired the ability of the hospital to provide acute care using the medical machines inside the hospital, (② in graph (A), Figure 3-23), the limit stress of acute care dropped (28% → 12% capacity) (② in the graph (E), Figure 3-23). After the re-evacuation, there was no more displacement of patients. So, the strain capacities for acute care gradually did recover (12% → 18% → 46% → 100% capacity, ① in Figure 3-23).

- Why is it important to understand the stress and strain placed on a post-disaster infrastructure?

  By applying a stress-strain analysis to the capabilities for acute care at Puli Christian Hospital (PCH) after the Chi-Chi earthquake, changes in the hospital's capacities for acute care can be understood in terms of the restored strain capacities of acute care capabilities over time. In particular, the stress and strain analyses allow for understanding and identifying the resources that limit the performance of acute care even with an increase in stress on PCH. If emergency- related managers at the Christian Hospital could identify the resources on which excessive stress was imposed, it would have helped them to design

strategies to relieve the stress on them and ultimately sustain the functionality of their acute care properly.

3.5.2   Chi-Chi Earthquake: High Stress on Taiwan Power Company (Taipower)

- 1999 Chi-Chi earthquake

When the Chi-Chi earthquake happened, a power outage in central Taiwan occurred because of substantial damage to the power facilities (Schiff and Tang 2000). In particular, the earthquake led to a large number of transmission line failures because of damaged foundations supporting the transmission line towers. Because of the imbalance in the spatial distribution of power stations, the transmission system played an important role in distributing power throughout the region. The difficulty in distributing the power supply throughout the nation caused local power stations, especially in Northern Taiwan, to frequently trip off because of the sudden loss of supply (Schiff and Tang 2000). These compromised capacities of the power facilities produced huge economic losses to semiconductor fabricating facilities as well as restrictions on critical facilities, i.e., hospitals (EQE International 1999). Compared to the past earthquakes that happened in the U.S., the comprehensive failure of the transmission lines network due to the failure of unstable foundation was not the general cause of the power outage (Schiff and Tang 2000). The position of the transmission line located above unstable soil reflected the features inherent in Taiwan where both a high population density and the high cost of land made it hard to find a safe route for transporting power.

- High stress on Power Facilities in Taiwan

The power facilities in Taiwan consist of Taiwan Power Company (Taipower), the Taiwan Water Corporation, and other independent generators (Taipower 2013). Considering all the capacities of these power facilities, the total generating capacities were 27,244 MW and the peak demand for the power was 24,206 MW (Schiff and Tang 2000). The demands and generating capacities of each region, i.e., Southern, Central, and Northern Taiwan are shown in Table 3-8. According to Table 3-8, even though the peak demand for electricity in Northern Taiwan is around 45.56 % of the total demand, the regional capacities are

24.69 % of the total generating capacity. In normal conditions, the excess of power generated in Southern and Central Taiwan must be transmitted to Northern Taiwan to meet the demand there. However, because of the devastating impacts of the Chi-Chi earthquake, the failures of transmission towers were widely prevalent, which impaired the capacities to supply electricity to Northern Taiwan (Schiff and Tang 2000).

Table 3-8 Power Generating Capacities and Peak Demands for Electricity in Taiwan

Region	Capacity (MW)	Peak demand (MW)	Regional capacity / total capacity (%)	Regional peak demand / total peak demand (%)
North	6,726	11,028	24.69	45.56
Central	10,005	6,294	36.72	26.00
South	10,513	6,884	38.59	28.44
Total	27,244	24,206	100	100

In addition to the damage to the transmission line networks, the infrastructure units for generating and distributing the power were severely damaged, and that further worsened the situation for meeting the peak demands in Northern Taiwan. Table 3-9 shows the damaged components associated with that provision of power (Schiff and Tang 2000). The physical impacts on the power transmission system hampered the generated power from spreading throughout the nation. In particular, Northern Taiwan, where the power facility cannot meet its peak daily demand by only relying on its local capacities, experienced enormous stress so it had to lower the performance level, i.e., load shedding, in order to accommodate the regional demand for electricity within its still available capacities.

Table 3-9 Summary of Damage to Power Transmission System (Schiff and Tang 2000)

Item	Quantity	Description
Substation Buildings	14	Wall cracked
345 kV Tower	1	Collapsed
345 kV Towers	6	Leaning
345 kV Towers	124	Distorted
345 kV Towers	227	Foundations Sunk/Cracked
345 kV Towers	4	Foundations Displaced
345 kV Lines	28	Damaged
161kV Towers	10	Collapsed
161kV Towers	7	Leaning
161kV Towers	42	Distorted
161kV Towers	143	Foundations Sunk/Cracked
161kV Towers	3	Foundations Displaced
161kV Lines	30	Damage
69kV Towers	4	Collapsed
345 kV CCPT	53	Porcelain Housing Broken
345 kV Surge Arresters	46	Porcelain Housing Broken
345 kV Support Insulators	3	Broken
345 kV Gas Insulated Lines	334m	Distorted
345 kV Gas Insulated Switchgear	28 sets	Foundations Sunk
345 kV Bus	4	Damaged

The 1999 Chi-Chi earthquake damaged the capacities of the power facilities in Taiwan. The damaged components (e.g., switchyards), at power stations and the environment that make them trip off because of demand exceeding the generating capacities disabled the generation of enough capacity (Cause 5, Figure 3-24) (Schiff and Tang 2000). In addition, the issues of the damaged components also affected the ability of substations to transform high power voltage to lower voltage power before sending it to users (Cause 4, Figure 3-24). In particular, in Northern Taiwan, the power facility cannot meet peak demand by merely relying on its regional capacity (Cause 1, Figure 3-24). That is, the imbalance between demand and capacity of power requires the national power system to have a well operated transmission system, so extra electricity from the South and Center of Taiwan can be transmitted to the North. The failure of transmission line systems thus led to a reduced supply of these supplementary capacities from outside during peak demand time (Causes 2 and 3, Figure 3-24). As a result, due to both compromised capacities and unbalanced regional demands, especially in Northern Taiwan, the power facilities had to withstand

excessive stress. In an effort to cover the demands within their available capacities, frequent load shedding was designed (Schiff and Tang 2000).
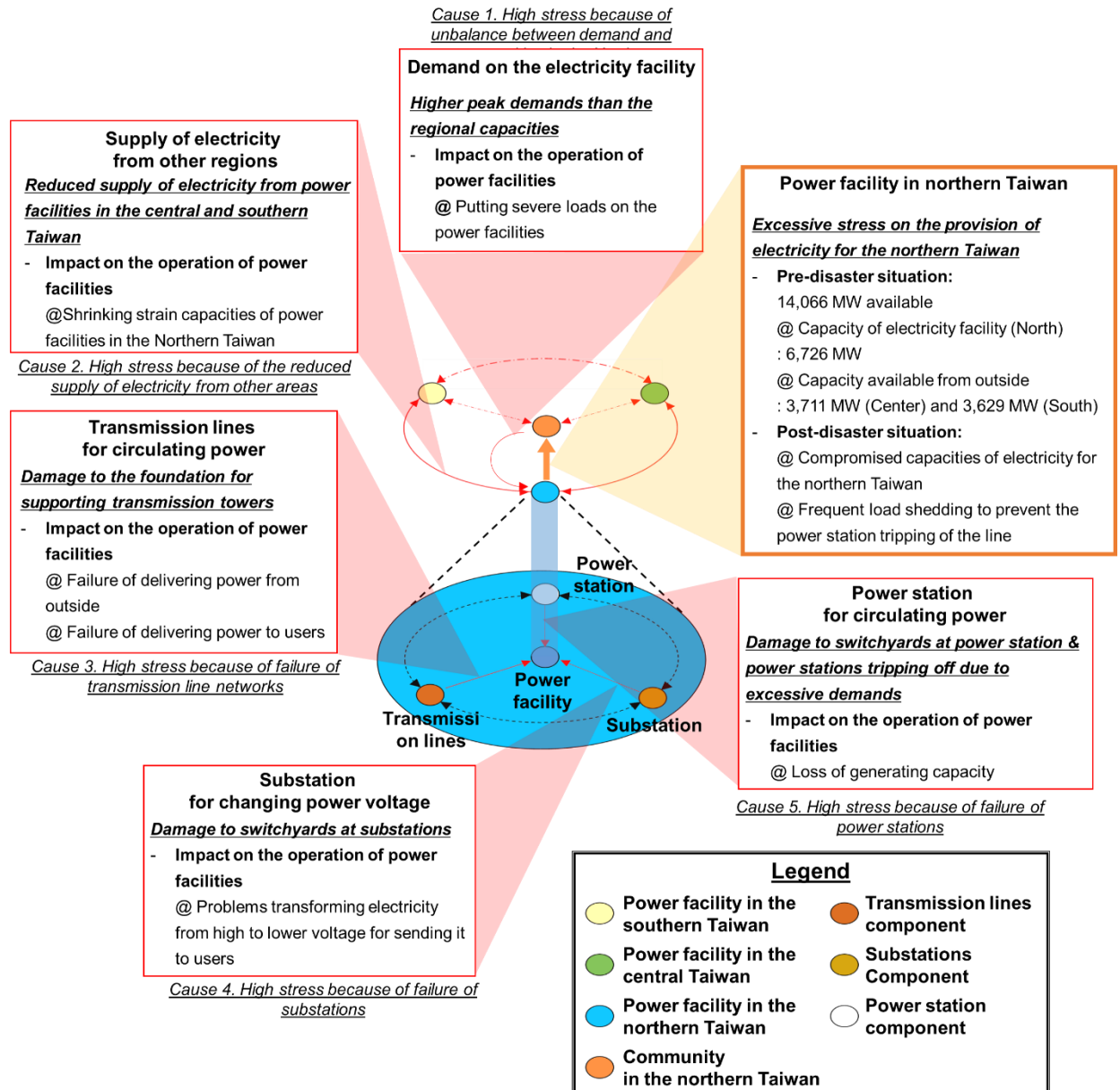
Figure 3-24 Causes of Limiting the Strain Capacities of the Power Facility in Northern Taiwan (Schiff and Tang 2000)

- What are the stress and strains of a post-disaster infrastructure?

Considering the aim of these case studies, which is to understand stress and strain of a post-disaster infrastructure, further discussion on the stress and strain is continued via targeting the stress and strain of the power facility in Northern Taiwan. Moreover, the stress and strain are measured with data on a state-owned electric power utility, Taiwan Power Company (Taipower).

Based on the definition of stress and strain, the stress of Taipower when supplying the electricity to the north is defined as the required amount of electricity supplied to residential users during one day, i.e., one day as the unit time. The strain from the supply of power to the north came from the rate at which the amount of electricity available to the north was being used. The maximum amount of electricity, i.e., limit stress that Taipower can handle depends on the stress conditions of its own resources, i.e., power station, substation, and transmission lines and on the support of power facilities in other regions, i.e., the South and the Center of Taiwan.

For a stress and strain analysis of power facility in Northern Taiwan, this case study regards the mentioned resources as infrastructure units and support from other areas as strategies used to relieve the stress on the Northern power facility. In order to generate and supply the required amount of electricity to the North, the power facility there also has performance expectation from its infrastructure units. The corresponding demands are made on each unit and serve as the stress and strain in the system. In this way, the stress and strain of these infrastructure units are defined as in Table 3-10.

Table 3-10 Stress and Strain of Infrastructure Units for a Power Facility System

Power Facility Resources	Stresses	Strains
Power station	- Required amount of generated electricity	- Rate at which available generation resources are used
Substation	- Ratio of required amount of electricity to transform high voltage to lower voltage to total amount of generated electricity	- Rate at which available resources for transforming voltage of electricity are used
Transmission lines	- Ratio of required amount of electricity to transmit to total amount electricity being generated	- Rate at which available capacities for transmitting electricity are used

- How and why can limit stress vary?

As discussed in the previous section, the capabilities of the power facility (Taipower) in Northern Taiwan depend on the stress and strain of the infrastructure units. Since the power facility is comprised of linked and coupled infrastructure units, i.e., power station, substation and transmission, at least one of the infrastructure units serve as the limiting factor to the functioning of the power facility, i.e., restricting strain capacities to meet its required demand.

As shown in Table 3-9, the Chi-Chi earthquake damaged the components that were associated with generating and distributing electricity. As a result, the capabilities of Taipower to provide electricity for Taiwan were affected. In particular, the available capacities of the power facility in Northern Taiwan were severely reduced because of their damaged infrastructure units. By contrast, the demand on the power facility in the north increases due to the reduced supply of electricity from outside the region. These reduced strain capacities resulted in a reduction in the maximum stress which the facility could handle, i.e., limit stress.[2] Table 3-11 reflects this impact on the capabilities of Taipower to support Northern Taiwan. Before the Chi-Chi earthquake on September 21, the available capacities of Taipower for both the North and other regions abruptly dropped to 5,000 MW.

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[2] Due to limited information about the margin of safety for the power facility in Northern Taiwan, we only considered the stress limit.

 As the infrastructure units were restored and repaired, the capability of Taipower also recovered. During the recovery time period between September 21, the time of outbreak of the earthquake, and October 10, most systems recovered, the power facility for Northern Taiwan experienced varying stress and limit stress, and took a measure, i.e., load shedding, to relieve the stress level in the system.

Table 3-11 Available Capacities of Power Facility (Taipower) vs. Northern Taiwan Power Demands

	Total capacity [MW] (T)	Adjusted demand[1] [MW] (D)	Available capacity[2] [MW]		Normal demand[3] [MW]		Demand after doing load shedding[4] [MW]		Extra capacities from outside region[5] [MW]	
			North (24.69% × T)	External (75.31% × T)	North (45.56%× D)	External (54.44%× D)	North	External	Normal	Shedding
09/18	22,000	19,547	5,431	16,569	8,905	10,641	7,607	9,090	5,927	7,479
09/19	22,000	19,547	5,431	16,569	8,905	10,641	7,607	9,090	5,927	7,479
09/20	22,000	19,547	5,431	16,569	8,905	10,641	7,607	9,090	5,927	7,479
09/21	5,000	19,547	1,234	3,766	8,905	10,641	7,607	9,090	-6,876[6]	-5,324[6]
⌇					…					
09/26	5,000	19,547	1,234	3,766	8,905	10,641	7,607	9,090	-6,876[6]	-5,324[6]
09/27	17,000	19,547	4,197	12,803	8,905	10,641	7,607	9,090	2,162	3,713
⌇					…					
10/02	17,000	19,547	4,197	12,803	8,905	10,641	7,607	9,090	2,162	3,713
10/03	15,000	19,547	3,703	11,297	8,905	10,641	7,607	9,090	655	2,207
10/04	19,000	19,547	4,691	14,309	8,905	10,641	7,607	9,090	3,668	5,220
⌇					…					
10/10	19,000	19,547	4,691	14,309	8,905	10,641	7,607	9,090	3,668	5,220

1) Assuming that the portion of electricity which power companies supply is adjusted to the ratio of total capacity and total peak demand (27,244:24,206, Table 3-8), the adjusted peak demand is 19,547 MW.
2) Available capacities refers to the capacities available for supplying electricity to Northern Taiwan. It is assumed that 24.69% of these total capacities (T) is generated in the north, and the remaining is generated in the center and south (in a ratio of 24.67:75.31, Table 3-8).
3) Normal demand in the north and other regions is their peak demand divided according to the ratio of 45.56:54.44, (Table 3-8).
4) Extra capacities are the remaining electricity outside the electricity consumed by users in Central and Southern Taiwan.
5) Load shedding was implemented by having residential customers divided into two groups, each experiencing 7-hour power outages on alternate days.
6) The negative sign indicates no extra electricity. Rather, other regions experience a power shortage.

Based on Table 3-11, the stress and strain of the power facility for Northern Taiwan are measured and plotted by time (see Figure 3-25). Stress applied to the power facility was

the demand on the facility for Northern Taiwan. It was either 8,905 MW (normal demand) or 7,607 MW (after load shedding). From September 18 to 20, 1999, before the Chi-Chi earthquake, the limit stress of the power facility was above the applied stress with standard performance level. It is worth noting that standard performance level means that residential users can access electricity throughout each day. During this time period, even though the local capacities in the North were not sufficient for covering the peak demand in the North, the gap was filled by supplying extra electricity from other areas, the South and the Center. That is, the strain capacities, which considered both regional capacities and the additional capacities from outside, were sufficient to meet the demand, as the strain could remain at 0.784 (Figure 3-25). This region is called an elastic zone in which the Taipower can accommodate the required demand in the North without load shedding. However, shortly after the Chi-Chi earthquake, the power facilities throughout the nation found they were impacted by the disaster.

\<Power facility for Northern Taiwan\>

\<Stress-strain curve of the power facility\>
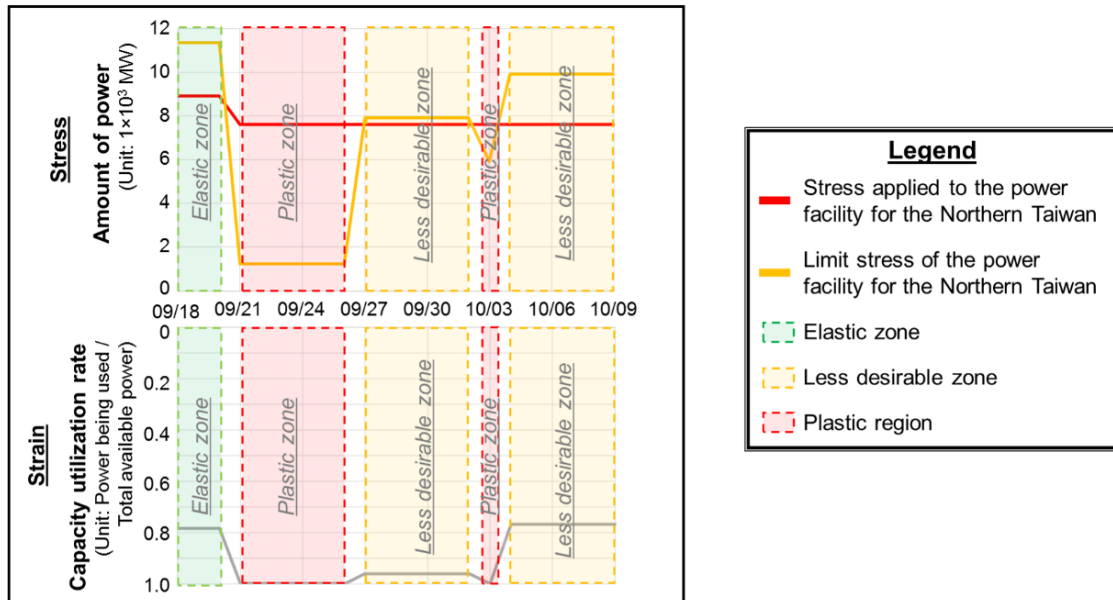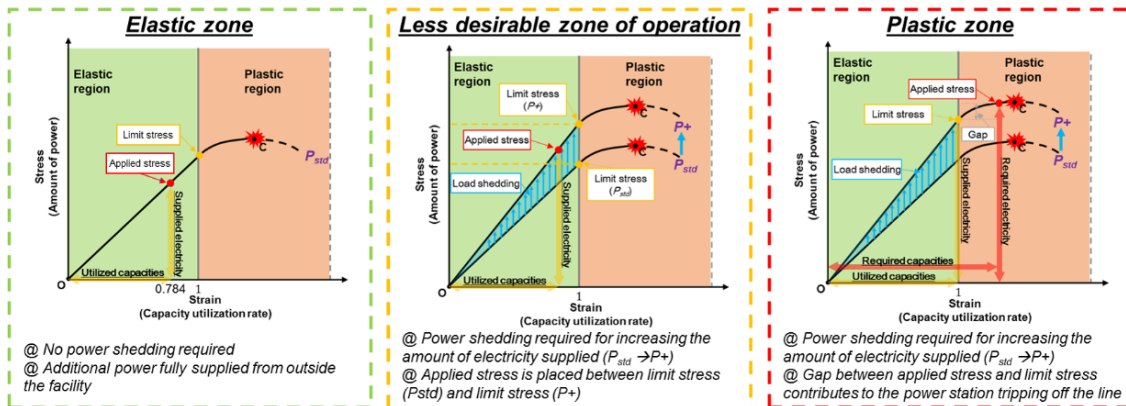
Figure 3-25 Stress and Strain Analysis of a Power Facility in Northern Taiwan

In addition to the power facilities in the North, the capacities of power facilities in the Center and South of Taiwan also suffered from the shortage of electricity. As a result, the power facility in Northern Taiwan implemented rotational load shedding in order to prevent system failure and cover all the demand. However, during the first six days after the disaster, the applied stress exceeded the strain capacities which were increased by lowering the performance level (i.e., load shedding). Shortly after the earthquake, the most northern Taiwan were not able to access electricity because the sudden loss of the supply

of electricity from outside caused the power station in the north to trip off the line (Schiff and Tang 2000). The station which tripped off took a long time to renew the system. This region is called the Plastic zone (Figure 3-25) wherein available strain capacities fall short of the strain capacities required to stretch.

As the power system was restored, the power facilities could keep the applied stress level below the limit stress while still keeping load shedding from September 27 to October 2. Even though the stress level was within the strain capacities, i.e., limit stress, the power system could not get back to its standard performance level because the current strain capacities with the stand performance level could not withstand the applied stress (applied stress is still above limit stress (P_{std}) in the operable zone, Figure 3-25). So, this zone is called the less desirable zone of operation. Due to the drop in the generating capacity in Taipower, the power facility in Northern Taiwan entered the plastic zone again. Then, during the time period between October 4 and October 9, the power facility in the North was able to get back to the less desirable zone. During that time, even though the limit stress of the power facility in Northern Taiwan is greater than the applied stress, the power facility could not get back to its standard service because of high applied stress. It is important noting that the demand in Northern Taiwan largely relies on the supply of the center and south of Taiwan. Therefore, returning to the standard performance level, i.e., 24-hour availability, will reduce the available electricity from outside while it will increase the demand of the north, which will cause the power facility to stick to the load shedding.

- Why is it important to understand the stress and strain of a post-disaster infrastructure?

In this case study, the stress and strain analyses were applied to the power facility in Northern Taiwan. In a stress analysis, the varying stress applied to the system is observed in terms of its limit stress, which helps us to understand when the facility can cause the power shortage issues because of insufficient capacities and how much stress the facility can actually handle. In a strain analysis, analysts can perceive how much capacity is being used to respond to the applied stress over time. As it is assumed that an infrastructure cannot consume more than what it has, i.e., above its maximum strain of 1.0, then the current strain in response to the stress implies how much additional stress the power facility

can withstand. Also, both a stress and a strain analysis can help emergency- related managers design their strategies. From a stress analysis, managers can know how many capacities they have to add to strain capacities, so a power facility can get out of the plastic zone.

Strain analysis also provides insight into the possibility that an applied stress level can exceed strain capacities. As discussed in Section 3.4.2., stress analysis cannot reflect all the information at every small point of time due to the relatively big size of the unit time. In other words, even though the stress and strain analysis of the power facility show the applied stress below the strain capacities of the power facility, there may be a small point of time, e.g., an hour, when the demand on electricity exceeds the strain capacity of the power facility. Thus, based on both analyses and this uncertainty with the measurement, emergency managers need to select the most appropriate strategies.

3.6   Need for an Infrastructure Stress Assessment Using a System-of-Systems Perspective

As discussed in the two case studies, the capabilities of post-disaster infrastructure depend on the capacities of the infrastructure units and the demands placed on them. However, due to the nature of the interdependencies of infrastructure, the measurement of stress and strain requires full consideration of different types of relevant infrastructure. Figure 3-26 shows the different layers involved in the provision of medical service and electricity, respectively. For Puli Christian Hospital (PCH), the applied stress could vary, depending on the available number of patients being transferred to other neighboring hospitals. Moreover, provision of service for each unit, e.g., electricity, water, and medical staff, depended on the capacity of its system.

In the instance of electricity, the supply of electricity to the hospital depends on the capacities of three regional power facilities, i.e., the North, the Center and the South in Taiwan. Also, in the case of power facility for Northern Taiwan, the demand on the regional facility in the North could vary, depending on how much electricity was available from other areas, each of which handled its own regional demand. Moreover, within its infrastructure units, there was a subsystem associated with supplying the service for the

upper system. For example, the transmission unit is required to transmit electricity from substations to users. This transmission service depends on how many transmission towers can function well.
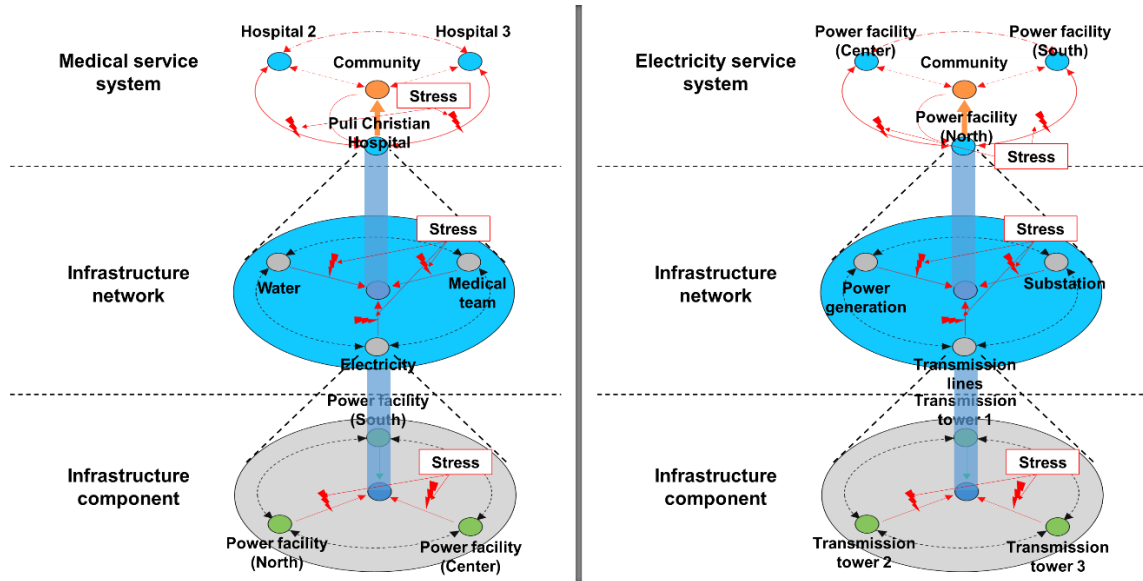
Figure 3-26 The Infrastructure System-of-Systems for the 1999 Chi-Chi Earthquake

Analyzing the stress and strain of a post-disaster infrastructure is demanding work in and of itself. Yet, if a complex system consists of multiple systems, each of which is operationally and managerially independent, then a system-of-systems approach will be effective (DeLaurentis 2005). Because of the interdependent nature of the operational and managerial post-disaster infrastructure, applying a system-of-systems approach can be the candidate approach to addressing this issue positively.

3.7 Conclusion

This chapter developed a novel principle for understanding the stress imposed on a post-disaster infrastructure. Based on a literature review of infrastructure under high stress and the existing approach to stress in various areas of study, the mechanism for recognizing and dealing with the stress-related issues of infrastructure service was developed.

Based on the mechanism and the stress-strain principle found in the mechanics of material, a new stress-strain principle for post-disaster infrastructure was proposed. The stress and strain analyses developed here are expected to offer relevant emergency-related managers further understanding of the nature of the stress and strain in post-disaster infrastructure, and benefits in terms of developing mitigation and preparation strategies for future disasters. Through a stress and strain analyses, they will get insight into how much stress specific infrastructure facilities can handle with respect to their available strain capacities. From the perspective of developing new strategies, stress analysis helps managers know when an infrastructure facility is likely to enter the plastic region and then which infrastructure units in that system will cause it to enter that region. Moreover, by looking at the strain on the system, emergency managers can better perceive how much additional stress they can withstand, which will help them determine how to make mitigation strategies for securing the operation of the infrastructure facility in the elastic region.

In two case studies of infrastructure facilities involved in the 1999 Chi-Chi earthquake, the operations of the Puli Christian Hospital and the power facility in Northern Taiwan were reinvestigated in terms of their stress and strain. Due to restricted available data, a quantitative analysis was not available, but data did show how each stress and strain might be applied to a post-disaster infrastructure and how the developed analysis can help emergency managers to prepare for the proper functioning of infrastructure by answering three questions in each case. Since infrastructures are comprised of multiple systems, each of which are managerially and operationally independent, there was a difficulty in analyzing their stress and strain. As a solution, the need for a system-of-systems approach was discussed, and that discussion will guide the following research.

CHAPTER 4. STRESS AND STRAIN ASSESSMENT TOOL (SSAT) FOR A POST-DISASTER INFRASTRUCTURE FACILITY

4.1   Introduction

If the relevant managers understand the probable, even likely, stress that will be placed on infrastructure ahead of time and learn how to relieve that stress, this will reap major benefits in helping the infrastructure to be well-prepared against conditions causing excessive stresses, i.e., disasters. As discussed in the previous chapter, a careful analysis of both stress and strain on a post-disaster infrastructure is indispensable for accomplishing this goal. However, because of the interdependent nature of post-disaster infrastructure, the capture of stress and strain for them is a challenge from a conventional system engineering perspective, which can require a comprehensive analysis to integrate complex systems (Keating et al. 2008).

Based on the developed stress and strain principles for a post-disaster infrastructure, this chapter proposes a comprehensive framework for evaluating the stress and strain of a post-disaster infrastructure. In order to address the issues related to complicated infrastructure systems, it applies the system-of-systems approach for understanding the behaviors and features of a system, which further facilitates modeling these otherwise complicated systems. Further, a discrete event simulation was employed in order to design the operations of infrastructure facilities actually capable of reflecting and addressing dynamic disaster conditions. As a result, the stress and strain assessment tool (SSAT) for a post-disaster facility was developed. The SSAT enables emergency managers to know the probable stress on their systems and then guide them to design appropriate strategies for managing that stress in advance of any disasters.

To validate the applicability of the developed SSAT, the tool was applied to a health care facility under simulated earthquake conditions for a case study. In this case study, the dynamic stress and its corresponding strain on the health care facility were evaluated at

each unit time after the earthquake, a process that is important when making stress-relief strategies during a disaster.

4.2   Literature Review

Based on the stress-strain principle for a post-disaster infrastructure that was developed in the preceding chapter, this study sought to develop a stress assessment tool for a post-disaster infrastructure. In any post-disaster situation, the performance of a specific post-disaster infrastructure is influenced by the functionality of its supporting infrastructure in a post-disaster situation. Since the functionality of supporting infrastructure is likely to vary as the damaged infrastructure is recovered, the strain capacities and corresponding limit stress of the dependent facility will be changed. In this context, the understanding of the recovery process of post-disaster infrastructure is important. In this chapter, the literature review was on the dynamic condition of post-disaster infrastructure. Furthermore, for the purpose of validating and calibrating the developed SSAT, the tool was applied to a post-earthquake health care facility. As such, the function of a medical facility is reviewed in terms of its role in a post-disaster situation.

4.2.1   The Dynamic Functionality Curve of a Post-Disaster Infrastructure

In a post-disaster situation, interruptions in essential infrastructure facilities are predominant, and those issues in turn disrupt the mundane typical activities of communities to produce social and economic losses (Deshmukh et al. 2011). For communities to be resilient, they need to withstand the effects of disasters without significant degradation in their mundane life (FEMA 2003). Therefore, how fast a supporting infrastructure can be restored, i.e., the rapidity, and how effectively the community can withstand the loss of the function without undue suffering, i.e., its innate robustness, are important areas to review (Chang and Shinozuka 2004). However, estimating the recovery process of post-disaster infrastructure remains difficult and complicated since it can be affected by time dimensions, spatial dimensions, and the different recovery efforts being made by various stakeholders (Cimellaro et al. 2009). Since a comprehensive understanding of the recovery process

requires capturing multi-dimensional levels of information, estimating the actual recovery process of any post-disaster infrastructure remains a difficult challenge.

Considering the system and society preparedness, Cimellaro et al. (2009) simplified and categorized these complex recovery functions into three types, namely, linear, exponential, and trigonometric (Cimellaro et al. 2009). According to Cimellaro et al. (2009), in the case where no information about the preparation and availability of recovery resources is available, the linear recovery function ((a), Figure 4-1) can be used to estimate the recovery process. The trigonometric recovery ((b), Figure 4-1) can be utilized when system recovery is dominated by limited organizational and recovery resources. The exponential recovery function well describes the recovery process of a system where its response to disasters is driven by a sufficient amount of recovery resources; however, the rapidity of that recovery then gradually decreases as it approaches completion ((c), Figure 4-1).
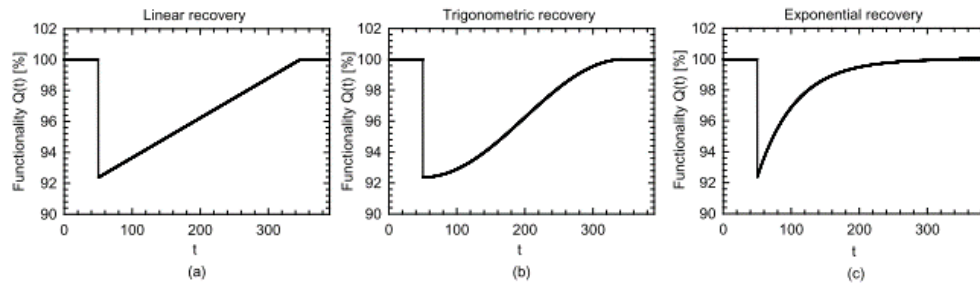
Figure 4-1 Functionality Curves (a) Average Prepared Community, (b) not well Prepared Community, (c) well Prepared Community (Cimellaro et al. 2009)

- Damage and the restoration period

In addition to the types of recovery processes, the degree of initial impact from a disaster and the length of subsequent disruption are important to determine the recovery processes for post-disaster infrastructures (Nojima and Kato 2013). In terms of the capabilities of the recovery, the resilience stands for both the robustness and the rapidity of a resilient system's properties. Figure 4.2 illustrates this robustness and rapidity in terms of the change occurring in system performance over time, i.e., system recovery after a disaster (Chang and Shinozuka 2004). In this figure, the initial degradation in the functionality of the system (r_0) is associated with its resilience property or "robustness." If the system

responds to the disaster without substantial impact on its functions, i.e., having the minor value of r_0, then the system is regarded as having good robustness. Also, depending on the time required for the system to recover to its pre-disaster performance level, i.e., the value of T_0 in Figure 4-2, rapidity performance is determined, and given less the value of T_0 for the system, then the higher will be the rapidity performance of the system.
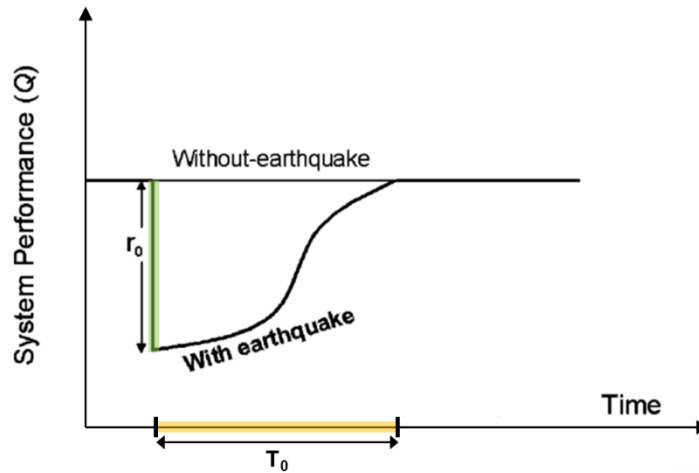
Figure 4-2 Resilience Measurement Framework (Chang and Shinozuka 2004)

Considering the nature of disasters where demands overwhelm the coping capacities of a system (Shaw et al. 2007), essential infrastructure facilities in a post-disaster situation are likely to suffer from a shortage of their recovery resources. Therefore, as addressed by Kato and Nojima (2013) who measured a residual capacity of a lifeline infrastructure post-earthquake, a post-disaster infrastructure is likely to recover by following the trigonometric functions.

4.2.2 Health Care Facility System

- Medical and Health Operations Area of Function

In disaster conditions, health facilities are expected to remain sustained and perform emergency- related functions while coordinating with other emergency responses, such as law enforcement, evacuation, and others. Barbera and Macintyre (2002) proposed a requirement- based operation model – the Medical and Health Incident Management

(MaHIM) – which specifies that both internal and external functional components are essential when responding to a mass casualty event. As a planning tool, MaHIM describes the other emergency functions needed to process medical service and guidelines for how to coordinate with them with a common goal of minimizing adverse health impacts (e.g., deaths, injuries, etc.) on communities. In this regard, there are 7 medical and health operation-related functions and sub-functions: Medical and Health Operations Staging; Incident Epidemiological Profiling Function; Pre-Hospital Care; Medical Care; Mental Health' Hazard/Threat Disease Containment; and Mass Fatality care (Figure 4-3) (Barbera and Macintyre 2002).
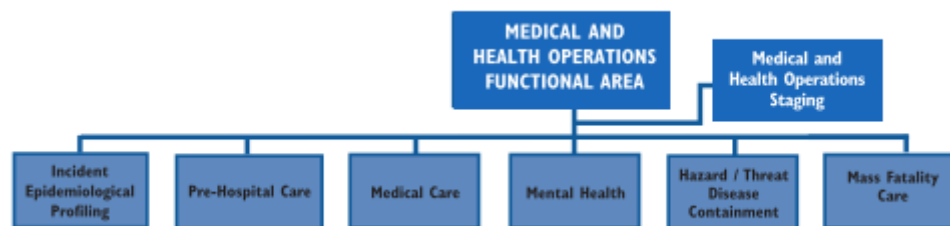
Figure 4-3 Functional Areas of Medical and Health Operations (Barbera and Macintyre 2002)

This functional category encompasses the initial stage of medical functions, such as the organization of arriving operational medical resources and tracking incidents, for the provision of relevant medical cares. Arboleda (2006) further emphasizes three primary functional areas in which major interactions between the external and internal capabilities of operating medical systems during catastrophic events occur: Pre-hospital care, medical care, and general emergency response;

- **Pre-hospital Care:** Pre-hospital care is medical treatment conducted in pre-hospital settings. This care includes first responder contact with patients through their arrival at the hospital. During this stage, EMS and operational medicine assets, such as Special Weapons And Tactics (SWAT), etc., are involved in the pursuit of i) extracting patients from the hazardous environment; ii) doing triage; iii)

transporting and distributing patients to relevant medical facilities; and iv) providing initial treatment to stabilize their health conditions.

- **Medical Care:** Medical care encompasses all medical interventions are conducted by facilities or organizations to meet their patients' medical demands. Medical care functions includes i) the assessment and provision of medical treatment for the injured; ii) the provision of continued medical care services after acute care; iii) observation and diagnosis of patients' medical conditions after giving therapy; and iv) transfer of patients, if they will benefit from that movement. In particular, facility- based medical treatments are divided into two types: Out-of-hospital care and emergency and hospitalized care. In the case of the latter care, a health care facility is required to have sufficient capacities for coping with demand surge during mass casualty events.

- **General Emergency Response:** In emergency situations, various emergency functions exist, which do not directly affect medical care, but do support the delivery of medical services. Generally, medical authority does not directly include the management of these functions; however, the direct involvement of some non-medical functions is required in order to perform medical functions in an efficient manner. These can include fire suppression, scene security, traffic control, law enforcement, mass evacuation, etc.

In the medical operation function, various external functions are involved in performing the corresponding function (Arboleda et al. 2007; Barbera and Macintyre 2002). For example, in pre-hospital care, the coordination of EMS and other civic emergency agents is essential when searching for and rescuing patients at the scene of accidents or a disaster. Also, in order to move patients to relevant health facilities, the road network connecting to those facilities should be secure. In the function of medical care, the sharing of information about patients' medical conditions with first responders is important so as to provide timely and much-needed treatments. Any insufficient supply of utility services, i.e., water and electricity, restricts the operation of medical machines and thus impairs the hospital's medical performance. In any general emergency response, multiple non-medical emergency functions are required to be able to facilitate the medical and health activities.

Arboleda (2006) summarizes the interaction between internal and external capabilities of these medical responses in Table 4-1 below.

Table 4-1 Major Functions for Medical Response (Arboleda 2006)

Function	Internal Capacities	External Systems	Type of Flow	Participants
Pre-Hospital Care	- Emergency Rooms (ER)	- Transportation - Communication - Information Systems	- Patients - Data	- Emergency Medical Services (EMS) - Fire Department - Law Enforcement - Rescue Teams
Medical Care	- ER - Intensive Care Units (ICU) - Operating room (OR) - Wards	- Energy - Water - Gas - Communication - Information system - Transportation	- Patients - Data - Commodities - Medical Supplies	- Medical Staff - Security - EMS - Non-government Organizations (NGOs)
General Emergency Response	- ER - ICU	- Transportation - Health care Networks	- Patients - Data	- Fire Department - Rescue Teams - Law Enforcement - Civic Agencies - EMS

- Emergency Department

In the context of a disaster that is producing a large number of victims who need medical treatments, the effective operation of medical facilities becomes critical for both mitigation and recovery of the affected communities (Paul et al. 2007). As such, during emergency situations, such as disasters, medical facilities take measures to accommodate as many medical demands as they can in the most effective way, for example, rearrangement of the admission process (Xiao et al. 2009), cancellation of elective surgeries and admissions to vacate occupied resources (Verni 2012), increases in medical staff (Arboleda 2006; Tennessee DOH 2007). However, because of both sudden and substantial increases in medical demands and the potential compromised capabilities of hospitals to deliver medical services, medical hospitals are likely to experience excessive stress (Stallings 1970).

In particular, emergency departments have been criticized for their limited resources amid a growing demand (Xiao et al. 2009). According to the recent report on the surge capacities of emergency rooms of hospitals located in New Jersey, most emergency departments would not meet the required medical demands if a disaster happened (DeLia 2005). Usually, after natural disasters, visits to the emergency department of a hospital rise by three to five times the number of patient visits during a pre-disaster condition (Cimellaro et al. 2010). Since other follow-up internal service functions (i.e., ICU, OR, and wards) are interlinked with the emergency room, inefficient disposition of patients from ER often will produce a bottleneck for those admitted patients requiring further treatment (Asplin et al. 2003).

- Emergency Room Operation

To address the issues of overcrowded emergency rooms, Asplin et al. (2003) developed a conceptual model to help understand the mechanisms that cause overcrowding in emergency rooms (See Figure 4-4). This conceptual model has three interdependent components, i.e., input, throughput and output. The input indicates any conditions that may cause an increase in demand. Once patients enter an emergency room for any reason, including emergency care, unscheduled urgent care, and safety net care, they move through the care process, namely, triage and room placement, diagnostic evaluation and treatment, and follow-up care following treatment in the emergency room. Any lack of available internal hospital resources – such as staffed inpatient beds – causes these inpatients to remain in emergency rooms and prevents new patients' arriving at the same emergency rooms from receiving medical treatment. Throughput represents the stay of patients in emergency rooms. Output indicates the results from the disposition of patients from emergency rooms. It is worth noting that inpatients who are already treated in emergency rooms will affect the emergency room operation, depending on the availability of inpatient care in that hospital.
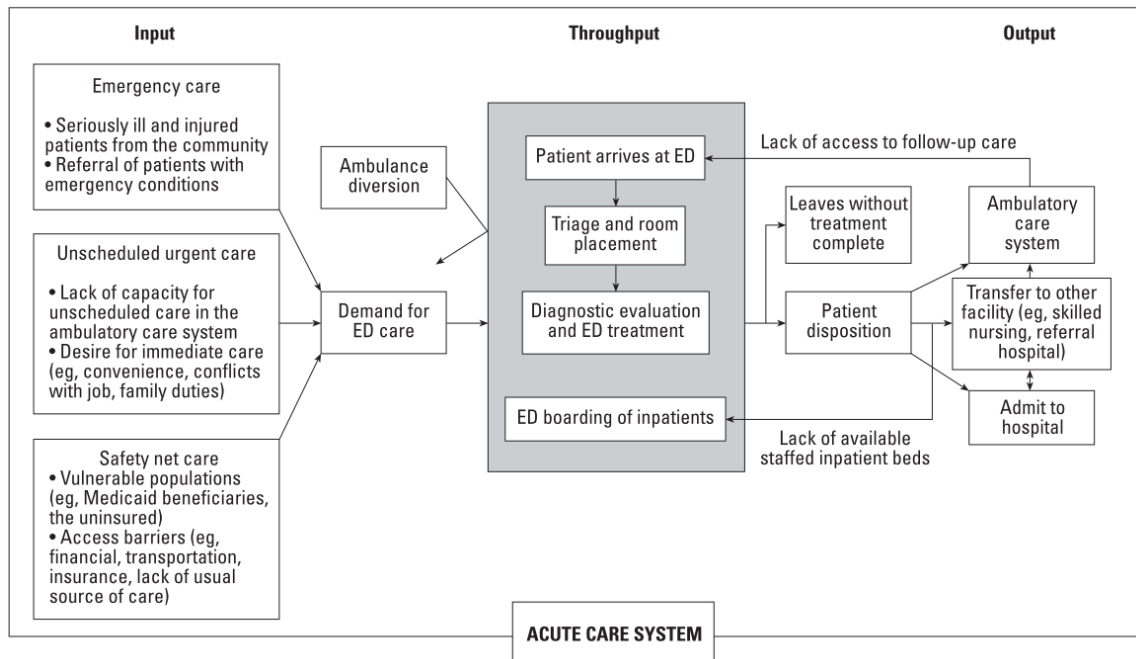
Figure 4-4 Input-Throughput-Output Conceptual Model for ED Crowding (Asplin et al. 2003)

Yi (2005) developed a simulation model to understand the utilization of hospital resources over time during the Northridge earthquake situation. Depending on their injury type and consequent medical needs, patients who arrive at emergency departments are either discharged or admitted to a hospital for further treatment in other internal service areas of that hospital, such as the operation room, intensive care unit, laboratory, or wards.

Xiao et al. (2009) designed the operation of the emergency department for a disaster situation (See Figure 4-5). Once patients reach the emergency rooms (ER) either by ambulance or by themselves, they go through registration at reception and wait in the waiting room for triage. After triage, the patients are classified according to a five-level classification system ESI (Emergency Severity Index) with level one indicating the most severe condition and level five indicating minor health problems. After ER nurse assessment and treatment by ER technicians in ACU (Alternate Care Unit), these patients are either discharged or routed to relevant ER care units (i.e., an Intermediate Care Unit or a Critical Care Unit) depending on their ESI level.

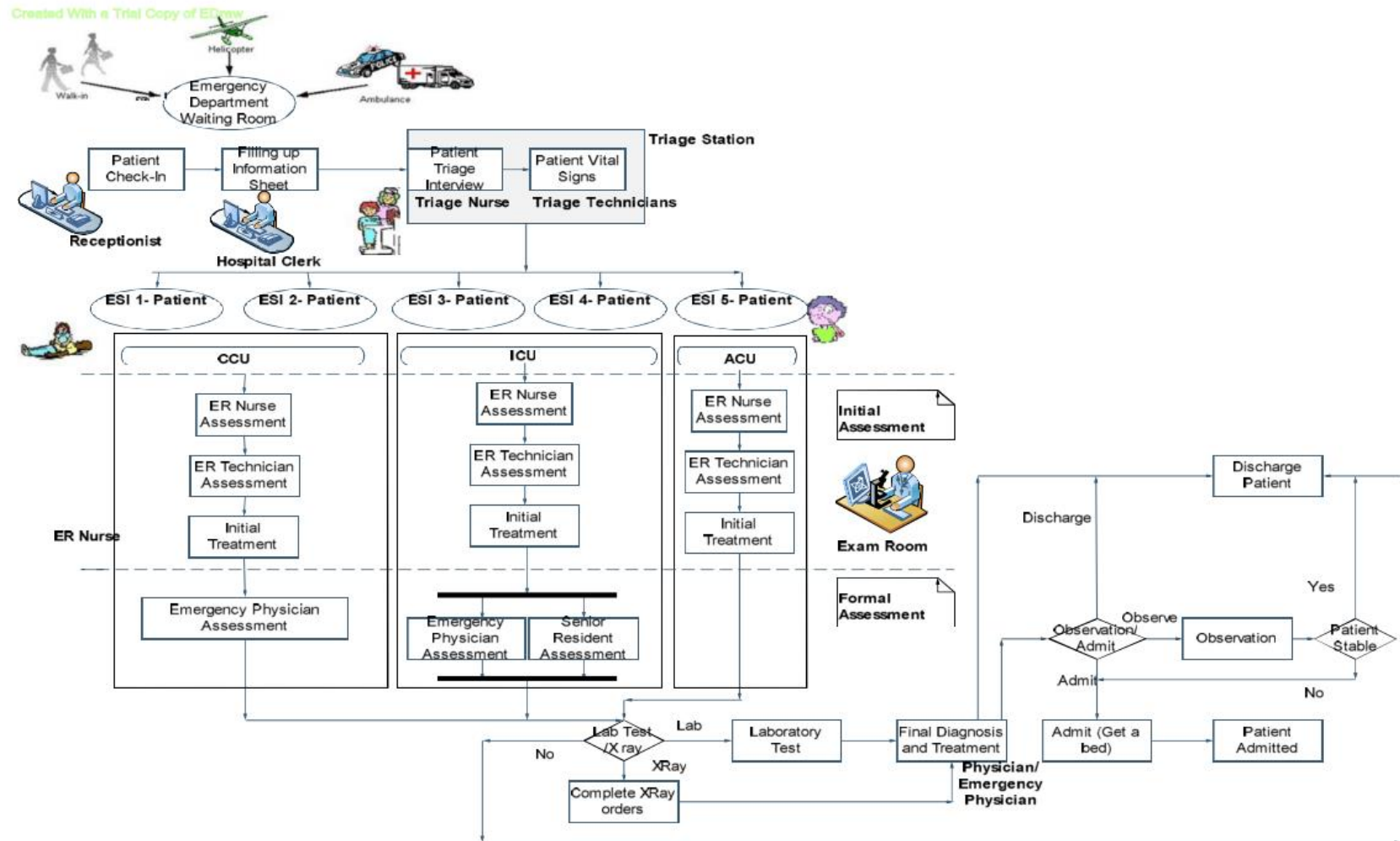Figure 4-5 Flow Chart for an Emergency Department (Xiao et al. 2009)

4.2.3   Summary

In disaster situations, depending on the functionality of its supporting infrastructure, the strain capacities of the infrastructure facility will vary during the recovery phases. Because of its difficulty in calculating precise functionality of infrastructure, the simplified functionality curve, i.e., trigonometric recovery process, will be taken into account for developing SSAT. Moreover, the function of a health care facility in a post-disaster situation is reviewed. It is turned out that the operational capabilities of the emergency departments play an important role in treating patients after a disaster. Therefore, the operation process in the emergency department is reviewed and understood.

4.3   The Stress Assessment Framework for a Post-Disaster Infrastructure Facility

To properly understand the stress on a post-disaster infrastructure and its impact on the services being offered to affected communities requires a novel approach to analyzing disaster impacts of both supply (e.g., infrastructure facilities) and demand (e.g., communities). Applying this purpose, the stress-strain principle for a post-disaster infrastructure was developed in Chapter 3. It is capable of measuring the effects of degradation in essential services for communities that result from changes in both the demands on and the capacities of community infrastructure. However, the developed principle itself does not have the capability of implementing a stress and strain analysis because of the dynamic features of disasters, e.g., the restored capacities of infrastructures, the varying demands of communities over time, and the interdependencies of the affected infrastructures. To address this issue, a stress and strain assessment tool (SSAT) for a post-disaster infrastructure was developed in this chapter.

In order to evaluate the stress and strain of a post-disaster infrastructure, this tool has the following requirements.

- Identify and understand the interdependencies with other supporting infrastructure and the interactions with users (Req. i);
- Define the scope of stress and strain assessment for the interdependent infrastructures (Req. ii);

- Reflect the disaster impacts on the operation of the infrastructures in terms of serviceability for communities and industries (Req. iii);

- Record the stress and strain of a post-disaster infrastructure for every unit of time during the simulation (Req. iv);

- Assist in making strategies to relieve stress based on the outputs of the stress and strain analysis (Req. v).

The framework for this stress and strain analysis for a post-disaster infrastructure consists of 7 steps as shown in Figure 4-6. In order to facilitate better understanding of the framework, the Taiwan Power Company (Taipower) in Taiwan is used as a hypothetical example for each step.
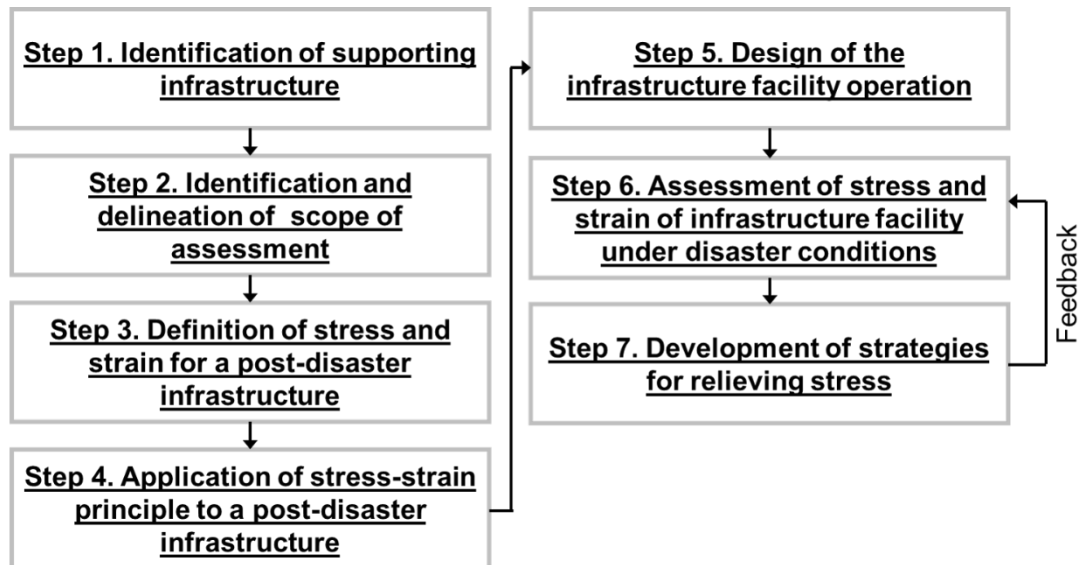
Figure 4-6 Framework of the Stress and Strain Assessment Tool for a Post-Disaster Infrastructure

Step 1. Identification of supporting infrastructure (Req. i)

Once an essential facility is selected for an analysis of stress and strain in a post-disaster situation, the relevant data, i.e., technical, social, and economic, are needed to identify its supporting infrastructure and its functions for communities and industries. Using that technical data, the interdependencies among the infrastructures are identified, and using the social and economic data, the demand the facility needs to satisfy is determined for

supporting both economic and social activities of communities (Req. i). In the instance of a hypothetical power facility, the technical data provides information on the network of components, e.g., substations, transmission towers, power stations, etc., interactions with other power facilities and users, and social and economic data determines how many users the facilities are in charge of providing electricity.

Figure 4-7 Identification of its Functions and Supporting Infrastructure

Step 2. Identification and delineation of scope of the assessment (Req. ii)

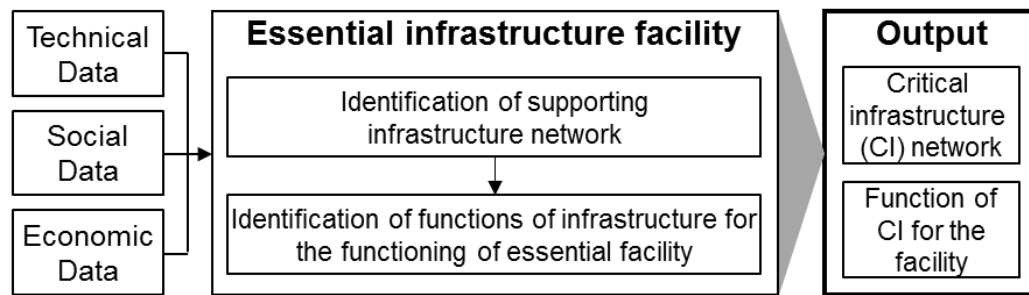As discussed in Chapter 3, operation of a post-disaster infrastructure is associated with addressing a system-of-systems (SoS) problems. Because of the interaction between the elements of a complex infrastructure system, the stress and strain on a single post-disaster infrastructure facility can vary depending on the impact of the disaster on other relevant infrastructures. The SoS lexicon has two major structures: categories of systems and levels of organizations, each of which will help understand the interaction within and across all systems and levels (DeLaurentis 2005). According to DeLaurentis and Callaway (2004), the lexicon and taxonomy of a SoS help define the breadth of the problem and then effectively guides modeling and simulation. Table 4-2 describes the proposed lexicon for a stress-strain analysis of a post-disaster infrastructure system. By using this lexicon, the stress and strain analysis of a post-disaster infrastructure can be designed focusing on the most appropriate layers and considering the interactions within and between them. For instance, in the stress-strain analysis of a post-disaster power facility, the SoS is formed by entities associated with generating and supplying electricity with the goal of the reliable provision of electricity. On the other hand, the need to supply electricity in response to demands can direct the entities in performing their tasks while social and economic

constraints can sometimes hamper powered electricity from improving the reliability of the system.

In terms of levels, α level indicates the individual components that are individual substations, transmission lanes, and power stations for the power facility. In the β level, there is an aggregate of individual components to support the functioning of the facility, e.g., substation units for transforming electric voltage before supplying it to communities. The γ level is a single infrastructure facility, i.e., a power facility in this example, supported by the infrastructure unit in level β. Level δ describes the interaction within the network of infrastructure facilities, i.e., interaction with other regional power facilities, while the ε level represents the meta level of the network, i.e., operations of national power facility system. Depending on the scope of the analysis, the most appropriate level and category can be selected (Req. ii) (Naderpajouh and Hastak 2014).

In this hypothetical power facility example, the stress and strain analysis is performed by focusing on the interaction of the infrastructure units (i.e., power station unit and power distribution unit) and service performance (the highlighted row in Table 4-2).

Table 4-2 System-of-Systems (SoS) Lexicon of a Stress-Strain Analysis on a Post-Disaster Infrastructure (e.g., a Power Facility)

Category	Description
Resource	Entities that facilitate the provision of essential services (e.g., entities supporting the generation and supply of electricity)
Economics	Promotion of reliable and stable service (e.g., Goal being stable and reliable supply of electricity)
Operations	Provision of essential services (e.g., supply of electricity)
Policy	Social and economic constraints (e.g., budget efficiency to improve the reliability of the power systems)
Levels	**Description**
α	Individual components (e.g., substation, transmission lanes, power stations)
β	Infrastructure unit (e.g., substation unit, transmission unit, power station unit)
γ	Infrastructure facility (e.g., the power facility)
δ	Network of infrastructure facilities (e.g., network of all the power facilities
ε	Meta_network (e.g., City/state power facility system)

Step 3. Definition of stress and strain for a post-disaster infrastructure

The next step in the framework is to apply the stress and strain principle to the post-disaster infrastructure facility (Figure 4-8). According to the stress and strain principle, the stress and strain are configured to reflect the facility's specific circumstances, i.e., its supporting infrastructure units and its system goal, etc. In order to formulate the stress and strain of this facility, it is necessary to determine the system goal or the system criteria. For instance, in the hypothetical case of a power facility, the system goal is assumed to provide electricity service for all the users even at the lower performance level (i.e., load shedding). Under this goal, the infrastructure units, i.e., the power station unit and the distribution unit (e.g., substation, transmission tower, etc.), have different performance expectations depending on their functions. The expected performance and demands on these units will determine the stress imposed on them, thus increasing the strain. Table 4-3 shows the different types of stress for infrastructure units (resources) and their corresponding strain responses.

Table 4-3 Stress and Strain of a Power Facility

| Resources of a power facility	Stress	Strain
Power station	- Required amount of generated electricity to cover all demands	- Rate at which available resources for power generation are being used
Power distribution	- Required ratio of users who receive electricity to total users	- Rate at which available resources for distributing the required amount of electricity are being used
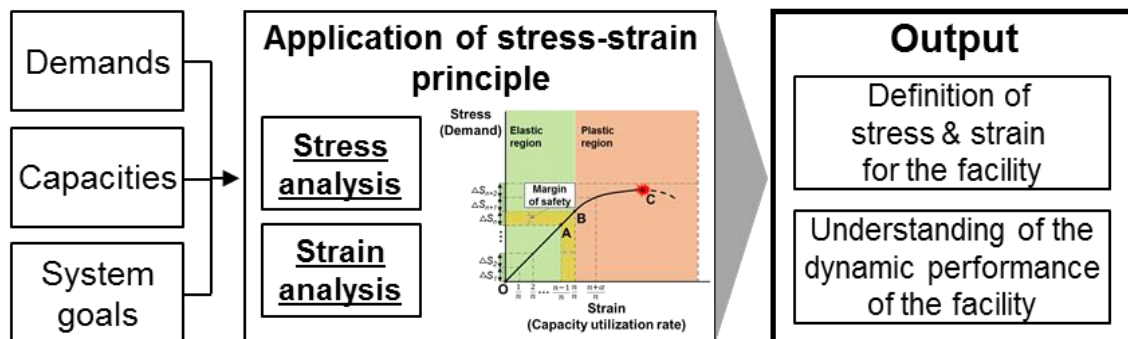
Figure 4-8 Application of the Stress-Strain Principle on a Post-Disaster Infrastructure

Step 4. Application of Stress-Strain Principle to a Post-Disaster Infrastructure

In this step, based on the definition of both stress and strain, the allowable stress and limit stress levels are measured (Figure 4-9). To understand the behaviors of infrastructure facilities in response to growing stress, the measurements of allowable stress and limit stress are important.
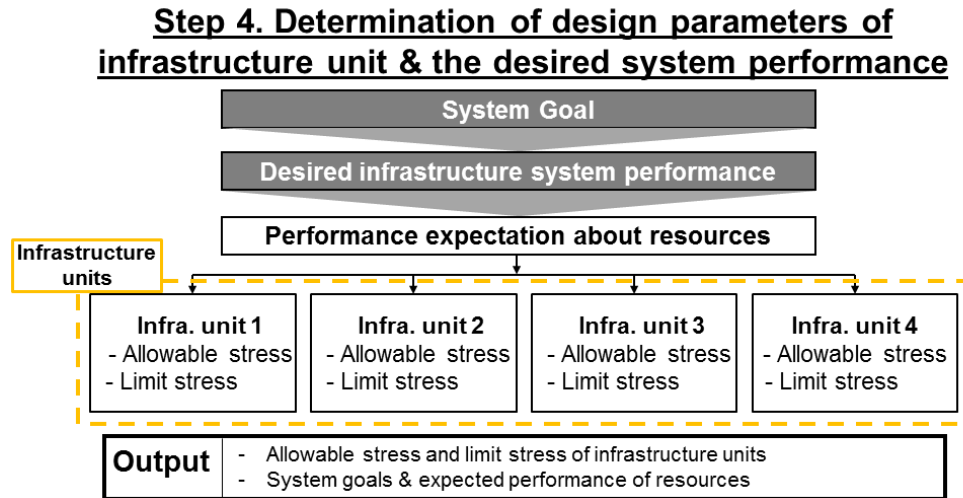
Figure 4-9 Determination of Design Parameters for Infrastructure Units and System Goals

As illustrated in Figure 4-9, the determination of a system goal is important since it serves as the metric for determining a desired system performance level and thereby varying both the limit and the allowable stress of the facility and its supporting infrastructure units. For instance, in a pre-disaster situation, this hypothetical power facility is able to produce and supply electricity to all users by assuming that total capacity of power facility is 22,000 MW/day and daily peak demand: 19,547 MW/day. However, in a post-disaster situation, all the infrastructure units associated with the production and distribution of electricity, e.g., the power station unit and the distribution unit, are likely to be compromised, thus reducing the coping capacity of this power facility (Schiff and Tang 2000) (i.e., assuming here that the total capacity of the power facility at 22,000 MW/day is reduced to a capacity of 5,276 MW/day due to the disaster impact). With this reduced strain capacity and the same performance level as the pre-disaster situation, i.e., at 24-hour availability to users,

the peak demand (19,547 MW/day) exceeds the coping capacity (5,276 MW/day). That is, in order to accommodate all the demands, the power station unit needs to exert all its capacity (i.e., strain stretch out to one), while the limit stress of the power facility is still 26.99% (i.e., serviceability = met demand/ total demand, 5,276 MW/19,547 MW=0.2699), which falls short of the demand. If the power facility lowers the performance level by putting restrictions on the use of electricity for users, i.e., load shedding[3], then the strain capacity of the power facility will increase to 31.6%. This increase will reduce the required demand for the infrastructure units in an effort to meet the system goal. Specifically, a power station unit is required to produce at least 19,547 MW/day to offer 24-hour availability of electricity to its users in a pre-disaster situation, but after load shedding, the required demand goes down to 16,696 MW/day. In other words, the strain capacity of the power station increases because of lower amount of required electricity to accommodate all the users.

In this context, the allowable and limit stress for the hypothetical post-disaster power facility with no compromised capacities can be calculated as an example as shown in Table 4-4. It is worth noting as well that the time unit is set to a single day. Allowable stress is assumed to be the same as the daily peak demand with the standard performance level while limit stress is equivalent to the maximum capacities for power electricity.

Table 4-4 Allowable Stress and Limit Stress for a Hypothetical Power Facility

Design parameters	Standard performance level (i.e., 100% serviceability with 24-hour availability)
Allowable stress	19,457MW/day
Limit stress	22,000MW/day

Step 5. Design of the infrastructure facility operation (Req. iii)

In this step, the operation of a post-disaster infrastructure facility is designed using a simulation technique. Considering the appropriate abstraction level[4] where the real world

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[3] Load shedding is assumed to be designed so that residential customers are divided into two groups, each of which experiences 7-hour power outage on alternate days (Schiff and Tang 2000).

[4] Abstraction level is associated with selecting the scope of the problems addressed in Step 2.

is mapped to the simulation, the simulation approach can be selected. This model describes the functioning of an infrastructure facility (e.g., power facility) and reflects its interdependencies with its supporting external systems (e.g., power generation, substation, transmission lines) for its service provision to the community. It is also important to design a model that reflects disaster conditions, i.e., increasing demands on an infrastructure facility and impairing its coping capacities (Req. iii). The main purpose of this step is to measure the stress and strain of the infrastructure units and thus of the full infrastructure facility at each unit time based on a simulated post-disaster environment. Figure 4-10 illustrates the overall process for simulating the operation of an infrastructure facility under disaster conditions and showing the impact on its system performance.
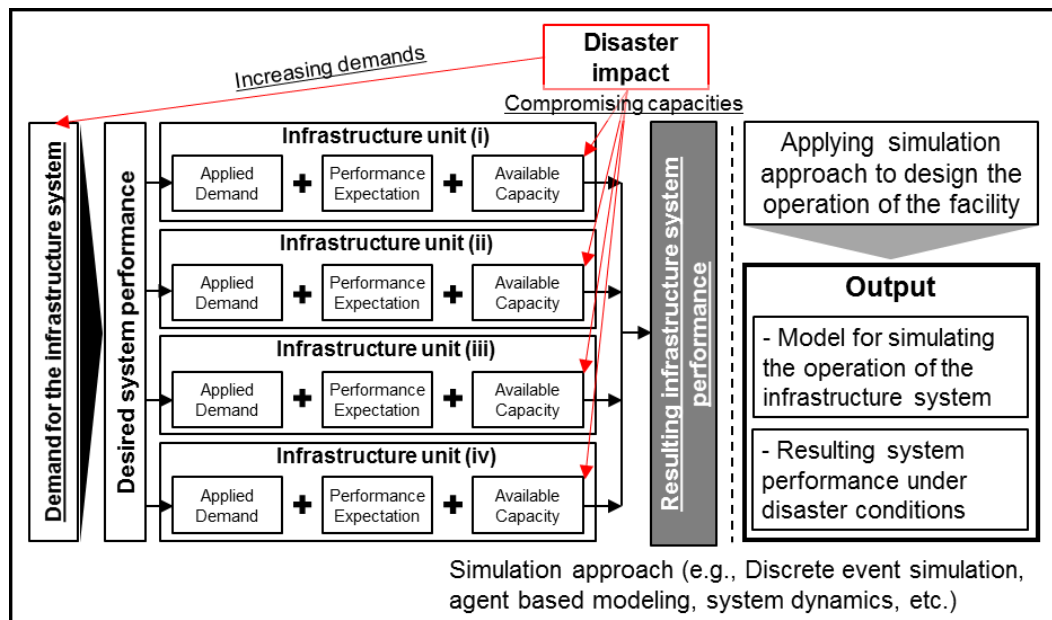
Figure 4-10 Design of Operations for a Post-Disaster Infrastructure Facility

For the hypothetical power facility, Figure 4-11 shows how its operation is designed to consider disaster impacts. In providing electricity to the community, the role of a power station is to generate an adequate amount of electricity to meet the community's demand and the power facility's service-related policy, i.e., its system goal. The role of power distribution unit is to supply the electricity generated by the power station to communities without any significant loss. In a post-disaster situation, the supporting infrastructure units,

i.e., the power station unit and the power distribution unit, are damaged by the disaster, which then affects the strain capacities of both units while the community's demands and the facility's policy may remain the same. As a result, the power facility is likely to experience a high stress above its limit stress during the recovery time following the disaster. This effect in turn affects the power facility's policy, i.e., initiating load shedding in order to gain more strain capacity to satisfy the additional demand. Infrastructure units, i.e., power stations and power distribution units, and the power facility will need to be able to measure stress and strain for each unit of time.
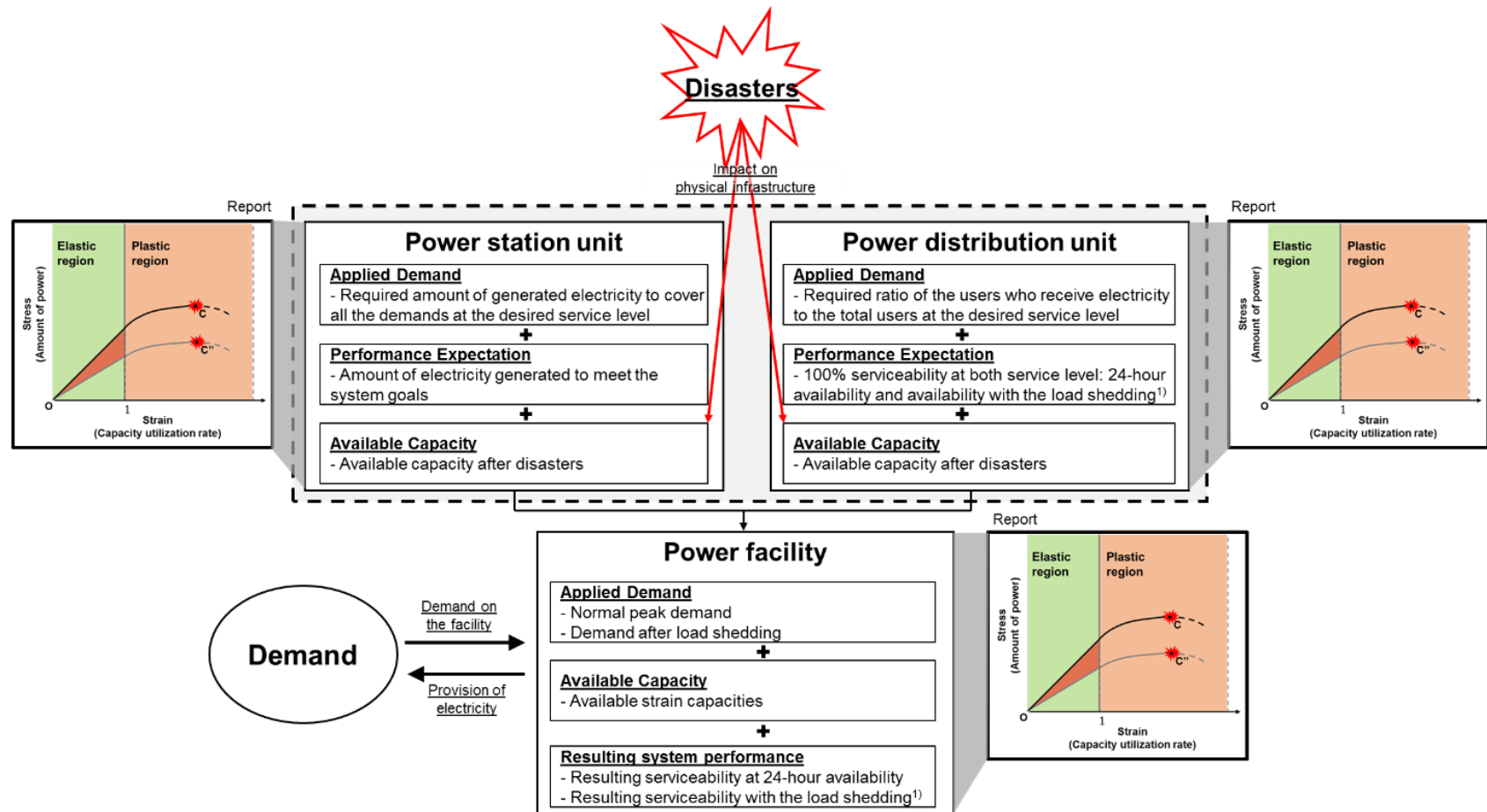
Figure 4-11 Operation of a Hypothetical Power Facility during Disaster Conditions

Step 6. Assessment of stress and strain of infrastructure facility during disaster conditions (Req. iv)

In this step, the stress and strain of the infrastructure units and the facility as measured for each time unit are discussed (Req. iv). Depending on the applied stress and available strain capacity, the infrastructure facility and the units are placed under three zones, an elastic zone, a less desirable zone, and a plastic zone. The elastic zone represents normal operations in which stress is either below or equal to the allowable stress. The less desirable zone indicates either operational conditions in which the stress is between its allowable stress and the limit stress or operational conditions in which the infrastructure facility has to lower its performance level to accommodate applied stress. From the perspective of the service reliability, this operational condition is not desirable since infrastructure engineers leave any additional capacities above the allowable stress with the standard performance level for the margin of safety. The plastic zone indicates the almost functional failure or unsustainable condition in which to operate where the capacities are much overwhelmed by demands. A post-disaster infrastructure facility shows the different behaviors, as the stress steadily increases. In the elastic region, an infrastructure facility can provide the required service for communities while holding on to additional capacities as a margin of safety. However, as stress increases, an infrastructure facility will enter the less desirable zone. In this zone, the infrastructure facility manages to withstand the applied stress still with acceptable service. With the further increase in stress, the infrastructure will endeavor to keep the stress within the available strain capacity by lowering its performance level to its communities.

In the elastic region, the strain does not exceed the certain value above which there is still a margin of safety. In contrast, the strain can be stretched out to 1.0 both in the less desirable zone and in the plastic region. It is worth noting as well that if the performance level is changed, then the strain capacity is proportionatly changed.

In the hypothetical power facility, the stress and strain assessment follow as shown below. The stress and strain assessment are conducted assuming that the serviceability of the distribution unit and the power station unit are assumed to vary and follow the curves shown in Figure 4-12.
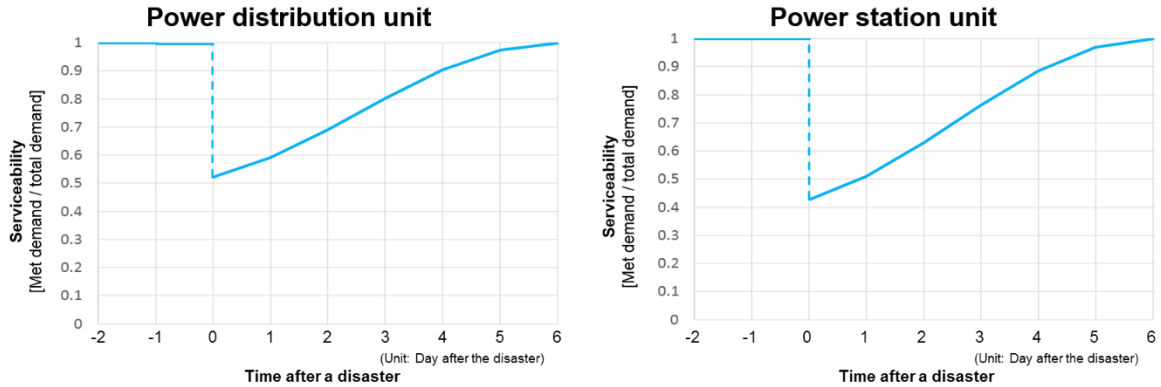
Figure 4-12 Functionality Curves for the Hypothetical Power Facility

As a result of the simulation, the stress and strain analysis for the power station unit is configured as shown in Figure 4-13. As documented for the last two days before a disaster, the power station can generate the required amount of electricity by keeping its margin of safety, i.e., in the elastic zone. In this zone, the strain remains 0.8885, thereby leaving 0.1115 as the margin of safety. However, after the disaster, the capacity of the power station unit is compromised, and both its limit stress and allowable are reduced. Since the applied stress remains the same while its capacity substantially drops, the power facility initiates load shedding[5] in order to gain more strain capacity. After this load shedding (i.e., lower performance level), the amount of electricity it is required to generate in response to the demand decreases, which then increases the limit stress of the power facility and its infrastructure unit, i.e., its power station unit.

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[5] Load shedding was implemented, and residential customers are divided into two groups, each of which experiences a 7-hour power outage on alternate days.
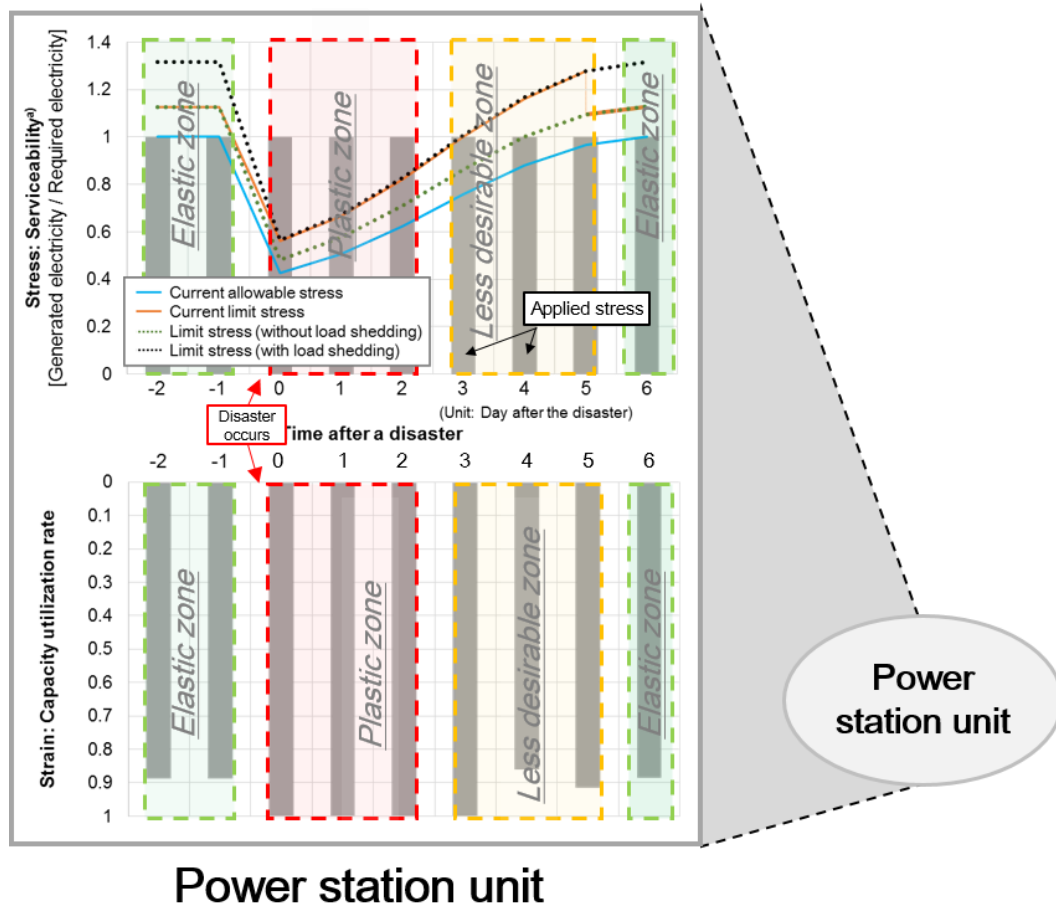
Figure 4-13 Stress and Strain Analysis for the Power Station Unit

However, as shown in Figure 4-13, the applied stress exceeds the limit stress between day 0 and day 2, so that the power facility enters the plastic zone. For example, shortly after the disaster, only 56.1 % of required electricity can be generated at day 0 under the condition of performing a load shedding. As the power station is restored, the power station unit is able to generate the required amount of electricity three days after the disaster, while considering the condition of load shedding. If the power facility stops its load shedding and tries to make the electricity available to communities all day, only 82.2 % of all the demand can be met (i.e., the limit stress at the standard performance level is 0.822 as shown in Figure 4-13). In Figure 4-13, during the three to five days after the disaster, the power station unit remains in the less desirable zone. It is worth noting as well that during day 2 and day 3 after the disaster, the strain is one, but in different zones – less desirable and

plastic zones, respectively. Thus, even though the station is still in the less desirable zone, keeping the strain at one is not proper because of the risk of entering the plastic region. At six days after the disaster, the power station unit can be recovered to the pre-disaster condition and enter the elastic zone.

Figure 4-14 shows the stress and strain analysis for the power facility, including the power station unit and the power distribution unit. In particular, at day 3 after the disaster, even though the power station unit is in the less desirable and thereby generating the required amount of electricity with the load shedding, the power facility still remains in the plastic region because the limit stress for the distribution unit is not enough when compared to its required distribution rate. That is, even though a sufficient amount of electricity is sent to the power distribution unit, the distribution unit loses a significant amount of electricity when distributing it before it reaches the communities. Figure 4-15 notes the details of the stress and strain principle under different conditions.
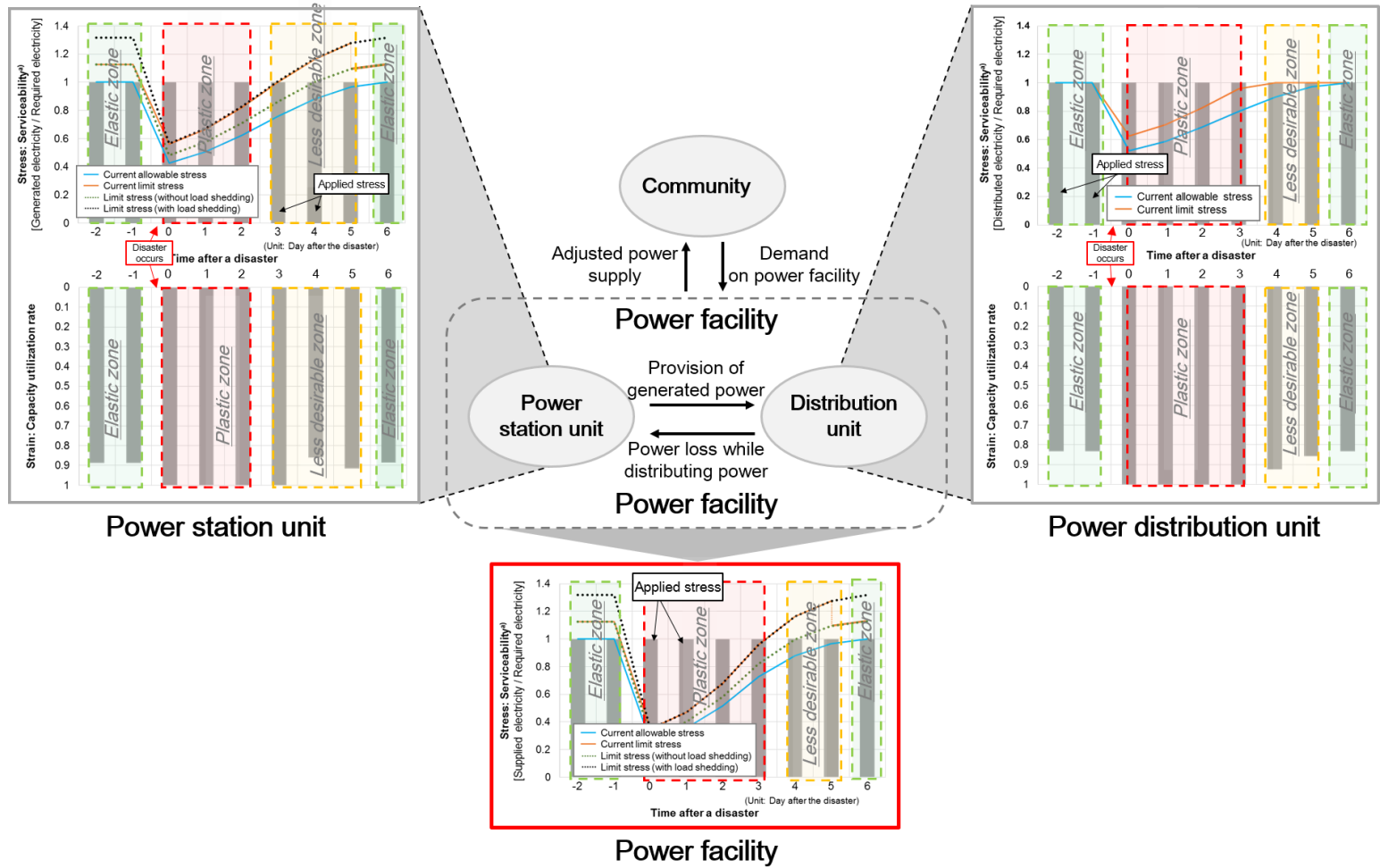
a) The excess of serviceability above 1.0 indicates the margin of safety of the infrastructure unit and the stress stands for the relative additional capacities with respect to its peak demand (i.e., serviceability = 1).

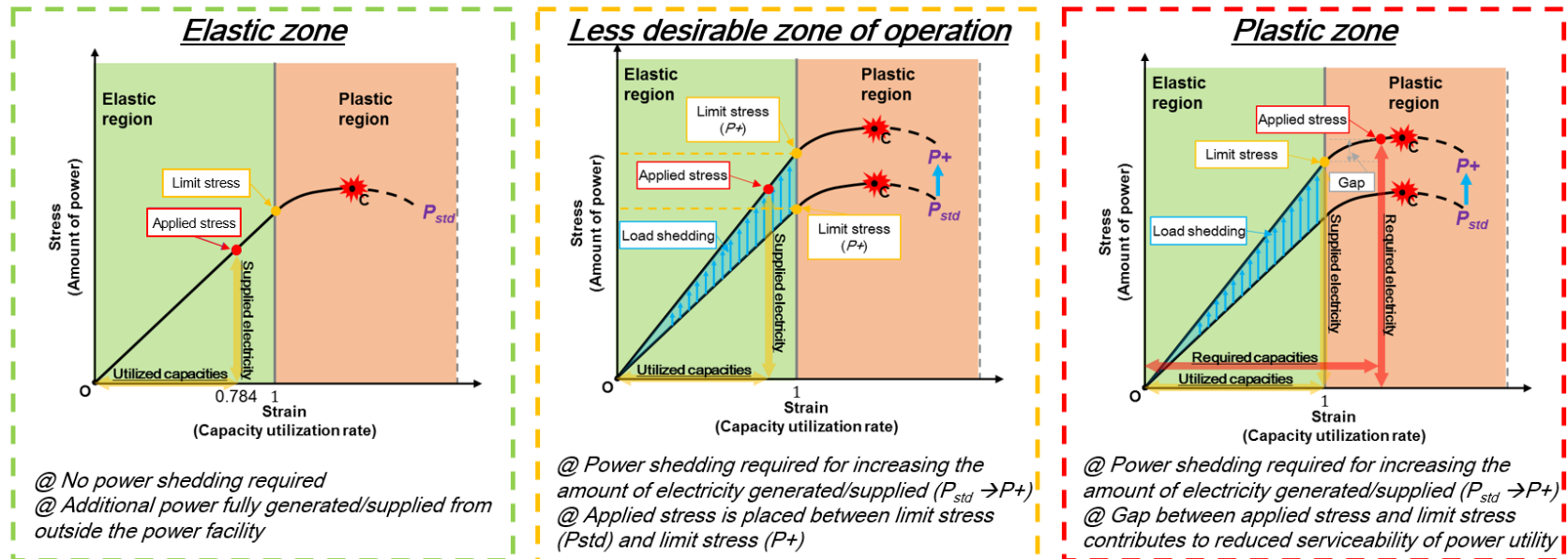Figure 4-14 Stress and Strain Analysis for the Hypothetical Power Facility

\<Stress-strain curve of the power facility\>

Figure 4-15 Behavior of the Hypothetical Power Facility in Response to Varying Levels of Stress

Step 7. Development of strategies for relieving stress (Req. v)

As a result of the simulation analysis, the emergency managers are able to know what infrastructure units they need to take care of and what level they have to add more capacities to them. Under this purpose, this step will guide them by conducting a sensitivity analysis by varying amount of added capacities. By adding more capacities to the limiting infrastructure unit in which strain capacity is less than the applied stress, the post-disaster infrastructure facility can keep the stress within its strain capacities. As such, it will help emergency managers to design mitigation strategies for improving the resilience of their infrastructure facility

4.4 Case Study: Stress and Strain Assessment of a Health Care Facility in an Earthquake Scenario

In this chapter, the proposed framework for analyzing the stress and strain of a post-disaster infrastructure is implemented within a case study. The case study includes application of the stress and strain assessment tool (SSAT) to a health care facility in an earthquake situation. Health care facility is selected as the case study for SSAT because it is one of the essential infrastructure facilities in a post-earthquake situation; the number of patients seeking treatment generally increases as much as 3 to 5 times the number of patients serviced in normal operating conditions (Cimellaro et al. 2009) and it must serve an important role in saving them (Mulyasari et al. 2013). In this context, the increase in the number of patients is translated into increase in stress on the infrastructure. Therefore, medical resources would be insufficient compared to the medical demand and can cause extended patient waiting time for treatment. As discussed in previous chapter this translates into increase in the strain. If patients fail to receive needed treatment within the critical waiting time since their arrival, their health condition is likely to worsen, and the medical facility cannot function as communities expect it to function. This is reflected as often pushing the facility to plastic region.

For the case of a hospital, a medical facility in a major city (of more than one million people) was selected and the relevant information was derived from an existing study (Arboleda 2006). Since patients in a post-disaster situation are mainly admitted to the

hospital via the emergency room, this research separated the hospital operation into two parts: emergency room operation and hospitalization. Further, according to the Joint Commission's emergency plan, hospitals are required to self-sustain their operation for up to 96 hours (VHA Center for Engineering & Occupational Safety and Health 2011). After 96 hours, a medical facility expects replenishment of its required resources from external organizations. Therefore, in this case study, all the external systems, i.e., water, electricity, and transportation for the hospital, are assumed to recover to their pre-disaster condition within 4 days after the earthquake, and the stress and strain of the hospital are measured for the 7 days afterwards. In other words, this case study is designed to evaluate the stress and strain of the operation of a health care facility during the first 7 days (= 168 hours) after an earthquake.

Other general assumptions that are necessary to model the operation of the facility in a post-disaster situation are given below. These assumptions may be changed and modified to create different scenarios and perform sensitivity analysis, thus calibrating the final results of the stress and strain analysis.

- The understudied hospital is not directly damaged by an earthquake;
- All the patients arriving at the hospital need medical treatment and they would not leave intentionally before receiving treatment unless they are transferred to other hospitals by the hospital itself;
- All the patients are admitted to the hospital after treatment in the emergency room depending on the assessment of their health conditions;
- Arrival rate of the patients follows a non-homogeneous Poisson distribution, i.e., the inter-arrival times have an exponential distribution (Cimellaro et al. 2009).
- Lifeline infrastructure, i.e., water and electricity, provide the requested demand of the hospital. That is, even though the demand of the hospital may be greater than the capacities of the lifeline infrastructure, the load shedding on the hospital is not considered in this case study.

This case study was carried out following the seven steps developed in the preceding subchapter. At the first stage, the supporting infrastructure for the operation of a hospital are identified. Then, the stress-strain principle is adapted to a post-disaster medical facility.

By using the System-of-Systems lexicon proposed by DeLaurentis and Callaway (2004), the scope of the analysis is delineated. In the next step, the data specific to a hospital's operational policies are collected from the existing study, and the data related to disaster conditions and the medical operation are collected using a literature review. After determining the design parameters, the emergency operation of a hospital is simulated. The stress and strain of that hospital and its infrastructure units are analyzed, followed by a guide for developing strategies to relieve stress.

4.4.1 Identification of Supporting Infrastructure Units

Operation of the health care facility involves other external systems such as gas, water and power for performing medical treatment, and transportation for patients' accessing the hospital, etc. (Arboleda 2006). Figure 4-16 shows the interdependencies of a medical facility with other infrastructure units and their function for the operation of the medical facility.
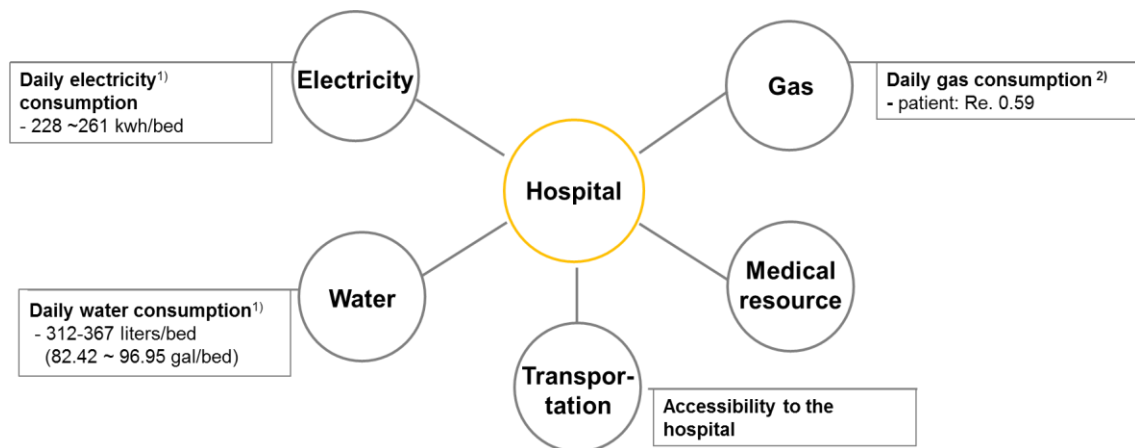
Figure 4-16 A Health Care Facility and its Supporting Infrastructure Units (ESC 2007; Tabish and Qadiri 1994)

Further, a medical facility, especially in a post-disaster situation, plays an important role for the public health of the affected communities due to the surge in demand for medical service. In an earthquake situation, the number of patients who visit a hospital generally goes up to three to five times the number of patients seeking medical care in a pre-disaster situation (Cimellaro et al. 2009). Since the affected communities expect that their medical

facilities are properly operational (Cimellaro et al. 2009), the failure of the hospital to treat them as they expect can have a major impact on the society.

4.4.2   Identification and Delineation of the Scope of the Assessment

Since the operation of a medical facility involves multiple external systems (i.e., electricity, water, and gas, etc.) mere analysis of the stress and strain of the medical facility may complicate design of the system for the operation of the facility. By taking advantage of the SoS lexicon of SSAT developed in the preceding Section 4.3, the scope of the stress and strain analysis for the post-earthquake health care facility can be defined. In this research, the analysis is focused on the interaction of one hospital with its supporting and associated infrastructure units, i.e., medical resource unit, electricity infrastructure unit, and water infrastructure unit (shaded rows in Table 4-5). The levels of interest for this case study of stress and strain analysis are represented in Figure 4-18. Even though there are other systems existing at different levels as shown in Figure 4-18, in this specific case analysis, the SSAT will be undertaken by focusing on the β and γ levels.

Table 4-5 System of Systems (SoS) Lexicon for SSAT for a Health Care Facility

| Category	Description
Resource	Entities that facilitate the provision of medical services
Economics	Promotion of public health
Operations	Provision of services
Policy	Social and economic constraints
Levels	**Description**
α	Individual components (e.g., human resources, electrical component, water component, etc.)
β	Infrastructure unit (e.g., medical resource unit, electrical system, water system, etc.)
γ	Medical facility (e.g., a hospital)
δ	Network (e.g., network of hospitals)
ε	Meta_network (e.g., City/state health care system)
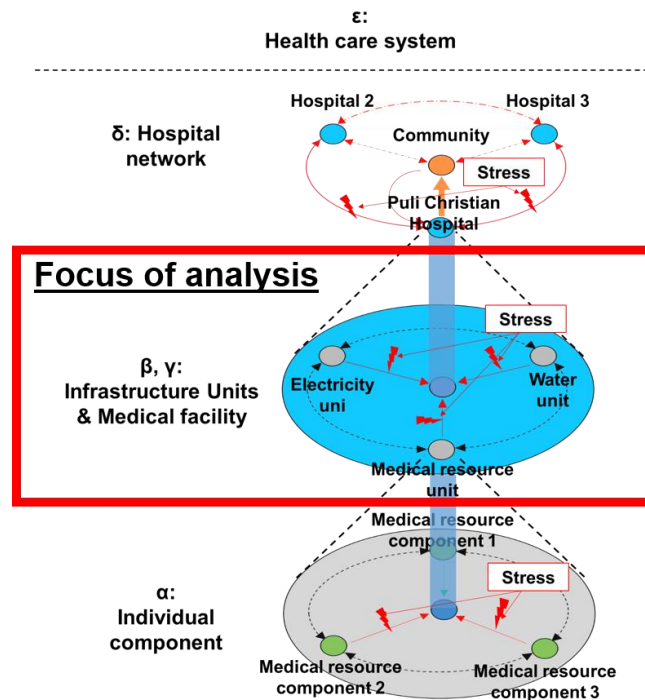
Figure 4-17 Case Health Care Facility System-of-Systems (Layers of Interest: β and γ)

The disruption of infrastructure, i.e., water and electricity infrastructure units, by an earthquake extends patient waiting times for receiving required treatments in different facilities: triage, acute care, emergency care, and hospitalization[6]. The unavailability of utility infrastructure units restrains the medical team's ability to treat patients with efficiency, e.g., restriction on the use of medical machines because of power outage and thus delay in treatment of the patients. Moreover, insufficient capacities of medical resource units, e.g., medical teams and beds, act as a limiting factor in the treatment rate of a hospital. The effects of delayed medical treatment emerge in terms of patients' extended waiting times. In this case study, the effects of the disruption of lifeline infrastructure on four health care facilities within one hospital is analyzed, i.e., triage, acute care, emergency care, and hospitalization.

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[6] Depending on the patients' health conditions, treatment in the emergency department is generally divided into two service facilities-- acute care and emergency care. Acute care is defined as treatment provided for those who need more advanced treatment; emergency care is defined as treatment provided to outpatients who do not need inpatient care (Cole 2006).
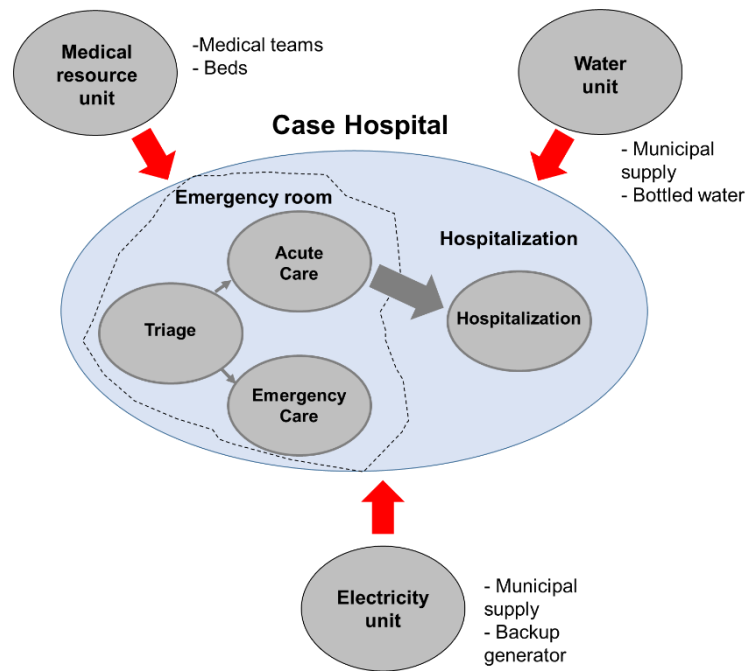
Figure 4-18 Impact of Disruptions to Infrastructure Units for Case Hospital Operations

As shown in Figure 4-18, three service facilities, i.e., acute care, triage, and emergency care, are part of the emergency room, while the hospitalization facility is separate since it has a different degree of dependence on external infrastructure units. For example, in hospitalization, the hospital might need more electricity to treat admitted patients than the emergency room does for its patients.

In terms of the interaction within the case of hospital, after patients are received in the triage facility they are routed to either the acute care facility or the emergency care facility depending on their condition. Those who have minor health problem and can be discharged after treatment in the emergency room are sent to the emergency care facility, while patients whose conditions are unstable go through the acute care and ultimately head to the hospitalization unit. The stress and strain analysis is implemented to examine the functioning of these four service facilities under simulated earthquake conditions.

4.4.3 Data Collection

The data collection consisted mainly of two parts: the data related to the functionality of post-disaster external systems, such as available serviceability of water and electricity, and data on the medical resources, such as medical teams, medical beds, etc. The performance of the external infrastructure after a disaster is configured based on a literature review. The data related to treatment by the hospital are derived from Arboleda (2006), using a literature review as a supplementary source.

4.4.3.1 Lifeline Infrastructure Performance during a Simulated Earthquake Scenario

In order to simulate an earthquake impact and relate it to the operations of the medical facility, the serviceability of the external infrastructure unit for the hospital is estimated. As discussed in the literature review (Section 4.2.1), depending on the recovery resources, the infrastructure system can recover following one of the three recovery processes- linear, trigonometric, or exponential recovery (Cimellaro et al. 2009). In this case study, the serviceability of the post-disaster infrastructure is assumed to change following the trigonometric recovery process. In order to determine the specific curves for each infrastructure unit, the properties of the infrastructure units for the case hospital are derived from the vulnerability analysis done by Arboleda (2006) in which the author measured the impact of an earthquake on the supply of municipal utility to a health care facility. Table 4-6 shows the properties for determining the serviceability of water and electricity, and Figure 4-19 illustrates the serviceability curves drawn using these properties.

Table 4-6 Properties of the Recovery Process for External Infrastructure

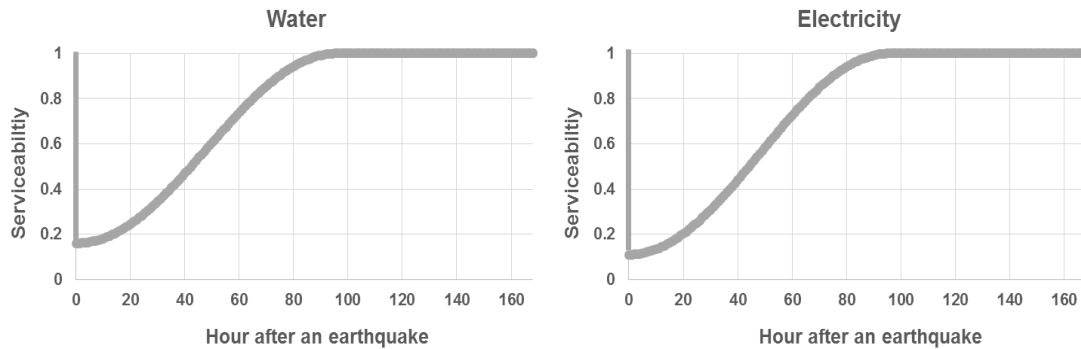| Properties to determine recovery process	Water (post-/pre-disaster level)	Electricity (post-/pre-disaster level)
Initial impact (Reduction in serviceability)	0.16/1.0	0.11/1.0
Recovery duration	96 hours	96 hours

Figure 4-19 Functionality Curves of Post-Earthquake Infrastructure for Health care Facility

In Table 4-6, the 4-day recovery process is assumed for a medical facility, but not for the entire city. And the 7-day operation of the health care facility was considered in terms of stress and strain aspects. The pre-disaster level, i.e., the time before zero in Figure 4-19, is considered as equal to one, which means that all demands on the infrastructure are met. Reduction in serviceability indicates the unsatisfied demands because of the compromised capacities of the infrastructure.

4.4.3.2   Demands on a Post-Earthquake Health care Facility

In post-earthquake situation, the demands on a health care facility are likely to grow exponentially compared to the pre-disaster visits to a hospital. Depending on the road accessibility to a medical facility and the number of injured individuals in need of medical treatment, the patient arrival rate at the hospital may vary. In this case study, as one of the disaster conditions, the arrival rate at the hospital per hour is assumed to increase following the pattern of patients that were trying to reach the emergency department during the Northridge earthquake in 1994 (Table 4-7) (Yi 2005). During the first day after the Northridge earthquake, the patient arrival increased up to 370% of the pre-disaster arrival rate. As time passed, the patient arrival steadily decreased and at day 4 after the disaster, the patient arrival rate was back to the pre-disaster rate.

Table 4-7 Northridge Arrival Patient Rate (Yi 2005)

Time	Start time (hours)	Duration (hours)	Numb. Of patients	Arrival rate (patients/ hour)	Increase in demand (% of normal demand)
Day 0	-24[1]	24	125	5.208	100%
	0	4	48	12.000	230%
	4	4	77	19.250	370%
	8	4	58	14.500	278%
	12	4	57	14.250	274%
	16	4	52	13.000	250%
Day 1	20	4	51	12.750	245%
	24	4	36	9.000	173%
	28	4	36	9.000	173%
	32	4	34	8.500	163%
	36	4	34	8.500	163%
	40	4	32	8.000	154%
Day 2	44	4	31	7.750	149%
	48	4	31	7.750	149%
	52	4	31	7.750	149%
	56	4	29	7.250	139%
	60	4	29	7.250	139%
	64	4	27	6.750	130%
Day 3	68	4	26	6.500	125%
Day 4	72	24	125	5.208	100%

[1] -24 hours in the column of start time indicates the pre-disaster patient arrival rate.

In a devastating event, such as mass casualty incident, it is important to provide relevant medical actions for those in need of medical service in a timely manner. Delayed medical treatment above the critical waiting time from the time that patients arrive may severely affect their health conditions. As such, the resulting operation of the case of medical facility in a post-earthquake situation is evaluated in terms of its system goal, i.e., treating all the patients within their critical waiting time for each service: triage, acute care, emergency care, and hospitalization. Since the critical waiting time of patients is different depending on the severity of their medical needs, the system goals can also be different for each

service facility. In this case, the system goal for the hospital is determined as shown in Table 4-8.

Table 4-8 System Goals for a Case Medical Facility

Parameter	Triage	Acute Care	Emergency Care	Hospitalization
Critical time	13 minutes 34 seconds[1]	1 hour[2]	3 hours[3]	1 hour[4]

[1] The maximum waiting time of 13 minutes and 34 seconds is the system goal for the triage unit. It is the average waiting time for 257 patients (Lyons et al. 2007)

[2] The maximum waiting time of 1 hour is the system goal for the acute care facility. Patients' needing further treatment after the emergency room need medical staff response between 1 hour (Baren et al. 2007) to 1 hour and 20 minutes (Cimellaro et al. 2009)

Patients with more severe conditions need a prompt response.

[3] The maximum waiting time of 3-hours is the system goal for the emergency care facility. Patients in this emergency unit can wait for an extended time up to 6 hours and 30 minutes without health-related risks (Cimellaro et al. 2009). As a policy, the system goal is set to 3 hours.

[4] The system goal for the hospitalization unit is the same as for the acute care facility.

4.4.3.3 Data on Medical Resource Units

Table 4-9 shows the operation-related information for the hospital. Since this study focuses on the stress and strain of the hospital as triggered by the disruption of a lifeline infrastructure and an increase in the number of patients, the information relevant to the operational capabilities of the hospital is collected.

Table 4-9 Information on the Hospital Operation (Arboleda 2006)

Variable	Emergency Room			Hospitalization
	Triage	Acute care	Emergency Care	
Number of beds	-	80		450 (licensed beds)
Medical staff (Teams)	8	8	8	
Standard treatment time	3.3 minutes[1]	2 hours[2]	2 hours [3]	120 hours [4]
Reserve capacity[5] (Electricity)	60 % of the normal operation			30% of the normal operation
Reserve capacity[5] (Water)	80 % of the normal operation			70% of the normal operation
Time pressure[6]	Up to 60% reduction in standard treatment time			

[1] The mean triage time: 3.3 minutes over 260 patients (Travers 1999)
[2] The standard treatment time for acute care: 2 hours (Arboleda 2006); 1.5 ~ 4 hours (Baren et al. 2007)
[3] The standard treatment time for emergency care: 2 hours (Arboleda 2006); 1 ~ 2 hours (Baren et al. 2007)
[4] The standard treatment time for hospitalization: 120 hours (Arboleda 2006)
[5] Without any replenishment from outside sources, the hospital can self-sustain its operation capacity at the specified percentage of performance during the first four days after an earthquake.
[6] If medical personnel perceives a large number of patients waiting for treatment, they may be willing to reduce the treatment time given to patients in order to increase the number of patients served per hour (Arboleda 2006)

The reserve capacity indicates the level of pre-disaster operational capabilities of the hospital without the municipal supply of utility for four days. For electricity, that reserve capacity is related to the capacity of a back-up generator. For water, the reserve capacity is related to the amount of bottled water or alternative products. The cutting corners effect is also defined as the ability of a medical staff to expedite the needed medical treatment. Arboleda (2006) measured the cutting corners effect through interviewing and found that the medical personnel in the hospital could expedite medical treatment up to 60% faster based on the number of patients that are waiting.

4.4.4   Definition of Stress and Strain of a Health Care Facility

In order to assess the stress and strain of a health care facility under disaster situations, the stress and strain must be defined. Since there are four types of service facilities, i.e., triage, acute care, emergency care, and hospitalization, the stress and strain are defined for each

service facility and its supporting infrastructure units. Table 4-10 shows the defined stress and strain for four service facilities and their individual supporting infrastructure units.

Table 4-10 Stress and Strain for a Post-Earthquake Hospital Case Study

Medical Facility (Service facilities)	Stress	Strain
Triage	- Number of patients in the triage facility at the unit time	- Rate at which the supporting infrastructure units are being used to meet the demand of the triage
Acute care	- Number of patients in the acute care facility at the unit time	- Rate at which the supporting infrastructure units are being used to meet the demand of the acute care
Emergency care	- Number of patients in the emergency care facility at the unit time	- Rate at which the supporting infrastructure units are being used to meet the demand of the emergency care
Hospitalization	- Number of patients in the hospitalization facility at the unit time	- Rate at which the supporting infrastructure units are being used to meet the demand for the hospitalization
Infrastructure units	Stress	Strain
Medical resources (Medical teams)	- Number of patients in the medical facility at the unit time	- Rate at which the medical teams are utilized in response to the applied stress
Electricity	- Electricity demand to satisfy the required medical operation	- Rate at which available capacities (municipal and reserve capacities) are being used
Water	- Water demand to satisfy the required medical operation	- Rate at which the reserve capacity (i.e., bottled water, etc.) is being used

4.4.5 Application of Stress-Strain Principle to a Health Care Facility

According to the proposed definition of the stress and strain principle of a post-disaster infrastructure, the allowable stress and limit stress for the medical facility are defined to reflect the contexts of the case medical facility as shown in Table 4-11.

Table 4-11 Definition of Allowable Stress and Limit Stress for the Case of Medical Facility

Infrastructure Units	Allowable Stress	Limit Stress
Medical resources (Medical teams) [1]	- Maximum number of patients that can be treated during one hour based on <u>a regular shift hour (e.g., 8-hour shift)</u>	- Maximum number of patients that can be treated during one hour based on <u>extended working hours (e.g., 10-hour shift)</u>
Electricity	- Serviceability of electricity unit relying on <u>municipal supply</u>	- Serviceability of electricity unit relying on <u>both municipal supply and reserve capacity</u>
Water	- Serviceability of water unit relying on <u>municipal supply</u>	- Serviceability of water unit relying on <u>both municipal supply and reserve capacity</u>
Medical Facility	**Allowable Stress**	**Limit Stress**
Triage, acute care, emergency unit, hospitalization[1]	- Maximum number of patients treated during one hour, relying on planned capacities of infrastructure units (underlined resources in the Allowable Stress column)	- Maximum number of patients treated during one hour relying on both planned and reserve capacities of infrastructure units (underlined resources in the Limit Stress column)

1) The allowable and limit stress of medical facility and medical team unit can vary depending on the performance level and the supply of utility service.

The allowable and limit stress of medical facility and its supporting infrastructure units are determined based on the patients' waiting time. That is, in the case where the medical facility encounters an excessive number of patients above their current capacity of treating patients, it is willing to fortify their strain capacities by either lowering the performance level or using its reserve capacities. The detailed discussion about the application of the stress-strain principle to the case health care facility under an earthquake scenario is followed below.

- Medical team unit

For the medical team unit, the stress is the medical demands, i.e., the number of patients in the medical facility. Allowable and limit stress of the medical team units represent how many patients the medical team can treat during the given time. As the stress goes up approaching its strain capacities, the medical team strives to cover all the demands within

its full strain capacities by either i) lowering the performance level, i.e., reducing treatment time, or ii) using reserve capacities, i.e., increasing shift hours. For example, Figure 4-20 illustrates how design parameters of medical team unit can vary under the condition of increasing stress. In a normal situation, the medical team can cover all the patients with the standard performance, i.e., the number of patients per doctor is less than its strain capacity of 4 patients/shift/doctor ((A) in Figure 4-20). However, in the case that the individual medical team needs to treat 5 patients during a shift time, medical team units no longer cover medical demands while keeping the same treatment time for patients. In an effort to treat all the demand within its full strain, the medical teams may improve their strain capacities from 4 patient/shift/doctor (A) to 6.67 patient/shift/doctor (A') by lowering the medical treatment time (①️ in Figure 4-20). When more patients come and individual doctors need to take care of 8 patients during their shift, medical teams may consider working extended working hours, within the time limit above which in turn may impact the team both physically and psychologically, for accommodating more patients (and consequently result in residual strain in the resources). By working 2 extended hours (R), the individual medical doctors can treat up to 8.33 patients during their shift (B') (②️ in Figure 4-20).
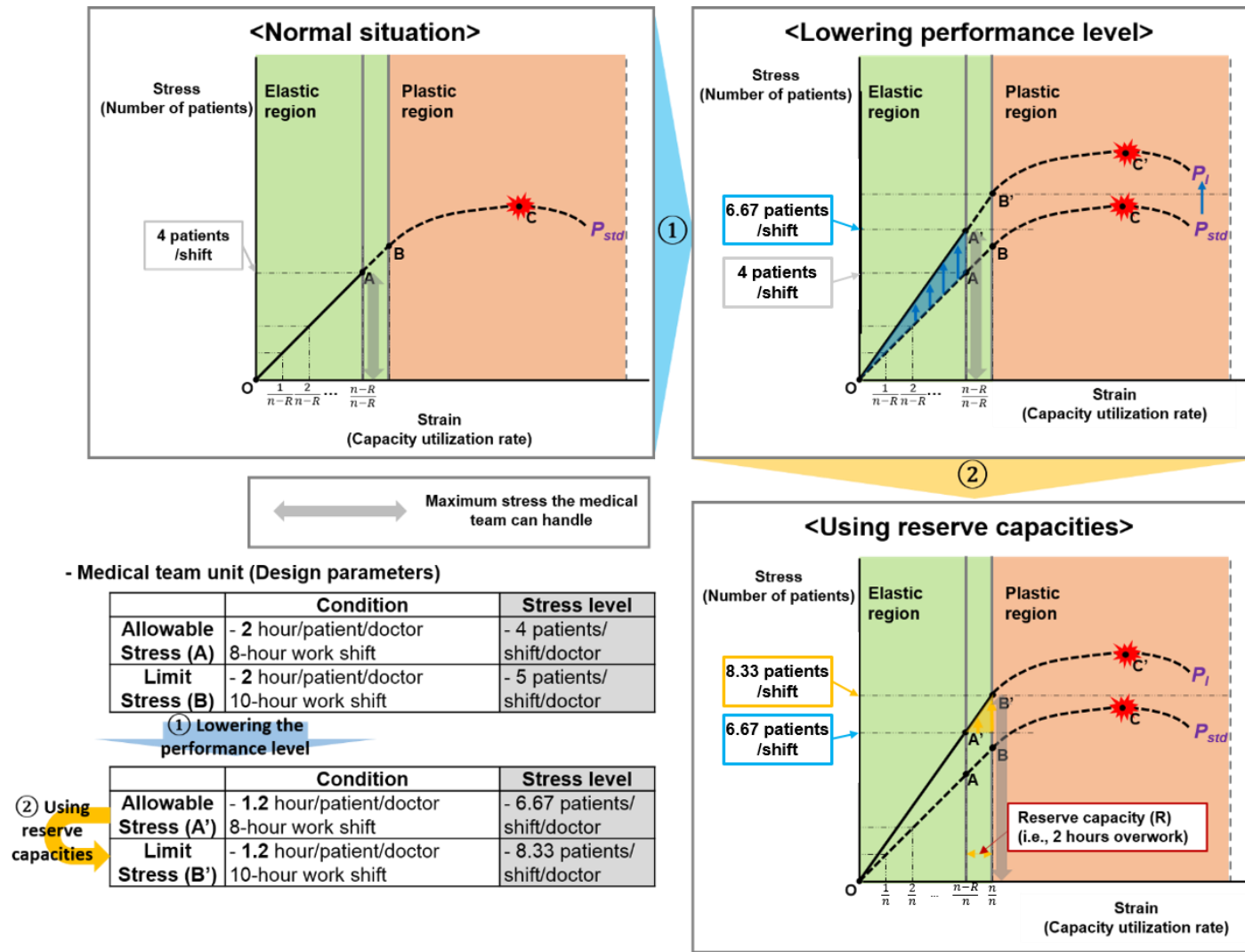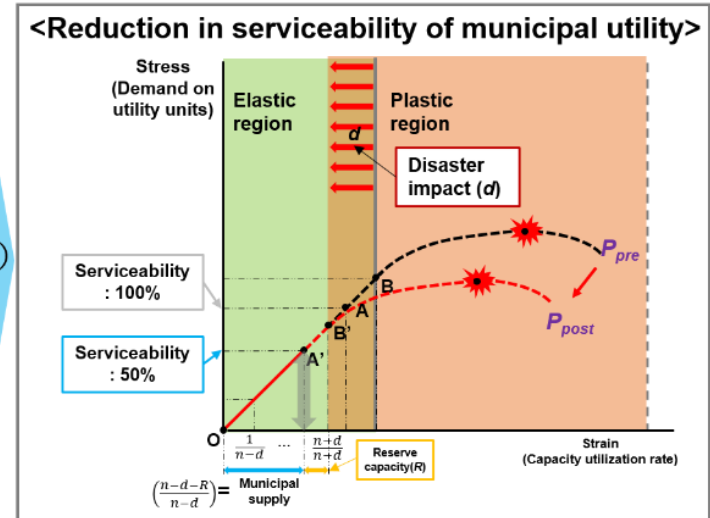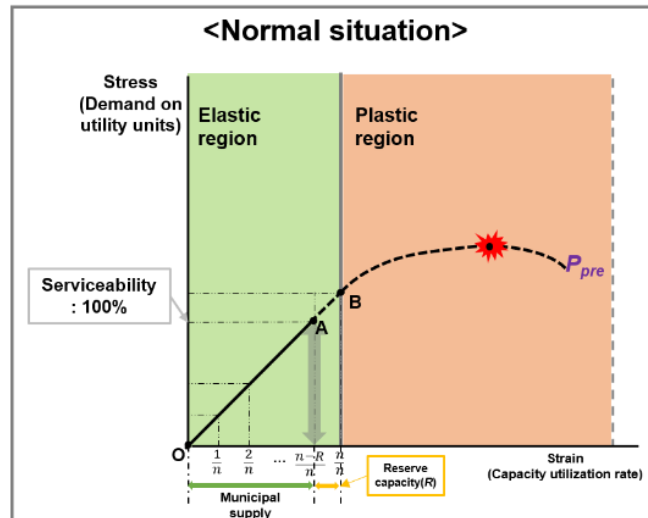
Figure 4-20 Change in Strain Capacities of Medical Team Units under the Condition of Increasing Stress

- Utility unit (Electricity & Water)

Stress on utility units is defined as the utility demand for treating patients. Demand on the utility units is associated with the operational capabilities of the medical facilities in this case study. For example, if there is power load shedding on the medical facility so that the medical teams cannot maintain ventilators and other medical equipment, medical teams cannot treat patients in a timely and efficient manner. As stress increases, utility units for the case of hospital try to provide required utility service by relying on municipal supply and, if needed, reserve capacity. To be more specific, Figure 4-21 shows the process of improving strain capacities in a post-earthquake situation. In a normal situation, the utility demand for treating patients is fully satisfied, i.e., 100 % serviceability, by relying on the municipal supply ((A) in Figure 4-21). However, in a post-earthquake situation where the capacities of lifeline infrastructure are damaged by the earthquake impacts (d), only 50 % of utility demands for treating patients can be met by the municipal supply (①) in Figure 4-21). In order to meet the remaining utility demands, the hospital utilizes reserve capacities (R), e.g., backup generators for electricity units and bottled waters for water units (② in Figure 4-21). By using both municipal supply (50%) and reserve capacities (30%), the 80% of utility demands of the medical facility can be met, which is regarded as the limit stress (B') in this instance. Despite using the full strain capacities of utility units, only 80% of utility demands can be supplied, which in turn affects the strain capacities of the medical facility by limiting the productivity to 80 % of pre-earthquake productivity, i.e., the number of patients treated during the given period.
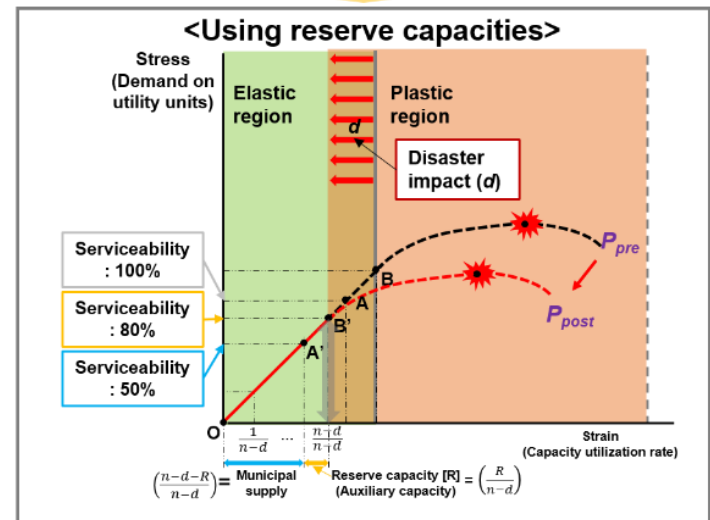
Figure 4-21 Change in Strain Capacities of Utility Units under the Disaster Conditions

- Medical facility (Coupled system)

Stress on the medical facility is defined as the total number of patients in the medical facility. In a post-disaster situation where the demand on the facility increases while the serviceability of utility units are reduced, the medical facility strives to accommodate all the medical demands within its available strain capacities. For example, Figure 4-22 shows the measure of the medical facility in order to improve their strain capacities in response to the excessive stress in the facility. In a post-earthquake situation, the capacities of external infrastructure, i.e., utility service, is likely to be compromised. As a result, the supply of utility service is reduced. The utility units which do not provide enough service after considering both the municipal supply and reserve capacities of the hospital govern the productivity of the medical facility. In Figure 4-22, due to the 80 % reduced serviceability of utility units by an earthquake, the allowable stress of the medical facility, i.e., 30 patient/hour (A), is down to 24 patient/hour (A') (① in Figure 4-22). As stress increases over the 24 patients during an hour (A'), the medical facility needs to reduce the treatment time in order to increase the strain capacity from 12 minutes for patients to 10 minutes for patients thereby increasing the allowable stress to 36 patients/hour (A'') (② in Figure 4-22). Despite the lowered performance level, i.e., reduced treatment time, if the medical demands exceed the allowable stress (A''), the medical facility is likely to manage the shift hours of medical teams for them to work extended times (R in Figure 4-22). Therefore, the medical facility can treat 50.4 patients per hour in a post-disaster situation (B'' in Figure 4-22).

- Medical facility unit (Design parameters)

	Condition	Stress level
Allowable Stress (A)	- 12 minutes/patient/doctor - 6 doctors (Standard shift duration)	- 30 patient/hour
Limit Stress (B)	- 12 minutes/patient/doctor - 6 doctors (1.2 times standard shift duration)	- 42 patient/hour

① 80% reduction in serviceability of utility units

	Condition	Stress level
Allowable Stress (A)	- 10 minutes/patient/doctor - 6 doctors (Standard shift duration)	- 24 patient/hour
Limit Stress (B)	- 10 minutes/patient/doctor - 6 doctors (1.2 times standard shift duration)	- 33.6 patient/hour

② Lowering performance level

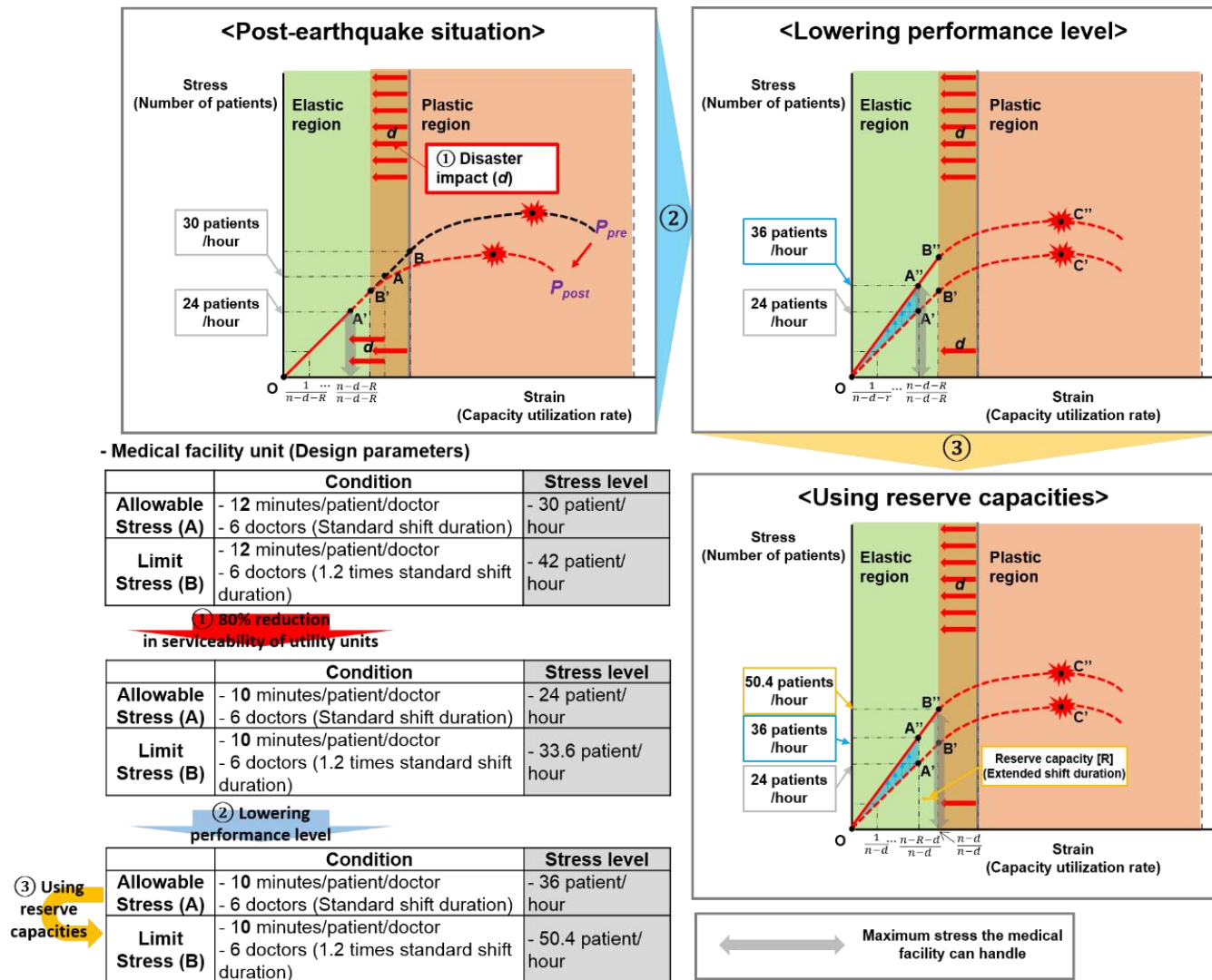|	Condition	Stress level
Allowable Stress (A)	- 10 minutes/patient/doctor - 6 doctors (Standard shift duration)	- 36 patient/hour
Limit Stress (B)	- 10 minutes/patient/doctor - 6 doctors (1.2 times standard shift duration)	- 50.4 patient/hour

③ Using reserve capacities

Figure 4-22 Change in Strain Capacities of Medical Facility under the Disaster Conditions

It is important noting that even with the same serviceability of the utility units, the resulting capacities of medical facilities can vary depending on the performance level and medical team units' reserve capacities being used.

4.4.6 Design of Emergency Operations of a Health Care Facility in an Earthquake Scenario

The operation of a post-earthquake medical facility is simulated using a discrete event simulation approach offered by the simulation tool, Anylogic© . Data on the capacities of the health care facility, i.e., number of beds, medical teams, etc., is used to determine the capabilities of four service facilities to offer relevant service for patients: Triage, acute care, emergency care, and hospitalization. Furthermore, varying serviceability of the utility services for the hospital and patients' arrival rates are considered as input data for the simulation model to trigger the dynamic stress level in the system. The simulation is run for 168 hours with the assumption that an earthquake happens at the time 0. In this case study, the consideration of the effects of disrupted utility units by an earthquake on the hospital is the most important components in the stress and strain analysis. The specific assumptions considered in the analysis are as follow.

- Before the earthquake, 250 patients are already being treated in the hospitalization facility. The discharge rate is 2.08 per hour that reflected in the simulation by its equivalent of 50 patients discharged every 24 hour during the first 120 hours.
- The disruption of utility units proportionally affects the operation of the health care facility (e.g., 50 % serviceability of utility units for the hospital reduces the productivity of the medical facility by 50%).
- The excessive number of patients over the capacity of the medical resources for keeping the required patients' critical waiting time are transferred to other hospitals. Availability of other hospitals in the health care network is beyond the scope of this simulation;
- After triage, 5% of patients are transferred because of the lack of medical specialties. 68.4% of remaining patients are treated in the emergency care facility, and the rest

of the patients are treated in acute care facility and then admitted to the hospital for the advanced treatment.

- The improvement in the strain capacities of medical team units and facility made by the extended shift duration is not considered in this case study. That is, medical team units cannot carry the stress over their allowable stress;

- The insufficient utility service affects the outputs of triage, acute care and emergency care facilities by extending the treatment time for patients while it impacts the outputs of the hospitalization facility by reducing operable number of licensed beds.

- The case hospital tries to maintain the pre-earthquake operational level by relying on both municipal supply and reserve capacities if there is reduction in the serviceability of the utility network for the hospital. That is, even though the required utility demand for treating existing patients is less than the available utility service, the case hospital strives to keep the 100 % operational level by using its full strain capacities.

- There are two operational scenarios. In **Scenario i**, all the medical facilities treat patients with the standard performance level, i.e., standard treatment time while in **Scenario ii** the acute care and emergency care facilities treat patients by reducing the treatment time to 60% of the standard treatment time to help the two facilities to encounter excessive stress at the post-disaster period.

- Process of operation for a post-disaster health care facility

The flow of patients after arriving at the emergency department is shown in Figure 4-21. Upon arrival, patients wait for the triage in the waiting room. If their names are called when the triage nurses are available for upcoming patients, they are triaged and categorized into three treatment category depending on their conditions: transfer because of no specialty of treatment, acute care, and emergency care. [7] Patients who are categorized for transfer because the hospital has no specialty of treatment are those who need special treatment.

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[7] Acute care includes patients with Severity 2~4 while emergency care covers patients with Severity 1 (Severity 1-4 is the patient type used in HAZUS (FEMA 1999)).

Remaining patients in a different category will go through different processes since their critical waiting time and required treatment may be different. Patients in need of emergency care will have minor problems and can wait up to 3 hours before relevant resources, i.e., one medical team and a bed are available for them. Patients in need of acute care have a severe condition, so any delayed treatments may affect their recovery and survivability. They are assumed to have to wait up to 1 hour before receiving treatment. After acute care, patients will receive further treatment and will be admitted to the hospital (i.e., hospitalization) meaning that they will have to wait for availability of inpatient care. After their health conditions are stabilized in acute care, it is assumed they are able to wait another hour for hospitalization. In all the treatment facilities, if patients have to wait longer than their critical waiting time, they are transferred regardless of availability of other hospitals. Once patients do receive their required treatments, they are discharged.
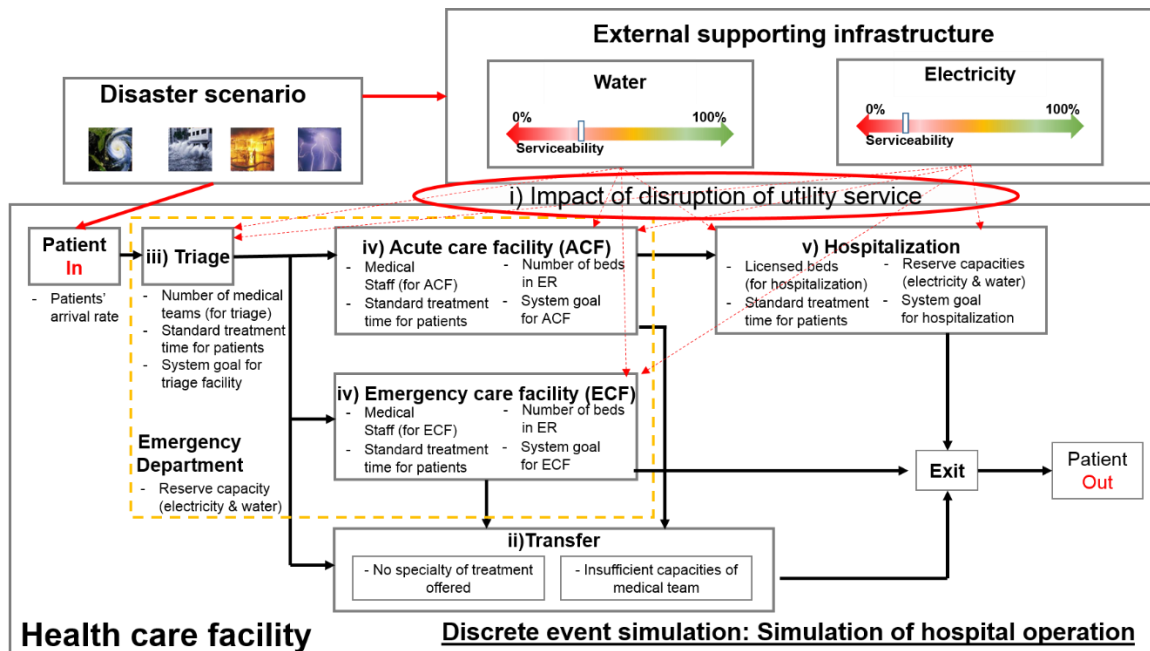
- iii)~v) are medical service facilities offered to patients
- i) and ii) are factors that affect the performance of service facilities.

Figure 4-23 Flow of Operations for a Post-Earthquake Health Care Facility

The detailed description of the processes shown in Figure 4-23 is described below:

i) Impact of the disruption of utility service

As a result of an earthquake, the supply of utility service to the health care facility is reduced. The impact of such disruption of utility service depends on the dependencies of the treatments and the auxiliary capacities, i.e., reserve capacities, of the hospital. Depending on its dependencies on the supply of municipal utilities, the impact of disrupted municipal utility service is calculated as a ratio of the post-disaster productivity to the pre-disaster productivity. For instance, the lookup table[8] shown in Figure 4-24 explains the impact of disruption of municipal supply of electricity on the operation of emergency room, i.e., triage, acute care and emergency care facility.
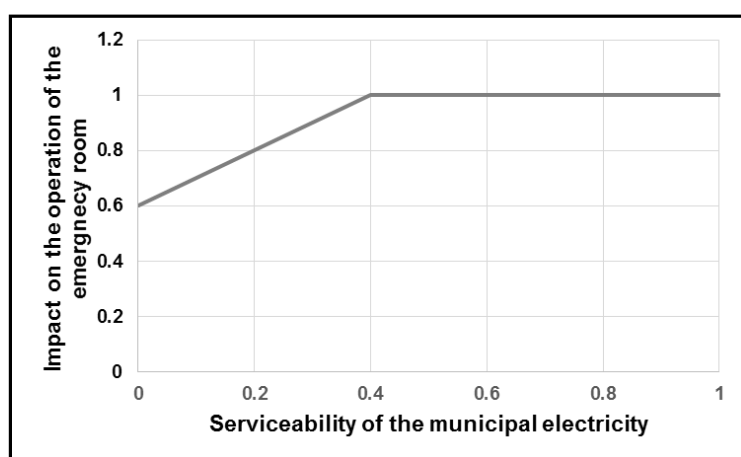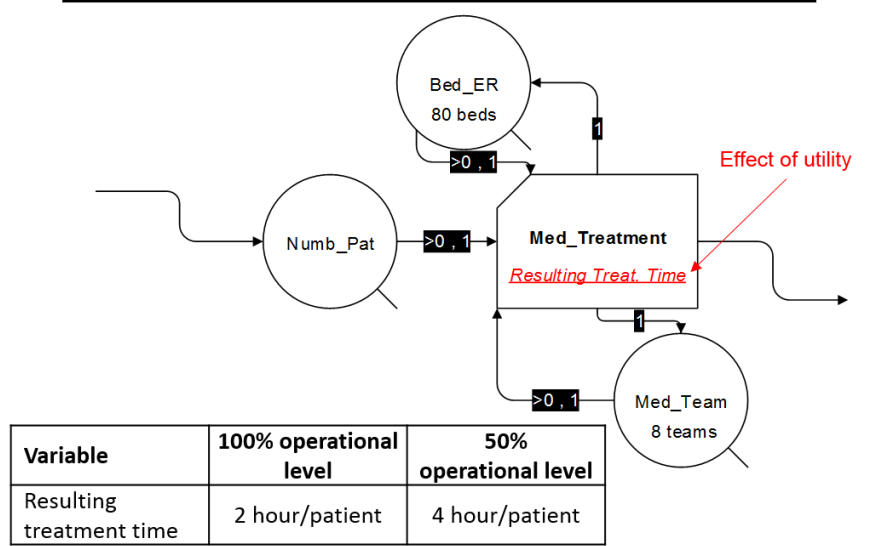
Figure 4-24 Impact of Reduced Serviceability of Power Supply Network on the Operation of the Emergency Room

As the impact of an earthquake on a municipal utility is measured in terms of serviceability (demand satisfied with the utility service/total demand on the utility service), the serviceability of municipal supply of electricity is used as an input to determine the operational level of the medical facilities in the emergency room (Figure 4-24). For example, if there is no supply of power from the municipal utility to the hospital, the emergency room can still maintain 60 % of its pre-disaster operations capacity since the emergency operation will be sustained by relying on its reserve capacity, e.g., back-up generators.

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8 Other lookup tables which shows the impact of disrupted municipal supply of utility on the operational level of medical facilities are attached in the Appendix A.

The connection of the effects of utility units derived from the lookup table and the discrete event simulation is explained in Figure 4-25 and Equations (4.1-4.4). The lookup table for the utility units, i.e., electricity and water, and the serviceability of municipal supply of utility service, shown in Figure 4-25, determine the operational level of medical facilities (Equation 4.1 and 4.2). The minimum operational level among two utility conditions is only considered, which means that the lower operation level by one utility condition, e.g., water among water and power units, governs the operation of medical facilities until the operation level reaches the operation level by other utility condition, e.g., power unit. For triage, emergency care and acute care facility, where utility conditions are associated with the efficiency of medical teams' treatment, the resulting operational level affects the medical operation by impacting treatment time (Equation 4.3). For instance, if the treatment time is 2 hours per patient at 100% operation level, i.e., in a pre-earthquake situation, the resulting treatment time is extended to 4 hours at the governing operation level of 50% ((a) in Figure 4-25 and Equation 4.3). In the case of hospitalization facility where the medical facility admits patients depending on the number of operable beds, the governing operation level affects the operation of hospitalization by influencing the number of operable beds ((b) in Figure 4-25 and Equation 4.4). For example, the hospitalization facility admits and treats 450 patients during 120 hours in a pre-earthquake situation while only 225 beds and patients are managed at 50 % operational level.

(a) Triage, acute care, and emergency care facility

Variable	100% operational level	50% operational level
Resulting treatment time	2 hour/patient	4 hour/patient

(B) Hospitalization facility

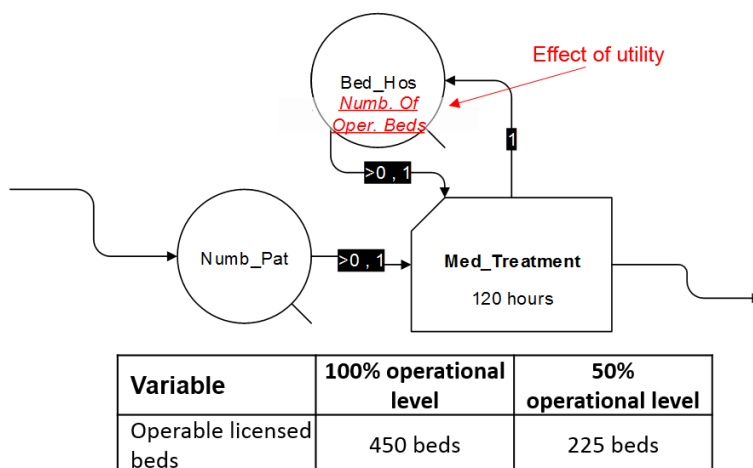| Variable	100% operational level	50% operational level
Operable licensed beds	450 beds	225 beds

Figure 4-25 Effect of Utility Units in the Operation of Medical Facilities

Impact of water unit = Effects of water on the medical operation (Serviceability of municipal supply of water)........... ....(4.1)

Impact of power unit = Effects of power on the medical operation (Serviceability of municipal supply of power) ....(4.2)

Resulting_Treat_Time = (Treatment time)*[1/MIN (Serviceability of water unit, Serviceability of power unit)] ....(4.3)

Number of Operational Beds = (Number of licensed beds)* MIN (Serviceability of water unit, Serviceability of power unit)...(4.4)

ii) Transfer

According to the Emergency Medical Treatment and Active Labor Act (California Medical Association 2001), "*patients who are not stabilized can only be transferred to another facility if the medical benefits of the transfer of the emergent patient prior to stabilization outweigh the risks incurred by the transfer.*" Therefore, if the health care facility does not have the capabilities to provide required treatment within patients' critical time, then the medical facility considers a transfer option for patients. Since the focus of the stress and strain analysis is placed on the lifeline infrastructure, the number of patients exceeding the capacities of medical team unit itself is transferred to other hospitals within the health care network.

Table 4-12 shows the conditions for determining whether patients in each service facility are transferred or not. Integration of these conditions for transfer option shown in Table 4-12 into the discrete event simulation is illustrated in Figure 4-26 and Equations $(4.5 - 4.8)$.

Table 4-12 Conditions for Transferring Patients to Other Hospitals

Reasons	Conditions for the Transfer function (If function)
No specialty of treatment (after triage facility)	After the triage, for the 5% of all triaged patients, it yields "True" since the hospital has no capability to provide specialized treatment for them while it yields "False" for the remaining 95%.
No medical resource available (Acute & emergency care)	If the required productivity exceeds its hourly productivity, i.e., patients treated during hour, of medical team unit, it yields "True" since the hospital because of insufficient medical resources.
No medical resource available (Hospitalization)	If there are no beds either are available now or available within one hour, it yields "True" since the hospital because of insufficient medical resources.

(a) Acute care, and emergency care facility
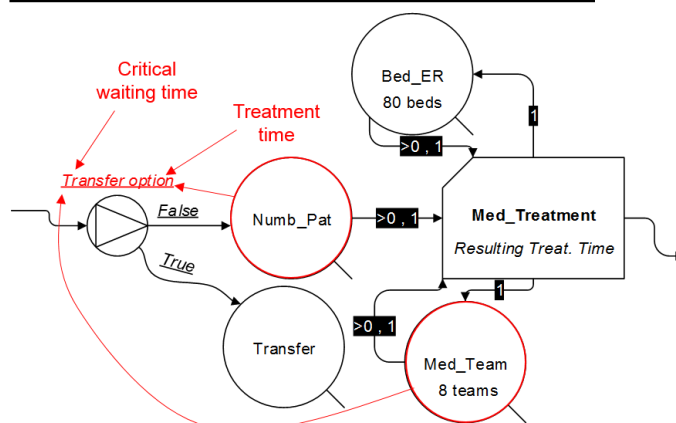
Number of patients arrival	Number of medical teams	Treatment time	Critical waiting time	Output
20 patients during an hour	8 teams	2 hour/patient/team	3 hours	First 20 patients: *"False"*

(B) Hospitalization facility
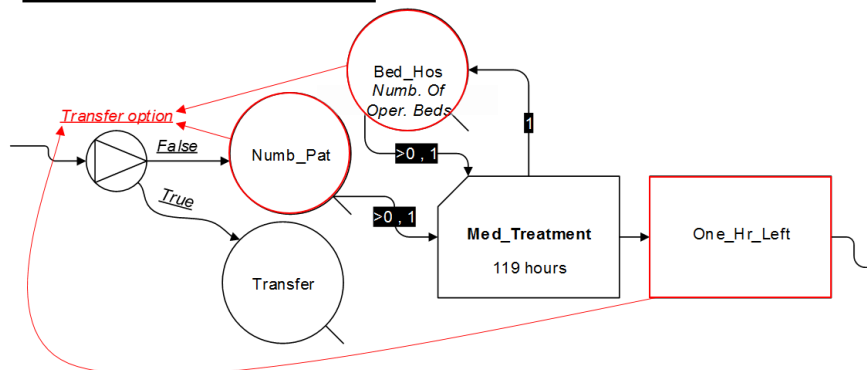
Number of patients arrival	Available number of operable beds	Number of patients who will be discharged within one hour	Output
50 patients	0 beds	3 patients	First 3 patients: *"False"* Next 47 patients: *"True"*

Figure 4-26 Function of Transfer Option in the Case Health Care Facility

Required Productivity of medical team units = (Total number of patients in the medical facility – Number of medical teams) / Patients' critical waiting time ....(4.5)

Hourly productivity of medical team units = (Number of medical teams) / (Treatment time)...(4.6)

Medical option (A) = If (Required productivity of medical team units >=Hourly Productivity of medical team units, "True", "False")..(4.7)

Medical option (B) = If (Available number of operational beds == 0, if (Number of patients arriving to the hospitalization > number of patients being discharged within 1 hour, "True", "False"), "False")……………………………………………………………………....(4.8)

In the case of the transfer option for acute care and emergency care facility, patients' critical waiting time, the total number of patients and the number of medical teams are used for configuring the required productivity of medical treatment having patient / hour as the unit (Equation 4.5). That is, if there are 20 patients arriving during an hour and 8 medical team can treat and discharge 12 patients within their critical waiting time of 3 hours, all of the remaining 8 patients can be treated at 3 hours, which requires medical teams to have 4 patients treated per hour ((a) in Figure 4-26). Hourly productivity of medical teams is calculated with the number of medical teams and treatment time, which in this case yields 4 patients treated per hour (Equation 4.7). Therefore, the medical facility can handle the total of 20 patients, above which the patients will be transferred to other hospitals.

In the case of hospitalization facility, the transfer option is the function of the number of patients arriving, the number of available operable beds and the number of admitted patients who will be discharged within 1 hour (Equation 4.8). For example, if there are no available beds, but 3 admitted patients are to be discharged within 1 hour, then all the 50 patients seeking hospitalization except 3 patients are transferred to other hospitals.

iii) Triage

Triage is the first treatment offered by the health care facility. Figure 4-27 and Equations 4.9 – 4.13 describe the process occurring within the Triage facility as well as how the stress and strain of triage facility and utility units are configured during the simulation time. In the simulation, patients arrive at the emergency room following the exponential distribution with the hourly arrival rate shown in Table 4-7. When a triage team is available for a new patient, a new patient will be triaged. Depending on the *Transfer option*, the triaged patients are categorized depending on their health conditions into two categories: transfer or treatment in the emergency room, i.e., acute care or emergency care.

Triage facility

Example
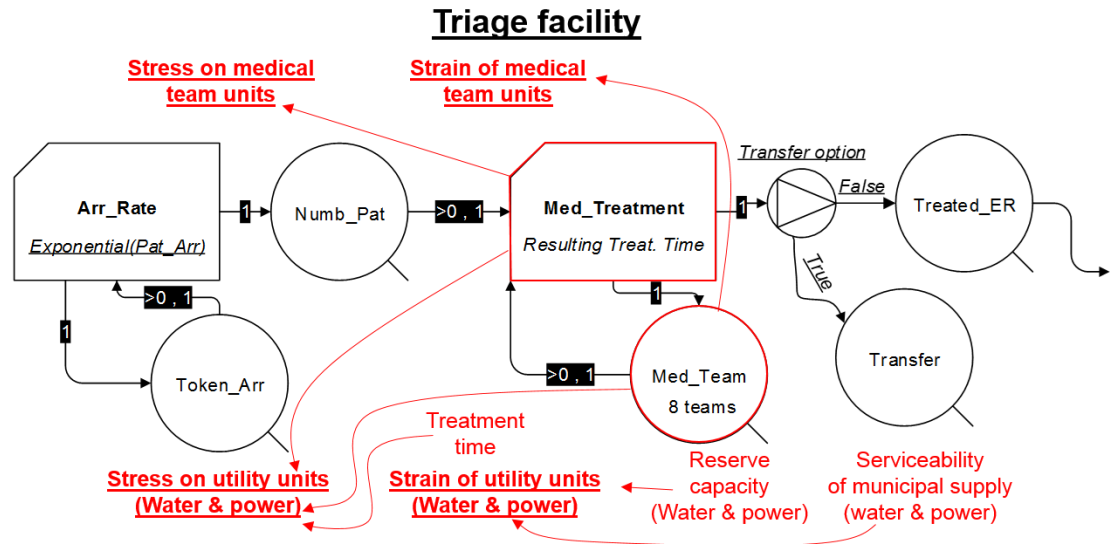
Total Number of patients in Triage	Total number of medical teams (Working teams)	Treatment time	Critical waiting time	Triage facility	
				Stress	**Strain**
Highest number of patients during hour: 3 patients	8 teams (3 teams)	3.3 min/patient/team	13 minutes 34 seconds	3 patients during hour	0.375 (=3/8)
Reserve capacity (Power)	**Available municipal supply (Power)**	**Reserve capacity (Water)**	**Municipal supply**	**Utility units (Power)**	
				Stress	**Strain**
60% serviceability	11% serviceability	80% serviceability	16% serviceability	71% serviceability	1.0 (=71%/71%)

Figure 4-27 Design of Triage Facility

Utility demand for treating patients in time = Min (Hourly productivity of medical team units, Total number of patients in the medical facility) / Hourly productivity of medical team units ....(4.9)

Stress on utility units = Max (Utility demand for treating Patients in time, available serviceability of utility units)...(4.10)

Strain of utility units = Stress on utility units / Available serviceability of utility units using municipal and reserve capacities....(4.11)

Stress on triage facility at unit time = Highest number of patients in medical facility during hour..(4.12)

Strain of triage facility at unit time = Number of working medical teams / total number of medical teams...(4.13)

The stress of the utility for triage facility is defined as the utility demands, especially power units, for treating patients. The medical facility requires utility service for maintaining desired operational conditions for treating current medical demands. Since the medical facility cannot treat patients more than what they can treat in the pre-disaster situation, i.e., *hourly productivity of medical team units*, the required power demands is defined as the required serviceability of power unit, which is calculated by dividing the minimum value of the current number of patients in triage facility and its hourly productivity by its hourly productivity (Equation 4.9). In the example shown in Figure 4-27, the hourly productivity is 145.46 patients treated per hour while the total number of patients is 3 patients. Therefore, the utility demand for treating the patients is 2.1% serviceability following Equation 4.9. However, since the triage facility remains the pre-disaster operational level, the triage facility utilizes the available capacities, including municipal and reserve capacities. Therefore, in this instance, the stress on power units is 71% of its serviceability (Equation 4.10).

The stress on medical facility is defined as the highest number of patients during an hour. In this case study, the stress and strain of the medical facility is measured at every 0.2 hour throughout the entire simulation time of 168 hours. It is important noting that since the unit time is set to an hour, the maximum value of number of patients measured during an hour is used for the stress at that unit time (Equation 4.12). The strain of medical facility is defined as the ratio of the number of working triage teams to the total number of triage teams (Equation 4.13). In the aforementioned example, the stress at that unit hour is 3 patients while the strain of the triage facility is 0.375 (See Figure 4-27).

iv) Acute care facility (ACF) and emergency care facility (ECF)

Once patients are triaged, they are routed to the appropriate medical facility (i.e., acute care unit (ACF) or emergency care unit (ECF). Figure 4-28 describes the process in the ACF and how the stress and strain of acute care facility is measured in the discrete event simulation. As the operation process within both ACF and ECF is the same, Figure 4-28 can be utilized for the ECF as well.
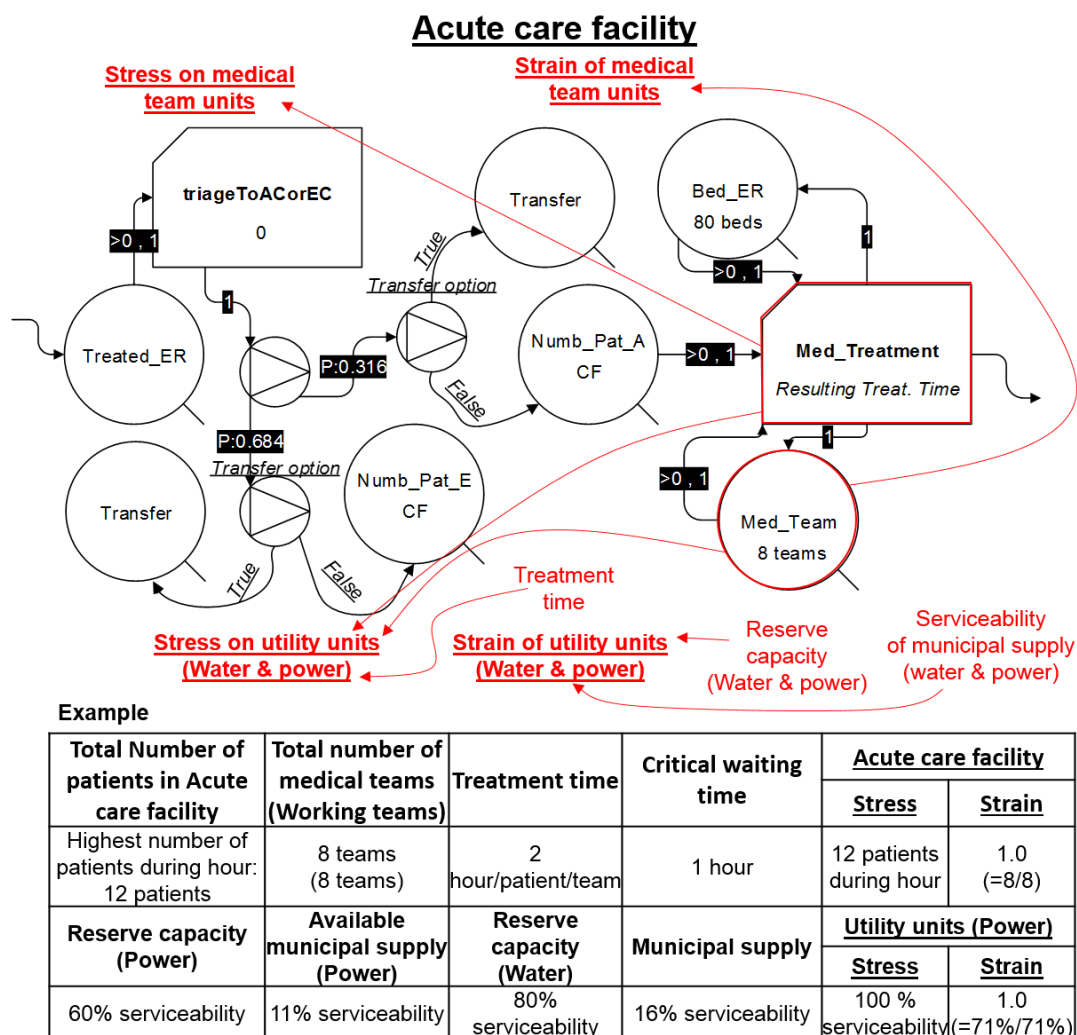
Figure 4-28 Design of Acute Care Facility (ACF)

Using Equations 4.9 – 4.13, the stress and strain of ACF and ECF can be measured during the simulation time. In the example given in Figure 4-45, the *Hourly productivity of ACF* is calculated as 4 patients treated per hour while the highest total number of patients is 12 patients during that unit hour (See Equation 4.9). Since the ACF cannot treat more than 4 patients per hour, the ACF requires the pre-earthquake operational level to obtain the productivity of 4 patients per hour, i.e., 100% serviceability (See Equation 4.10). In response to the stress on power units, the strain needs to be stretched out to the full capacities up to 1.0 (See Equation 4.11).

With regard to the stress on ACF, the stress is the highest number of patients in ACF during the unit hour, which is 12 patients (See Equation 4.12). Then, the strain of ACF is calculated as 1.0 (See Equation 4.13).

vi) Hospitalization

After patients are treated in the acute care facility, they need further treatments and are admitted to the health care facility. Figure 4-29 describes the process of hospitalization and how the stress and strain of Hospitalization is measured during the simulation time. In this case study, if there are no operable licensed beds in the facility and occupied beds, which will be discharged within 1 hour, then the transfer function is effectuated. Unlike other service facilities, i.e., triage, ACF, and ECF, where the impact of disrupted utility units causes the extended treatment time, the insufficient supply of utility incurs the reduction in operable licensed beds. In order to reflect the context of hospitalization facility, Equation 4.11 is used to measure the stress and strain of hospitalization and its supporting utility units.

The stress of utility units for hospitalization facility is defined as the utility demands for admitting and treating patients. The medical facility requires utility service for operating sufficient number of licensed beds for treating current medical demands. Since the medical facility cannot treat patients more than what they can treat in the pre-disaster situation, i.e., *the total number of licensed beds*, the required utility demands for achieving the required operational condition is defined as the required serviceability of utility unit, which is calculated by dividing the minimum value of the current number of patients in hospitalization facility and the total number of licensed beds by the total number of licensed beds (Equations 4.14 and 4.15). In the example shown in Figure 4-29, the total number of licensed beds is 450 beds while the total number of patients is 184 patients. Therefore, the utility demand, i.e., power facility, for treating the patients is 40.89% of the serviceability and since 40.89% serviceability is less than the 41% available serviceability of the power unit, the stress on the power facility is 41% following Equation 4.15. In response to the applied stress, the strain of power facility is the full strain of 1.0 (Equation 4.16).

The stress on hospitalization facility is defined as the maximum number of patients in hospitalization facility during the unit hour. In this case study, the stress and strain of the medical facility is measured at every 0.2 hour throughout the entire simulation time of 168 hours. It is important noting that since the unit time is set to an hour, the maximum value of number of patients measured during an hour is used for the stress at that unit time (Equation 4.17). The strain of medical facility is defined as the ratio of the number of occupied operable licensed beds to the total number of operable licensed beds (Equation 4.18). In the aforementioned example, the stress at that unit hour is 3 patients while the strain of the triage facility is 1.0 (See Figure 4-27).
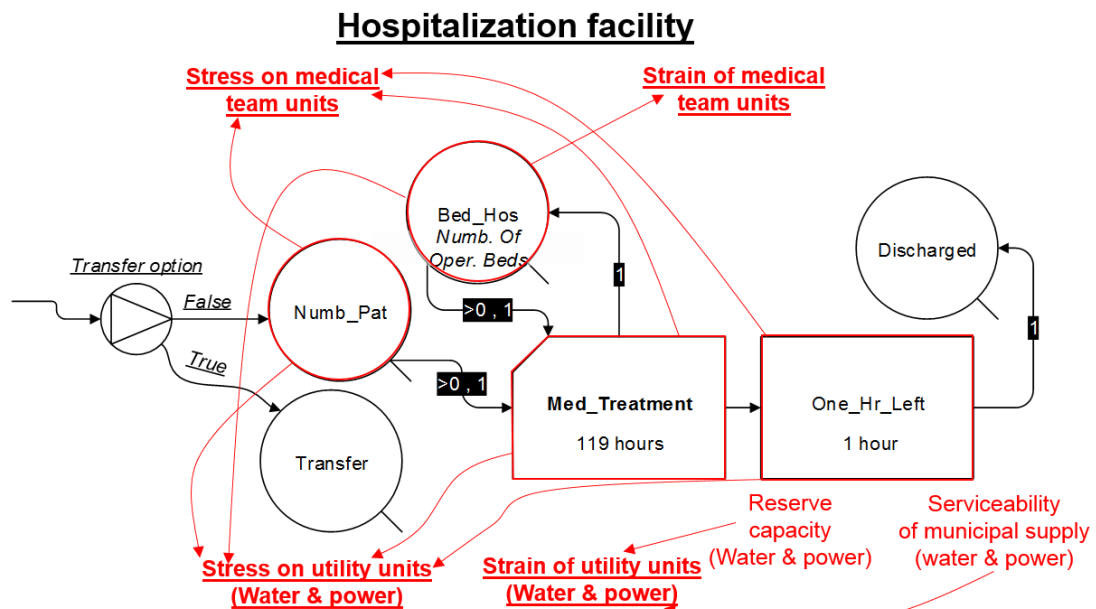
Hospitalization facility

Total Number of patients in Hospitalization	Total number of licensed beds (Operable beds)	Treatment time	Critical waiting time	Acute care facility	
				Stress	Strain
Number of patients during hour: 184 patients	450 beds (184 beds)	120 hour/patient/team	1 hour	184 patients during hour	1.0 (=184/184)
Reserve capacity (Power)	Available municipal supply (Power)	Reserve capacity (Water)	Municipal supply	Utility units (Power)	
				Stress	Strain
30% serviceability	11% serviceability	70% serviceability	16% serviceability	41 % serviceability	1.0 (=41%/41%)

Figure 4-29 Design of Hospitalization Facility

Hospitalization demand on utility units for admitting patients in time = [Min (Total number of patients in the hospitalization, Total number of licensed beds) / Total number of licensed beds] ....(4.14)

Hospitalization stress of utility units = Max (Hospitalization demand on utility units for admitting Patients in time, Available serviceability of utility units for the hospitalization) ....(4.15)

Hospitalization strain of utility units = Hospitalization stress on utility units / Available serviceability of utility units using municipal and reserve capacities for hospitalization ....(4.16)

Stress on hospitalization facility at unit time = Highest total number of patients in hospitalization facility during the unit time ....(4.17)

Strain of hospitalization facility at unit time = Number of occupied operable licensed beds / total number of operable licensed beds teams ....(4.18)

4.4.7   Stress and Strain Assessment of Emergency Operation of a Health Care Facility

Using the simulation model designed in the preceding section, the stress and strain of the health care facility under two disaster scenarios, i.e., Scenario i (Sc i) and Scenario ii (Sci ii), are analyzed. Table 4-13 shows the different design parameters, i.e., allowable stress and limit stress, under the two scenarios; all the input data for two scenarios are same except for these design parameters of the health care facility. In Scenario i, it is assumed that the medical facility treats patients with the standard performance level. By contrast, in Scenario ii, it is assumed that the acute care facility and emergency care facility treat patients with the 60% of the standard treatment time while triage and hospitalization keep its standard treatment time. The purpose of analyzing two scenarios is to investigate the effects of lowering performance level when encountering excessive stress.

Table 4-13 Design Parameters of the Care of the Health Care Facility under the Scenarios (Scenario i and Scenario ii)

Design Parameter (Facility)	Triage	Acute Care	Emergency Care	Hospitalization
Allowable stress (Sc i) [1]	145.46 patients (1 hour)	8 patients (2 hours)	8 patients (2 hour)	450 patients (120 hours)
Allowable stress (Sc ii) [1]		8 patients (1.4 hour)	8 patients (1.4 hour)	
Design Parameter (Electricity)	Emergency Room			Hospitalization
Allowable stress (Sc i, ii)	Serviceability of the municipal supply (100%)			
Limit stress[2] (Sc i, ii)	Municipal supply (100%) + reserve capacity (60%)			Municipal supply (100%) + reserve capacity (30%)
Design Parameter (Water)	Emergency Room			Hospitalization
Allowable stress (Sc i, ii)	Serviceability of the municipal supply (100%)			
Limit stress[2] (Sc i, ii)	Municipal supply (100%) + reserve capacity (80%)			Municipal supply (100%) + reserve capacity (70%)

[1] Number of patients treated during the treatment time in parenthesis.
[2] Only when there is a reduction in the serviceability of municipal supply does the hospital use auxiliary capacities. Otherwise, the limit stress does not appear as effective capacity.

As shown in Table 4-13, since the treatment time of acute care, emergency care and hospitalization facility is greater than the unit time of hour, the allowable stress during the unit time is directed to the available medical resource. For example, in the acute care facility, only 8 patients are allowed during an hour considering the available number of medical teams. If there are more than 8 patients during an hour, they have to wait for the available resource. Therefore, the effects of reducing treatment time will be shown in terms of how fast treated patients are discharged throughout the simulation time, not of the improvement in the design parameters, allowable stress. But, in the case of the triage facility where the treatment time is less than the unit time of hour, the allowable stress is related to the productivity, i.e., how many patients can be treated during an hour. Therefore,

the effects of lowering performance can be directly represented in the terms of the increase in the allowable stress.

Figure 4-30 shows the hourly average patient waiting time under each scenario. Each medical facility has its own system goal for providing medical service for all its patients within their critical timeframes. As a result of the simulation, only the emergency care facility failed to achieve the system goal in both two scenarios. That is, due to the excessive demand on the emergency care facility, the medical facility cannot properly treat patients in terms of the system goal.

Therefore, in this case study, the stress and strain for the emergency care facility under two different scenarios are discussed while other stress and strain analysis are included in the appendix. Then, in the next step "Development of strategies," how the stress and strain analysis can help to design strategies for mitigating excessive stress is dicussed.
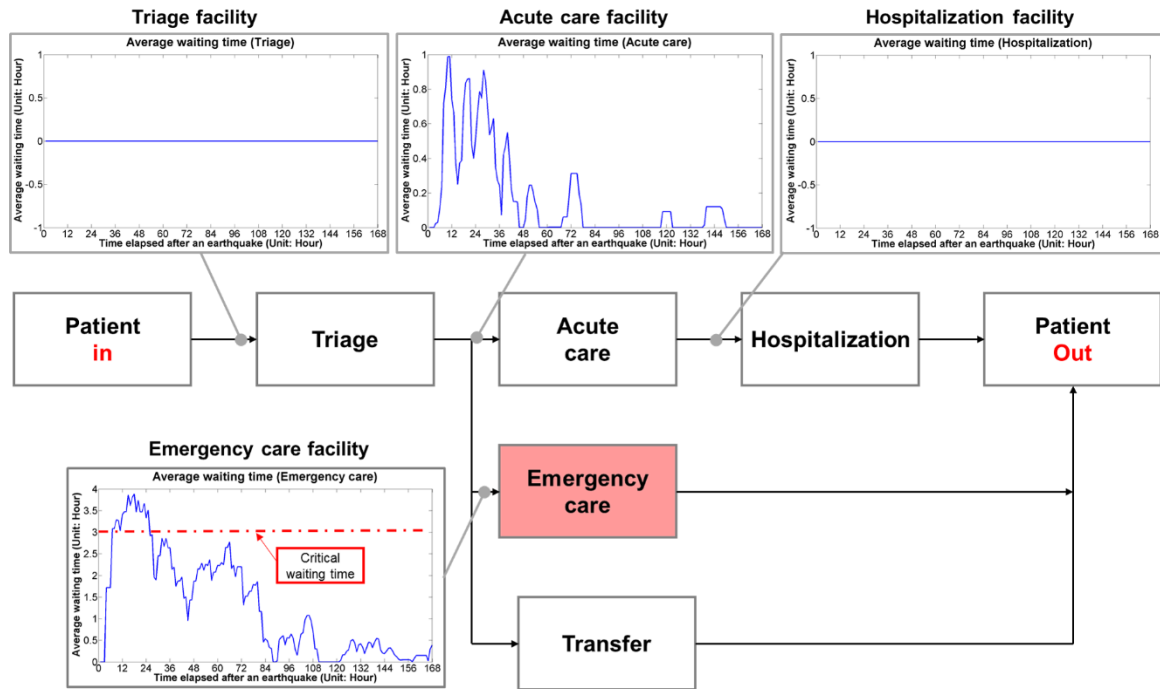
Figure 4-30 Average Patient Waiting Time in Each Medical Facility (Case i: Standard performance level and Case ii: 60% reduced performance level)

<u>- Emergency care facility</u>

The operation of an emergency care facility depends on its supporting infrastructure units, i.e., medical team, electricity, and water units. In this case study, the medical resources, i.e., beds and medical teams, are assumed to have enough capacities to achieve the system goal[9]; therefore, the focus is placed on the assessment of the resulting strain capacities of the two utility units, i.e., water and electricity, based on the imposed stress on the facility. Figure 4-31 illustrates the stress and strain analysis of the utility units for an emergency care under the scenario i. As shown in Figure 4-31, the power unit cannot provide sufficient electricity for the emergency care facility as required for the first 38 hours after an earthquake while the water unit cannot supply required water for the first 14 hours after an earthquake.

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[9] The excess of number of patients above the capacities of medical resources is transferred to other hospital (See the description about Transfer option in Section 4.4.6).
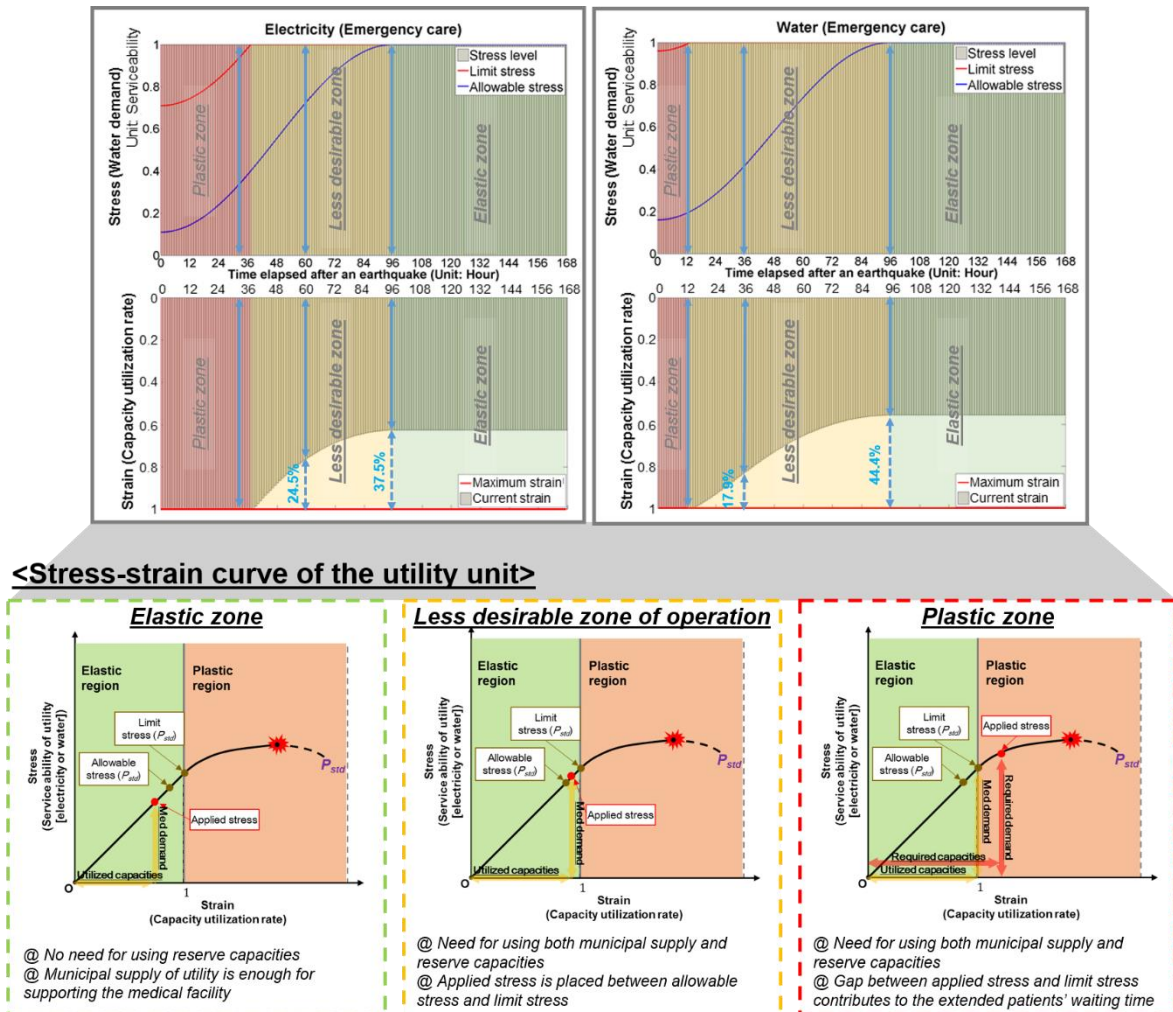
Figure 4-31 Stress-Strain Analysis of Utility Units for an Emergency Care Facility
(Scenario i)

Since in this timeframe, the utility units are not stretched out above their full strain of 1.0. i.e., entering the plastic zone, the gap in strain capacities of utility units is generated. The generated gap in the strain capacities results in the increase in the number of patients waiting throughout the simulation time. Since the accumulation of the backlog of the strain capacities makes it difficult for the emergency care to achieve the system goal, this zone is called as the "Plastic zone." During that timeframe, as the emergency care facility was not supported with the required utility service, the number of patients the medical team can treat during the unit time can be limited. As municipal supply of utility for the hospital gets

restored with time, both utility units are returned to "elastic zone" through "less desirable zone of operation."

In terms of strain capacities of utility units, Figure 4-31 shows the improvement in the strain capacities of power and water units since the municipal supply is restored with time. In the case of the power unit, the strain in plastic zone is required to be stretched out to its full strain of 1.0 in response to the required power demand of 100% serviceability. However, as time goes by, less strain is required even in response to the same demand of serviceability of 1.0. For example, at the simulation time 60 hours, because of the 24.5% improvement of strain capacities, only 0.655 of strain is required while 0.625 strain is needed because of the further improvement at 96 hours. In the case of the water unit, the strain of 0.821 at 36 hours and the strain of 0.556 at 96 hours are required in response to the water demand of 100% serviceability.

Figure 4-32 shows the stress and strain of the utility units for an emergency care facility in Scenario ii. Like Scenario i, the utility units are required to maintain at the 100% serviceability throughout the simulation time. Since the result of the utility units is the same with Scenario i, the discussion for the utility units in Scenario ii is the same with Scenario i.
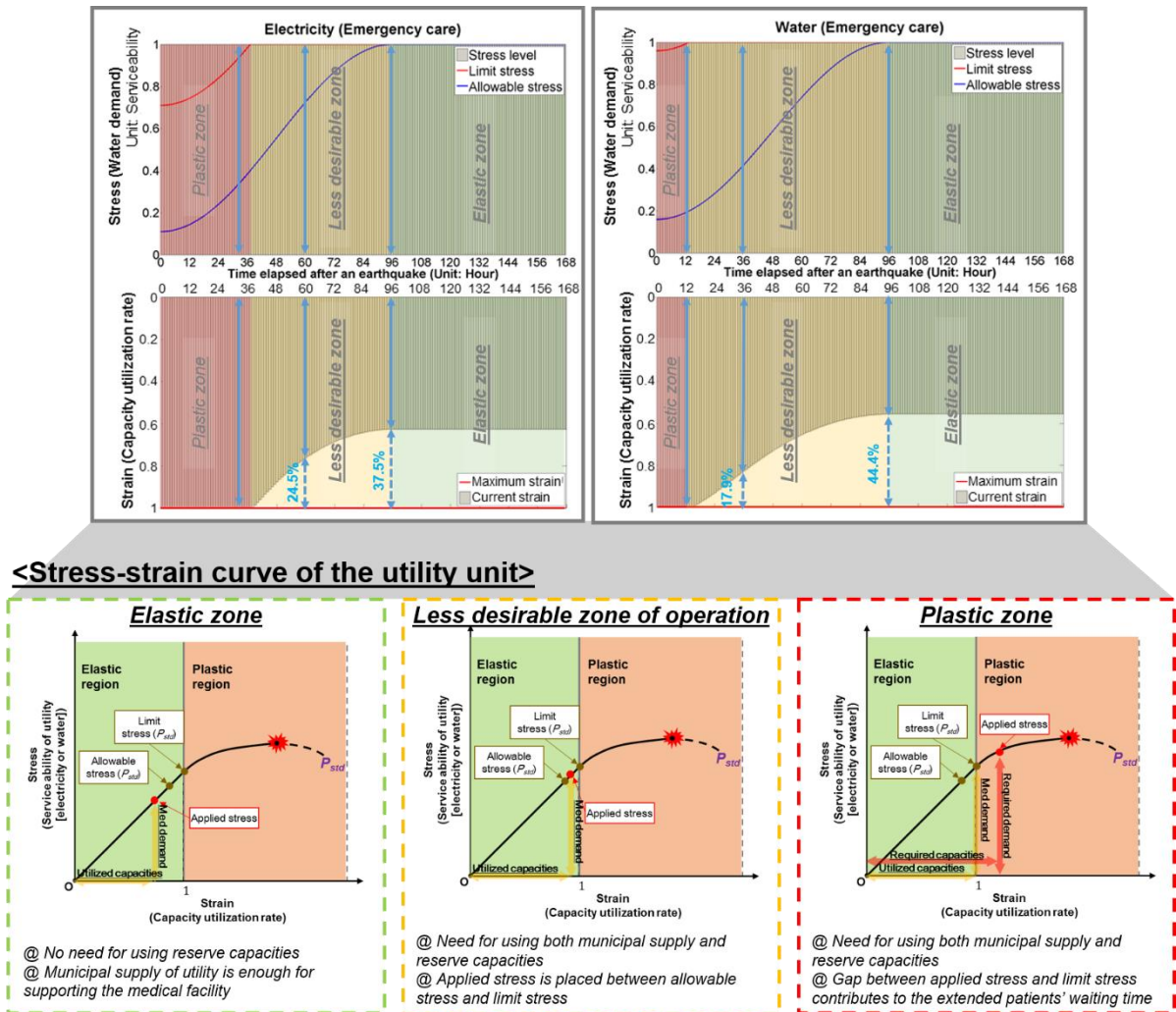
Figure 4-32 Stress-Strain Analysis of Utility Units for an Emergency Care Facility
(Scenario ii)

As discussed in Section 4.4.1 and 4.4.2, the emergency care facility is a coupled system, i.e., interlinked to other supporting infrastructure units. That is, the inappropriate supports from any infrastructure units will serve as a resource that limits the functioning of the medical facility. Figure 4-33 shows the stress and strain analysis of this coupled system. In order to achieve the required treatment time before serving patients, medical team unit may have to place certain demand on the utility services which exceeds their strain capacities (① in Figure 4-33). In turn, depending on the available serviceability of utility services, the medical teams are able to treat their patients thereby adjusting its treatment productivity. The delay of medical treatments due to insufficient utility service will move additional

patients to successive unit hour, which will generate more utility demands for treating more patients in time (② in Figure 4-33).
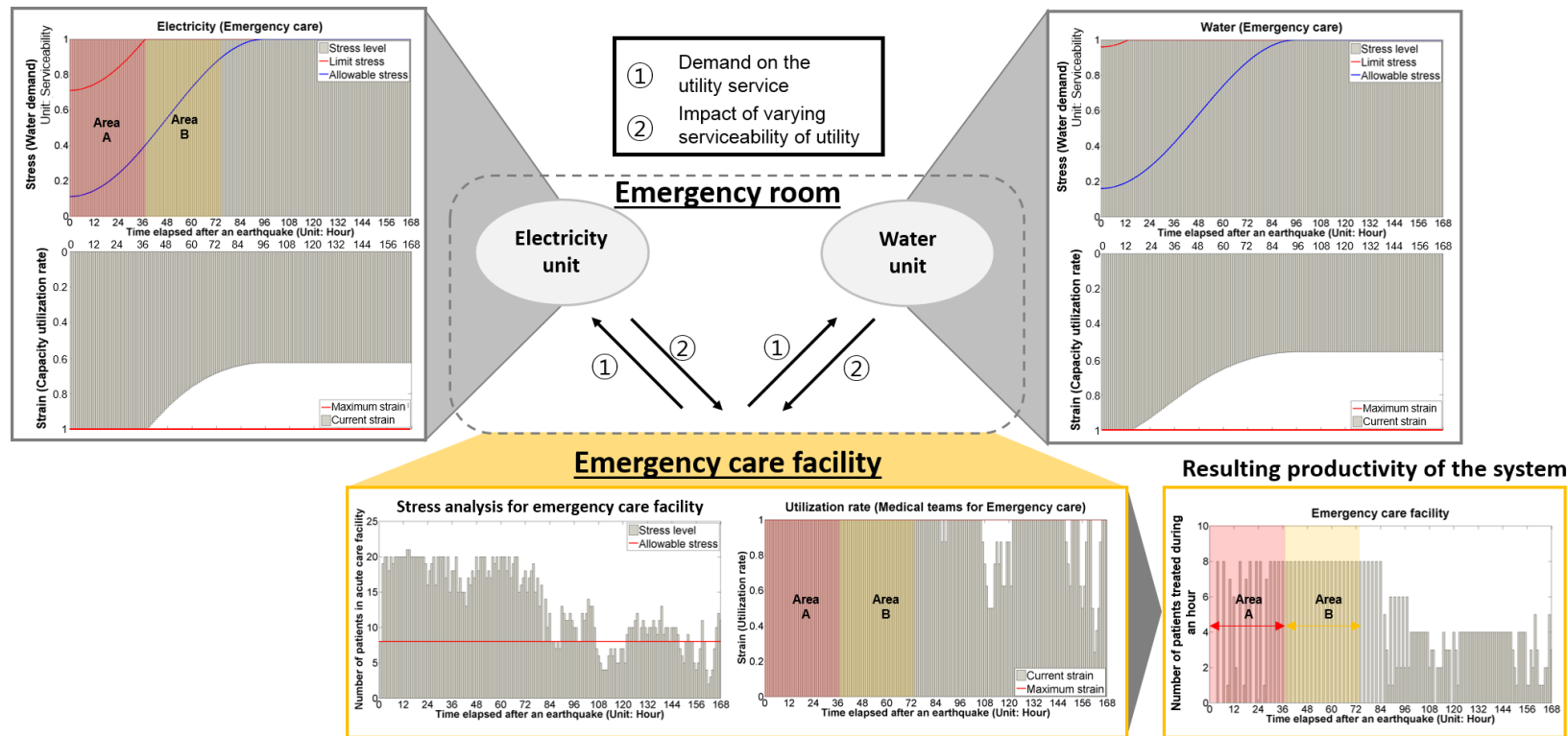
Figure 4-33 Stress and Strain Analysis of the Coupled Acute Care System (Scenario i)

As shown in Figure 4-31 and 4-33, the electricity unit cannot provide sufficient power for the operation of the emergency care facility during the first 38 hours, which dominates the functioning of the emergency care facility (Area A in Figure 4-33). After 38 hours, both the power and water unit can provide required service for the emergency care facility (Area B in Figure 4-33). During the same timeframe of 38 hours (i.e., Area A and Area B), the strain of the emergency care facility is required to maintain at the full strain of 1.0 since there are so many patients in the emergency care facility above its capacities of 8 patients (See the graph "Stress analysis for emergency care facility" in Figure 4-33). However, since the function of the medical facility in Area A is limited by the insufficient power service, the productivity of the emergency care facility is much less than the productivity of treatment in Area B where both power and water demands are fully satisfied (See the graph "Resulting productivity of the system" in Figure 4-33). Since the treatment time for patients is extended because of the insufficient utility, the space within Area A is sparser than Area B in the graph "Resulting productivity of the system," Figure 4-33, which means less patients are discharged within the same timeframe. In other words, the strain capacities of the emergency care facility in Area B is higher than its strain capacities in Area A.

Figure 4-34 shows the result of stress and strain of the emergency care facility under Scenario i. It is important noting that the number of patients waiting, i.e., the backlog of strain capacities of the emergency care facility, and the patients' average waiting time are different even within the same timeframe of Area A and Area B; Area B has less the number of patients waiting and smaller patients' waiting time.
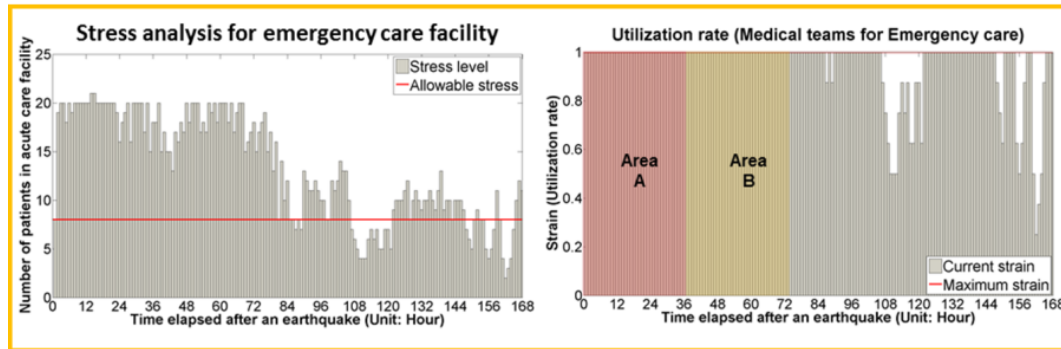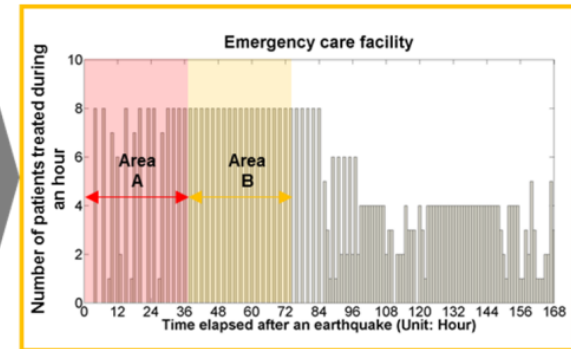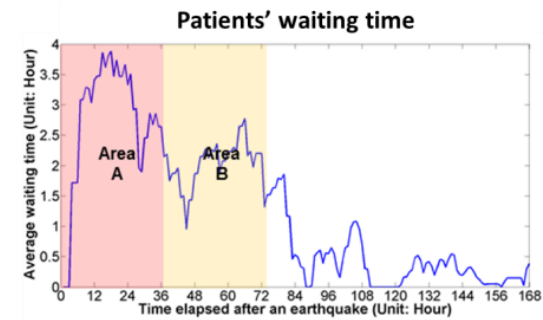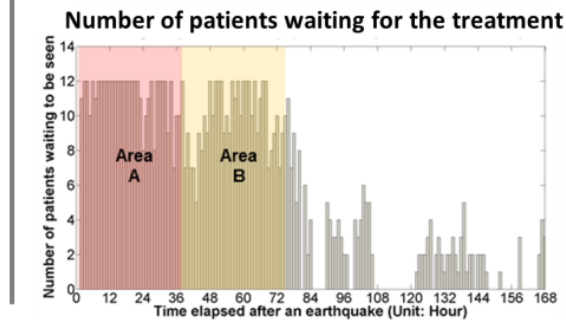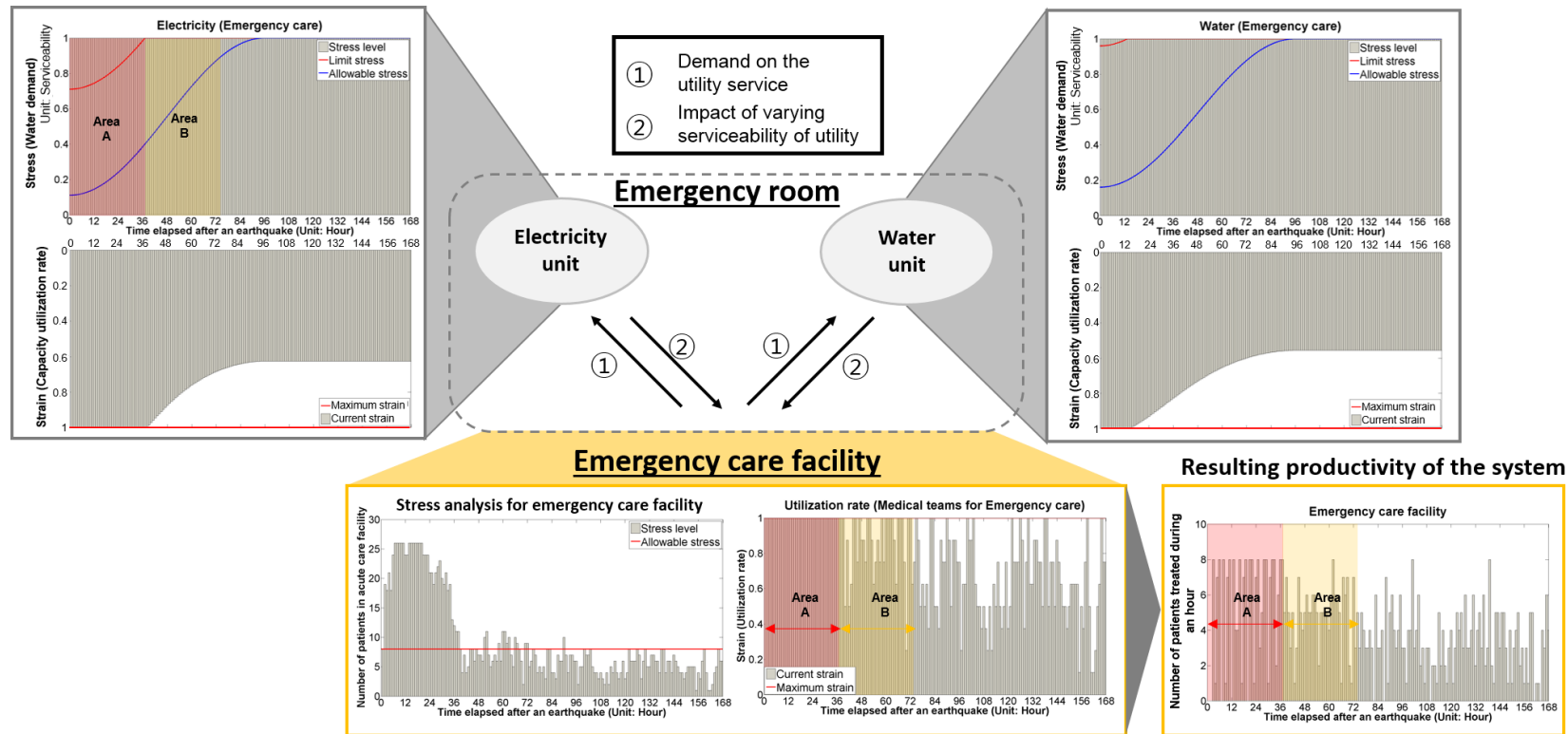
Figure 4-34 Outputs of the Stress-Strain Assessment for the Emergency Care Facility (Scenario i)

Figure 4-35 shows the stress and strain analysis of the coupled emergency care facility system in Scenario ii. In scenario ii, the treatment time for patients is reduced to 60% of the standard treatment time, which mitigate the treatment operation delayed by insufficient supply of utility units, i.e., water and electricity. It is important to note that like Scenario i, Area A and Area B are set based on the plastic zone of the power unit, but unlike Scenario i where the strain of the emergency care facility is required to be the full strain of 1.0 in all of the two areas, only Area A is required to remain the full strain of 1.0 while there is surplus strain capacities for sometimes in Area B in Scenario ii. In other words, reduced treatment time, i.e., lowering performance level, helps to reduce the number of patients waiting, i.e., the backlogs of the strain capacities.

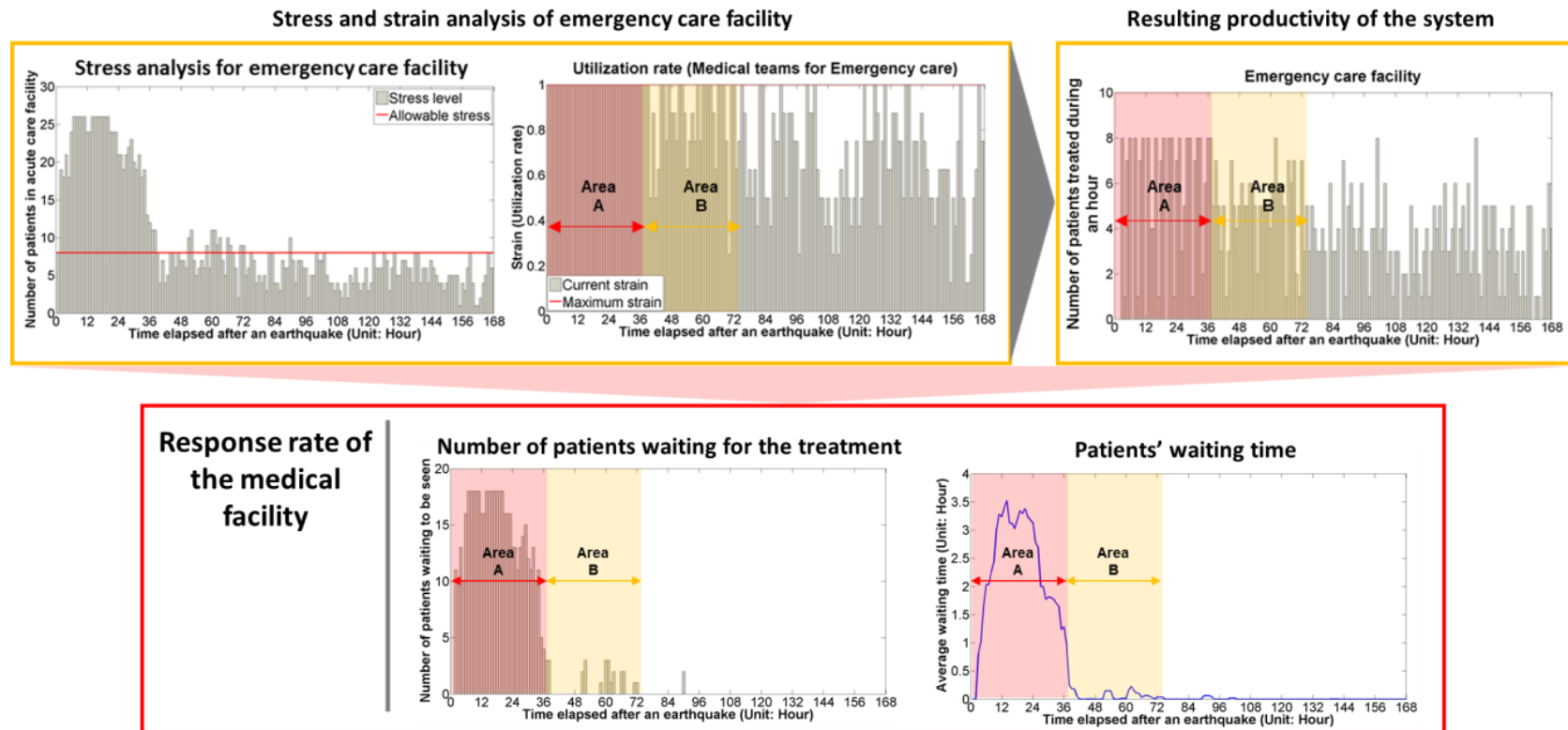Figure 4-35 Stress and Strain Analysis of the Coupled Emergency Care System (Scenario ii)

Figure 4-36 Outputs of the Stress-Strain Assessment for the Emergency Care Facility (Scenario ii)

Figure 4-36 demostrates that there are much less patients who are waiting for the treatment in Area B than in Area A. Also, compared to Scenario i, the patients' average waiting time is reduced to 3.526 hours from 3.885 hours in Scenario i. Figure 4-37 shows the comparison of the post-earthquake operation of the emergency care facility under each scenario. As shown in Figure 4-37, by lowering the performance level, i.e., reducing the treatment time, the emergency care facility is able to improve the strain capacities as the strain in Area A is required to be the full strain of 1.0 in both scenarios, but more number of patients are treated in the Area A, Scenario ii, than in the Area A, Scenario i. The improvement in the strain capacities of the facility leads to the reduction in patients' waiting time.
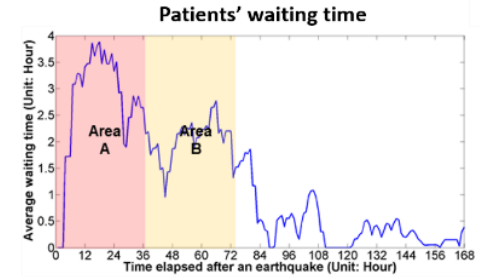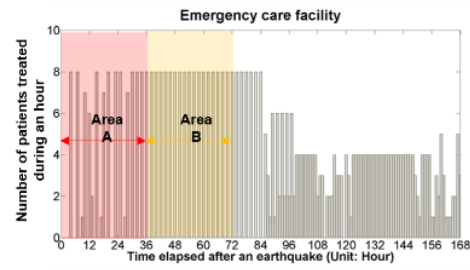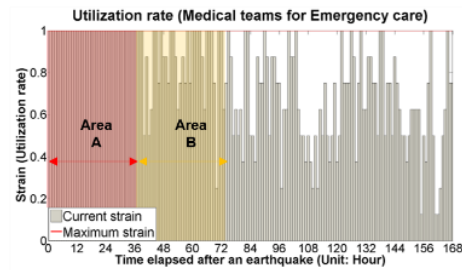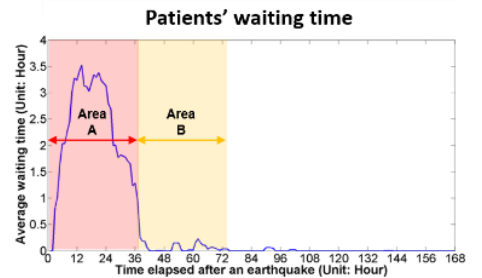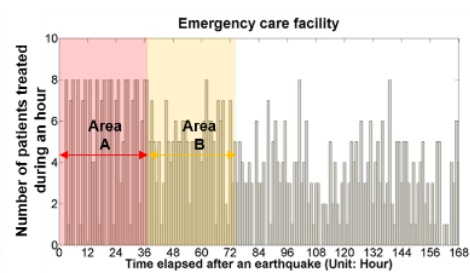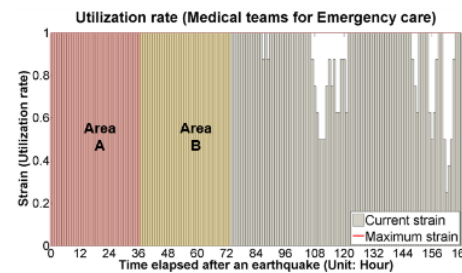
Figure 4-37 Comparison of the Operations of the Emergency Care Facility under Two Scenarios (Scenario i VS Scenario ii)

As a strategies, if the emergency care facility reduces the treatment time for patients, the facility can cover more patients even with the same resources. However, even in Scenario ii, the average patients' waiting time, 3.526 hours, is above its critical waiting time, 3 hours. In the next section, the development of strategies is illustrated based on Scenario ii.

4.4.8   Development of Strategies for Relieving Stress

This section describes how the developed stress and strain assessment tool helps in developing mitigation and preparation strategies. The process of developing these strategies is illustrated in Figure 4-38. As the first step, the limiting resource(s) among the coupled infrastructure system, i.e., electricity in this case, need(s) to be identified. Based on the stress and strain analysis, the gap in the strain capacities of the limiting resource(s) is determined. Then, more resources, e.g., bottled water for the water unit and a portable generator for the electricity unit, were added to improve the limit stress of the limiting resource(s) up to the next limiting resource. After re-identifying the limiting resource(s) and the gap that needed to be filled, relevant resources were added. In the last stage, the functioning of the facilities was assessed again in terms of patient waiting time. This process enables a sensitive analysis varying the added capacities to the limiting resource(s), which helps emergency managers to know what stress level they need to mitigate based on the resulting average patients' waiting time.
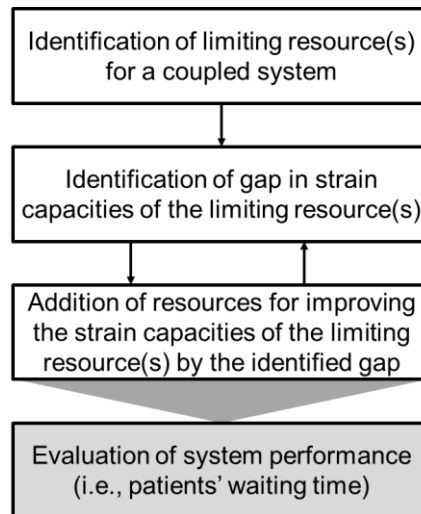
Figure 4-38 Flow for Developing Strategies for Relieving Stress

i) Identification of limiting resource(s) for a coupled system

Limiting resources are defined as the infrastructure units in which the required strain exceeds the full strain of 1.0 thereby generating the backlogs of resources in supporting the operation of the facility. Among the limiting resources, the infrastructure units, the gap of which has the largest impact on the strain capacities of the medical facility, is the dominating limiting factor for which emergency managers mainly need to take measures. According to Figure 4-32 and Figure 4-35, the electricity unit for the emergency care facilities is the dominating limiting factor while the water unit is the limiting factor after the power unit. Thus, the development strategies will be implemented focusing on the power facility first, and then, if needed, the further strategies are designed for both power as well as water units to achieve the system goal of treating patients within their critical waiting time of 3 hours.

ii) Identification of gap in strain capacities of the limiting resource(s)

Table 4-14 shows the applied stress on electricity and water units with its limit stress for the emergency care in Scenario ii. Since the utility demand remains at the serviceability of 100% throughout the simulation time while the municipal supply of utility is restored to the pre-earthquake level with time (See Figure 4-32 and Figure 4-35), the gap at the

simulation time of 1 hour is the largest gap in the limit stress of utility units for the emergency care facility.

Table 4-14 Gap in the Limit Stress of Power and Water Units for the Emergency Care Facility

Simulation time (hr)		1	2	3	4	5	6	7	8
Electricity	Applied stress (Serviceability) [A]	1	1	1	1	1	1	1	1
	Limit stress (Serviceability) [B]	0.710	0.711	0.712	0.714	0.716	0.718	0.721	0.725
Gap (= [A]-[B])		0.290	0.289	0.288	0.286	0.284	0.282	0.279	0.275
Water	Applied stress (Serviceability) [A]	1	1	1	1	1	1	1	1
	Limit stress (Serviceability) [B]	0.960	0.961	0.962	0.963	0.965	0.968	0.971	0.974
Gap (= [A]-[B])		0.040	0.039	0.038	0.037	0.035	0.032	0.029	0.026

As shown in Table 4-14, the largest gap in power units for the emergency care facility is the serviceability of 0.290 (29.0%) while the largest gap in water units for the emergency care facility is 0.040 (4.0%). Since the utility unit which has the larger gap in the limit stress dominates the operation of the entire medical facility, the strategy for mitigating excessive stress is designed for the power facility with the range from the serviceability of 0 to the serviceability of next limiting resource level, i.e., water, 0.250. The added capacities of power units above the serviceability of 0.250 do not influence the operation of the emergency care facility since water units start dominating the operation of the medical facility.

iii) Addition of resources to improve the strain capacities of the limiting resources and iv) evaluation of system performance

Based on the stress and strain analysis, emergency managers are able to know which infrastructure units are limiting resources and what stress level they need to mitigate in terms of the system goal, i.e., keeping patients' waiting time within their critical waiting time. In order to strengthen the benefits of using the stress and strain assessment in making strategies, a sensitivity analysis is conducted varying the added capacities to electricity unit.

The range of added capacities is the serviceability level of 0% to 25%. Since other medical facilities, i.e., triage and acute care facility, also rely on the power and water units, the effects of added capacities on the operation of other facilities is represented in terms of patients' waiting time. Table 4-15 and Figure 4-39 illustrates the results of the sensitivity analysis.

Table 4-15 Effects of Added Capacities on Patients Waiting Time in Service Facilities

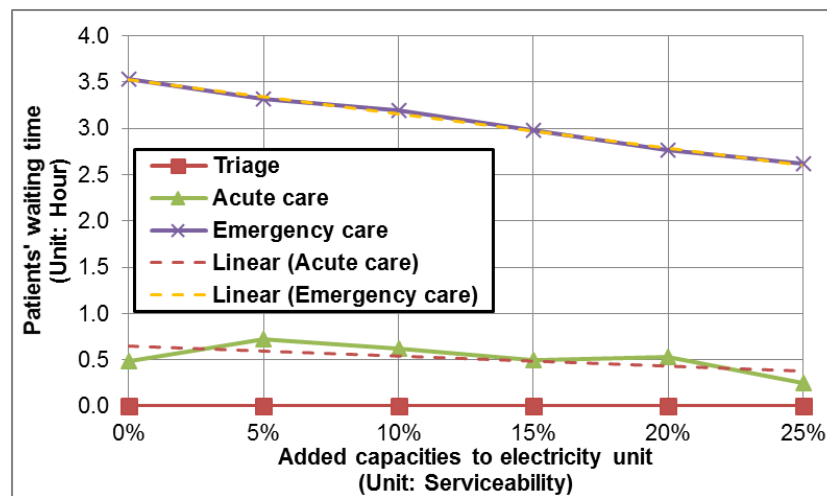| Added capacity to electricity unit		0%	5%	10%	15%	20%	25%	30%
Triage	Waiting time (hr)	0	0	0	0	0	0	0
Acute care	Waiting time (hr)	0.482	0.724	0.621	0.495	0.535	0.245	0.245
Emergency care	Waiting time (hr)	3.526	3.315	3.189	2.984	2.761	2.614	2.614

Figure 4-39 Effect on Varying Added Capacities to Electricity Units

As more capacities is added to the power units, Figure 4-39 shows the trends of decreasing the average patients' waiting time in the emergency care facility and acute care facility. For the development of strategies for the emergency care facility, emergency managers may choose 15% of serviceability to add since the average patients' waiting time starts being within the critical waiting time of 3 hours.

Unlike the emergency care facility which shows the consistent trends of decreasing patients' waiting time, the acute care facility has two times of increasing patients' waiting time even

by adding more capacities to the power unit. This is because the arrival rate of patients varies following the predefined exponential distribution; therefore, even though the productivity of medical treatment is improved by the added capacities to the power unit, the random arrival rate of patients could increase the patients' waiting time.

As shown in Figure 4-40, in the case where the capacities corresponding to 5% of serviceability is added to the power unit for the acute care, there are two peak patients' waiting times: 0.7085 at the simulation time of 9 hours and 0.7245 hours at the simulation time of 23 to 24 hours (a) in Figure 4-40) while there is only one peak time of 0.4824 hours in the situation of no strategies (b) in Figure 4-40).
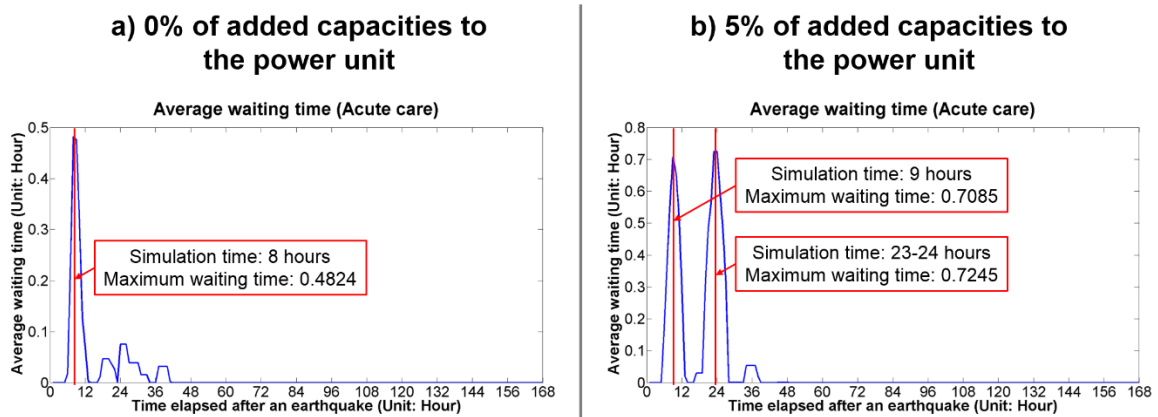

Figure 4-40 Average Patients' Waiting Time [a): No Strategies and b) 5% of Added Capacities to the Power Facility]

Figure 4-41 demonstrates the randomness of patients' arrival rate. As shown in Figure 4-41, there are more patients in the case of 0.5% added capacities than in the case of no strategy; there are 6 more patients at the simulation time of 9 hours and more 14 to 16 patients at the simulation time of 23 to 24 hours in the case of 0.5% added capacities.
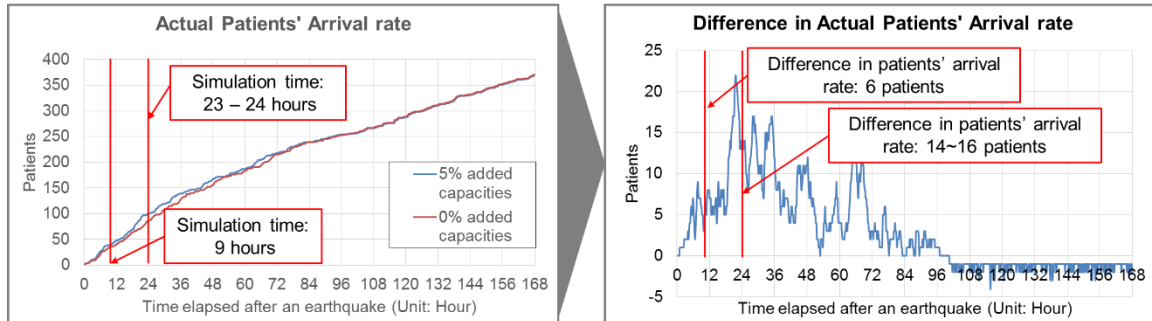
Figure 4-41 Comparison of Actual Patients' Arrival Rate

Therefore, even though the acute care facility does not show the consistent trends of decreasing patients' waiting time, the added capacities to the limiting resource, i.e., power unit, help to mitigate its excessive stress.

4.4.9   Discussion

The purpose of this section is to examine the validity of the simulation model made for the stress and strain analysis. As a way to calibrate the outputs of the simulation for the stress-strain analysis of the post-earthquake health care facility, a sensitivity analysis was conducted. As discussed in previous sections, the operation of the health care facility is evaluated based on the patients' average waiting time; if the average waiting time is greater than patients' critical waiting time of their arrival, the operation of the health care facility is not sustainable. According to Pannell (1997), a sensitivity analysis is the well-known approach for addressing the uncertain input parameters to the economic model to get robust results. The verification of the simulation model is conducted by observing the simulation outputs by animating them (Law 2008). Additionally, to validate the result of the simulation, interviews with three facilities managers who work in the health care facility were conducted.

4.4.9.1   Calibration, Validation and Verification

- Sensitivity analysis

Sensitivity analysis is widely used by economists as a way to investigate possible variations and errors in the parameters of an economic model in terms of their impacts on results

drawn from the simulation model (Pannell 1997). When a simulation approach is based on parameters that have uncertainty, then the sensitivity analysis tests the robustness of the outputs of the simulation in the face of the different variables (Pannell 1997).

Therefore, in this research, the purpose of this sensitivity analysis is to understand the sensitivity of patients' resulting waiting time of each medical facility under the condition of varying the available number of patients for transfer during unit hour. Depending on the number of patients who are available for transfer, the patient crowding in the facility is relieved via the transfer option. Therefore, the availability of the transfer plays an important role in controlling patients' waiting time.

In order to determine the range of variance for the input parameter, i.e., the number of patients transferred to other hospitals was measured every hour during the simulation. Figure 4.42 indicates how many patients are transferred from each medical facility per hour during the simulation. As shown in Figure 4-42, 10 patients as the maximum are transferred from the emergency care facility and 4 patients as the maximum are transferred from the hospitalization facility. Based on this result, the range for the input parameter is set to between 0 and 12.
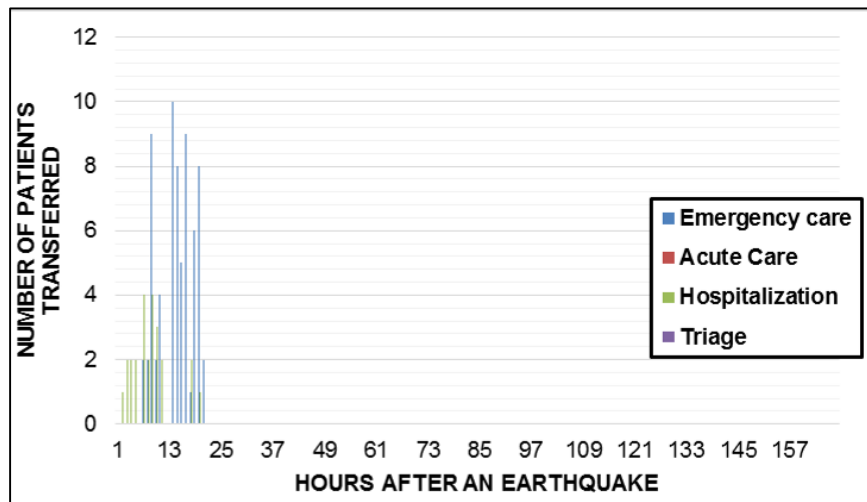
Figure 4-42 Number of Patients Transferred to Other Hospitals during the Simulation (Scenario ii)

While varying the number of patients available for the transfer within the range, the sensitivity analysis for its effect on patients' waiting time was conducted. Figure 4-43 illustrates the results of the sensitivity analysis, and Table 4-16 shows the detailed numerical values.

Table 4-16 Sensitivity Analysis (Variable: Number of Patients Available to Transfer)

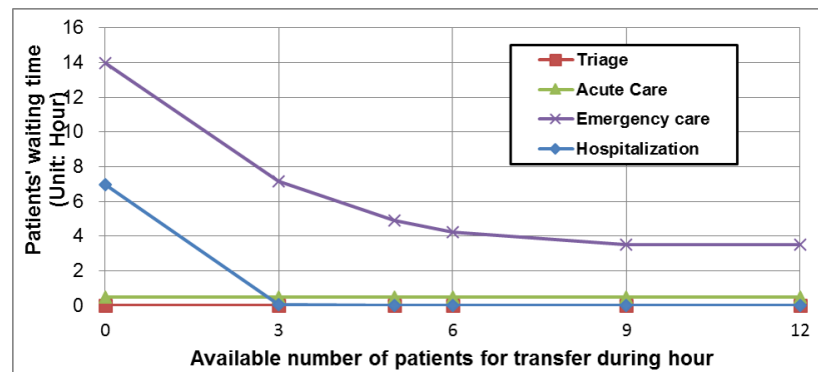| Facility	Limited number of patients transferred	0	3	5	6	9	12
Hospitalization	Waiting time (hr)	6.99	0.08	0.00	0.00	0.00	0.00
Triage	Waiting time (hr)	0.00	0.00	0.00	0.00	0.00	0.00
Acute care	Waiting time (hr)	0.48	0.48	0.48	0.48	0.48	0.48
Emergency care	Waiting time (hr)	13.98	7.14	4.91	4.25	3.53	3.53

Figure 4-43 Effect of a Varying Number of Patients Available for Transfer on Patients' Waiting Time

As the maximum number of patients being transferred per hour increases, the patients' waiting times for hospitalization, acute care, and emergency care facility decline. Since the transfer option is considered only when the number of patients needing medical services exceeds the capacities of medical resources, no change in patient waiting time implies the point when all the demands on a health care facility can be met under pre-disaster conditions, i.e., the full serviceability of all the utility service. In other words, the point when the sensitivity of patients' waiting time to varying number of patients available for the transfer disappears indicates that all of the remaining patients in the health care facility

can be met under pre-disaster conditions. By contrast, the number of patients transferred is associated with the amount of medical demands, which the medical facility cannot cover because of the insufficient capacities of medical resources, such as beds, medical staffs, etc. For the hospitalization, the gap in the serviceability of the facility is 3 patients, for acute care, the gap in the serviceability is 0 patients/hour, for emergency care, the gap in the serviceability is 10 patients/hour and for triage, the gap in the serviceability is 0 patient/hour.

- Validation and Verification

This study uses the simulation approach to validate the implementation of the developed stress and strain assessment tool. Using the discrete event simulation tool, offered by the simulation tool Anylogic, the simulation model is created. To debug and verify the designed simulation model, two techniques were used: i) running the simulation under a variety of settings for input parameters and checking the outputs; and ii) observing an animation of the simulation outputs (Law 2008). The effects of varying input parameters on the outputs of the simulation, i.e., patient waiting time and serviceability of the health care facility, is analyzed through sensitivity analysis and calibration. The latter is performed through the function of the simulation offered by Anylogic, which allows simulators to observe animated real-time outputs while running the model.

As a way to validate the results of the simulation model, the interview with experts and comparison of the simulation results with their opinion help to have face validity (Law 2008). Therefore, the interview with the three facility managers in a health care facility, a 180-licensed bed hospital, was conducted. By checking whether the overall simulation results were consistent with experts' opinions, the author tried to ensure partial validation of the simulation model.

4.5   Conclusion

In this chapter, the stress and strain assessment tool was developed for post-disaster infrastructure. Since understanding stress on a single infrastructure facility requires the consideration of multiple supporting infrastructure systems, the system-of-systems

approach was applied to finding appropriate level of systems. Based on the developed stress-strain principle for post-disaster infrastructure, the stress-strain assessment tool (SSAT) was made using a discrete event simulation technique. The proposed SSAT has the capabilities of measuring stress and strain of the post-disaster infrastructure and its supporting infrastructure unit at each time unit during the simulation, which may facilitate allocation of resources for mitigating excessive stress when there are resource constraints. Furthermore, in the development strategy section, it describes how stress and strain assessment can help to design strategies for mitigating excessive stress.

In order to validate the implementation of the developed SSAT, the SSAT was applied to a health care facility under simulated earthquake conditions. Throughout the simulated recovery process, it is observed that the health care facility experienced varying stress levels with respect to its strain capacities. To refine and calibrate the outputs of SSAT, sensitivity analysis was conducted by putting the limit and varying the number of patients available for transfer.

CHAPTER 5. SUMMARY AND CONCLUSION

5.1 Summary of Research and Results

In a post-disaster situation, the capacities of critical infrastructure which are essential for the wealth of communities are likely to be compromised by the impacts of that disaster. Moreover, the increased demands of disaster-affected communities on their infrastructures sometimes can rise exponentially. In post-disaster situations, infrastructure facilities are likely to be overwhelmed by the enormity of stress put on them, thus often providing unacceptable service for their communities. Since a degraded infrastructural service cannot support communities as well or produce recovery efforts as efficiently, it is important to ensure that post-disaster infrastructure facilities have enough capacities to cover the demands of communities, i.e., keeping their stress within those available capacities. This research thus focused on how emergency managers can better evaluate the available strain capacities based on the stresses imposed on their infrastructure in post-disaster situations and thus, if needed, take actions for improving the strain capacities in time.

Since there has been little research to date on understanding the stresses on post-disaster infrastructure, this research developed a new approach using an analogy for the stress-strain principle taken from mechanics of material. According to this developed principle, stress is associated with the demands on post-disaster infrastructure while strain is associated with its coping capacities. In order to perceive this stress and its impact on the functioning of the facility, the allowable stress and limit stress are defined as planned capacities and full strain capacities, including reserve capacities, respectively.

Depending on the applied stress for these two design factors, the functioning of a post-disaster infrastructure can be characterized with the three zones, namely, an elastic zone, a less desirable zone, and a plastic zone. In the elastic zone for a post-disaster infrastructure, the stress level is below the allowable stress while the stress level lies between its allowable

and limit stress in the case of a less desirable zone. In the plastic zone, the applied stress exceeds the limit stress of the infrastructure, so that the post-disaster infrastructure in the plastic zone will start suffering from excessive stress. Therefore, it is pivotal for emergency managers to keep the stress applied to their facilities below their limit stress during the recovery phases. The developed stress and strain principle for post-disaster facilities is further discussed using actual cases of Taiwan infrastructure facilities, i.e., a health care facility and power facility, during the 1999 Chi-Chi earthquake.

Because of the interdependent nature of post-disaster infrastructure, the application of the developed stress and strain principle to the analysis of infrastructure is very demanding. In order to address this gap, a stress and strain assessment tool (SSAT) was developed using a system-of-system approach. Furthermore, this research developed a discrete event simulation model to validate the proposed SSAT by targeting a health care facility in a post-earthquake situation. The SSAT for the post-earthquake facility measured stress and strain for each time unit and its allowable stress and limit stress, which enabled emergency managers to assess the probable stress and, if needed, design strategies for relieving that stress on its limiting resources. In the end, this research proposes a process for developing strategies that clearly illustrate how emergency managers can relieve excessive stress and thereby secure the proper functioning of a post-disaster infrastructure.

5.2   Contributions of the Research

This research developed a stress and strain principle to understand the imposed stress on a post-disaster status of infrastructure facility and analyzing its impact on the resulting service provided to disaster- affected communities. The developed principle allows for better understanding of how stress affects the functionality of an infrastructure and what operational strategies are needed to keep the applied stress within the infrastructure's strain capacities in response to growing stress. In addition, to facilitate this stress and strain analysis for post-disaster infrastructure, a stress and strain assessment tool (SSAT) was developed while considering their interdependencies. The tool measures the probable stress and strain of a post-disaster infrastructure and its supporting infrastructure units at every time unit to facilitate the development of effective strategies. Emergency managers will

know when an infrastructure is likely to suffer from excessive stress. Using the proposed stress and strain principle, SSAT enables emergency managers to identify infrastructure units that may encounter the plastic zone and to know what stress level they need to mitigate, which helps to make design strategies for relieving stress and better ensure the proper functioning of that infrastructure facility even during a post-disaster situation.

5.3   Limitations of the Research

In this research, if a target infrastructure facility is supported by lifeline infrastructure units, e.g., electricity and water, then the performance of its post-disaster infrastructure is configured using the reduced serviceability of the infrastructure units. In the metrics used for calculating that performance, it is assumed that all the infrastructure units contribute equally to supporting the infrastructure facility. As such, the infrastructure unit with the greatest reduction in serviceability for the target facility will govern the performance of that system. In reality, however, the contribution of infrastructure units may vary from infrastructure facility to infrastructure facility.

The system goal is used for the metrics for putting stress on a post-disaster infrastructure. Since the operational strategies of infrastructure facilities may be more related to their organizational goals, e.g., economic and social benefits to the facilities, more information about the operations of the infrastructure is still needed.

In order to validate the implementation of the developed stress and strain assessment tool (SSAT), this thesis applied the SSAT to a post-earthquake health care facility. As full disaster impact analysis on an external system, i.e., water and electricity, is beyond the scope of this research, the functionality of these systems for that health care facility was assumed to have certain trigonometric recovery patterns. If disaster impact analysis on the external system is fully integrated into the SSAT, it will be more helpful and have the infrastructure facilities well prepared against disasters specific to them.

As discussed in the development of strategies, due to the randomness of the input variable, i.e., patients' arrival rate, this research cannot observe the consistent trends of decreasing patients' waiting time. The higher credibility of the simulation results can be obtained

through sufficient simulation run under the condition of varying seed values as random numbers.

After the stress and strain assessment, this research discussed how that assessment helps to develop mitigation and preparation strategies. If the developed stress-strain assessment framework is used hand-in-hand with the decision-making model, which enables the selection of economically optimal strategies, that framework will assist emergency managers in finding and developing more viable stress-relief strategies.

Furthermore, the ongoing resilience of communities and organizations depends on the functioning of seven infrastructures, i.e., civil, civic, social, financial, environmental, educational, and cyber infrastructure. Since the purpose of this research is to define the stress placed on post-disaster infrastructures and to develop a new approach for evaluating it, only civil infrastructure, i.e., electricity and water, were considered. An integrated SSAT will be further explored in future research.

5.4   Recommendations for Future Research

The stress and strain principle, and its assessment tool for post-disaster infrastructure have great potential as a novel impact analysis method to use for positive disaster management. Still, further research is needed for the concept to become a more feasible and beneficial disaster impact assessment tool.

For example, to simplify the system problem, this research developed a stress and strain assessment tool, but only by considering civil infrastructures and the interaction with their dependent facility. In fact, the functioning of post-disaster infrastructure and its impact on communities should include full consideration of seven types of coupled infrastructures: Civil, civic, social, financial, educational, environmental, and cyber infrastructure. Therefore, further integration of the supports of these seven infrastructures into a disaster assessment is still needed. In addition, in the case study of the stress and strain assessment on the health care facility, impacts on external system, i.e., water and electricity, were assumed to follow certain trigonometric recovery patterns. If a disaster impact analysis is included in that assessment, the results of stress and strain analysis become more credible. In the end, when proposing mitigation and preparation strategies, this research has assumed

that required resources are available during recovery phases, but without any consideration of the economic viability of such options. In reality, depending on the allocated budget for the preparation and mitigation strategies, decision makers may take measures focusing on the critical timeframe where the infrastructure facility experience excessive stress, not on the entire recovery phases as did in this study. So, the decision-making model for selecting optimized strategy needs further study.

In addition to further research on removing the constraints of the model, more research on the application of this stress and strain assessment tool to other infrastructures is needed even though this research proposed a generalized stress and strain principle and conducted cases studies. Further, the inclusion of a GIS interface to the stress and strain assessment, especially for municipal utility systems, will improve the readability of the results by showing the spots where communities are likely to suffer most from unacceptable services supplied by infrastructure facilities under excessive stress. This analysis will enable emergency managers to develop full mitigation and preparation strategies for those specific regions that may not be receiving adequate services and restore their infrastructure services in an efficient and timely manner within the resource constraints.

BIBLIOGRAPHY

BIBLIOGRAPHY

Adachi, T., and Ellingwood, B. R. (2008). "Serviceability of earthquake-damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability." *Reliability Engineering and System Safety*, 93, 78–88.

Aghamolaei, T., Eftekhaari, T. E., Rafati, S., Kahnouji, K., Ahangari, S., Shahrzad, M. E., Kahnouji, A. and Hoseini, S. H. (2014) "Service quality assessment of a referral hospital in Southern Iran with SERVQUAL technique: patients' perspective." *BMC Health Services Research*, 14(322).

Aleisa, E. and Savar, M. (2014). "Response Time Analysis of Firefighting Operations Using Discrete Event Simulation." *UKSIM' 14 Proceedings of the 2014 UKSim-AMSS 16th International Conference on Computer Modeling and Simulation*, 330-334.

Alvarez, A. N. A. R., Roibás, D., and Wall, A. (2012). "Reserve Capacity of Public and Private Hospitals in Response to Demand Uncertainty." *Health economics*, 851, 839–851.

Arboleda, C. A. (2006). "Vulnerability Assessment of the Operation of Health Care Facilities During Disaster Events." Purdue University.

Arboleda, C. a., Abraham, D. M., and Lubitz, R. (2007). "Simulation As a Tool to Assess the Vulnerability of the Operation of a Health Care Facility." *Journal of Performance of Constructed Facilities*, 21(August), 302–312.

Asplin, B. R., Magid, D. J., Rhodes, K. V., Solberg, L. I., Lurie, N., and Camargo, C. a. (2003). "A conceptual model of emergency department crowding." *Annals of Emergency Medicine*, 42(2), 173–180.

Babu, N. P., Kuakkel, J., Loucks, D. P., and Walker, W. E. (2011). "Capacity Planning under Nonstationary Uncertainties." *Vulnerability, Uncertainty, and Risk*, 829–835.

Bacon, P. (2014). Human Security and Japan's Triple Disaster: Responding to the 2011 earthquake, tsunami and Fukushima nuclear crisis, Routledge, London.

Barbera, J. A., and Macintyre, A. G. (2002). *Medical and Health Incident Management (MaHIM) System: AComprehensive Functional System Description for Mass Casualty Medical and Health Incident Management,* George Washington University Institute for Crisis, Disaster, and Risk Management, Washington, D.C.

Baren, J. M., Rothrock, S. G., and Brennan, J. A. (2007). *Pediatric Emergency Medicine*. Elsevier Health Sciences.

Baxter, P., and Jack, S. (2008). "Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers." *The Qualitative Report*, 13(4), 544–559.

Ben-Akiva, M., Humplick, F., Madanat, S., and Ramaswamy, R. (1993). "Infrastructure Management under Uncertainty: Latent Performance Approach." *Journal of Transportation Engineering*, 119(1), 43–58.

Berg, S., and Padowski, J. C. (2007). *Overview of water utility benchmarking methodologies: from indicators to incentives*. PURC Working Paper.

Borshchev, A., and Filippov, A. (2004). "From System Dynamics and Discrete Event to Practical Agent Based Modeling : Reasons , Techniques , Tools." *22nd International Conference of the System Dynamics Society*, 959–966.

Brailsford, S., and Hilton, N. (2001). "A comparison of discrete event simulation and system dynamics for modelling health care systems." *Proceedings from ORAHS 2000*, 18–39.

Bristow, E., Brumbelow, K., and Kanta, L. (2007). "Vulnerability Assessment and Mitigation Methods for Interdependent Water Distribution and Urban Fire Response Systems." *World Environmental and Water Resources Congress 2007*, 1–10.

Bristow, E. C., and Brumbelow, K. (2012). "Simulation to Aid Disaster Planning and Mitigation: Tools and Techniques for Water Distribution Managers and Emergency Planners." *Journal of Water Resources Planning and Management*, (August), 202.

California Medical Association. (2001). *California's Emergency Services: A System In Crisis*.

Carlock, P. G., and Fenton, R. E. (2001). "System of Systems (SoS) Enterprise Systems Engineering for Information-Intensive Organizations." *Systems Engineering*, 4(4), 242-261.

Cavallo, A., and Ireland, V. (2014). "Preparing for complex interdependent risks: A System of Systems approach to building disaster resilience." *International Journal of Disaster Risk Reduction*, 9, 181–193.

Çelen, A., and Yalçın, N. (2012). "Performance assessment of Turkish electricity distribution utilities: An application of combined FAHP/TOPSIS/DEA methodology to incorporate quality of service." *Utilities Policy*, 23, 59–71.

Chang, S. E. (2003). "Evaluating Disaster Mitigations: Methodology for Urban Infrastructure Systems." *Natural Hazards Review*.

Chang, S. E., McDaniels, T. L., Mikawoz, J., and Peterson, K. (2007). "Infrastructure failure interdependencies in extreme events: Power outage consequences in the 1998 Ice Storm." *Natural Hazards*, 41, 337–358.

Chang, S. E., and Shinozuka, M. (2004). "Measuring improvements in the disaster resilience of communities." *Earthquake Spectra*, 20(3), 739–755.

Cimellaro, G. P., Fumo, C., Reinhorn, A. M., and Bruneau, M. (2009). *Quantification of Disaster Resilience of Health Care Facilities*. MCEER Technical Report, University at Buffalo, The State University of New York, Buffalo, NY.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). "Framework for analytical quantification of disaster resilience." *Engineering Structures*, Elsevier Ltd, 32(11), 3639–3649.

Clinton, W. (1998). *Presidential Decision Directive PDD-63*: *Protecting America's Critical Infrastructure*, Washinton, DC.

Cole, D. (2006). "Three contexts of planning and decision analysis for disaster mitigation in hospitals: Taiwan, Vancouver, and Los Angeles." Master's Thesis: University of British Columbia, Vancouver, BC Canada.

Cutter, S. L., Boruff, B. J., and Shirley, W. L. (2003). "Social vulnerability to environmental hazards." *Social Science Quarterly*, 84(2), 242–261.

Daniell, J. E. (2014). "The Socioeconomic Impact of Earthquake Disasters." *Earthquake Hazard, Risk and Disasters*, 203–236.

DeLaurentis, D. (2005). "Understanding transportation as a system-of-systems design problem." *43rd AIAA Aerospace Sciences Meeting and Exhibit*, (January), 1–14.

DeLaurentis, D., and Callaway, R. K. "Cab." (2004). "A System of Systems Perspective for Public Policy Decisions." *Review of Policy Research*, 21(6), 829–837.

Deshmukh, A. (2010). "Severity of Social and Economic Impact Due To Flood Damaged Critical Infrastructure on Associated Communities and Industries." Purdue University.

Deshmukh, A., Oh, E. H., and Hastak, M. (2011). "Impact of flood damaged critical infrastructure on communities and industries." *Built Environment Project and Asset Management*, 1(2), 156–175.

Disaster Research Center. (1967). *The Disaster Research Center Simulation Studies of Organizational Behavior under Stress: DRC Staff Report #6,* Disaster Research Center, the Ohio State University, Columbus, OH.

Dong, W., Johnson, L., Morrow, G., Van Anne, C., Tanaka, A., Segawa, S., Kagawa, H., Yeh, C.-H., Chou, L.-C., Wen, K.-L., Tsai, Y.-B., Chiang, W., and Hsu, W. (2000). *Event Report: Chi-Chi, Taiwan Earthquake. Risk Management Solutions.*

Dudenhoeffer, D. D., Permann, M. R., and Manic, M. (2006). "CIMS: A Framework for Infrastructure Interdependency Modeling and Analysis." *Proceedings of the 2006 Winter Simulation Conference*, 478–485.

Egan, M. J. (2007). "Anticipating future vulnerability: Defining characteristics of increasingly critical infrastructure-like systems." *Journal of Contingencies and Crisis Management*, 15(1), 4–17.

Eisenberg, D. P., Taylor, M. J., Jimenez-Rios, J. L., and Rabin, Y. (2014). "Thermal expansion of vitrified blood vessels permeated with DP6 and synthetic ice modulators." *Cryobiology*, Elsevier Inc., 68(3), 318–26.

Environment Science Center (ESC). (2007). *Greener hospitals: Improving environmental performance*. University Augsburg, Germany.

EQE International. (1999). *Chichi , Taiwan Earthquake of September 21, 1999(M7.6): An EQE Briefing,* Oakland, CA.

Eusgeld, I., Nan, C., and Dietz, S. (2011). "System-of-systems approach for interdependent critical infrastructures." *Reliability Engineering and System Safety*, Elsevier, 96(6), 679–686.

Fagan, B. (2013). "As Extreme Weather Increases, Bangladesh Braces for the Worst." http://e360.yale.edu/feature/as_extreme_weather_increases_bangladesh_braces_for_the_worst/2659 (Feb. 19, 2015).

Faust, K., Abraham, D. M., and DeLaurentis, D. (2013). "Assessment of stakeholder perceptions in water infrastructure projects using system-of-systems and binary probit analyses: A case study." *Journal of Environmental Management*, Elsevier Ltd, 128, 866–876.

Florida Department of Transportation. (2013). *2013 Quality/Level of Service Handbook*.

Fekete, a. (2009). "Validation of a social vulnerability index in context to river-floods in Germany." *Natural Hazards and Earth System Science*, 9, 393–403.

FEMA. (1999). "Example Applications of the NEHRP Guidelines for the Seismic Rehabilitation of Buildings." FEMA 276, Federal Emergency Management Agency and U.S. Army Corps of Engineers, Washington D.C.

FEMA. (2009). *Mitigation Assessment Team Report: Midwest Floods of 2008 in Iowa and Wisconsin*.

Furstenberg, F. F., and Wellford, C. F. (1973). "Calling the police: The evaluation of police service." *Law & Society Review*, 7(3), 393–406.

Gere, J. M. (2003). *MECHANICS of MATERIALS*. Thomson Learning, Inc, Belmont, CA.

Government Accountability Office. (2009). The Department of Homeland Security's (DHS) Critical Infrastructure Protection Cost-Benefit Report.

Hamilton Spectator. (2012). "India blackout ends, but nobody knows what caused world's worst power outage." <http://www.thespec.com/news-story/2251588-india-blackout-ends-but-nobody-knows-what-caused-world-s-worst-power-/> (June 6, 2015).

Holt, L. (2005). "Utility service quality—Telecommunications, electricity, water." *Utilities Policy*, Gainesville, Florida.

Hollnagel, E., Nemeth, C. P., and Dekker, S. (2008). *Resilience engineering perspectives: remaining sensitive to the possibility of failure*. Ashgate Publishing, Ltd., London.

Hwang, H. H. M., Lin, H., and Shinozuka, M. (1998). "Seismic Performance Assessment of Water Delivery Systems." *Journal of Infrastructure Systems*.

Iowa Public Television (2008). "Iowa Flood Stories 2008: Cedar Rapids." <http://www.iptv.org/iowajournal/story.cfm/396/feature> (Mar. 16, 2015).

Keating, C., Rogers, R., Unal, R., Dryer, D., Sousa-Poza, a., Safford, R., Peterson, W., and Rabadi, G. (2008). "System of systems engineering." *IEEE Engineering Management Review*, 36(3).

Kelen, G. D. and McCarthy, M. L. (2006). "The Science of Surge." *Academic Emergency Medicine*, 13, 1089-1094.

Kennedy, M., MacBean, C. E., Brand, C., Sundararajan, V., and McD Taylor, D. (2008). "Review article: Leaving the emergency department without being seen." *EMA - Emergency Medicine Australasia*, 20, 306–313.

Lam, S. S. K. (1997). "SERVQUAL: A tool for measuring patients' opinions of hospital service quality in Hong Kong." *Total Quality Management*, 8(February 2015), 145–152.

Lee, S., Han, S., and Peña-mora, F. (2007). "Hybrid System Dynamics and Discrete Event Simulation for Construction Management." *In: COMPUTING IN CIVIL ENGINEERINF, 2007*, (2007), 232–239.

Lian, C., Santos, J. R., and Haimes, Y. Y. (2007). "Extreme risk analysis of interdependent economic and infrastructure sectors." *Risk Analysis*, 27(4), 1053–1064.

Lindell, M. K., and Prater, C. S. (2003). "Assessing Community Impacts of Natural Disasters." *Natural Hazards Review*, 4(4), 176–185.

Lu, M., Dong, Z. Y., and Saha, T. K. (2005). "Transmission expansion planning flexibility." *2005 International Power Engineering Conference*, 1–6.

Luna, R., Balakrishnan, N., and Dagli, C. H. (2011). "Postearthquake Recovery of a Water Distribution System: Discrete Event Simulation Using Colored Petri Nets." *Journal of Infrastructure Systems*, 17(March), 25–34.

Maguire Group, I. (2008). *Statewide Supplemental Water Supply Feasibility Assessment Phase II: Executive Summary*.

Maidstone, R. (2012). "Discrete Event Simulation, System Dynamics and Agent Based Simulation: Discussion and Comparison." *System*, 1–6.

Maier, M. (1998). "Architecting principles for system-of-systems," *Systems Engineering*, 1(4), 267–284.

Martinez, L. S., Reich, A. J., Ndulue, U. J., Dalembert, F., Gute, D. M., and Peréa, F. C. (2013). "Employing a Community Based Participatory Research Approach to Bear Witness: Psycho-Social Impact of the 2010 Earthquake on Haitians in Somerville, MA." *Journal of Immigrant and Minority Health*, 1–7.

McGrath, J.E. (1976). Stress and behavior in organizations. M.D. Dunnette (Ed.), Handbook of industrial and organizational psychology, Rand McNally, Chicago, IL.

Mendonça, D., and Wallace, W. a. (2006). "Impacts of the 2001 World Trade Center Attack on New York City Critical Infrastructures." *Journal of Infrastructure Systems*, 12(December), 260–270.

Meyer, M. (2008). *Design standards for US transportation infrastructure: The implications of climate change. Transportation Research Board*, Washington, D.C.

Morlok, E. K., and Chang, D. J. (2004). "Measuring capacity flexibility of a transportation system." *Transportation Research Part A: Policy and Practice*, 38, 405–420.

Mostafavi, A., Abraham, D., DeLaurentis, D., Sinfield, J., and Queiroz, C. (2012). "Innovation Policy Assessment for Civil Infrastructure System-of-Systems." *ASCE Construction Research Congress 2012*, 2300–2400.

Mostafavi, A., and Abraham, D. M. (2014). "Resilience-based Planning in Civil Infrastructure Using System-of-Systems Analysis." *Construction Research Congress 2014*, 1249–1258.

Mulyasari, F., Inoue, S., Prashar, S., Isayama, K., Basu, M., Srivastava, N., and Shaw, R. (2013). "Disaster preparedness: Looking through the lens of hospitals in Japan." *International Journal of Disaster Risk Science*, 4(2), 89–100.

Naderpajouh, N., and Hastak, M. (2014). "Quantitative analysis of policies for governance of emergent dynamics in complex construction projects." *Construction Management and Economics*, 32(12), 1222–1237.

NIST NCSTAR 1A. (2008). *Final Report on the Collapse of World Trade Center Building 7*.

Nojima, N., and Kato, H. (2013). "Application of an Assessment Model of Post-Earthquake Lifeline Serviceability to Recent Earthquakes in Japan." *International Efforts in Lifeline Earthquake Engineering*, 11–18.

O'Rourke, T. D., Lembo, A. J., and Nozick, L. K. (2003). *Lessons Learned from the World Trade Center Disaster about Critical Utility Systems*. *Beyond September 11th: An Account of Post-Disaster Research*, Boulder, Colorado.

OCHA (Office for the Coordination of Humanitarian Affairs). (2013). "Philippines: Typhoon Haiyan Situation Report No. 19 (as of 29 November 2013)." 19, OCHA Philippines.

Oh, E. H. (2008). "Identification of the Impact of Critical Infrastructure on Associated Industries: Analysis of a Flood Disaster Event," Master's Thesis: Purdue University, Indiana, USA.

Oh, E. H. and Hastak, M. (2008). "Impact Analysis of Natural Calamities on Infrastructure and Industries," Proceedings of the 4th i-REC conference, April 30-May 2, 2008, Christchurch, New Zealand

Oh, E. H. (2010). "Impact Analysis of Natural Disasters on Critical Infrastructure, Associated Industries, and Communities." PhD Dissertation: Purdue University, Indiana, USA.

Oh, E. H., Deshmukh, A., and Hastak, M. (2010a). "Disaster impact analysis based on inter-relationship of critical infrastructure and associated industries: A winter flood disaster event." *International Journal of Disaster Resilience in the Built Environment*, 1(1), 25–49.

Oh, E. H., Deshmukh, A., and Hastak, M. (2010b). "Vulnerability Assessment of Critical Infrastructure , Associated Industries , and Communities during Extreme Events." *Construction Research Congress 2010*, 449–458.

Oh, E. H., Deshmukh, A., and Hastak, M. (2012). "Criticality Assessment of Lifeline Infrastructure for Enhancing Disaster Response." *Natural Hazards Review*.

Oh, E. H., and Hastak, M. (2008). "Impact Analysis of Natural Calamities on Infrastructure and Industries." *Proceedings of the 4th i-REC conference*, Christchurch, New Zealand.

O'Shea, J. S. (2007). "The Crisis in America's Emergency Rooms and What Can Be Done." <http://www.heritage.org/research/reports/2007/12/the-crisis-in-americas-emergency-rooms-and-what-can-be-done> (Mar. 15, 2015).

Okuyama, Y., and Santos, J. R. (2014). "Disaster Impact and Input–Output Analysis." *Economic Systems Research*, 26(March 2015), 1–12.

Parfomak, P. W. (2005). *Vulnerability of Concentrated Critical Infrastructure: Background and Policy Options*.

Patel, S., and Hastak, M. (2013). "A framework to construct post-disaster housing." *International Journal of Disaster Resilience in the Built Environment*, 4(1), 95–114.

Patel, S. M. (2010). "A Strategic Framework to Construct 200 Homes in 30 Days after Disaster." Master's Thesis: Purdue University, Indiana, USA.

Picou, J. S., and Martin, C. G. (2006). "Community Impacts of Hurricane Ivan : A Case Study of Orange Beach, Alabama." *Natural Hazards Center Quick Response 190*, 24(190).

Preetha, M. S. (2012). "Electricity infrastructure under stress - The Hindu." <http://www.thehindu.com/news/cities/Coimbatore/electricity-infrastructure-under-stress/article3815365.ece> (Feb. 16, 2015).

Quarantelli, E. L. (2006). Catastrophes are Different from Disasters: Some Implications for Crisis Planning and Managing Drawn from Katrina. <http://understandingkatrina.ssrc.org/Quarantelli/> (Jan. 24, 2015).

Reed, D. a., Powell, M. D., and Westerman, J. M. (2010). "Energy Supply System Performance for Hurricane Katrina." *Journal of Energy Engineering*, 136(December 2005), 95–102.

Rinaldi, S. M., Peerenboom, J. P., and Kelly, T. K. (2001). "Identifying, understanding, and analyzing critical infrastructure interdependencies." *IEEE Control Systems Magazine*, 21, 11–25.

Robert, A. (2001). *Quality issues for system operators with special reference to European regulators*. Belgian Transmission System Operators (ELIA), Brussels.

Rodríguez, H., and Aguirre, B. E. (2006). "Hurricane Katrina and the healthcare infrastructure: A focus on disaster preparedness, response, and resiliency." *Frontiers of health services management*, 23(1), 13–23; discussion 25–30.

Rose, A., and Liao, S.-Y. (2005). "Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions*." *Journal of Regional Science*, 45(1), 75–112.

Rose, A., Oladosu, G., and Liao, S. Y. (2007). "Business interruption impacts of a terrorist attack on the electric power system of Los Angeles: Customer resilience to a total blackout." *Risk Analysis*, 27(3), 513–531.

Schiff, A. J. and Tang, A. K. (2000). *Chi-Chi, Taiwan, Earthquake of September 21, 1999: Lifeline Performance,* Technology & Engineering, ASCE Publications.

Scholl, H. J. (2001). "Agent-based and system dynamics modeling: a call for cross study and joint research." *Proceedings of the 34th Annual Hawaii International Conference on System Sciences*.

Schriber, T. J., and Brunner, D. T. (2006). "Inside Discrete-Event Simulation Software: How It Works and Why It Matters." *Proceedings of the 2006 Winter Simulation Conference*, 118–128.

Shi, Y., Jin, S., and Seeland, K. (2015). "Modeling business interruption impacts due to disrupted highway network of Shifang by the Wenchuan earthquake." *Natural Hazards*, 75, 1731–1745.

Shultz, J. M., Espinel, Z., Cohen, R. E., Smith, R. G., and Flynn, B. W. (2006). *Disaster Behavioral Health: All-Hazards Training*. Center for Disaster and Extreme Event Preparedness (DEEP Center), University of Miami Miller School of Medicine, Miami, FL.

Siebers, P. O., Macal, C. M., Garnett, J., Buxton, D., and Pidd, M. (2010). "Discrete-event simulation is dead, long live agent-based simulation!" *Journal of Simulation*, 4(3), 204–210.

Soong, T. T., Author, C., Yao, G. C., and Lin, C. C. (2000). "Damage to Critical Facilities Following the 921 Chi-Chi,Taiwan Earthquake (1999-2000)." (1), 33–44.

Staal, M. A. (2004). *Stress , Cognition , and Human Performance : A Literature Review and Conceptual Framework*. Hanover, MD.

Stallings, R. A. (1970). "Hosptlal Adaptations to Disaster : Flow Models of Intensive Technologies." *Human Organization*, 29(4), 294–302.

Stokes, A.F., and Kite, K. (2001). On grasping a nettle and becoming emotional. P.A. Hancock and P.A. Desmond (Eds.), Stress, workload, and fatigue. L. Erlbaum, Mahwah, NJ.

Sultana, S., and Chen, Z. (2007). "Modeling of Flood-Related Interdependencies among Critical Infrastructures." *Geomatics Solutions for Disaster Management*, 369–387.

Sumalee, A., Luathep, P., and Lam, W. H. K. (2008). "Robust Transport Network Capacity Planning with Demand Uncertainty." *Traffic and Transportation Studies*, 408–419.

Sumari, S., and Ibrahim, R. (2013). "Comparing Three Simulation Model Using Taxonomy: System Dynamic Simulation, Discrete Event Simulation and Agent Based Simulation." *International Journal of Management Excellence*, 1(3), 4–9.

Tabish, S. A. and Qadiri, G. J. (1994). "Cost evaluation of medical gases facility at a tertiary care teaching medical institute." *Health and Population: Perspective and Issues*, 17(3&4), 219-229.

Tepas, D. I., and Price, J. M. (2001). *What is stress and what is fatigue?*. P.A. Hancock and P.A. Desmond (Eds.), Stress, workload, and fatigue, L. Erlbaum, Mahwah, NJ.

Tennessee DOH. (2007). *Rules of Tennessee Department of Health Board for Licensing Health Care Facilities*. Tennessee Department of Health Board, 1-64

Thissen, W. a H., and Herder, P. M. (2008). "System of Systems Perspectives on Infrastructures." *System of Systems Engineering: Innovations for the 21*, 257–274.

Tolone, W. J., Johnson, E. W., Lee, S.-W., Xiang, W.-N., Marsh, L., Yeager, C., and Blackwell, J. (2008). "Enabling System of Systems Analysis of Critical Infrastructure Behaviors." *CRITIS 2008 Proceedings of the 3rd International Workshop on Critical Information Infrastructures Security*, 5508, 24–35.

Transportation Research Board. (2013). *Quality of Service*, Transit Capacity and Quality of Service Manual.

Travers, D. (1999). "Triage: how long does it take? how long should it take?" *Journal of emergency nursing: JEN : official publication of the Emergency Department Nurses Association*, 25(3), 238–240.

Ullman, D. G. (2010). *The Mechanical Design Process*. (R. Srinivasan and B. Stenquist, eds.), McGraw-Hill, New York, NY.

Verni, C. (2012). "A hospital system's response to a hurricane offers lessons, including the need for mandatory interfacility drills." *Health Affairs*, 31(8), 1814–1821.

VHA Center for Engineering & Occupational Safety and Health. (2011). *Emergency Management Program Guidebook*. Washington, DC.

Wang, S., Hong, L., Chen, X., Zhang, J., and Yan, Y. (2011). "Review of interdependent infrastructure systems vulnerability analysis." *Proceedings of the 2nd International Conference on Intelligent Control and Information Processing, ICICIP 2011*, 446–451.

Warren, K. (2012). "Understanding and Managing the Threat of Disruptive Events to the Critical National Infrastructure." *Proceedings of the 30th International Conference of the System Dynamics Society*.

Wilkinson, J. (2010). "Aging sewer system under stress." <http://www.thestate.com/2010/03/14/1200071/aging-sewer-system-under-stress.html> (Feb. 19, 2015).

Woods, D. D., and Wreathall, J. (2008). Stress-strain plots as a basis for assessing system resilience. Remaining sensitive to the possibility of failure. Ashgate Publishing, Ltd., London.

World Health Organization (WHO) (2011). Hospital emergency response checklist-An all-hazards tool for hospital administrators and emergency managers. The Regional Office for Europe of the WHO.

Xiao, N., Dutta, S., Sharman, R., and Rao, H. R. (2009). "A Simulation Based Study in a Hospital Emergency Department: Capacity and Workflow Issues." *Proceedings of the Fifteenth Americas Conference on Information Systems*.

Yerkes, R. M., and Dodson, J. D. (1908). "The relation of strength of stimulus to rapidity of habit-formation." *Journal of Comparative Neurology and Psychology*, 18(5), 459–482.

Yi, P. (2005). "Real-time generic hospital capacity estimation under emergency situations," PhD Dissertation, Department of Industrial Engineering, State University of New York at Buffalo, Buffalo, NY.

Zagst, R. (2002). "Using Scenario Analysis for Risk Management," *Allgemeines Statistisches Archiv*, 86, 97-117.

Zimmerman, R. (2001). "Social Implications of Infrastructure Network Interactions." *Journal of Urban Technology*, 8(3), 97–119.

Zimmerman, R. (2003). *Public Infrastructure Service Flexibility for Response and Recovery in the Attacks at the World Trade Center, September 11, 2001*. Boulder, Colorado.

APPENDICES

Appendix A　Impact of Disrupted Lifeline Infrastructure on the Operation of the Health Care Facility

Emergency room operation (Electricity)	Emergency room operation (Water)
Hospitalization (Electricity)	Hospitalization (Water)
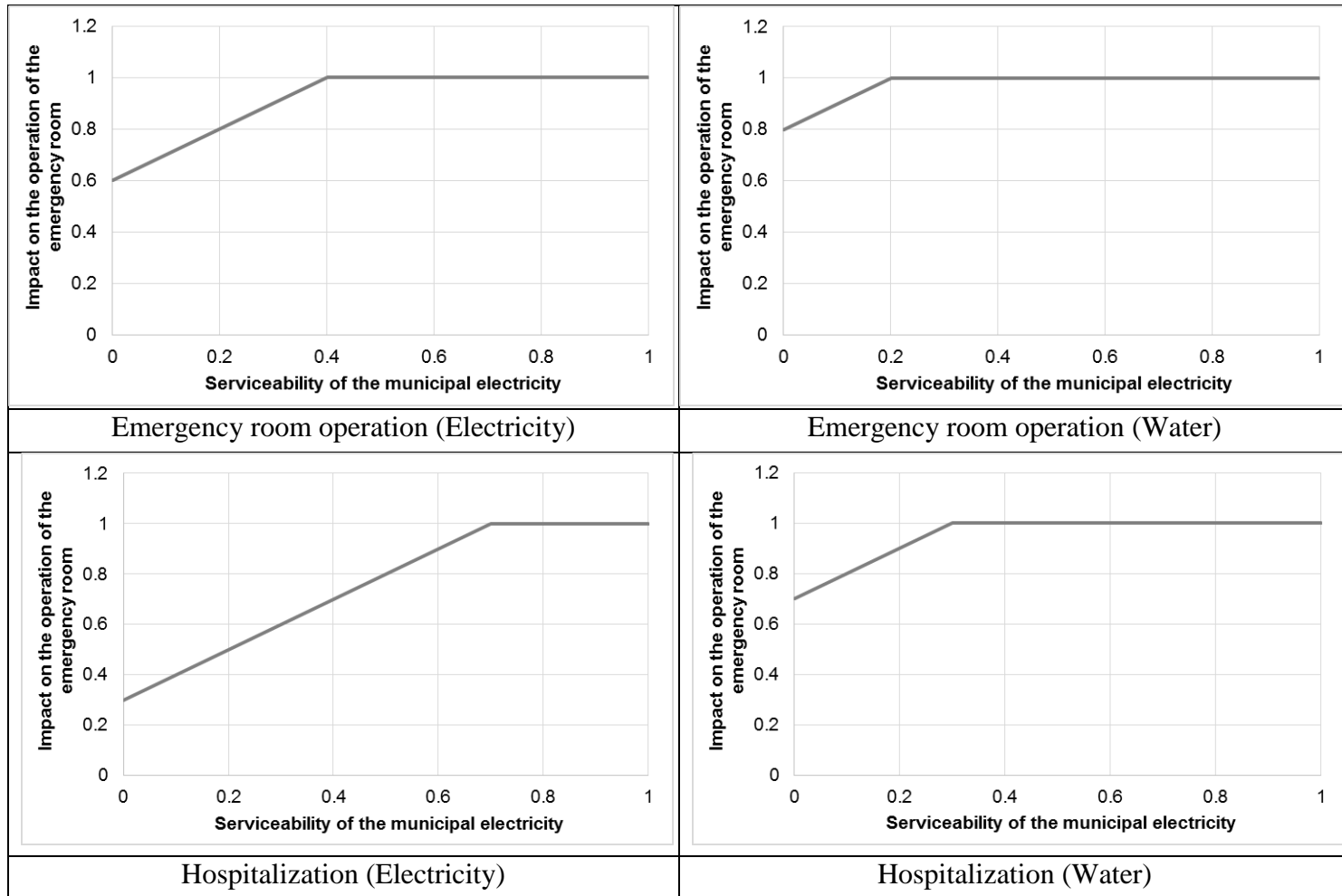
Appendix B   Stress-Strain Analysis for the Acute Care Facility
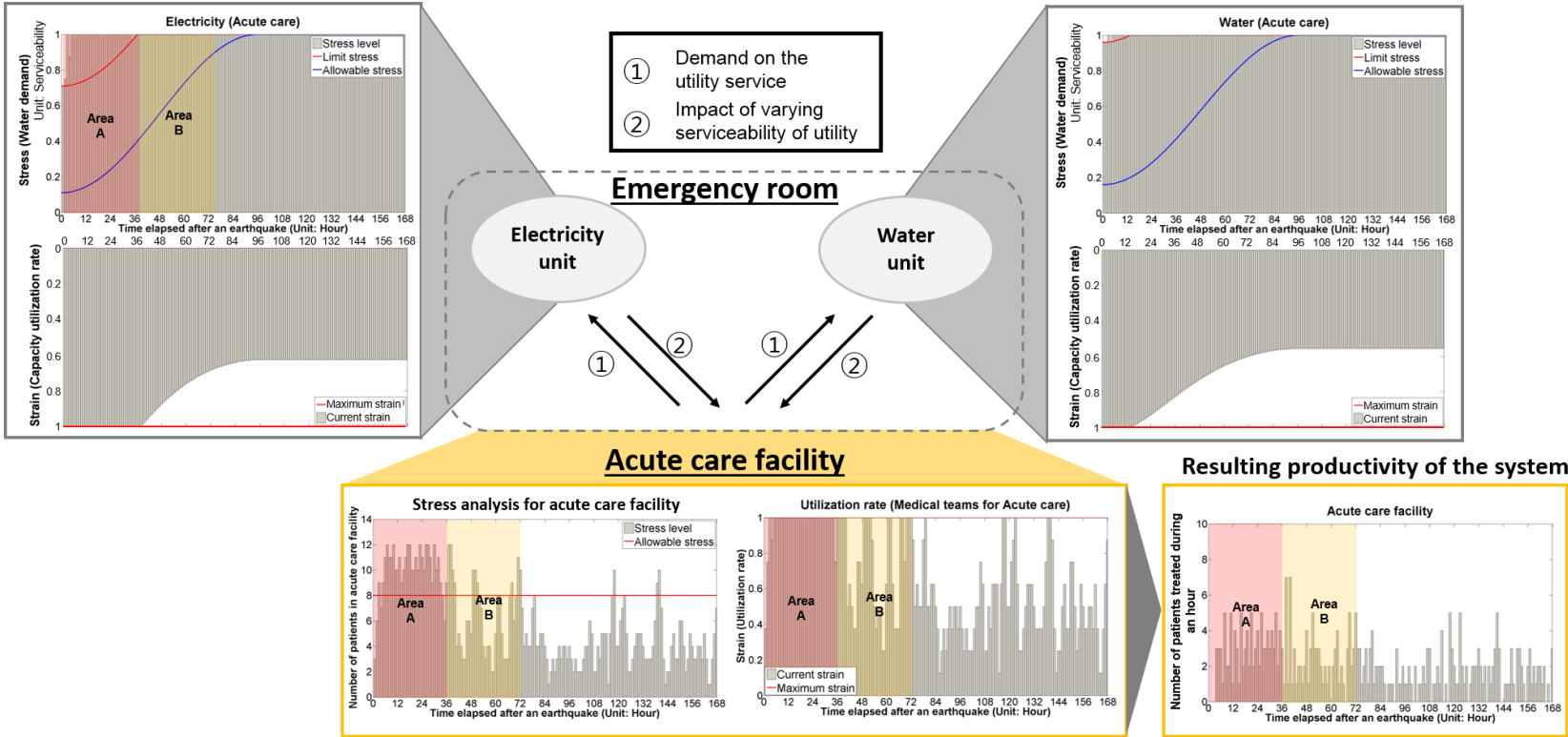
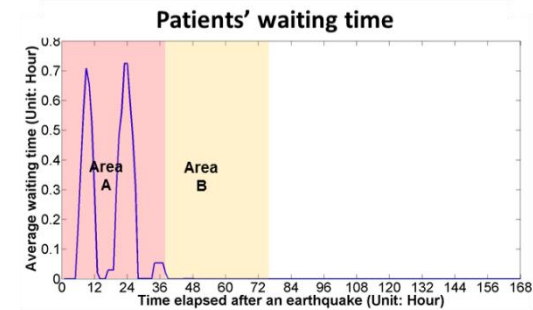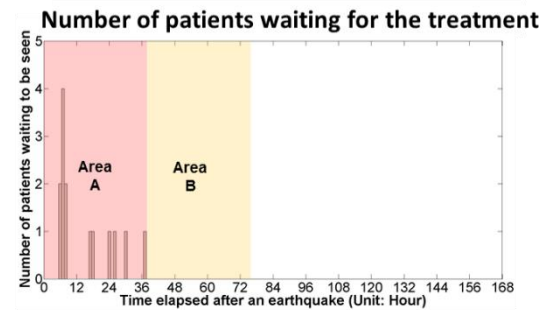Stress and Strain Analysis of the Coupled Acute Care System (Scenario i)
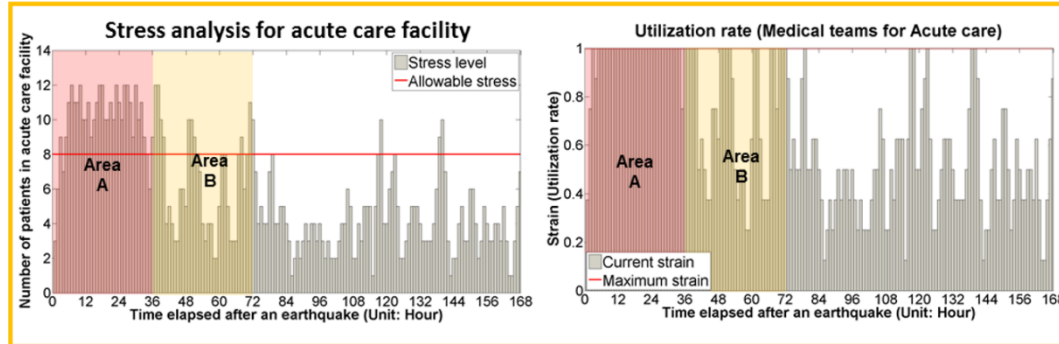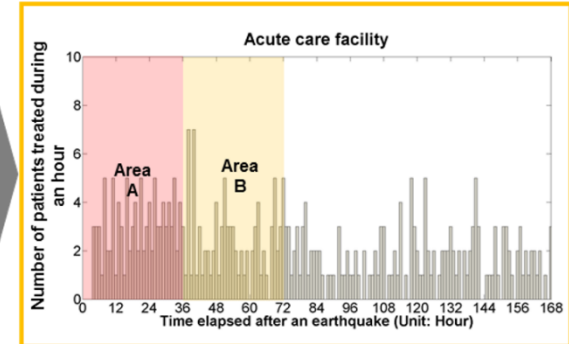
Outputs of the Stress-Strain Assessment for the Acute Care Facility (Scenario i)
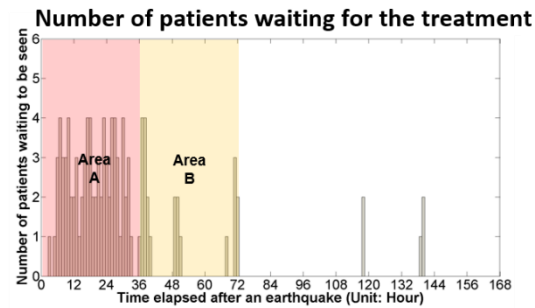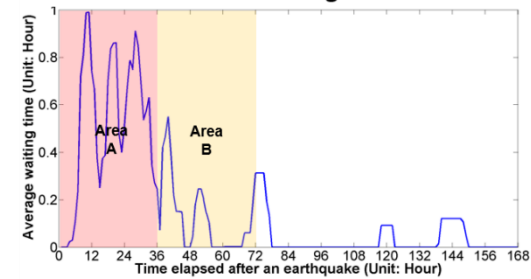
Stress and Strain Analysis of Utility Units for the Acute Care Facility (Scenario i)
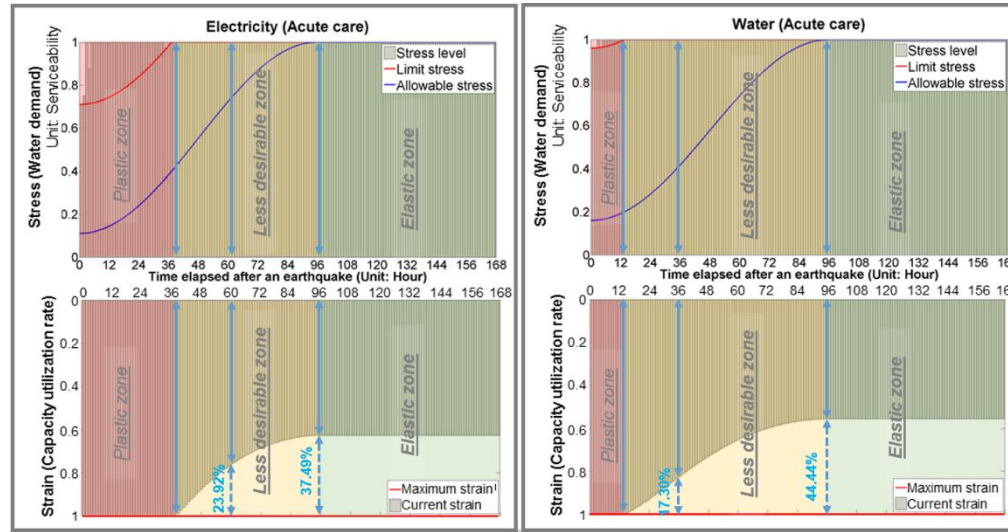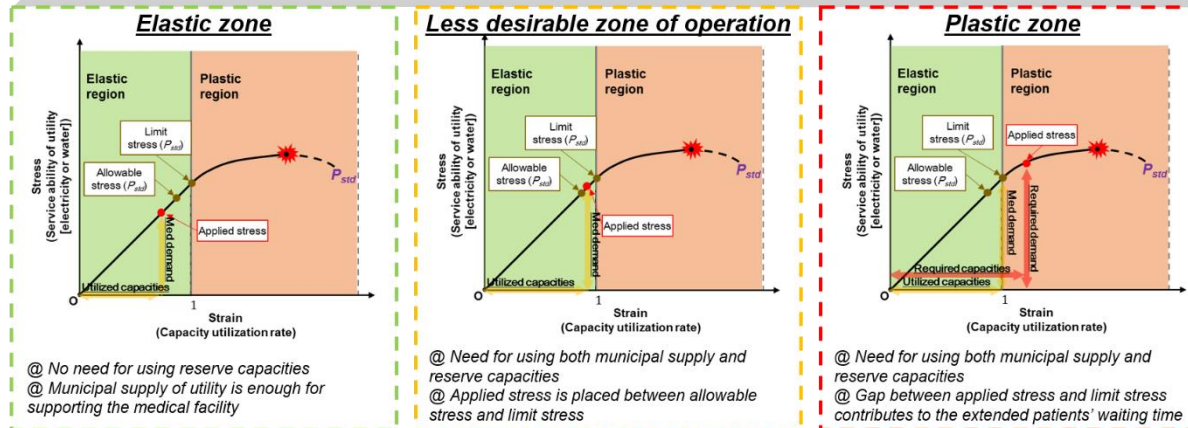
Stress and Strain Analysis of the Coupled Acute Care System (Scenario ii)
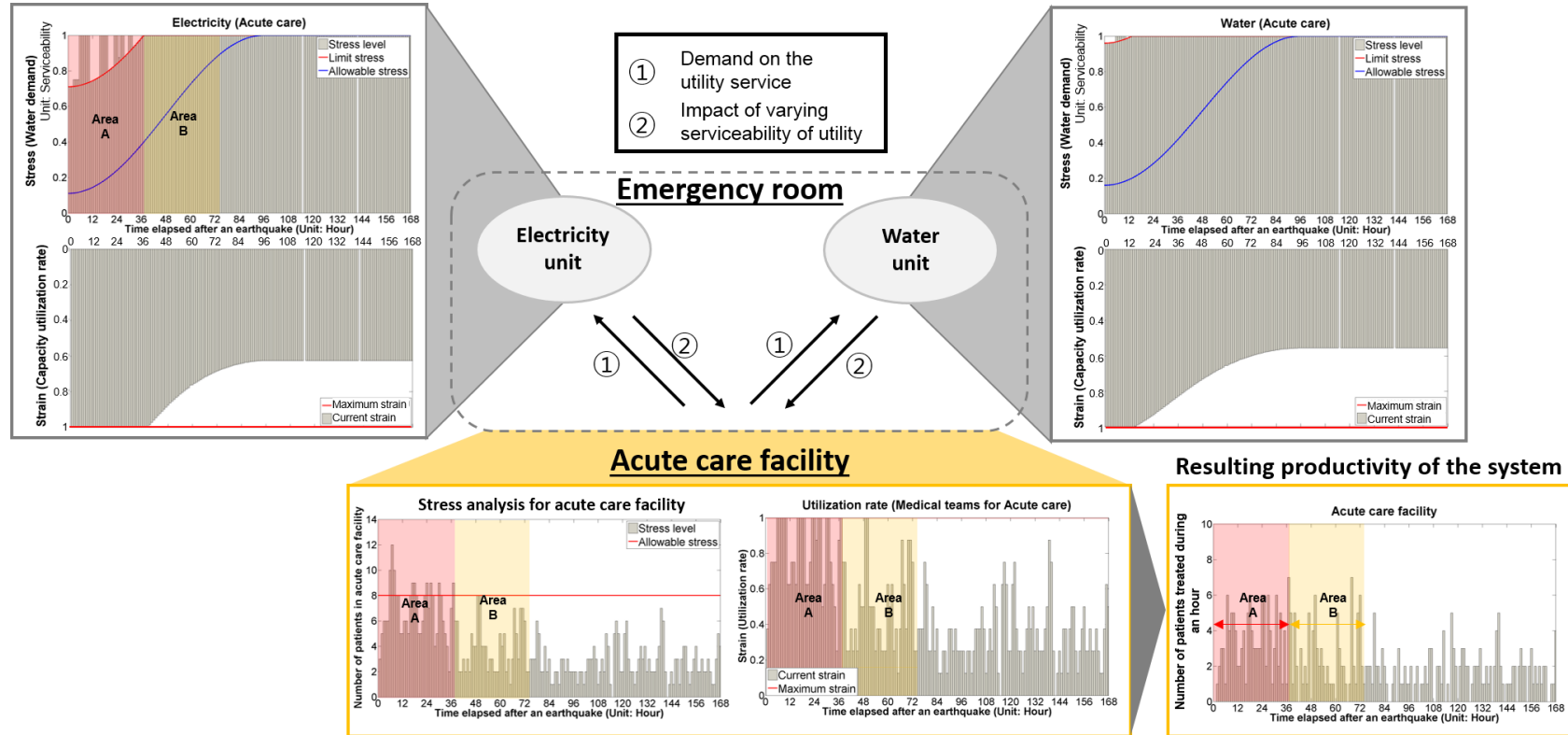
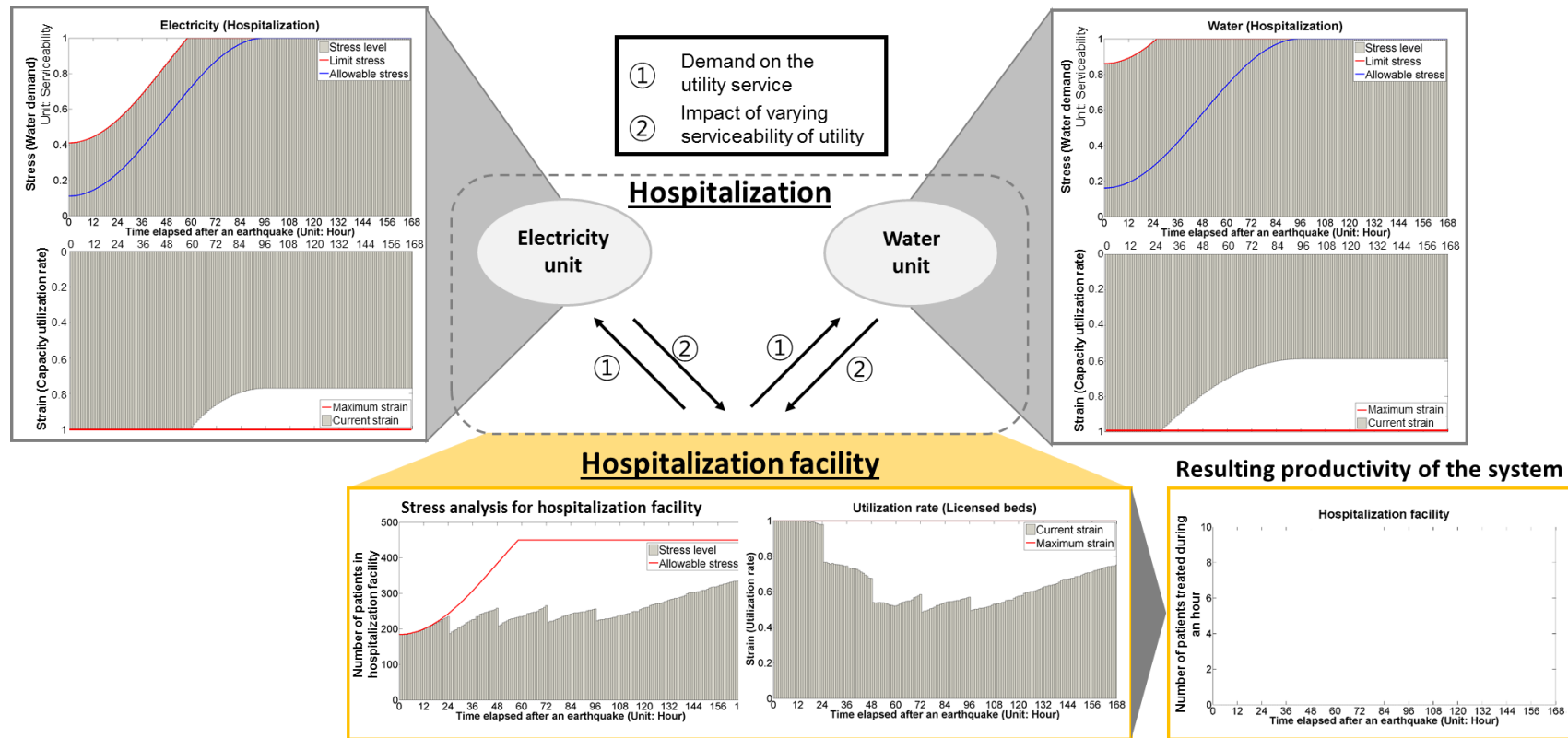Outputs of the Stress-Strain Assessment for the Acute Care Facility (Scenario ii)
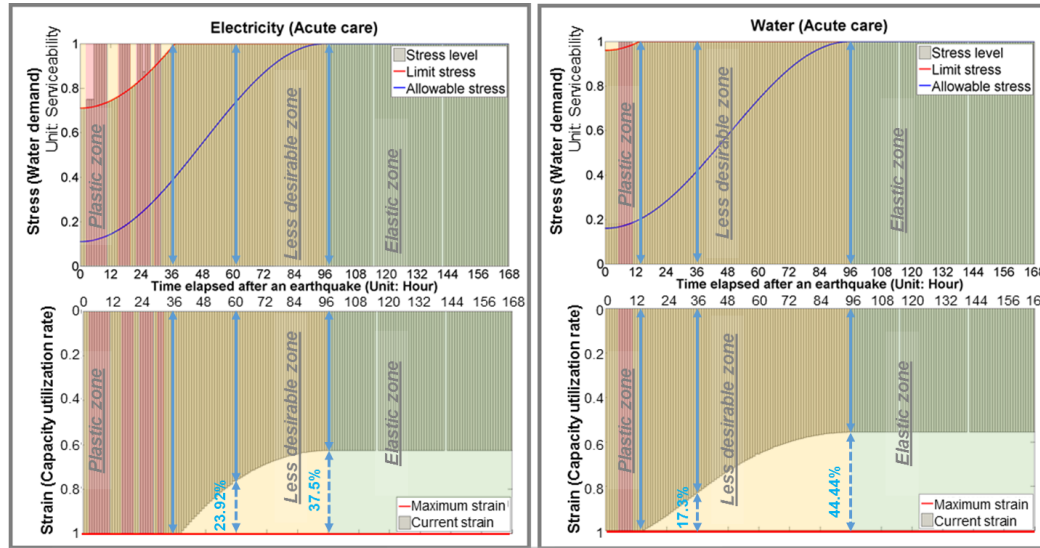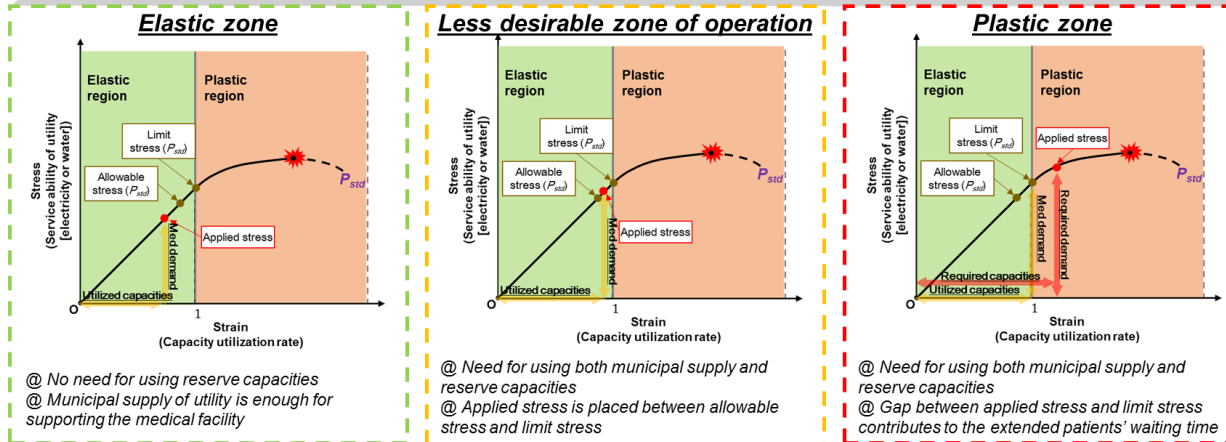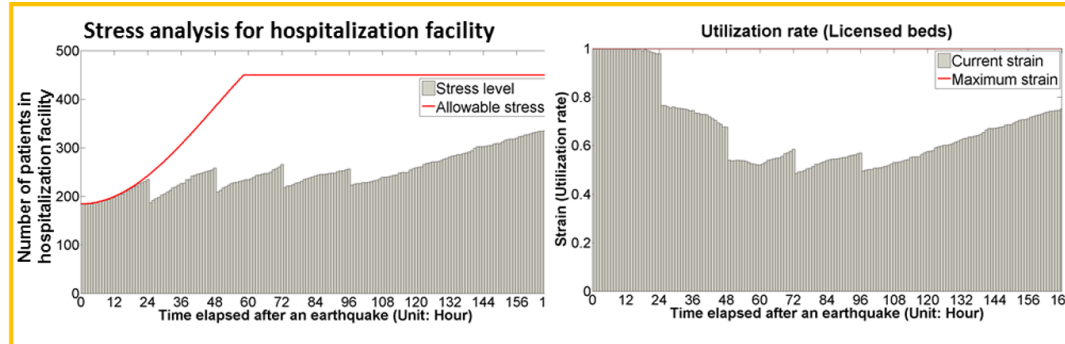
Stress and Strain Analysis of Utility Units for the Acute Care Facility (Scenario ii)

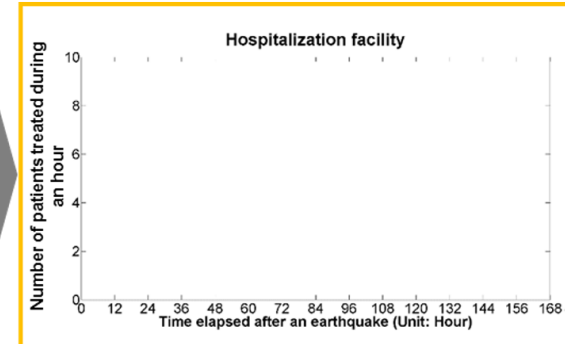# Appendix C   Stress-Strain Analysis for the Hospitalization Facility

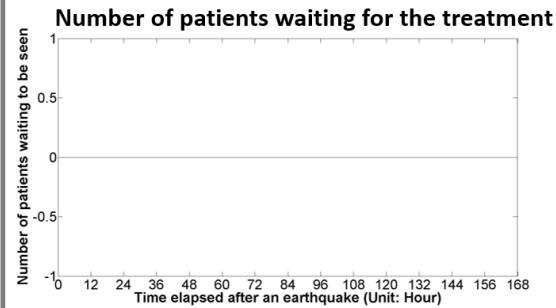Stress and Strain Analysis of the Coupled Hospitalization System

Outputs of the Stress-Strain Assessment for the Hospitalization Facility

Electricity (Hospitalization)

Stress (Water demand)
Unit: Serviceability

- Stress level
- Limit stress
- Allowable stress

Less desirable zone
Elastic zone

Time elapsed after an earthquake (Unit: Hour)

Strain (Capacity utilization rate)

Less desirable zone
Elastic zone

13.89% 23.07%

- Maximum strain
- Current strain

Water (Hospitalization)

Stress (Water demand)
Unit: Serviceability

- Stress level
- Limit stress
- Allowable stress

Less desirable zone
Elastic zone

Time elapsed after an earthquake (Unit: Hour)

Strain (Capacity utilization rate)

Less desirable zone
Elastic zone

30.09% 41.17%

- Maximum strain
- Current strain

<Stress-strain curve of the utility unit>

Elastic zone

Elastic region | Plastic region

Stress (Service ability of utility [electricity or water])

Limit stress (P_{std})
Allowable stress (P_{std})
Applied stress
Med demand
P_{std}
Utilized capacities

O

Strain (Capacity utilization rate)

@ No need for using reserve capacities
@ Municipal supply of utility is enough for supporting the medical facility

Less desirable zone of operation

Elastic region | Plastic region

Stress (Service ability of utility [electricity or water])

Limit stress (P_{std})
Allowable stress (P_{std})
Applied stress
Med demand
P_{std}
Utilized capacities

O

Strain (Capacity utilization rate)

@ Need for using both municipal supply and reserve capacities
@ Applied stress is placed between allowable stress and limit stress

Plastic zone

Elastic region | Plastic region

Stress (Service ability of utility [electricity or water])

Limit stress (P_{std})
Allowable stress (P_{std})
Applied stress
Required demand
Med demand
P_{std}
Required capacities
Utilized capacities

O

Strain (Capacity utilization rate)

@ Need for using both municipal supply and reserve capacities
@ Gap between applied stress and limit stress contributes to the extended patients' waiting time

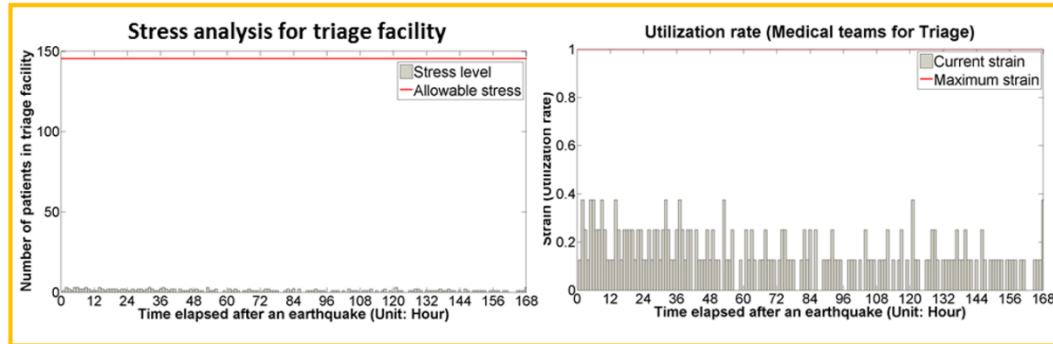Stress and Strain Analysis of Utility Units for the Hospitalization Facility

Appendix D   Stress-Strain Analysis for the Triage Facility
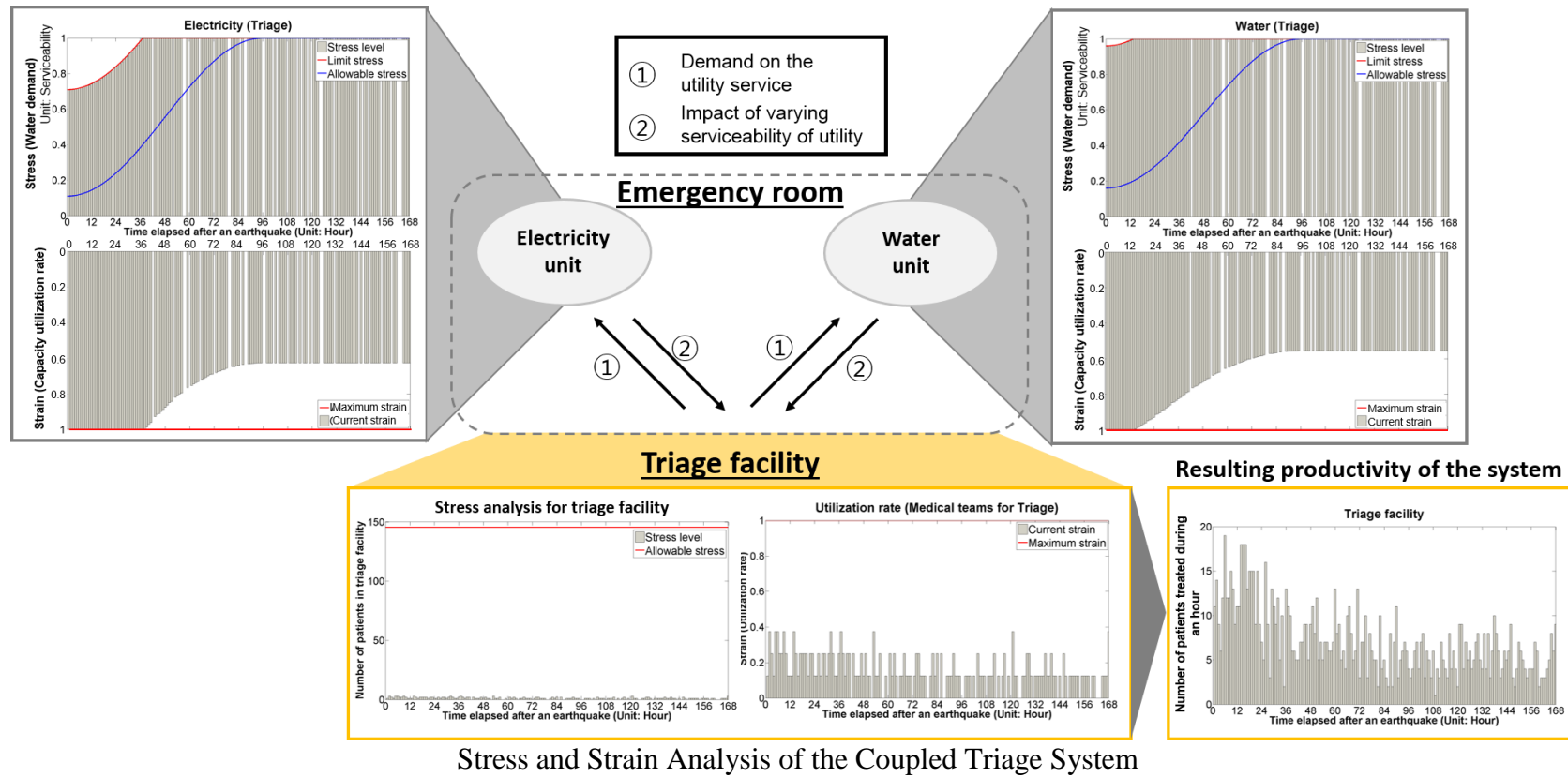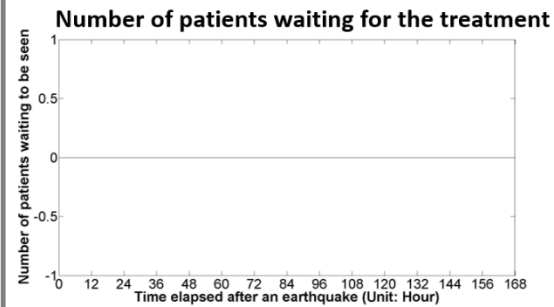

Stress and Strain Analysis of the Coupled Triage System
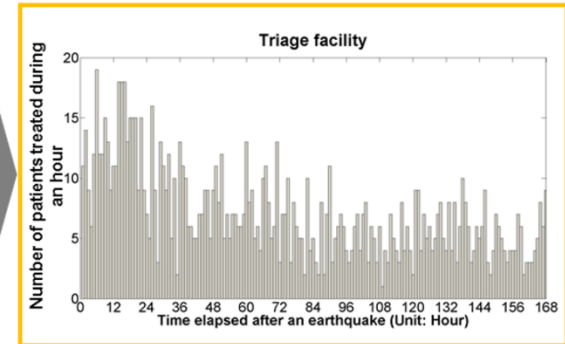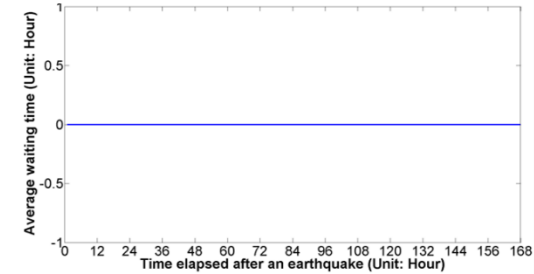
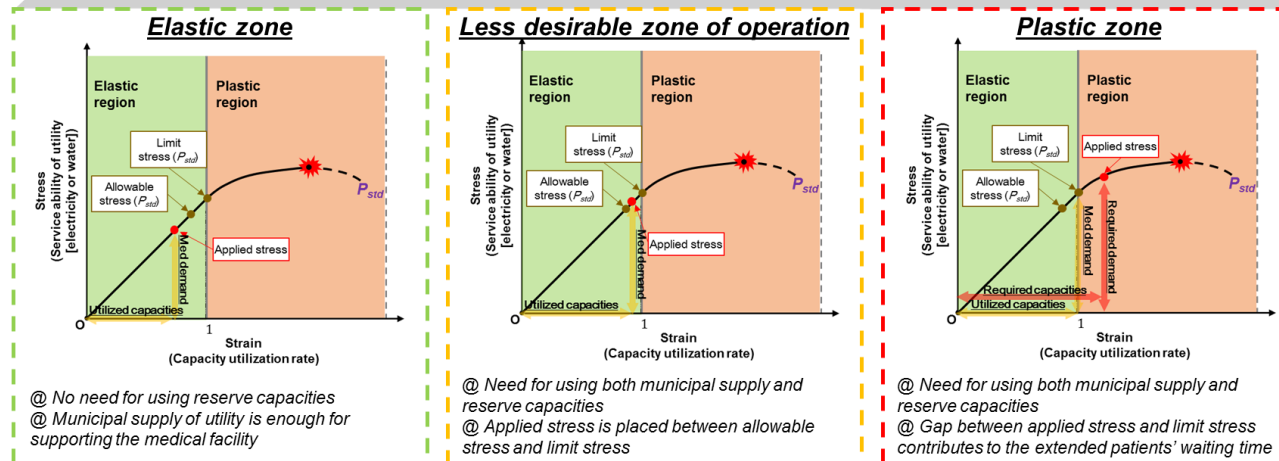Outputs of the Stress-Strain Assessment for the Triage Facility

<Stress-strain curve of the utility unit>
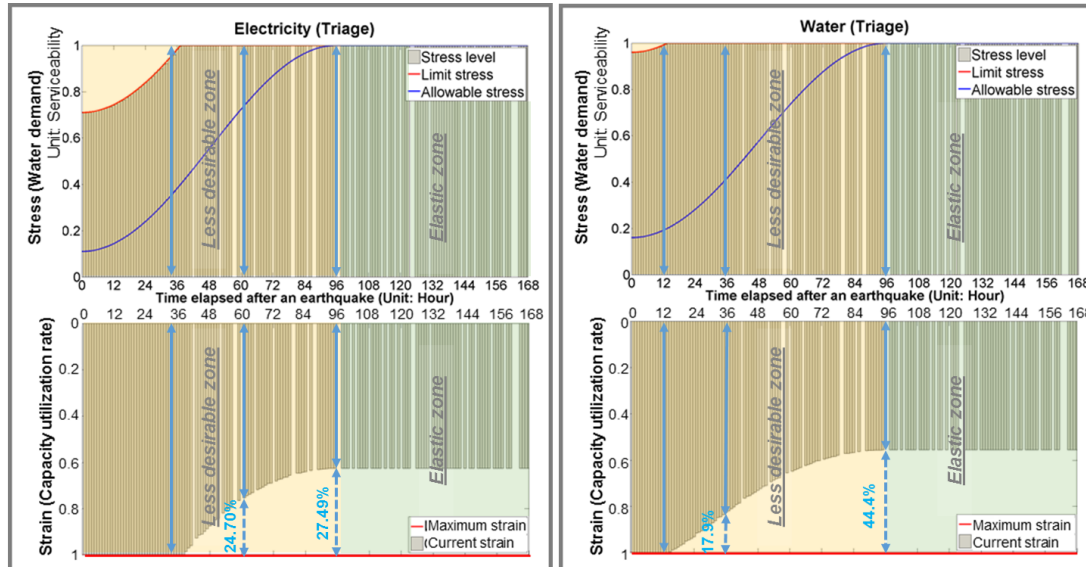
Stress and Strain Analysis of Utility Units for the Triage Facility