Chapter

Introductory Chapter: Innovative Manifestations of Reliability-Based Design

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1. Introduction

Reliability and reliability-based design have emerged, over the past several decades, as integral and essential concepts in structural design. Engineering design problems are known to deal with several uncertainties, from material properties to load conditions, values, and combinations [1–3]. Thus, the concept of 100% safe designs does not exist in real life. Therefore, it is only realistic to express all designs in terms of the lowest acceptable probability of failure which results in acceptable reliability for these designs. That is what we all agree to refer to as reliability-based design [1–3].

Another essential concept emerged because of the increasing demand for sustainable design and performance of all engineering systems, which is structural resilience [4]. The ability of any system to recover after a major event and perform satisfactorily is another major concern. Due to climate change, the noticeable increase in the severity and frequency of environmental events affecting civil systems; buildings, roads, highways, and infrastructure, dictated that structural resilience and the response to all types of disasters, natural and/or man-made, emerged as essential factors in engineering design [5].

The attainment of a reliable and resilient design gave way to the emergence of innovative ideas in dealing with uncertain and continuously evolving design criteria. The recent interest in ensuring sustainability and sustainable design and the commitment by the United Nations in issuing its 17 Sustainable Development Goals (SDGs) would further strengthen the need to develop innovative design approaches that would satisfy all relevant concerns and criteria.

It is further important to emphasize that any such innovative approaches need to be reliability based to suite the nature of the highly uncertain problem that defines engineering design. As an example, the emergence of smart structural systems and the concept of structural health monitoring are meant to ensure the sustainable and reliable design of engineering systems.

It is essential though to indicate what does a sustainable design entail. Sustainability is a holistic concept that could be translated into several design criteria, such as reliable, smart, optimum, and recyclable [6]. In other words, any design approach that would result in less material use, optimum material use, recycling of material waste, reliable, and resilient system could be considered a sustainable design.

In this book, a range of innovative reliability-based solutions are presented to address the ever-changing engineering design problem. Such solutions range from considering stability issues of rock formations and thus their effect on the reliability of any proposed stabilizing system, to the issue of disaster response and how is that related to the resilience of engineering systems.

This introductory chapter will also attempt to present a range of innovative solutions that are bound to represent the Avantgarde direction of travel when dealing with reliability-based design. In the following discussion, the impact of the innovative concepts, in general, on the resulting reliability of engineering systems is discussed and portrayed. Such concepts include sustainability, smart, health monitoring, disaster response, and resilience.

2. Sustainability and reliability

Recent design criteria should not neglect an increasingly important factor that now, more than ever, is emerging as an integral design criterion. Sustainability and sustainable design are now considered to be one of the most important design criteria that needs to be integrated within all design activities [6]. Due to the climate change effects and the recent interest by the United Nations in devising the 17 Sustainable Development Goals, all designed systems shall ensure their sustainable performance throughout their expected lifetime [5]. Several sustainable goals are targeted when designing any of such systems, namely, goal 9 which relates to resilient infrastructure and goal 11 which relates to resilient and sustainable cities.

The main concept of sustainable design is one that should result in an environmentally friendly system. The concept of sustainable design, when considered, has always referred to the employment of recyclable material. In spite of using recyclable material being an important sustainability target, in its own right, yet there are other factors that would result in a sustainable design such as one that is optimum, smart, reliable, resilient, and green.

The most important design objectives are recyclable, optimum, and reliable. Thus, the smart characteristic of today's systems emerges as an important and critical attribute. In other words, the design of a system that is capable to adjust its physical properties to respond favorably to an unexpected event, natural and/or man-made, is much better, sustainable, and reliable than one that is designed to resist a load condition that it might not encounter during its lifetime. Therefore, smart systems are now considered a reliable sustainable option as compared to conventional systems.

It is important to emphasize that reliability emerges as a key factor in the design process; thus, the need for reliability-based design, yet such designs must be achieving advanced and continuously changing design criteria, such as sustainability. Another factor that has recently been identified as an important design objective, which is resilience, is due to the new approach toward performance-based design. Naturally, when considering a smart system that embodies several smart features that allow self-learning and continuous adaptation to uncertain events, this would result in a resilient system.

3. Smart systems and reliability

Smart structural systems are defined as ones that demonstrate the ability to modify their characteristics and/or properties to respond favorably to unexpected severe loading conditions. Conventional structural systems are usually designed to resist predefined loading conditions. However, due to the uncertain nature of engineering systems, and the lack of complete and accurate information about some types of highly uncertain loads, such as earthquakes, smart structural systems have emerged as a potential solution for such problems. Instead of designing systems to withstand a single extreme earthquake event that may or may not occur in its lifetime, new designs of smart systems could emerge where the system can respond favorably, in a smart manner, to any type of loading that was not introduced at the design stage [7]. The significance of such systems is even enhanced when modeled systems are unconventional such as historic buildings and/or structures.

The design of such systems requires the integration of sets of additional components within regular systems. These components belong to three major categories, sensors, processors, and actuators. The following section presents a summary about the nature of such components.

3.1 Basic components

For smart systems to behave as outlined above, they need to extend their capabilities through the employment of three basic component categories, i.e. sensors, processors, and actuators, [8, 9]. First, sensors are required to collect real-time data regarding the performance of the system in question. Acceleration and/or displacement transducers are considered as suitable devices for sensing any instantaneous state changes. Second, gathered real-time data are communicated to either a central processing unit or a set of decentralized processing units. The processing unit should be capable of identifying the current state of the system and, accordingly, suggesting corrective action if the response is beyond predefined and acceptable limits. Smart structural systems are designed to mimic the mechanical behavior of a human body. Therefore, any potential processor needs to possess cognitive features that are like those of the human brain. Such features include an auto-adaptive nature, parallel processing capability, and pattern recognition skills. Neural networks and/or fuzzy logic can simulate such cognitive features. Neural networks possess an adaptive self-learning capability, while fuzzy logic is capable of modeling complex systems that incorporate the qualitative nature of the human brain [10–12].

Finally, the processing unit sends a proposed corrective action to a set of actuators that follow one of two potential approaches. The first is an external force application to balance the system. The second is through the adjustment of the actuator's structural characteristics, thus, resulting in a more favorable response. External force application was one of the early forms of smart corrective actions [9, 13]. However, recent applications have shifted toward auto-adaptive actuators, which follow the second approach. Magneto-Rheological (MR) dampers are a good example of such actuators. MR dampers are proving to be very promising in civil and/or structural applications [14–16]. MR dampers respond to a magnetic field with a change in viscosity, thus, changing their response characteristics.

3.2 Reliability assessment framework

The main objective of this task is to outline a generic reliability assessment framework for evaluating the reliability of different types of components and ultimately the overall system reliability [17–21]. Being an integrated system, comprising a set of basic components, the individual component reliability is of major importance to the evaluation of the overall reliability of the system. As outlined above, smart structural systems require the integration of a set of sensors, at least a central processor unit and a set of actuators, in addition to several structural elements employed to build the system. By expressing such a system in a limit state format, one could easily employ standard algorithms in evaluating the reliability of each individual component and eventually the overall reliability of the system. The reliability assessment framework, for each type of integral component, necessary for the design of a smart structural system has been developed together with a sample limit state formulation that guide the specific development of individual component reliability schema. **Figures 1–4** show the developed reliability assessment frameworks for sensors, actuators, processors, and the overall system.

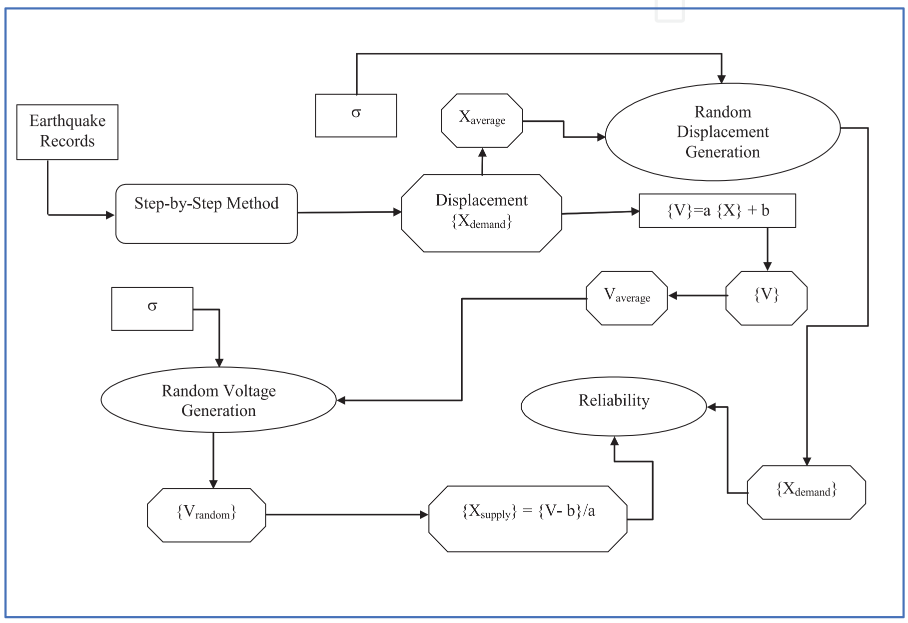

Figure 1.
Sensor reliability framework.

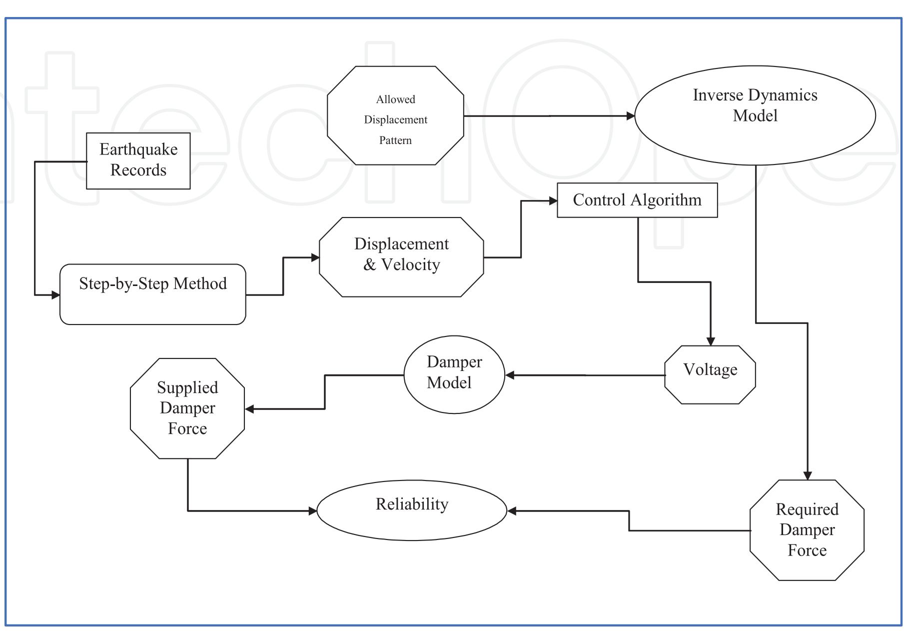

Figure 2.
Actuator reliability framework.

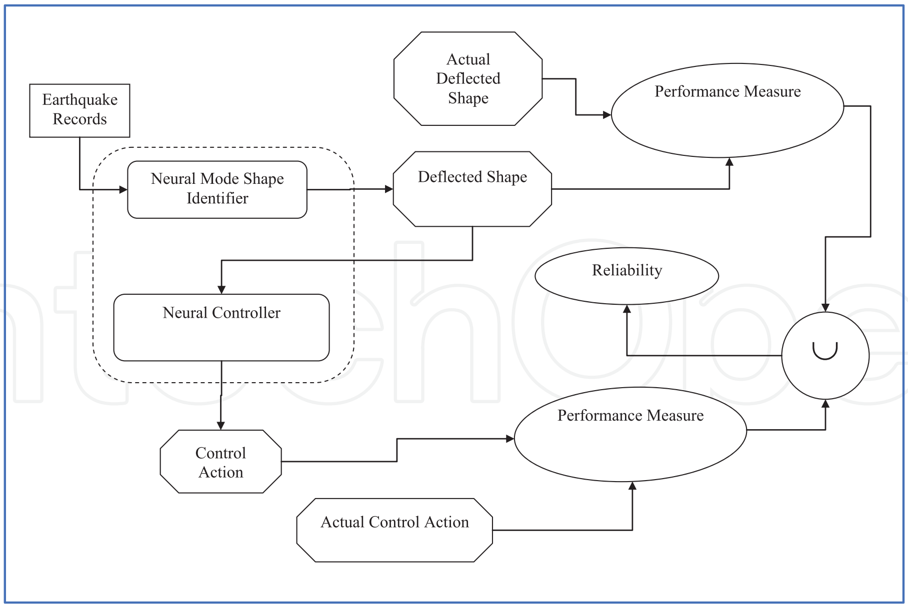

Figure 3.
Processor reliability framework.

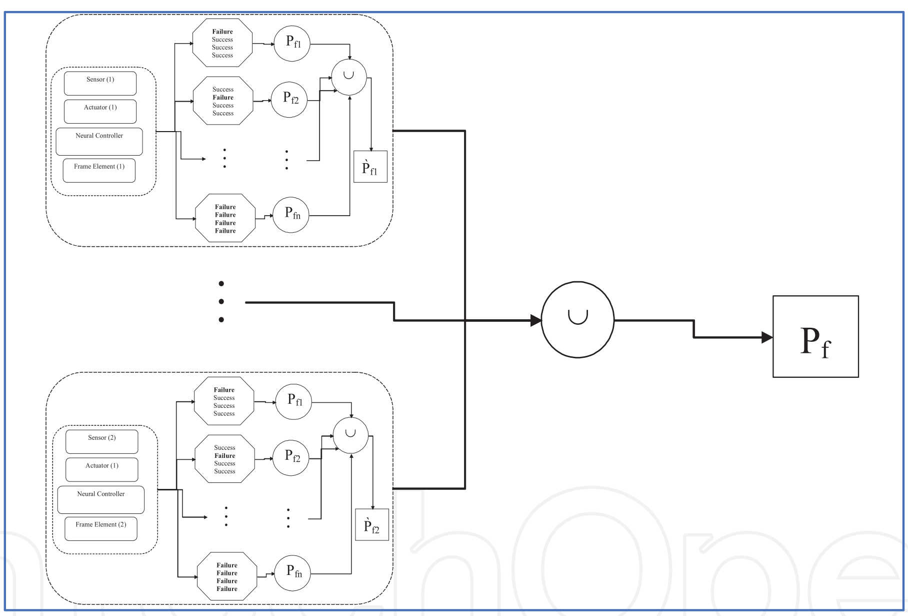

Figure 4.
System reliability framework.

4. Resilience and reliability

Disaster response is another major concern in the design of engineering systems. The ability of a system to recover after being exposed to a major event, whether that is a natural hazard and/or a man-made event, is one of the major concerns that engineering systems are now required to address [4, 5]. Resilience is known to reflect such ability, while reliability is meant to reflect the ability of such system to survive such events. Recent performance-based design approach led the way to further interest in structural resilience, which is concerned with such ability, at the component and system levels.

Resilience could be considered at three main levels, namely, structure and/or system level, infrastructure network level, and finally the community/urban level [5].

It is important to ensure the ability of systems, at all three levels, to recover and function satisfactorily after a major event.

At the structure and/or system level, this relates to structural systems and their redundancy which allow them to operate and function safely and reliably, even after such an event and until regain of full capacity is achieved. This is achieved through an acceptable level of redundancy that allows continuing function even after a local damage and/or failure occurs to one or more underlying components.

At the infrastructure level, this relates to the ability of highways, power grids, and all other utility networks to function and their inherent redundancy to ensure sufficient operation of such networks, if some damage is incurred and to ensure that such local damage does not propagate through the whole network and cause full disruption of services.

At the community and/or urban level, this relates to the socioeconomic performance of communities after a major disruptive event and the ability to recover and function normally.

The performance at these three levels is expected to be evaluated and expressed in terms of reliability measures since all such events are uncertain in nature. There are several attempts to evaluate and assess resilience measures that are available in the literature [4, 5, 22].

5. Health monitoring and reliability

Health monitoring relates to the continuous supervising of the performance of civil structures and systems throughout their lifetime. The advances in electronic devices, computer systems, and sensor technology paved the way for the development of integrated applications that can monitor the performance of civil systems, real time [23], and send alerts and alarming messages to the relevant authorities about potential damage and or recommended maintenance procedures.

Such a mechanism would enhance the reliability of targeted systems and ensures their continuous uninterrupted operation throughout their lifetime. However, the reliability of such systems is of major concern, since they comprise several components that are expected to operate integrally within a preset framework and work seemingly within a certain system [23].

The integration of structural health monitoring, within an engineering system, is expected to enhance its reliability. It is important to consider the reliability, of such system, in two main levels, the first is the reliability of the structural health monitoring system itself and the second is the reliability of the monitored engineering system, including the health monitoring enhancement. There is not enough research activity in reliability of structural health monitoring systems and their impact on the reliability of monitored systems. This requires a targeted research effort in this area which would support the practical implementation of such systems, especially when dealing with the conservation of historic cultural heritage.

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