PhD Final Defense – Seyedarmin Tabandeh

Societal Risk and Resilience Analysis: A Multi-Scale Approach to Model the Dynamics of Infrastructure-Social Systems

Advisor: Professor Paolo Gardoni

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Abstract

The prosperity of modern societies and public well-being increasingly depend on critical infrastructure to enable continuous flow of essential resources and services to communities. Infrastructure loss of functionality in the aftermath of hazards can disrupt regular residential and commercial activities, hinder emergency responses, and adversely impact the ability of communities to recover. The severity of societal disruptions and the recovery progression can significantly vary among communities depending upon the socio-economic characteristics and infrastructure functionality. The scarcity of resources and the ever-growing demand on infrastructure call for resilient infrastructure which are in service for longer period of time and are more reliable in the face of future hazards. However, the consequences of past disasters around the world have raised concerns about the vulnerability of existing infrastructure and highlighted the significance of risk mitigation and management. To leverage limited resources and promote effective risk mitigation and management, there is a pressing need for a rigorous stochastic decision model that integrates the reliability and resilience analysis of deteriorating infrastructure with societal risk and resilience analysis.

This dissertation develops general probabilistic and stochastic models for the reliability analysis of infrastructure components. Specifically, probabilistic predictive capacity and seismic demand models are developed for the reliability analysis of typical reinforced concrete bridges, retrofitted with fiber reinforced polymer composites. The formulation of the probabilistic predictive models builds upon the governing laws of physics/mechanics and exploits the information from computer simulations, laboratory tests, and field data. A Bayesian hierarchical modeling is employed to account for the effects of statistical dependence among training data on the epistemic uncertainty of model parameters and, thus, on the reliability estimate. To model the time evolution of the complete probabilistic response and reliability of general nonlinear dynamical systems, a Bayesian nonparametric approach, called a Dirichlet process mixture model, is proposed. The proposed approach simplifies the governing stochastic differential equation of nonlinear systems based upon the information available a priori and observational data from a limited number of simulations. Dirichlet process allows the complexity of the model grows indefinitely (in a probabilistic sense) as the observed dynamics of the nonlinear system unveils new patterns.

The dissertation then develops a mathematical approach for the recovery modeling and resilience analysis of deteriorating infrastructure. The recovery of infrastructure components is modeled as a stochastic jump process that closely replicates the actual work progress. Analogous to the statistical moments of a random variable, resilience metrics are defined as the partial descriptors of the (predicted) recovery curve. The deterioration of infrastructure components due to regular use and the occurrence of extreme events adversely impacts their reliability and resilience. A stochastic life-cycle formulation is developed that models performance measures such as instantaneous reliability and resilience, accounting for deterioration effects. For regional resilience analysis, a mathematical approach is developed that models the physical recovery and time-varying performance of infrastructure under a developed recovery schedule, accounting for infrastructure interdependencies. For a developed recovery schedule, the performance analysis models the recovery of disrupted services in terms of the resilience metrics. The proposed approach is illustrated through a large-scale problem for the post-disaster recovery modeling of infrastructure in Shelby County, Tennessee.

Successful risk mitigation and management cannot be limited to engineering considerations. A novel approach is proposed for societal risk and resilience analysis, called a Reliability-based Capability Approach. The proposed approach develops a set of probabilistic models to predict the broad societal impact of hazards in terms of changes in dimensions of individuals' well-being, called capabilities. The probabilistic models are used in a system reliability analysis to estimate the probability that the state of individuals' well-being is above or below a desired level. To model societal recovery, the proposed approach integrates the recovery modeling of infrastructure and socio-economic characteristics into a time-dependent reliability analysis. To facilitate the probabilistic modeling, the time-dependent reliability analysis is implemented with a Dynamic Bayesian Network. Finally, the quantified risk and resilience are evaluated to provide insights about the severity levels of hazards. The proposed approach is explained through a real case study example to quantify the cascading impact of infrastructure disruptions.