Presentation to T-1

on

Design for Multi-Hazard (MH) Resilient Highway Bridges

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OUTLINE

• Examples of Current Needs
• Multi-Hazard Bridge Design
• Multi-Hazard Survey
• Framework Development
• Current Multi-Hazard Bridge Design Study
EXAMPLES OF CURRENT NEEDS
Examples of Current Needs

- $\gamma_{EQ}$ in Extreme Event I
- What loads to evaluate stability under check scour
- Are all Extreme Events treated equally
Examples of Current Needs

Live Load + EQ

• Load factor on Live Load
  – 0.0, 0.5, 1.0 ???
  – “This issue is not resolved”
  – Two time variable loads need to be combined
  – Dynamic interaction of live load and structure
    • May be important
    • Need baseline
Examples of Current Needs

Scour

- Design flood for design conditions
- Check flood for “stability”
  - “The consequences of changes in foundation conditions due to scour resulting from the check flood for bridge scour and from hurricanes shall be considered at the extreme event limit states”
Examples of Current Needs

Scour (cont’d)

• No other guidance appears to be provided
• How much scour for seismic checks?
• For vessel collision?
• For wind?
Examples of Current Needs

Extreme Event Compatibility

- Service limit state calibration
- Should a uniform Beta be the goal for extreme events?
- Should there be a goal?
- What are the Betas now?
Examples of Current Needs

Points of Current Study

• Focus on areas where guidance is mostly needed
  – Not necessarily new limit state equations
• Utilize framework developed in previous MCEER project funded by FHWA
• Lay the groundwork for common treatment of extreme events on the same platform
MULTI-HAZARD BRIDGE DESIGN
Multi-Hazard Bridge Design

What?
Why?
How?
Where to?
What?

- Risk-based design
- Straightforward implementation
- Consistent with current LRFD
Why?

- Need more consistent safety
- Need less waste in over-design
- Need ease of future development
Multi-Hazard Bridge Design

How?

- LRFD design formula:
  \[ \sum \eta_i \gamma_i Q_i \leq \phi R_n \]
Multi-Hazard Bridge Design

How?

1. **Framework:** Development of principles for multi-hazard (MH) bridge design principles (completed—MCEER)

2. **Trial Calibration:** Multi-hazard bridge design (current project)

3. **Future deployment:** Adoption of MH-LRFD
Multi-Hazard Bridge Design

Where to?

- WSD
- LFD
- LRFD (non-extreme loads)
- MH-LRFD (all loads)
- MH-LRFD (performance-based)
- Sustainability Design
MULTIPLE-HAZARD SURVEY
Objectives

- Record professional opinion of experienced bridge engineers on the importance of various hazards and load combinations
- To stimulate discussion
- To identify needs in the practical application of existing specifications and guidelines
- To identify variations in extreme load usage
- Intuitive answers based on:
  - Experience and precedence
  - Geographical variation—terrain, weather, seismicity, …
  - Bridge site conditions—navigability, urbanization
  - Professional judgment
  - Budget constraints
  - Risk management: life cycle cost, consequence measurement
  - Public expectation
Dear Recipient:

This poll is being sent to you as part of a FHWA funded research project being conducted by MCEER. A principal objective of this project is to develop multiple hazard design principles for bridges. In support of this goal, a special workshop on extreme load effects is being organized and we are asking for your input to the following questions to facilitate discussion. Please respond within by February 22 if possible.

Thank you very much in advance.

The Workshop Steering Committee
Harry Capers, John Kulicki, George Lee, Tom Murphy and Phillip W. H. Yen

QUESTIONNAIRE

<table>
<thead>
<tr>
<th>Name:</th>
<th>State:</th>
<th>Tel#:</th>
<th>E-mail</th>
</tr>
</thead>
</table>

Note: The researchers who designed this survey are not interested in official state or AASHTO policy or practice, but rather the professional opinion of experienced bridge engineers who can help shape future guidance on the design of bridges for multiple hazards. Your response should be relevant to your region of the country, rather than to the US as a whole.

The probability-based approach used in the LRFD Bridge Design Specification was developed to provide a fairly consistent level of reliability. This approach is desirable for extreme load combinations with safety factors in the conventional design loads found in AASHTO. As part of the project, we plan to evaluate the level of acceptable failure probability when a bridge is subjected to a single or combination of extreme loads, recognizing that each hazard may have a different return period.

Because a bridge’s exposure to hazards varies somewhat according to which part of the country it is in, the researchers are seeking input from bridge owners (the stakeholders) on the relative importance of different extreme loads and their possible combinations. This input may eventually lead to the development of multi-hazard (MH) LRFD design guidelines. With this in mind, please mark the following extreme load or load combination that, in your opinion, should be considered in your region. Please assume that the intensity of the hazard is sufficiently large that the design of bridge with design life of 75 – 100 years should consider it. Use the following scale:

1 to denote “I do not believe it is necessary to design for this,”
2 to denote “It should be investigated further and considered,”
3 to denote “I believe that we should always design for this.”

<table>
<thead>
<tr>
<th>Part I Single and Concurrent Events</th>
<th>Standard, Short/Medium Span Bridges (Say &lt;500’)</th>
<th>Special or Long-Span Bridges</th>
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</thead>
<tbody>
<tr>
<td>1.1</td>
<td>scour</td>
<td>1. No</td>
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<tr>
<td>1.2</td>
<td>vessel collision</td>
<td>2. Consider</td>
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<tr>
<td>1.3</td>
<td>vehicular collision</td>
<td>3. Always</td>
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<tr>
<td>1.4</td>
<td>fire</td>
<td>1. No</td>
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<tr>
<td>1.5</td>
<td>earthquake</td>
<td>2. Consider</td>
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<tr>
<td>1.6</td>
<td>storm surge</td>
<td>3. Always</td>
</tr>
<tr>
<td>1.7</td>
<td>wind</td>
<td>1. No</td>
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<tr>
<td>1.8</td>
<td>debris flow</td>
<td>2. Consider</td>
</tr>
<tr>
<td>1.9</td>
<td>other (specify)</td>
<td>3. Always</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part II Possibility of Two Concurrent Extreme Events</th>
<th>Standard, Short/Medium Span Bridges (Say &lt;500’)</th>
<th>Special or Long-Span Bridges</th>
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</thead>
<tbody>
<tr>
<td>2.1</td>
<td>scour + vessel collision</td>
<td>1. No</td>
</tr>
<tr>
<td>2.2</td>
<td>scour + earthquake</td>
<td>2. Consider</td>
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<tr>
<td>2.3</td>
<td>scour + storm surge</td>
<td>3. Always</td>
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<td>2.4</td>
<td>scour + wind</td>
<td>1. No</td>
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<tr>
<td>2.5</td>
<td>scour + debris flow</td>
<td>2. Consider</td>
</tr>
<tr>
<td>2.6</td>
<td>vessel collision + storm surge</td>
<td>3. Always</td>
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<tr>
<td>2.7</td>
<td>vessel collision + wind</td>
<td>1. No</td>
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<tr>
<td>2.8</td>
<td>vessel collision + debris flow</td>
<td>2. Consider</td>
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<tr>
<td>2.9</td>
<td>vehicular collision + wind</td>
<td>3. Always</td>
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<td>2.10</td>
<td>fire + wind</td>
<td>1. No</td>
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<tr>
<td>2.11</td>
<td>earthquake + wind</td>
<td>2. Consider</td>
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<td>2.12</td>
<td>storm surge + wind</td>
<td>3. Always</td>
</tr>
<tr>
<td>2.13</td>
<td>wind + debris flow</td>
<td>1. No</td>
</tr>
<tr>
<td>2.14</td>
<td>other possible combinations (specify)</td>
<td>2. Consider</td>
</tr>
</tbody>
</table>
Part 1. Single Extreme Event
(scour, vessel collision, vehicular collision, fire, earthquake, surge, wind, debris)
or
Combination of Events
(two or three concurrent events)

Part 2. Cascading Events
(e.g. vehicular collision → fire)
(e.g. wind → surge + vessel collision)

Part 3. Comments
(explanation or concern over other hazards)
Survey Results

- Data were numerically and graphically analyzed
- Comments were studied
- An MCEER Report was published
- 35+ states responded
Multi-Hazard Survey

Earthquake

Standard Bridges

Special Bridges
Multi-Hazard Survey

Fire

Standard Bridges

Special Bridges
Multi-Hazard Survey

Vehicular Collision

Standard Bridges

Special Bridges
Multi-Hazard Survey

Storm Surge + Wind (Concurrent)

Standard Bridges

Special Bridges
Multi-Hazard Survey

Single Event - Typical Bridges

- **Scour**: 1-No, 0, 0%; 2-May, 2, 6%; 3-Always, 30, 94%
- **Vessel Collision**: 3-Always, 10, 31%; 2-May, 16, 50%; 1-No, 9, 28%
- **Earthquake**: 1-No, 7, 22%; 2-May, 9, 28%; 3-Always, 2, 6%
- **Storm Surge**: 1-No, 13, 41%; 2-May, 17, 53%; 3-Always, 2, 6%
- **Vehicular Collision**: 1-No, 1, 3%; 2-May, 18, 56%; 3-Always, 13, 41%
- **Fire**: 1-No, 0, 0%; 2-May, 10, 31%; 3-Always, 10, 31%
- **Wind**: 1-No, 1, 3%; 2-May, 10, 31%; 3-Always, 5, 15%
- **Debris Flow**: 1-No, 5, 15%; 2-May, 22, 69%
Multi-Hazard Survey

Single Event & Concurrent Events

Typical Bridges

Ranked by score:
1 Scour
2 Wind
3 Vehicular collision
4 Earthquake
5 Vessel collision
6 Debris flow
7 Scour + other
8 Storm surge

... 17 Fire
Multi-Hazard Survey

River and Coastline Issues

5 Vessel Collision

6 Storm Surge

U.S. Inland & Intracoastal Waterways

- Don't Consider
- Possibly Consider
- Always Consider

Nearly 12,000 Mile System
191 Lock Sites / 237 Chambers Active
Replacement Value $125+ Billion
Scour + Debris Flow

Don’t Consider
Possibly Consider
Always Consider

Standard - 1
Multi-Hazard Survey

Potential Socio-economical Factors (Consequence of Damage)

3 Vehicular Collision

4 Earthquake
Potential Boundaries

I: High seismicity, non-hurricane coastal wind
II: Long-term high seismicity, Inland wind
III: Inland wind
IV: Hurricane zone
V: Long-term high seismicity, hurricane zone
Multi-Hazard Survey

Preliminary Observations

• Regional patterns were revealed.
• Consequence seems to be built into the assessment of risk.
  – Potential fatalities & economic disruption rather than just potential for structural failure
  – Population density and traffic volumes are indicators
• Hazards
  – Scour ranks high in survey and in lists of failures
  – Collision ranks high in survey and in lists of failures
  – Fire is not ranked high but is a significant cause of bridge failure
  – Wind ranks high but has not been a cause of failure
FRAMEWORK DEVELOPMENT
Framework Development

Quantified “Safety”—Reliability Index

\[ \beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \]

- Kulicki et al. (1991): Calibration for dead load and live load

AASHTO Standard Specifications

Proposed LRFD Specifications

\[ \beta = 3.5 \]
Framework Development

Steps for Calibration of LRFD (DL+LL)

- Framework Development
- Dead Load
- Truck Load
- Load Distribution Models
- Load Combinations
- Target Bridge Reliability
- Bridge Failure Probability
- Design Limit State Equations
- Load and Resistant Factors

Bridge Capacity Model
Experience and Judgment
LRFD and Supporting Guidelines for Extreme Loads

Framework Development

- Dead Load
  - Strength limit states
  - Service limit states
  - Fatigue limit states
    - (LRFD)

- Live Load

- Earthquake
  - Extreme event limit state
    - (Seismic Guidespec)

- Surge
  - Extreme event limit state
    - (Vessel Collision Guidespec)

- Collision

- Flood
  - Check flood
    - (HEC-18)

Not all risk-based and not calibrated consistently
MCEER Framework for the Development of MH-LRFD (DL+LL+ Extreme Loads)

- Dead Load
- Live Load
- Earthquake
- Surge
- Collision
- Flood

Risk-based and consistently calibrated
The MCEER Framework

- Reliability-based platform including load (and equivalent load) effects of all hazard that may cause structural damage / failure of bridges (components)
- Systematic approach for handling multiple time-variable loads
- Method to derive design limit state equations (DLSE’s) from calibration data
- Calibrating with loads and other effects (such as scour)
Accomplishment of required reliability

\[ \beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \]

\[ \mu_Q \neq \mu_{Q1} + \mu_{Q2} + \mu_{Q3} + \cdots \]

- Considering two time-variable loads, the effect cannot be a direct summation
- Potentially decreased load factors representing the less-likely
Somewhat increased risk of high intensity
Load Combinations of Interest

Important frequent-infrequent load combinations based on input from SCOBS (responses from 35+ states in 2010), FHWA and selected Bridge Engineers:

- DL+LL+EQ
- DL+LL+SC+EQ
- DL+LL+SC+CV
- DL+LL+EQ+Wind (more significant for Signature Bridges)
- DL+LL+CT+ Subsequent Fire
Development of Future MH-LRFD (A Case Study)

Combinations of Dead Load, Live Load and Earthquake: A case study
Framework Development

A Case Study (Cont’d)

1. Bridge Capacity Model
   - Experience and Judgment

2. Target Bridge Reliability
   - Bridge Failure Probability
   - Design Limit State Equations
   - Load and Resistant Factors

3. Load Distribution Models
   - Dead Load
   - Truck Load

4. Load Combinations

5. Infrequent, Extreme Loads and Effects
   (earthquake, wind, scour, vessel collisions, etc.)

6. STEP
   - Framework Development
   - A Case Study (Cont’d)
Step 1. Selection of representative bridges.

- One typical example
  - Three spans are 100, 120, 100 ft in length, respectively
  - Superstructure is one continuous cast-in-place concrete box girder
  - Two 4ft diameter columns at each bent, with clearance height of 20 ft
  - This bridge is located in San Francisco, CA
Step 2. Establish the statistical data base for load and resistance parameters

- **Live loads**
  - Normal distribution (Moses*)
    - Mean value: 68 kips
    - Standard deviation: 18 kips (COV = 26.5%)
  - Rate: 5,000 / day

- **Earthquake**
  - USGS Hazard Map

Step 3. Development of load and resistance models

- **Resistance Model**
The nominal value of resistance is calculated based on the current LRFD. Resistance follows a lognormal distribution with the COV of 0.13.
A Case Study (Cont’d)

AASHTO LRFD Bridge Design Specifications

\[ \mu_R = \lambda_R \times R_n \]
\[ \mu_L = \lambda_L \times L_n \]

Mean resistance

Mean Value

Maximum Load Distribution

\[ f_L(x) \]
\[ f_R(x) \]

Nominal load

Nominal resistance

Design load and resistance

\[ L_n \]
\[ R_n \]
Framework Development

A Case Study (Cont’d)

Step 3. Development of load and resistance models (Cont’d)

♦ Live Load Effect Model: Obtained using structural mechanics principles

![Diagram of a bridge with a truck and bending moment graph]
Step 3. Development of load and resistance models (Cont’d)

- Earthquake Load Effect Model: Obtained using time-history analysis
  - Obtain the PGA (peak ground acceleration) distribution from USGS
  - Discretize the PDF (probability density function) for one earthquake using an specified interval (0.01g)
  - Use a series of earthquake ground motion records for each level of PGA to analyze the time-history response of the column
Step 3. Development of load and resistance models (Cont’d)

- Earthquake Load Effect Model: Obtained using time-history analysis
- Record the maximum load responses in abscissa of PMF (probability mass function)
A Case Study (Cont’d)

Step 3. Development of load and resistance models (Cont’d)

♦ Earthquake Load Effect Model: Obtained using time-history analysis

➢ Modify the PMF (discretized PDF) to ensure the sum of probability equals to 1
Framework Development

A Case Study (Cont’d)

Step 3. Development of load and resistance models (Cont’d)

- Combined Load Effect Model

**EQ**

Earthquake Time-history

**LL**

Bending Moment (kip-ft)

Combined Load Effect Model

- Maximum response

Corresponding probability of PGA

PMF in 75 years
Step 3. Development of load and resistance models (Cont’d)

- **Combined Load Effect Model**
  Modify the PMF (discretized PDF) to ensure the sum of probability equals to 1
Step 4. Development of the reliability analysis procedure

- Partial and total failure probabilities
- Principle of Comprehensive Reliability

\[
\begin{align*}
  p_f^E &= 4.78 \times 10^{-6} \\
  p_f^{EL} &= 7.72 \times 10^{-4} \\
  p_f^L &= 3.50 \times 10^{-22} \approx 0
\end{align*}
\]

- Earthquake
- Combined
- Live load (disregarded)
Framework Development

A Case Study (Cont’d)

1. Bridge Capacity Model

2. Infrequent, Extreme Loads and Effects (earthquake, wind, scour, vessel collisions, etc.)

3. Load Distribution Models

4. Load Combinations

5. Target Bridge Reliability

6. Load and Resistant Factors

Experience and Judgment

Design Limit State Equations

Bridge Failure Probability

STEP 1

STEP 2

STEP 5

STEP 4

STEP 6

Dead Load

Truck Load
Framework Development

A Case Study (Cont’d)

Step 5. Selection of the target reliability index

- Parametric Study (selection of different bridges)

![Bridge Diagram]

Steps:
- 70’
- 120’
- 200’
Step 5. Selection of the target reliability index (Cont’d)

- Parametric Study (selection of different bridges)
Step 5. Selection of the target reliability index (Cont’d)

- Determine the reliability of current design

Current EQ

Side Span (ft)

Average \( \beta = 2.5 \)
Step 5. Selection of the target reliability index (Cont’d)

- Determine the reliability of current design
  - Why $\beta = 2.5$?
    - 2.5 = Average reliability index for 9 bridges designed using current AASHTO LRFD
    - Same approach used for establishing the LRFD DL and LL:
      - Average $\beta = 3.5$
Step 6. Calculation of load and resistance factors

- Least Square Method (curve fitting)

\[
\begin{bmatrix}
L_1^{(1)} & L_2^{(1)} & \ldots & L_m^{(1)} \\
L_1^{(2)} & L_2^{(2)} & \ldots & L_m^{(2)} \\
\vdots & \vdots & \ddots & \vdots \\
L_1^{(n)} & L_2^{(n)} & \ldots & L_m^{(n)}
\end{bmatrix}
\begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\vdots \\
\gamma_m
\end{bmatrix}
= \Phi
\begin{bmatrix}
R_1^{(1)} \\
R_2^{(2)} \\
\vdots \\
R_m^{(n)}
\end{bmatrix}
\]

\[\gamma_L = 1.38; \quad \gamma_E = 0.74\]
A Case Study (Cont’d)

Comparison between current LRFD and MH-LRFD based on Case Study for DL+LL+EQ

LRFD: Extreme event limit-state equation

- $\gamma_p \cdot DL + \gamma_{EQ} \cdot LL + 1.0 \cdot EQ$ ($\gamma_p = 0.9\sim1.25$, $\gamma_{EQ} < 1.0$ or $\gamma_{EQ} = 0.5$)
- General design equations (for column, girder, bearing, etc.)
- Not yet calibrated by reliability-based design methodology

MH-LRFD

- $\gamma_p \cdot DL + 1.38 \cdot LL + 0.74 \cdot EQ$ ($\gamma_p = 0.9\sim1.25$)
- Specific equation for column bending moment
- Generated by MH reliability-based design principles, need to be further calibrated using sufficient cases
CURRENT MULTI-HAZARD BRIDGE DESIGN STUDY
Implementation of MCEER Framework

- Target the development of a guide document on bridge design against extreme events suitable for adoption by AASHTO with consistent design principles
- Expand on the MCEER work to include work by others
- Explore the potential of balanced design of typical bridges between safety and cost
Some Significant Research Challenges

– To include all important frequent and infrequent loads and their combinations to quantify their relative importance
– To study the appropriateness by approximating random processes as random variables
– To establish all-inclusive failure probability equations
– To establish design limit state equations and to extract load and resistance factors and their calibration
Potential DLSE’s

- LL+SC (scour)
- LL+CV
- LL+EQ
- LL+Wind (WS, WL)
- LL+CV+SC
- LL+EQ+SC
- LL+SC+Wind

Note: each combination may be one or more DLSE’s
Key Issues for Load Combination

- It does NOT always mean the consideration of concurrent events.
- Increased risk from a single load, but not overly conservative by directly combining high loads.
- Complex theory and development, simple design limit state equations
Current Multi-hazard Bridge Design Study

Key Issues for Load Combination

Load Combination ≠ Concurrence

Likely Concurrence
- Design flood with LL (Current LRFD for all non-extreme DLSEs)
- Drifting barge collision with scour (current LRFD ½ scour depth with empty barge weight)
- Earthquake with live load

Unlikely Concurrence
- Design flood (scour with design earthquake)
- Check flood with other loads except DL
- Earthquake with vessel collision
Some High Priority Subjects

- Critical variables in design
- Scour/foundation modeling
- Resistance modeling
- Efficient and reliable probability analysis
Potentially Critical Variables in Design

- Element force
- Displacement
- Type of bridge component
- Hazard variation (temporal and spatial)

Not considered:
- Human factors
- Interactive properties among different hazards (except strayed empty barge)
Scour/foundation modeling

- Types of foundation system
- Probabilistic characteristics of scour
- Soil failure vs. foundation element failure
- Positive and negative effect
Future Research Challenges

• Explore cascading multiple hazard load effects for critical bridge components
• Develop approaches to establish failure probability of the bridge as a system of components
• Select and prioritize research projects to provide guidance in hazard mitigation studies
Current Multi-hazard Bridge Design Study

Project Execution

- FHWA funding for Multi-hazard Bridge Design
- Research Team
  - Genex Systems
  - MCEER
  - Modjeski and Masters
  - Arora and Associates
  - FHWA: W. Philip Yen (COR)