RESILIENT INFRASTRUCTURE PRINCIPAL FEATURES: A REVIEW

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ABSTRACT

Urban society is highly reliant on the functioning of its linear infrastructure such as telecommunications, electricity, water and transportation networks. This dependence is highlighted when infrastructure systems fail in a time of crisis or disaster. To overcome this issue, and follow on complications, there is a need to have resilient infrastructure which can survive after a crisis. Resilient infrastructure itself is a combination of different principal features and properties, the definitions of which are distributed in the literature. The purpose of this paper, therefore, is to identify the principal features of resilient infrastructure from the literature, as a first step towards uniting them into a uniform concept for resilient infrastructure. The review identified eight main principal features of resilient infrastructure from the literature which together form the basis for transforming the resilience of infrastructure.

Keywords: Resilient Infrastructure, Infrastructure, Resilience

INTRODUCTION

Urban society is highly reliant on the functioning of its linear infrastructure such as telecommunications, electricity, water and transportation networks. This dependence is highlighted when infrastructure systems fail in a time of crisis or disaster. In addition, because of their network properties, damage to infrastructure in one place may interrupt service over a large geographic area. The social disruption caused by the loss of infrastructure is disproportionate to the actual amount of physical damage. Indeed, having resilient infrastructure is extremely important to prevent follow on complications when a disaster happens (Chang, 2009). Not surprisingly, the resilience of systems and networks has become an important matter of interest for many researchers (McDaniels et al., 2008).

According to O'Rourke (2007) to help improve the basic principles that govern the performance and clarify interrelationships, it is useful to unite all thinking into a uniform concept and a smaller number of sectors on the basis of common characters. In this matter resilient infrastructure is no exception.

This study aims to firstly investigate different definitions for resilient infrastructure. Having achieved this, it intends to identify principal features of resilient infrastructures from the literature, as a first step towards uniting them into a uniform concept for resilient infrastructure.

RESILIENT INFRASTRUCTURE

Since resilience is a broad concept that has been used in a variety of studies in different fields of science and engineering during recent years (Norris and Stevens, 2007), it is important to understand the meaning of resilience for any particular theme of research. Indeed, there are almost as many definitions of resilience as there are people defining it, but in all cases resilience is linked to the concept of recovery after physical stress (Moteff, 2012; O'Rourke, 2007). Also, according to Petit et al. (2012), most of the definitions agree that resilience is the ability to:

- Absorb acceptable shock or deformation in a time of crisis;
- Recover the functionality of the system after a disaster or a sudden shock; and
- Operate appropriately even if some parts of the system fail.

Bruneau et al. (2003) indicated that resilience is frequently used to represent both flexibility and strength concepts. In other studies both Hollnagel (2004) and Leveson (2002) argued that resilient engineering is a practical attitude that looks at ways to strengthen the capacity of a system, to clearly control risks, and to make appropriate cooperation between required security levels, production and economic pressures.

In contrast, according to De Bruijne and Van Eeten (2007), resilience of infrastructure is wider than protection and focusing primarily on survival. In this matter, resilience comprises strategies for the rescue and functioning of the infrastructure in the event of crisis or disaster, although some elements of the infrastructure may not survive. Resilience takes some of the pressure off protection. It also considers how a building or other component of the critical infrastructure is prepared and protected. As a result, responders or the civic community can benefit where there are alternative plans for continued operation in a time of crisis.

All these concepts of resilience are combined in the definition proposed by the National Infrastructure Advisory Council (NIAC). NIAC (2009) documents resilience as “the ability to reduce the magnitude and/or duration of disruptive events”.

Regardless of the above definitions, when a new concept or idea like resilience is implemented in the real world, the human dimensions of organisations and communities should be considered significant (O'Rourke, 2007).

RESILIENT INFRASTRUCTURE PRINCIPAL FEATURES

A review of the current literature identified eight principal features that infrastructure should possess in order to be considered resilient. A summary of extant literature on resilient infrastructure features and properties is shown in Table 1. Each of these is discussed in turn in the following sections.

Robustness

Many authors view robustness as one of the main features of resilience and resilient infrastructure (Bruneau et al., 2003; McDaniels et al., 2008; NIAC, 2009; Petit et al., 2012; Tierney and Bruneau, 2007). Robustness refers to ''the ability…. to withstand a given level of stress…without suffering degradation or loss of function'' (McDaniels et al., 2008).

Carlson and Doyle (2002) stated that in engineering science robustness refers to maintaining system or network performance when it faces external, unforeseeable disturbances. They also indicated that robustness is the ability to retain the desirable features of a system despite changes in the function of its components and situation. A rapid decrease in performance is one of the considerable issues after a disaster. The degree to which system behaviour is sustained after a disaster indicates the robustness of that system (McDaniels et al., 2008).

According to Anderies et al. (2004) when examining the robustness of infrastructure as a system, following questions should be answered at start point: (1) what is the system applicable for? (2) What are the desired system features? and (3) When does the failure of one component in the system result to losing its robustness? For example, when a particular part of an infrastructure fails, but the whole infrastructure continues to work because of its capability to use other resources and being compatible with maintained abilities, does that system remain robust? Or does the whole infrastructure lose its robustness because of losing a particular part?

Redundancy

Bruneau et al. (2003) and De Bruijne and Van Eeten (2007) agreed that redundancy is another principal feature of resilient infrastructure. However, some see considered redundancy as a subcomponent of robustness (NIAC, 2009; Petit et al., 2012).

Table 1 Principal Features of Resilient Infrastructure

No.	Reference/ Literature	Robustness	Redundancy	Resourcefulness	Rapidity	Capacity	Flexibility	Tolerance	Cohesiveness
1	Hanseth et al. (1996)						•		
2	Zimmerman (2001)		•						
3	Easterling (2001)		•						
4	Levy et al. (2002)		•						
5	Carlson and Doyle (2002)	•							
6	Bruneau et al. (2003)	•	•	•	•				
7	Anderies et al. (2004)	•							
8	Woods (2006)					•	•	•	
9	Mendonca & Wallace (2006)					•			•
10	O'Rourke (2007)	•	•	•	•				
11	Tierney & Bruneau (2007)	•							
12	Bruneau et al. 2007			•					
13	De Bruijne and Van Eeten (2007)		•						
14	Hollnagel et al. (2007)								•
15	McDaniels et al. (2008)	•			•		•		
16	NIAC (2009)	•		•	•				
17	Jackson (2009)					•	•	•	•
18	Jackson (2010)					•	•	•	•
19	Petit et al. (2012)	•		•	•				

Redundancy is a property that allows for alternative choices, decisions and substitutions in systems or organisations in the case of disaster or under pressure (O'Rourke, 2007). Levy et al. (2002) stressed the critical importance of the concept of redundancy: "In practice, all structural failures can be considered due to a lack of redundancy". Specifically, they highlighted that the advantage of structural redundancy is that "It allows loads to be transported in more than one way, i.e., through more than one path through the structure ".

From the view point of infrastructure planning, redundancies between the different types of infrastructure offer functional flexibility and compromise within and between infrastructure systems (Zimmerman, 2001). Take the lines of communication between the redundant rail, highways and roads as an example, all of these infrastructure have the extra capability to serve if others fail, for example if railways fail in a time of crisis, the highway network can be a good alternative for substitution (Easterling, 2001).

Resourcefulness

Critical infrastructures are significantly interconnected and mutually dependent in complex ways. This interrelationship can be physical or through a host of information and communication technologies or both. Considering this characteristic, infrastructure can be defined as a system (Rinaldi et al. 2001).

Resourcefulness is one of the prominent principal features of resilient infrastructure systems (Bruneau et al., 2007; Bruneau et al., 2003; NIAC, 2009). Resourcefulness is the ability to "expertly get ready for, react to, and manage a disaster or disturbance as it occurs" (NIAC, 2009), that is the capacity to organize needed resources and services in a predicament (O'Rourke, 2007).

Resourcefulness starts before the event and continues until the reaction phase. It includes measures taken before an event to prepare the population, employees and management of potential threats, including the implementation of training and planning for the time that a mishap occurs. Resourcefulness can be seen as a counterpart of robustness. It helps the system or infrastructure to easily move from the response phase to the recovery phase (Petit et al., 2012).

Rapidity (Rapid Recovery)

Rapidity or rapid recovery was first proposed by Bruneau et al. (2003) and later verified by O'Rourke (2007), McDaniels et al. (2008) and NIAC (2009) and, finally, Petit et al. (2012) as a necessary feature of resilient infrastructure. Rapidity indicates ‘‘the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption'' (Bruneau et al., 2007). It is also the speed with which disruption can be overcome and safety, services and financial stability restored (O'Rourke, 2007).

After a disaster, given time, the system reaches a certain level of stability or equilibrium. The speed with which this recovery function is performed reflects the speed of the system recovery or its rapidity (McDaniels et al., 2008).

Capacity

This property was first introduced by Woods (2006) as one of the essential features of resilient infrastructure and was later included in Jackson's (2010) four main principles of resilient infrastructure.

Capacity is the ability to withstand the "known" disturbances and a resilient infrastructure should have this capability (Mendonca and Wallace, 2006). Capacity not only includes the ability to absorb such disturbances, but also it should be able to deal with higher than expected disturbances. Capacity also includes a physical and functional redundancy so that the infrastructure will be able to absorb additional demand in a time of crisis. Functional redundancy could mean, for example, a coastal city would have several possible ways for local people to evacuate the area in case of disaster and find shelter elsewhere. These could and would likely include the use of cars, trains, boats, airplanes, and other modes of transport. Clearly, in this example, as the options for evacuating increases the infrastructure would be considered more resilient (Jackson, 2009).

Flexibility

Flexibility is seen as another principal feature of resilient infrastructure according to some of the literature (Jackson, 2009; Jackson, 2010; McDaniels et al., 2008; Woods, 2006). Flexibility is the system's ability to restructure itself in response to external changes or pressures (Woods, 2006).

Jackson (2010) also stated that resilient infrastructure must be flexible - which means, more specifically, that the infrastructure system should be able to reorder itself in a time of crisis. This reorganization also includes the ability of the infrastructure to raise the levels of power in the event of disruption. Such elevation of authority is particularly common in the field of fire prevention.

The flexibility of a system can be described as a situation in which the functionality of other parts will be saved in terms of changes in one part of a system. The shapes of flexibility may be different in various systems. As an example, "standardisation in one part of the productive chain facilitates flexibility at the next" (Mulgan 1991); or for a modular infrastructure system, flexibility can result from creating different subgroups by picking and collaborating standardized modules (Hanseth et al., 1996).

Tolerance

Another factor of infrastructure that contributes to resilience is tolerance (Jackson, 2009; Jackson, 2010; Woods, 2006). Woods (2006) believed that tolerance is related to how a system behaves near its boundary – whether the system gracefully degrades as stress/pressure increases or collapses quickly when stress/pressure exceeds adaptive capacity.

According to Jackson (2010), resilient infrastructure should be "tolerant" of disturbances where tolerant refers to infrastructure that does not immediately lose all of its abilities after a break, but will instead gradually degrade. A good example of this is hospitals; hospitals have their own power supply in case the public supply network is disabled due to an earthquake or other major disruption. This makes hospitals tolerant to a disaster.

Cohesiveness (Inter-element Collaboration)

The last principal feature of resilient infrastructure is defined as cohesiveness between the various parts of the infrastructure (Jackson, 2009; Jackson, 2010). Jackson (2010) believed that one of the main properties of resilience for infrastructure is how well each sub part of the infrastructure relates to the others.

The concept of "cross-scale interactions" is used by Mendonca and Wallace (2006) and Hollnagel et al. (2007) to refer to cohesiveness of infrastructure. Hollnagel et al. (2007) also indicated that this term in resilient infrastructure can occur on three levels:

- The first level is communication, which asks, specifically, if each sub part of the infrastructure can "talk to one another”;
- The second level is cooperation. Even with no formal ties, the sub part of an infrastructure should have the ability needed to collaborate with one another; and
- The third and highest level of cohesiveness includes inter-element collaboration, which contains formal agreements between the sub parts of infrastructure to both help and provide resources to one another.

DISCUSSION AND CONCLUSION

The concept of resilient infrastructure is a result of a combination of many features and properties and this review brings together some principal features of resilient infrastructure as a first step towards uniting them into a uniform concept. This has resulted in eight principal features being identified from the literature, which together form an initial basis for transforming the resilience of infrastructure. A summary of available literature on these features is included in the preceding sections.

It is argued that although each main feature has its specific scope and definition, some features overlap with others. Furthermore, a logical interrelationship between some features has been observed. A good example of this is the similarity between the features of robustness and capacity. It can be observed that both concepts deal with the capability of infrastructure to resist external disturbances in a time of crisis. However, robustness is an inherent capability of infrastructure to resist while capacity is a wider concept. Capacity not only includes the inherent capability of an infrastructure but also considers some strategies to deal with disturbances higher than those predicted.

Another good example is the similarity between the two concepts of flexibility and redundancy. Both concepts rely on having backup plans and alternative choices in a time of crisis. However, redundancy is a property of having alternative choices and decisions, while flexibility includes the ability to reorder and reorganise an infrastructure when a disaster occurs.

All in all, this study investigated different features of resilient infrastructure. Moreover it explored various definitions of resilient infrastructure available in the literature. The main aim of this paper was to identify some principal features of resilient infrastructure as a first step toward uniting them into a uniform concept.

It is suggested that further research should be carried out in terms of finding concepts of resilient infrastructure in different fields of engineering and science. For example, what is the role of the construction industry in providing a resilient infrastructure? How to develop a measure for resilient infrastructure functionality in each theme of science and engineering? How different industries and fields of science can collaborate with each other to provide a more resilient infrastructure for the country.

The features of resilience are complex and inter-related, and as the field has matured additional features have been identified, but the way such features inter-relate is not yet well understood. Also the overlaps between principal features can be an interesting line of research for future studies.

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