Multi-Hazard Resilience of Transportation Infrastructure

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Research Focus and Topics of Interest

*Infrastructure risk and resilience modeling*

- Key emphases in the areas of
  - Structural vulnerability analysis and protection
  - Multi-hazard resilience assessment (hurricane surge, wave, earthquake, flooding, aging...)
  - Life-cycle analysis in hazard prone regions

- Application to transportation and energy infrastructure
Multiple Hazards Across U.S.

www.rethinkstormshelters.com
The costly year of 2017!

U.S. 2017 Billion-Dollar Weather and Climate Disasters

- North Dakota, South Dakota, and Montana Drought Spring–Fall 2017
- Western Wildfires, California Firestorm Summer–Fall 2017
- California Flooding February 8–22
- Colorado Hail Storm and Central Severe Weather May 8–11
- Midwest Severe Weather June 27–29
- Midwest Severe Weather June 12–16
- South/Southeast Severe Weather March 26–28
- Minnesota Hail Storm and Upper Midwest Severe Weather June 9–11
- Midwest Tornado Outbreak March 6–8
- Central/Southeast Tornado Outbreak February 28–March 1
- Missouri and Arkansas Flooding and Central Severe Weather April 25–May 7
- Southeast Freeze March 14–16
- Southern Tornado Outbreak and Western Storms January 20–22
- Hurricane Harvey August 25–31
- Hurricane Irma September 6–12
- Hurricane Maria September 19–21

This map denotes the approximate location for each of the 16 billion-dollar weather and climate disasters that impacted the United States during 2017.

https://www.ncdc.noaa.gov
Hurricane Harvey

- Landfall on Texas coast – August 26
- Slow movement causing record rainfall and flooding in Houston – August 27-30
- As many as 290 roads closed/flooded on September 2nd – a week after (Texas Tribune)
- Major highway 6 and surrounding roads flooded due to Addicks reservoir reopen – September 20

Houston Road Conditions after Harvey

August 27, 2017
http://traffic.houstontranstar.org/

September 12, 2017

Photo taken on September 14, 2017

https://www.ncdc.noaa.gov
Hazard Resilience of Infrastructure

• Ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event (NIAC, 2009)
• Ability to prepare for and adapt to changing conditions, and withstand and recover rapidly from disruptions (NIST)

(Lounis, Z., & McAllister, T. P., 2016).
Research Overview

Develop a probabilistic framework for quantifying the resilience of transportation infrastructure subjected to multiple hazards

Outline

- Vulnerability modeling
- Restoration modeling
- Functionality assessment
- Applications to hurricane and earthquake
Vulnerability Modeling
What is a Fragility Model?

Conditional reliability

\[ P_f = P[Demand > Capacity \mid im] \]

\[ P_f = P[Demand > Capacity \mid im, x_1, x_2, \ldots, x_n] \]
Multi-Threat Fragility Modeling of Bridges

• Dual layer metamodell based parameterized fragility assessment framework
  • Individual Hazards
  • Joint Threats
  • Simultaneous Hazards
Fragility Assessment Framework

**Step 1**
Hazard(s) and failure type
- Select IM(s)
- Model loads
- Identify failure type

**Step 2**
Parameter selection
- Select bridge parameters and random variables
- Perform experimental design

**Step 3**
Response assessment
- Create FE models
- Evaluate responses

**Step 4**
Metamodel fitting
- Brittle: classification
- Non-brittle: regression

**Step 5**
Parameterized fragility
- Train logistic regression models

\[
P(\text{Damage} | PGA, x_1, ..., x_n) = \frac{e^{\theta_0 + \theta_{\text{PGA}} \cdot PGA + \sum_{i} \theta_i x_i}}{1 + e^{\theta_0 + \theta_{\text{PGA}} \cdot PGA + \sum_{i} \theta_i x_i}}
\]
Example Metamodels: Non-brittle failures

- **Machine learning techniques** permit the use of finite element based non-linear time history analysis

\[
RMSE = \sqrt{\text{MSE}} = \sqrt{\frac{n_p}{n_p} \sum_{i=1}^{n_p} (y_i - \hat{y}_i)^2}
\]

\[
R^2 = 1 - \frac{\text{MSE}}{\sigma^2}
\]

\[
\text{RMAE} = \frac{\max |y_i - \hat{y}_i|}{\sigma}
\]
Example Metamodels: Brittle failures

- Machine learning techniques permit the use of finite element based non-linear time history analysis

\[ P_F = \frac{1}{1 + e^{-(\beta_0 + \beta_1 Z_c + \beta_2 H_{\text{MAX}})}} \]

Predicted

<table>
<thead>
<tr>
<th></th>
<th>Failure</th>
<th>Survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure</td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>Survival</td>
<td>c</td>
<td>d</td>
</tr>
</tbody>
</table>

\[ P_F = \text{majority vote} \{ P_n (Z_c, H_{\text{max}}) \}_{1}^{N_T} \]
Single Hazard, Joint Threats

- **Earthquake and aging fragility**

\[
P_f(t) = P[\text{Demand} > \text{Capacity} \mid pga, t]
\]

\[
\text{Fragility} = P[\text{Damage} \mid PGA, x_1, \ldots, x_m]
\]
Single Hazard, Joint Threats

- **Earthquake** and **truck load** fragility

\[ P_f = P[Demand > Capacity \mid pga, gvw] \]
Multiple Concurrent Correlated Hazards

- Storm surge and wave from hurricane fragility

\[ P_f = P[Demand > Capacity | H_{\text{max}}, Z_c] \]

(Ataei and Padgett, 2013)
Restoration Modeling
Need for New Restoration Models

• Damage-functionality relationships for bridges

Collapse damage state

Deck collapse; column hinging; bearing unseating

Moderate damage state

Deck misalignment; column cracking
Restoration Modeling

- Existing approaches
  - Expert opinion survey
  - Analytical

- Current limitations:
  - Generic % functionality or capacity
  - Lacking explicit connection to traffic restrictions
  - Needed for network modeling
How to build a new model?

• Damage-functionality relationships for bridges formed from data
• 2 main sources – empirical and survey based
• Use inputs to train logic tree models

Empirical data from reconnaissance reports

Survey on post event functionality and restoration
Questions on repair actions, repair time as well as traffic and lane restrictions included
Logic Tree Based on Bridge Functionality Data

Example of a trained logic tree: Likelihood of closure

Example of a trained logic tree: Duration of closure

\[ P(\text{bridge closure}) = 0.37 \]

\[ P(\text{bridge closure}) = 0.70 \]

\[ P(\text{bridge closure}) = 0.86 \]
Network Functionality Assessment
Network Modeling

Regional Network Modeling
• Roads – Links
• Bridges – Links or Nodes
• Intersections – Nodes

(a) Bridges as nodes

(b) Bridges as part of links

Charleston Road network

Source: ESRI, HERE, DeLorme, USGS, Intermap, InCREMENT Corp., NAVIONIC, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia. © OpenStreetMap contributors, and the GIS user community.
Common Network Functionality Metrics

- Connectivity between different points of network
- Increased travel time across network
- Increased travel distance across network
- Economic and social loss
- Freight demand carried
Connectivity Analysis

• Algebraic connectivity – availability of a path from “Source” to “Terminal” or called s-t connectivity
• Optimal for accessibility and evacuation based studies
• Can also be used for all nodes to all nodes connectivity study

s-t connectivity = 100%
All node to all node connectivity = 100%

s-t connectivity = 0%
All node to all node connectivity = 60%
Network Flow Analysis

• Travel demand based on Origin-Destination trips
• Traffic flow capacity modeling similar to FHWA and DOT models
• Disruptions and congestions leading to increased travel time and travel distance across network
• Assumptions on equilibrium model for travel time
• Opportunities for improvement

Memphis MPO Travel Demand Model
Regional Applications of Resilience Modeling Tools
Regional Hurricane Vulnerability Assessment

Houston and Galveston: Hurricane Ike Scenario
Bridge Vulnerability

Houston and Galveston: Hurricane Ike Scenario

Rollover Pass Bridge Actual Failure during Ike
Bridge Vulnerability

Houston and Galveston: 145 Ike Pt 8 Scenario

<table>
<thead>
<tr>
<th>Failure Probability (%)</th>
<th>No. of Bridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>69</td>
</tr>
<tr>
<td>5-25</td>
<td>7</td>
</tr>
<tr>
<td>25-75</td>
<td>8</td>
</tr>
<tr>
<td>75-100</td>
<td>52</td>
</tr>
</tbody>
</table>
Transportation Network Assessment

Galveston, TX: Hurricane Storm Scenario

**Hurricane scenarios investigated:**
- Storm realizations that “resemble” different intensities
  - Scenario 1 → Low intensity level ~ 100 yr
  - Scenario 2 → High intensity level ~ 500 yr
- Surrogate model-based hurricane hazard characterization
- Trained based on dataset from US Army Corps Engineers (USACE)

![Surge and Wave Height Maps](image)

**Locations:**
- Location 1
- Location 2
Transportation Network Model

Galveston Highway Network

Network details:
• 163 roadway links
• 144 nodes
  ➢ 25 bridge nodes
  ➢ 32 building cluster nodes → Nodes that accessibility is assessed
• Currently only bridge nodes can fail
• In the future incorporation of potential roadway link failure
Bridge Vulnerability

Fragility Model (Ataei and Padgett 2013):

\[ P[\text{fail}] = P[\text{bridge deck unseating}] = f(H_{\text{max}}, Z_c) \]

- \( H_{\text{max}} \): maximum wave height
- \( Z_c \): relative surge elevation
- \( SW \): span mass

Scenario 1

100 year storm event

Probability of failure
- 0.00 - 0.20
- 0.20 - 0.40
- 0.40 - 0.60
- 0.60 - 0.80
- 0.80 - 1.00

surge (m)

- 0.4
- 0.8

Scenario 2

500 year storm event

Probability of failure
- 0.00 - 0.20
- 0.20 - 0.40
- 0.40 - 0.60
- 0.60 - 0.80
- 0.80 - 1.00

surge (m)

- 0.70
- 0.90
Network Functionality Metric: Node accessibility or connectivity loss (CL) from inland to non-evacuees in damaged buildings on coast

Probability of non-connectivity: \( P_F(s, t) = 0.1\% \) for all terminal nodes

Parcel cluster with larger # of non-evacuees in damaged buildings and longer paths connecting this node with inland

Inland Source Node

Terminal Nodes

Low Intensity (Scenario 1)

(collaboration w/Rosenheim, Peacock, Johnson, Cox)
Network Functionality

Network Functionality Metric: Node accessibility or connectivity loss (CL) from inland to non-evacuees in damaged buildings on coast

Parcel cluster with larger # of non-evacuees in damaged buildings and longer paths connecting this node with inland

Inland Source Node

Terminal Nodes

High Intensity (Scenario 2)

Probability of non-connectivity: \( P_F(s, t) = 35\% \) for all terminal nodes

# of non-evacuees

\( CL(s, t) \)

Parcel cluster with larger # of non-evacuees in damaged buildings and longer paths connecting this node with inland

(collaboration w/Rosenheim, Peacock, Johnson, Cox)
Transportation Network Resilience Assessment

Shelby County, TN: Earthquake Scenario

Earthquake scenario investigated:
- 7.5 moment magnitude scenario with the rupture site along the New Madrid Fault

Before earthquake

Traffic flow in links

Shelby County Road Network

- Bridges
- Road Nodes

Shelby County Road Network Links

Earthquake rupture scenario

SA at 0.5 seconds
High: 3-2712
Low: 0-396522

Epicenter

Source: Esri, HERE, DeLorme, Intermap, incrementors P Corp, GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, ESRI Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community
Bridge Vulnerability and Network Disruption

\[ P_f = P(Demand > Capacity|SA_{0.5}, x_1, x_2, \ldots x_n) \]

\[ x_1, x_2, \ldots x_n \text{ – Bridge parameters such as column height, deck width} \]
Network Functionality Evolution: Traffic flow

Day 1 after earthquake

Day 7 after earthquake

Day 240 after earthquake
Network Functionality Evolution

Network Functionality Metric: Node connectivity ratio, Travel time in network and Travel distance in network

Connectivity Analysis

\[
\text{Connectivity Ratio} = \frac{\text{No. of Connected Nodes}}{\text{Total Nodes}}
\]

Network Flow Analysis
Conclusions

• Three important inputs for resilience assessment:
  ➢ Vulnerability assessment
  ➢ Restoration modeling
  ➢ Network functionality modeling

• Resilience assessment can support risk mitigation and pre-event planning or post-event response and recovery

• Future work to address limitations, e.g. resource constraints, damage to other components, etc.

• Opportunity for extension to other civil infrastructure, threats and exposure conditions
THANK YOU

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GRA and Post-Doctoral opportunities available