# Work in Progress: Design of “Risk and Resilience” Focused Courses for Undergraduate Engineering Education Towards a Hazard-Resilient Built Environment

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**Abstract:**

In the last few decades, there has been a significant increase in the number and magnitude of natural and man-made hazards, which imposes a tremendous risk to the built environment. In response to the urgent needs for engineering professionals to address these hazards and improve the resilience of our built environment, it is critical to develop a workforce with risk and resilience skills to meet the increasing demand for managing disaster-resilient built environment. This paper presents our work in progress to develop and integrate a set of “risk and resilience” focused courses into engineering education for workforce towards a hazard-resilient built environment. A set of three individual courses, namely, 1) Introduction to Risk and Resiliency in Engineering, 2) Reliability and Optimization Methods in Engineering, 3) Sensing and Data Analytics for Infrastructure Systems will be developed and incorporated into curriculum. These three courses have been designed to be help address the fundamental knowledge and techniques needed for engineers to conduct the assessment, design and management of engineering systems to achieve hazard resilience. The paper provides details about the rational and course objectives, course components, and sample course projects for design and development of these courses. The developed courses can provide useful reference for others institutions to design and implement risk and resilience related courses in the civil engineering curriculum.

## Introduction and Background

The past few decades have witnessed a significant increase in the number and magnitude of natural and man-made hazards, including Hurricane Katrina in 2005, Deepwater Horizon drilling rig explosion in 2010, Christchurch Earthquakes in 2011, Hurricane Sandy in 2012, Oso Washington Landslide in 2014, Hurricanes Irma and Harvey in 2017, which have caused not only significant damages to the built environment but also heightened levels of risk to lives and property. For example, during Hurricane Katrina in 2005, the storm overwhelmed the levee system and flooded 80% of New Orleans, caused about 1300 deaths and a total loss of $40 to $50 billion [1]. Deepwater Horizon drilling rig explosion in 2010 caused 11 deaths and created the largest environmental disaster in the United States history. In 2011, the earthquakes in Christchurch New Zealand caused over $30 billion of damages and 185 deaths. Disaster-related losses in the U.S. have exceeded $57 billion annually on average (and growing), and impose a tremendous threat to the welfare and security of the society [2]. Disaster resilience has become a priority of national needs to improve the performance of existing aging infrastructures and create smarter infrastructure systems to protect vital lifelines that help recover after a disaster and plan for future events [3].

Risk management and resilience are critical for planning, design, operation and maintenance of a variety of engineering systems for the built environment in the United States, including buildings, transportation, energy, water and food systems. For example, one of the prime lessons from Hurricane Sandy in 2012 was that we should design resilient infrastructure systems to ensure the adaptability for the future [4]. Currently, the importance of risk and resilience of engineering systems is increasingly appreciated in professional practice and research, yet these concepts continue to be absent from most traditional engineering curricula. Recent disasters and extreme events have further highlighted the need to produce engineering graduates with multi-disciplinary backgrounds and unique holistic perspectives and expertise to assess the risks and improve the resilience of our engineering systems through their life span. Indeed, the ASCE Vision for Civil Engineering in 2025 [5] portends a future in which engineers will be leaders in assessing and managing risk in all phases of their work toward hazard resilient built environment.

In response to the urgent needs for engineering professionals to address the increasing frequency of hazards and improve the resilience of our built environment, it is desirable to enrich the current curriculum of civil engineering and develop new courses to engage undergraduate engineering students in designing and constructing hazard-resilient engineering systems for the built environment. This paper presents our work in progress to infuse civil engineering and related engineering programs with transformative risk and resilience concepts via developing a set of “risk and resilience" focused courses. The developed courses will bridge the gap between existing civil engineering curriculum and the industry and societal needs for the new generation workforce. The "risk and resilience" focused courses include three courses: 1) Introduction to Risk and Resiliency in Engineering, 2) Reliability and Optimization Methods in Engineering, 3) Sensing and Data Analytics for Infrastructure Systems. The course "Introduction to Risk and Resiliency in Engineering" is currently being offered to our undergraduate students in Spring 2019. The other two courses will be offered in the semesters of Fall 2019 and Spring 2020, respectively.

**Overview of Risk and Resiliency Focused Courses**

The three developed courses are independent but complementary courses. These courses are integrated parts that address the fundamental knowledge and techniques needed for engineers to conduct the assessment, design and management of engineering systems to achieve hazard resilience, as illustrated in Figure 1. The "Introduction to Risk and Resiliency in Engineering" course (Course 1) will introduce natural and man-made hazards faced by engineering infrastructure and provide a comprehensive overview about the basic definition and engineering principles for risk and resilience assessment of various engineering systems. The "Reliability and Optimization Methods in Engineering" course (Course 2) will provide a general survey of the complete field of Reliability and Optimization in various engineering applications, and the course is designed to give a thorough philosophical base for Reliability and Optimization in engineering and mathematical techniques used along with frequent examples of application for engineering structures, components and systems. The "Sensing and Data Analytics for Infrastructure Systems" course (Course 3) will introduce the sensing and data analytics techniques across a broad range of engineering disciplines with a focus on infrastructure systems, and the course will empower students with a basic skill set on sensing and data analytics and an ability to directly apply these tools for practical engineering problems. These three courses are being taught in a collaborative effort by all authors listed in this paper. For each course, a principal instructor is in charge of the overall management of the course and instruction of its main components. However, other instructors will teach one lecture about applications of this course in their area of expertise, since these topics are multi-disciplinary in nature. These three courses have been included in the civil engineering curriculum as technical elective courses that are offered to undergraduate students during the junior and senior years. Collaborative class project will be incorporated into each course, which has been demonstrated as an effective approach to enhance students' engagement and self-efficacy [6-9]. We are currently implementing an evaluation plan for these three courses to assess the effects of collaborative class projects on the students' self-efficacy.

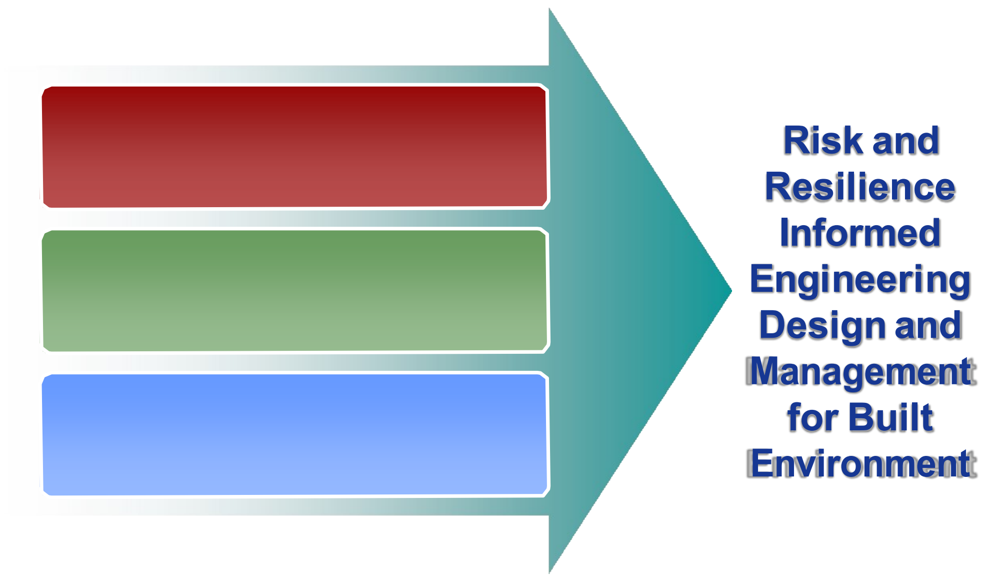


Figure 1. Overview of three developed risk and resilience focused courses

The following sections of this paper will discuss about details of each of these three developed courses including the rational and course objectives, course components, and sample course projects.

**Introduction to Risk and Resiliency in Engineering Course Information**

**Rationale and Objective:** The severe impacts of recent natural and man-made disasters have highlighted the importance of risk and resilience assessment of engineering systems, which are critical infrastructures to ensure public health, safety, security, and commerce. According to the Vision for Civil Engineering in 2025 [5], civil engineers should serve competently, collaboratively, and ethically to manage risk and uncertainty caused by natural events, accidents and other threats. The future development and the preservation and maintenance of national infrastructure will demand a more intense focus on risk assessment to mitigate hazards and improve engineering performance [10]. Understanding, managing, and reducing disaster risks provide a foundation for resilience against disasters. Resilience analysis is a proactive approach to enhance the ability of the infrastructure systems to prevent damages before the disturbance events (e.g., natural hazards), mitigate the losses during the events and improve recovery capability after the events [11]. This course aims to expose and prepare new generation of engineers with the fundamental principles of risk and resilience thinking for holistic design and management of engineering systems. The course will inform and empower students with in-depth, state-of-the-art knowledge on risk and resilience for real-world engineering applications [4, 12-15].

**Learning Outcomes:** After taking this course, the students will have a basic understanding of the natural and man-made disasters and their impacts on engineering systems. Students will be familiar with the risk and resilience concept, and the commonly used risk assessment methods used in practice. Students will be able to perform the risk and resilience assessment of a practical engineering problem.

**Course Content:** This three-credit course will provide a comprehensive overview about the basic definition and engineering principles for risk and resilience assessment of various engineering systems, including geotechnical, transportation, water resources, and electric power systems. Students will gain insight into the theories and methodologies of the following topics:

1) The nature of the disasters, effects of disasters on humans, historical event analysis and hazard prediction, and interaction of disasters with infrastructure and society. Various disasters will be introduced including natural disasters (e.g., earthquake, hurricane, tornado, landslide, and tsunamis) and man-made disasters (e.g., blasting, building fire, and terrorist attacks). For man-made disasters, the construction induced hazards and damages to buildings and infrastructure will also be discussed including the criteria for building damages and damages caused by deep excavations, tunneling, and etc.

2) Description and concept of vulnerability and risk, role of risk for engineering decision making, codes and standards, engineering hazards assessment and risk identification and evaluation using fault tree analysis, event tree analysis, failure mode and effects analysis. Various risk assessment methodology will be discussed including risk management and risk-informed decision analysis, fuzzy set and analytic hierarchy process (AHP) theory, decision tree and Monte Carlo simulation, formulation of risk-based design criteria, risk communication with stakeholders, decision makers,

and community. Among the risk assessment methods, AHP theory, decision tree and Monte Carlo simulations are used extensively in engineering practice.

3) Conceptual and analytical definition of resilience in engineering systems, various aspects of resilience such as robustness, rapidity, resourcefulness, redundancy, resilience metrics and measures, resilience capacity (absorptive, adaptive and recovery capacity), disaster cycle and role of intervention, resilience against multiple hazards, seismic resilience, network resilience, resilience assessment in asset management, resilience planning, resilience of interdependent infrastructure systems, community resilience for building and infrastructure systems, social-ecological and economic aspects of resilience.

The above topics will be complemented with case studies such as earthen levees, tunnels, water supply networks, nuclear power reactors, and electric power systems. Students will work in group of 2-3 on term projects involving risk and resilience assessment of engineering systems. MATLAB software and risk assessment software (PrecisionTree & TopRank) will be used as part of this course. The students need to be junior or senior standing to be eligible to take this course.

**Reliability and Optimization Methods in Engineering Course Information**

**Rationale and Objective:** Reliability and optimization methods are widely applicable engineering skills and increasingly gaining importance as decision support tools across engineering disciplines [16-22]. Engineers must deal with real-world uncertainty in design, planning and maintenance in which public safety is among the top priorities of any engineering problem. The need for mastering the advanced reliability and optimization techniques is even more pressing with the coming of the big data era for hazard resilience [23]. The course is designed to give students a solid foundation in the general concepts of reliability and optimization theory, equip students with an arsenal of techniques to solve real problems, and pave the way for students to develop new tools for decision making under various hazards and uncertain conditions. Examples will cover a range of different applications with the objective of helping the student to appreciate the challenges in design and production of complex products and engineering systems.

**Learning Outcomes:** After taking this course, the students will develop an understanding on uncertainty, reliability, and optimization concepts. Students will be familiar with the basic techniques used for reliability assessment and engineering optimization. Students will be able to perform the reliability assessment and reliability-based design optimization of a practical engineering problem in the face of uncertainty.

**Course Content:** This three-credit course will cover: 1) Fundamental understanding of concepts of uncertainty and reliability, random variables, fundamentals of sampling, Bayesian theory, Maximum likelihood principle, uncertainty propagation, reliability data collection and analysis, model calibration, and system reliability. 2) Development of stochastic simulation models, various reliability-based design and probabilistic methods including first-order second-moment method, first-order reliability method, point estimate method, and Monte Carlo simulations. 3) Introduction to optimization; optimality and convexity, general optimization algorithm, optimization methods including linear programming, network flow algorithms, integer programming, interior point methods, quadratic programming, nonlinear programming, heuristic methods and genetic algorithm; 4) Reliability based design optimization including reliability based robust design optimization and life-cycle reliability based design optimization. Among the reliability methods, first-order reliability method, point estimate method and Monte Carlo simulations are used extensively in engineering practice.

Numerous applications will be presented in civil, environmental, mechanical, electrical engineering, and industrial engineering. A term project is required on development of reliability-based design optimization in the face of uncertainty in a relevant engineering field. The state-of-the-art computer codes in MATLAB and Excel environment, as well as the commercial software @RISK and Evolver will be adopted in this course. Probability & Statistics is a pre-requisite.

**Sensing and Data Analytics for Infrastructure Systems Course Description**

**Rationale and Objective:** Currently, the use of advanced sensing and data analytics is rapidly increasing in research and practice, but the implementation of sensing and data analytics in the undergraduate civil engineering curriculum has not kept pace with advances in the state of practice. For example, the extensive sensing and data analytics-based tools have been implemented in various high profile infrastructure projects such as the Central Artery/Tunnel (CA/T) project in Boston [24, 25] and Transbay Transit Center project in San Francisco [26-28]. Civil engineers in the future will need to rely on and leverage the real-time data from myriad sensors dispersed throughout the natural and built environment for informed engineering decision to guarantee the integrity of infrastructures against deterioration and natural and man-made disasters [5, 29]. Sensing and data analytics play a vital role in enhancing the infrastructure resilience for smart cities through various applications such as intelligent infrastructure systems, infrastructure condition assessment, data management and communication, disaster management and early warning systems [30-35]. The objective of this course is to empower students with a fundamental and practical knowledge of sensing and data analytics and an ability to directly apply these state-of-the-art tools for practical engineering problems.

**Learning Outcomes:** After taking this course, the students will be familiar with various sensors used for monitoring and condition assessment of civil engineering infrastructure. Students will be able to plan, install and operate the commonly used sensors for civil engineering applications. Students will also be able to conduct the data analytics based on the sensing and monitoring data for infrastructure condition assessment.

**Course Content:** This three-credit course will address the increasing importance of automated measurements, instrumentation design, and the design of wireless sensor networks for data gathering across a broad range of engineering disciplines with a focus on the civil engineering domain. The following topics will be included: 1) Introduction to concept of sensors, sensors types, their applicability, and examples of their use (e.g., bridge, tunnel and water supply system monitoring); 2) Sensor planning, installation and operation; 3) Data processing and interpretation; 4) Data synthesis and visualization 5) Introduction to structural health monitoring for infrastructure condition assessment using wireless sensor networks. Students will learn the skills to select the suitable sensors for a specific application and the procedure to install and operate various sensors. Students will also learn about the suitability of different communication protocols (in terms of range and data rate) for use in sensor networks (e.g., ZigBee). Student will design their own data acquisition system and sensor networks and use MATLAB for their data processing, visualization and analysis. Available sensing data from the public database will also be used for teaching of data analytics. Class project in team of 2-3 students will be assigned to design the monitoring program and use the data for analysis of an engineering system. This course serves an introductory course where no prior knowledge about sensing and data analytics is needed;

however, students are expected to have taken undergraduate Calculus and Physics courses and Applied Numerical Method course.

**Sample Course Project**

For each of the courses, the students all need to complete a course project. The students are expected to work on a team and make a mid-term presentation and a final project presentation. The mid-term presentation will be in form of a research proposal that describes the work planned to be executed based on a comprehensive literature review and background study and the final project presentation will be a summary of all the project work in a professional manner. For the final term paper, each group is expected to present their work in an ASCE style paper. Each student will identify his or her role in both the project report and presentations. The faculty members will assist the students to select the project topics based on their interests. Below are a few proposed sample projects that can be introduced in the introduction to risk and resilience courses.

**Project 1:** Risk Assessment of Urban Infrastructure induced by Sea-level Rise and Storm Surge
**Brief Description of the Project:** This project will introduce students to investigate the effects of future relative sea level rise on the urban infrastructure using the risk assessment methodology. The inundation analysis based on the different hazards criteria will be performed combined with the GIS system to provide the hazard map for city planning and decision-making.

**Project 2:** Risk Assessment of Earthen Levees against Flood Hazards
**Brief Description of the Project:** This project will introduce student to perform the risk assessment of an earthen levee under the various expected flood levels. The students are expected to adopt the finite element method to model the levee behavior under various flooding hazards, and combine with the probability methods to evaluate the probability of failure and associated risk.

**Project 3:** Resilience Assessment of Underground Pipelines Network against Earthquake Hazards
**Brief Description of the Project:** This project serves to introduce students about the basic definition of resilience assessment metric and its applications in the seismic evaluation of underground pipeline network systems. The students will combine the GIS analysis and an

empirical model for estimation of probability of individual pipeline segment to quantify the seismic resilience of underground pipeline system in a selected city.

## Conclusions and future work

As our nation's infrastructures continue to age and the increased intensity and frequency of the natural hazards, a skilled engineering workforce is needed to address these challenges. This paper presents our work in progress to develop three "risk and resilience" focused courses for the civil engineering curriculum. This paper presents a detailed description of rational, object, and contents of each of the three courses, namely, 1) Introduction to Risk and Resiliency in Engineering, 2) Reliability and Optimization Methods in Engineering, 3) Sensing and Data Analytics for Infrastructure Systems. In the future, the authors plan to continue to implement these courses and collect the course evaluation data to assess the effects of these new courses on the students' engagement and self-efficacy in engineering, and explore most suitable pedagogic methods to teach the emerging engineering topics to undergraduate students.

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