Mitigating disasters in the 21st century

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Abstract

The term reliability, resilience, risk and redundancy are often used to convey similar or the same concept in literature. Typically, none of these terms are defined in a computationally rigorous manner. Each of these terms has a unique mathematical meaning. However, resiliency and robustness have the special distinction of being particularly powerful because they are completely threat independent. Although it is possible to design structural systems to resist virtually any threat, it is impossible to design these systems to resist all possible threats. Even if all threats could be defined today, they cannot account for unknown future threats that may occur during the life of the structure. As a result robustness evaluation could be useful in prioritizing buildings and critical infrastructure for the purposes of allocating mitigation dollars potentially allowing for a way to optimize both sustainably and effectively. In this paper, the basic concepts used in probabilistic assessment approaches are described and an argument is made for using robustness and resiliency as the primary means for evaluating, repairing and replacing our structural systems in the 21st century.
Keywords: risk, reliability, robustness, resiliency.

1 Introduction

Common engineering practice in multi-hazard design is to consider each natural hazard independently. The underlying assumption is that it is highly unlikely that one disaster will be closely followed by another sequentially. This approach dominated large part of the 20th century. As a result, today we have a good understanding of material constitutive modelling and efficient algorithms enabling large computer programs to run analysis on powerful computers. The engineering community has made large strides in designing structures to withstand known hazards, leading to improved reliability and safety of infrastructure. Improved reliability and safety in turn has supported population

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growth and increased prosperity. As witness to our success, it is common in developed nations to consider it unacceptable for a disaster to cause large scale devastation. However, the nature of the disasters has proved otherwise.

It is unlikely that one extreme event will have catastrophic consequences on communities, because we know how to prepare for a single event. Instead, as experience shows, disasters are more typically comprised by one event followed by one or more other events, exposing the vulnerability of our design assumptions. The most recent examples of multiple disasters are Indonesia (i.e., earthquake followed by tsunami followed by volcano) and Haiti (i.e., earthquake followed by cholera outbreak). Current methodologies for disaster preparedness and mitigation heavily rely on known methods of statistics and reliability theories to predict the outcome to a given series of events. This approach has a number of difficulties, such as: computers are not fast enough and answers are rarely definitive enough to make an informed and timely decision.

In summary, the 21st century challenges are different from the 20th century problems and require a different approach. This study is focused on discussing the research needs to create efficient, simple and reliable computational methodologies to predict and subsequently avert the effects of multiple sequential disasters on infrastructure systems.

2 Risk and reliability

Risk of failure is a concept that can be universally understood by infrastructure stakeholders as well as engineers. A traditional definition of risk is that it is equal to the product of probability of failure (assuming that the threat has been executed) and cost of failure. Hence, probability of failure needs to be computed to determine the risk. For the purpose of this paper let us assume an infrastructure type similar to a transportation or communication system, where performance is measured by the successful delivery of freight or data. This infrastructure will have a defined Capacity to perform (denoted as C) and a variable Demand (denoted as D).

It is intuitive that the infrastructure Demand and Capacity are dependent on each other. That is, if the infrastructure system is overloaded (i.e., the Demand is too great), its Capacity to perform goes down and nothing or very little freight or data gets successfully delivered (i.e., it fails). Similarly, if the infrastructure system is underutilized (i.e., the demand goes down) than its Capacity to successfully perform also decreases significantly (i.e., it has become obsolete).

To compute probability of failure, we have to define what constitutes failure. For our infrastructure example, let us assume that failure occurs when infrastructure is unable to fulfil its function, i.e., cannot deliver freight or data within acceptable parameters. Since demand and capacity are dependant variables, probability of failure for this infrastructure system is calculated as

$$P_f = \int_{-\infty}^{+\infty} \int_{C}^{+\infty} f(C, D) dD dC \tag{1}$$

where $f(C,D)$ is a joint probability density function for the infrastructure system.

Hence, to determine risk we have to estimate joint probability density function (PDF) of Equation (1), which represents a traditional systems reliability problem. The PDF has certain qualities which are easier to examine when Demand and Capacity are uncorrelated and independent variables.

Reliability techniques can be applied in engineering to compute the probability of failure based on a distribution of threats, or natural hazards, and a corresponding distribution of capacities to resist those threats. The probability of failure is determined based on the relative positions of the demand and capacity Probability Density Functions (PDFs) on a strength ordinate. Within the context of the definition of reliability, the probability of failure can be decreased by either: moving the relative positions of the PDFs to decrease overlap (decrease the load, increase the strength) or by decreasing the dispersion, or standard deviation of the PDFs (by increasing the certainty in the definition of either the load or the resistance).

When demand and capacity are uncorrelated and independent variables, Equation (1) is simplified into the expression for reliability:

$$P_f = \int_{-\infty}^{+\infty} f_D(D) F_C(D) dD \tag{2}$$

where $f_D(D)$ is PDF of infrastructure demand and $F_C(D)$ is a cumulative density function (CDF) of infrastructure capacity.

In this case, it is possible to visualize the system Demand and Capacity as two separate functions as shown on Figure 2. This figure provides a comparison of two system Capacities (A and B) for a defined Demand. Based on Figure 1, System A is not only stronger but also more reliable since the probability of failure of System A is less than System B.

Therefore, to calculate risk and reliability we must first estimate probability of failure given successful execution of a defined threat, and have an estimate of total consequence value. Unfortunately, realities of the 21st Century dictate that threat cannot always be predictable, and consequences can also be intangible due to cascading or other effects. The main challenge of today's engineering community is to develop an analytical procedure to mitigate effects of all possible threat conditions. This is achieved through sustainability, resiliency and robustness concepts.

3 Resiliency and robustness

ASCE recommends promoting sustainability and resiliency as an integral part of its infrastructure report card. In Ref [4] ASCE presents a qualitative description of resiliency in context of each infrastructure sector. However it falls short in providing clear definition of resiliency. It is implied that resiliency is measured as elapsed time from the destructive incident until full operation of the

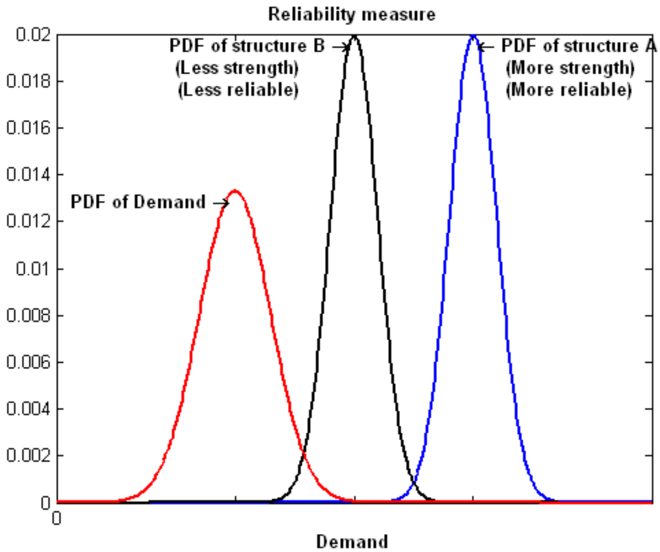

Figure 1: Demand and capacity are uncorrelated and independent.

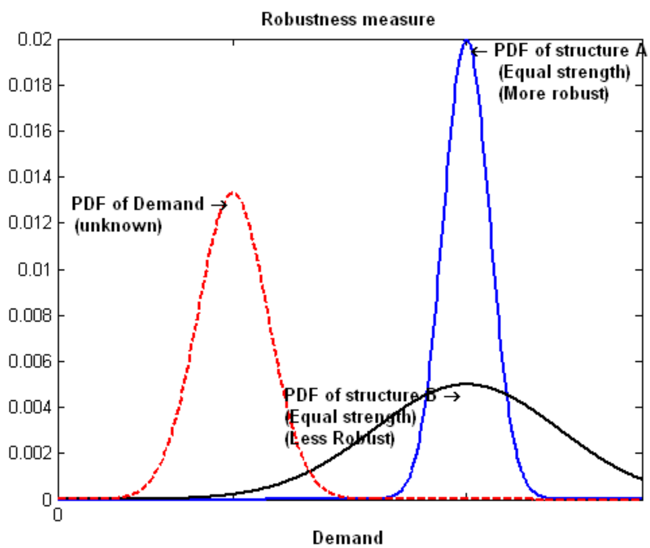

Figure 2: Illustration of robustness.

infrastructure system is restored. Therefore, resiliency not only depends on the properties system (although it is unclear how) but it also depends on the system's operation and repair-time.

Another important quality of an infrastructure system is robustness, which is solely a property of the system. Robust infrastructure is insensitive to small deviations in assumed design parameters. The concept of robustness is illustrated on Figure 3. Despite System A and System B having the same Capacity values, System A is more robust than Structure B, since the probability of failure for System A is less than that of System B. We may also note that System A is more reliable then System B without having more Capacity (i.e., the area under the curve for A and B is the same).

A subset of robustness is redundancy which is related to the existence of multiple and redundant sub-systems. These sub-systems may provide temporary and quick alternate way for the system to work around the damaged area and remain operational until full Capacity is restored.

4 Protective design of robust systems

Remarkably, there is little common ground regarding the definition of robustness. A quick look at the dictionary reveals five variations of the adjective with three of those five including the word "strong" or "strength". So, it is natural that engineers, when asked about the meaning of robustness, would reply with words like "strong", "resilient", and "redundant". There is currently no direct guidance out of the United States building codes standards that link robustness with a quantifiable definition. Be that as it may, other engineering and scientific disciplines have various specific definitions of robustness, and it is helpful to examine them here. Insight from outside of the structural engineering community combined with specific definitions of structural engineering metrics will lead to an adaptation to the definition of robustness and a novel way to evaluate infrastructure systems.

In November of 2005, the Joint Committee on Structural Safety (JCSS) and the International Association for Bridge and Structural Engineering (IABSE) working Commission 1 convened a workshop on the robustness of structures. The European establishment has shown itself to lead the Americans in the integration of reliability metrics into their building code, and it should come as no surprise that they are leading the discussion of structural robustness as well. At the conclusion of the conference it was agreed the robustness is the "product of several indicators," many of which might be expected to be associated with robustness. The indicators identified include many of the aforementioned metrics: redundancy, ductility, variability of resistance, interdependency of failure modes, and joint performance, just to name a few.

Based on these conclusions it is evident that robustness is a complex metric not solely related to strength, but rather it is part of a system of indicators (one of which is strength), and that the quantification has to do with the structure's sensitivity to stimulus, regardless of the magnitude of the stimulus.

In Protective Design, the threat is unpredictable because the nature of the threat is always changing, evolving, and (usually) increasing in frequency and magnitude (TSWG, 2004). In this practice, it is difficult to predict any structure's reliability given the great dispersion that is expected in the load scenario induced by the threat, though it is possible to determine and influence the dispersion of the resistance function. Increasing the certainty in the structural resistance by decreasing the standard deviation of the capacity – regardless of the expected value of the resistance (or strength) – increases the reliability for a constant threat PDF, and it also decreases the sensitivity of the system response to loading stimuli. The physical outcome of a narrow PDF for resistance is that the reliability of the structure will likely be unaffected by small perturbations in loading. This outcome is consistent with the Eurocode definition of robustness as well as the expected behaviour of robust systems in various scientific fields.

A common approach to estimate resiliency and robustness is based on introduction of damages into the system and determination how sensitive the system is to this damage (robustness) and how soon this system can recover (resiliency). Notable, these damages are almost universally related to damages due to a terrorist attack (i.e., a catastrophic event) and usually represented as an element removal (i.e., total destruction of the element). This approach requires enormous computational time as all damage scenarios as well as all response scenarios need to be determined and analyzed. This is a significant drawback of current approaches. Probabilistic techniques enable us to encompass all threats uniformly and as such will facilitate the design and improvement to infrastructure systems to withstand all threats, and natural hazards.

5 All hazards approach

The Fire Department of New York issued Terrorism and Disaster Preparedness strategy in 2007 [5], where it is strongly encouraged to “All-Hazard Preparedness”. The term all-hazard requires clarification to respond adequately to this challenge. How does one consider all hazards in the design and evaluation of our aging critical infrastructure? The table below provides examples of the assumptions made in the 20th century for the purposes of quantifying the effects of disasters are no longer accepted and are inconsistent with an all hazard approach.

In response to these shifts in our understanding of what a disaster is, the probabilistic concept of robustness provides a satisfying new approach, for it is truly threat independent.

6 Conclusions

In summary:

Today’s realities require our critical infrastructure in the 21st century to achieve resiliency through sustainability and system robustness in response to a complex evolving threat and hazard environment.

Our infrastructure needs to be designed to be able to resist hazards and threats which are evolving and complex.

Robustness represents an infrastructure’s ability to absorb small failures (perturbations) without affecting the overall integrity, and can be measured as a standard deviation of the resistance probability density function.

Table 1.

20th Century Design Assumptions	21st Century Realities
A terrorist attack consists of a single event at a single site (e.g., Oklahoma City Bombing).	Sequential or concurrent attacks at a single or multiple sites (e.g., nearly simultaneous events at WTC1, WTC2 and the Pentagon on 9/11).
Only one type of hazard or threat is considered to occur during an event. Fires, explosions, hurricanes and floods are considered separately (i.e., Hurricane Andrew).	Disasters often encompass multiple hazards or threats, such as flood and hurricane, explosion and fire, earthquake and tsunami. These combinations of factors need to be included in the design process. An example of this is Hurricane Katrina in which the effects of hurricane caused the levee failures which initiated catastrophic flooding. Another example is the impact of planes into WTC1 and WTC2 survived the plane impact, but failed catastrophically due to the subsequent airplane fuel fire.
The risk associated with natural disasters may be predicted based on past history.	The risk assumptions used for natural hazards no longer apply due to global warming, increased population growth and other factors.
The risks associated with terrorist attacks are too rare to predict with accuracy.	There are ways to reasonably predict terrorist risk.
One major attack may be assumed to occur during the life of the facility.	If one major attack occurs at a site, another will occur. For example, the World Trade Center was attacked in 1993 and again in 2001.
Saving lives is all we can afford to do to protect a civilian domestic building. The design objective is to prevent collapse long enough to safely evacuate.	Saving lives is a minimum standard. In some cases it is economically justified to design for higher level of protection. For instance, major federal buildings are now designed to sustain ‘moderate’ damage in addition to resisting progressive collapse.
Our infrastructure needs to be designed to mitigate the effects of defined magnitudes and locations for hazards and threats which are quantifiable.	Our infrastructure needs to be designed to be able to resist hazards and threats which are evolving and complex.

Infrastructure robustness and resiliency represent interdependent qualities of system. Robust systems are inherently more resilient. Probabilistic approach to robustness and resiliency encompass all threats. As such robust and resilient design represents a true independence from threat.

Further research into the concepts of robustness and resiliency to explore how they may be used to evaluate our existing aging infrastructure and allocate our limited resources wisely for the demands of the 21st century.

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