SHIP & BARGE COLLISIONS WITH BRIDGES

General Overview

AASHTO Code

moffatt & nichol

Michael Knott, P.E.
Dr. Eric Nichol, P.E.
Mikele Winters, P.E.
Background

Accidents do happen …
- It’s Only A Matter of Time (Risk)
- Knott’s Rule: If You Build It … They Will Hit It

36 Major Collapses since 1960 Due to Vessel Collisions
- 18 Collapses in the U.S.
- 340+ Fatalities

250+ Minor Vessel Collisions/Year

Major Bridge Collapses in the U.S.

<table>
<thead>
<tr>
<th>Bridge Location</th>
<th>Year</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Ponchartrain, LA</td>
<td>1964</td>
<td>6</td>
</tr>
<tr>
<td>Chesapeake Bay Bridge, VA</td>
<td>1970</td>
<td>0</td>
</tr>
<tr>
<td>Sidney Lanier Bridge, GA</td>
<td>1972</td>
<td>10</td>
</tr>
<tr>
<td>Chesapeake Bay Bridge, VA</td>
<td>1972</td>
<td>0</td>
</tr>
<tr>
<td>Lake Ponchartrain Bridge, LA</td>
<td>1974</td>
<td>3</td>
</tr>
<tr>
<td>Pass Manchac Bridge, LA</td>
<td>1976</td>
<td>1</td>
</tr>
<tr>
<td>Benjamin Harrison Bridge, VA</td>
<td>1977</td>
<td>0</td>
</tr>
<tr>
<td>Union Avenue Bridge, NJ</td>
<td>1977</td>
<td>0</td>
</tr>
<tr>
<td>Berwick Railroad Bridge, LA</td>
<td>1978</td>
<td>0</td>
</tr>
<tr>
<td>Sunshine Skyway Bridge, FL</td>
<td>1980</td>
<td>35</td>
</tr>
<tr>
<td>Hannibal Railroad Bridge, MI</td>
<td>1982</td>
<td>0</td>
</tr>
<tr>
<td>Lake Ponchartrain Bridge, LA</td>
<td>1984</td>
<td>0</td>
</tr>
<tr>
<td>Bonner Bridge, NC</td>
<td>1990</td>
<td>0</td>
</tr>
<tr>
<td>Judge Seeber Bridge, LA</td>
<td>1993</td>
<td>1</td>
</tr>
<tr>
<td>Bayou Canot RR Bridge, AL</td>
<td>1993</td>
<td>47</td>
</tr>
<tr>
<td>Queen Isabella Bridge, TX</td>
<td>2001</td>
<td>8</td>
</tr>
<tr>
<td>I-40 Bridge over Ark. River, OK</td>
<td>2002</td>
<td>13</td>
</tr>
<tr>
<td>Popps Ferry Bridge, MS</td>
<td>2009</td>
<td>0</td>
</tr>
<tr>
<td>Eggner Ferry Bridge, KY</td>
<td>2012</td>
<td>0</td>
</tr>
</tbody>
</table>
• People **do** die ... Really!
  – If it happened to you ....
    You wouldn’t like it either
• Oil spills from accidents **do** occur
  ... Really!
Modern Vessels Are Longer & Wider Than In The Past
Many older “Long Span” bridges aren’t long enough for today’s larger vessels.
Many bridge openings are too narrow for today’s larger/wider ships and barge tows.
Bridges are often located near congested marine terminal facilities.
- Too many bridges over navigable waterways in some locations
Background

- Frequency of ship & barge traffic has increased in many harbors and channels.
Background

• Vessels Get In Trouble Due to ...
  PILOT ERROR

• Some Causes ...
  – Inattentiveness
  – Drunkenness/Tiredness
  – Crew Misunderstandings
  – Poor Judgment
  – Violate Navigation Rules
  – Incorrect Evaluation of Wind/Current Conditions
Vessels Get In Trouble Due to ...
MECHANICAL FAILURE

Some Causes ...
- Engine Failure
- Steering Failure
- Other Mechanical & Electrical Equipment Failures
• Vessels Get In Trouble Due to ... ADVERSE ENVIRONMENTAL CONDITIONS

• Some Causes ...
  – Poor Visibility (Rainstorm, Fog)
  – High Density of Ship & Barge Traffic
  – Strong Currents
  – Wind Squalls
  – Poor Navigation Aids
  – Awkward Channel Alignments
Tjörn Bridge
Almo Sound, Sweden (1980)
Ulyanovsk Railway Bridge
Volga River, Russia (1983)

177 Fatalities when top deck of cruise ship was “decapitated”
Tasman Bridge
Derwent River, Hobart, Australia (1975)
Bonner Bridge
Oregon Inlet, NC (1990)
Claiborne Ave. Bridge
New Orleans, LA (1993)
Bayou Canot RR Bridge
Mobile, AL (1993)

Vessel Collision Design of Highway Bridges
Million Dollar Bridge
Portland, Maine (1996)

- Tanker Ship Accident (LOA=560’, Width=85’)
- Double Leaf Bascule Bridge (Horizontal Navigation Clearance = 95’)
- 170,000 Gallons of Fuel Oil Spilled

Vessel Collision Design of Highway Bridges
Queen Isabella Bridge
South Padre Island, TX (2001)
I-40 Bridge over Arkansas River
Webber Falls, OK (2002)
"There's 35,000 cars a day that goes across this bridge," A.J. Holloway said. "How there wasn't a car on there, or a vehicle, or a school bus at that time (7:20 AM), on that span, is just amazing to me."
Movable Bridges

- Get hit fairly often
  ... (like magnets to vessels)
Mast Collisions

- Occur frequently – but are usually not catastrophic
Legal Things You Should Know ...

• Bridges Are **Obstructions** to Marine Navigation

• Mariners Have the Right of Way … **Not Motorists**

• Bridges Must Provide for the **Reasonable** Needs of Navigation

• Bridges *are Permitted* to be Built as Obstructions to Navigation by the USCG

• Bridges **Must** be Maintained in Accordance with USCG Permits
“In navigable waterway areas, where vessel collision by merchant ships and barges may be anticipated, bridge structures shall be designed to prevent collapse of the superstructure by considering the size and type of the vessel, available water depth, vessel speed, and structure response.”

- Significant damage, even failure, of secondary members is permitted as long as redundant load paths exist and the superstructure does not collapse.

“Bridges over a navigable waterway meeting the guide specification criteria, whether existing or under design, should be evaluated as to its vulnerability to vessel collision in order to determine prudent measures to be taken for its protection.”
Pensacola Bay Bridge
Florida (1989)

Bridge Superstructure Survived Due To Structural Redundancy
Ship Collision Force on Pier

- Woisin’s large-scale dynamic model tests
Ship Collision Force on Pier

- Typical impact data from Woisin

\[ P_{\text{max}} = \text{Maximum Impact Force} \]
\[ P(t) = \text{Average Impact Force} \]

Average Impact Force vs. Time (t)

Average Impact Force vs. Bow Crushing Length (a)

\[ \bar{P}(t) = (1.25) \bar{P}(a) \]
Guide Commentary contains discussion of differences in ship collision forces between AASHTO, German, Asian, and Danish research.

Comparison of ship impact forces for 50,000 DWT Bulk Carrier (Tongji Univ., Shanghai, China)
Barge Collision Force on Pier

- Full scale barge impact testing by Florida DOT used by the University of Florida (2006) to develop and calibrate a FEM barge collision numerical model
  - St. George Bridge across Apalachicola Bay
Location of Impact Forces

- Examples of vessel bow overhang impact

Sunshine Skyway Bridge Collapse

Vessel Collision Design of Highway Bridges
Location of Impact Forces

- Example of ship bow overhang

Container Pier Accident

Vessel Collision Design of Highway Bridges
Location of Impact Forces

- Local Bow Crushing During Impact
Location of Impact Forces

- Local Bow Crushing During Impact

Container Pier Accident
AASHTO provides three alternative analysis methods for determining the design vessel for each bridge component in the structure in accordance with a two-tiered risk acceptance criteria.

- **Method I** is a simple to use semi-deterministic procedure
  - Limited to Barges in Shallow Draft Waterways
- **Method II** is a detailed risk analysis procedure
  - Required for Ships in Deep Draft Waterways
- **Method III** is a cost-effectiveness of risk reduction procedure
  - Based on a classical benefit/cost analysis

**Risk Acceptance Criteria**

- Critical Bridges: Risk of Collapse 1 in 10,000 years
- Typical Bridges: Risk of Collapse 1 in 1,000 years
Overview of Risk Analysis Procedure

**FLEET CHARACTERISTICS**
- Vessel Types & Sizes
- Loading Conditions (Ballasted/Loaded)
- Transit Speeds & Paths
- Number of Annual Passages

**BRIDGE & SITE CHARACTERISTICS**
- Bridge Type, Size & Location
- Span Lengths
- Pier Geometry
- Impact Resistance
- Geotechnical Data
- H&H/Scour Data
- Environmental Constraints

**RISK ANALYSIS (Methods I, II or III)**
- Risk of Collision/Collapse
- Collision Impact Loads
- Protection Alternatives
- Cost-Effectiveness

**MEETS ACCEPTANCE CRITERIA?**
- Risk (Annual Frequency of Collapse)
- Cost (Within Project Budget Constraints)

**LEAST COST PROTECTION SYSTEM?**
- Yes
- No

**FINALIZE PROTECTION & FENDER REPAIR/REPLACEMENT PLANS**

**REVISE BRIDGE, FLEET or WATERWAY CHARACTERISTICS**
- Yes
- No
The annual frequency of bridge element collapse shall be computed by:

\[ AF = (N)(PA)(PG)(PC)(PF) \]

where,

- **AF** = Annual frequency of bridge element collapse due to vessel collision
- **N** = Annual number of vessels classified by type, size, and loading condition which can strike the bridge element
- **PA** = Probability of vessel aberrancy
- **PG** = Geometric probability of a collision between an aberrant vessel and a bridge pier or span
- **PC** = Probability of bridge collapse due to a collision with an aberrant vessel
- **PF** = Adjustment factor to account for potential protection of the piers from vessel collision due to upstream or downstream land masses, or other structures, that block the vessel from hitting the pier.
Annual Frequency of Collapse

- Relatively straightforward analysis using programs like Excel or MathCAD to automate the repetitive analysis process
  - Setup for Each Specific Project
- Total bridge AF is the sum of the individual component AF's (piers exposed to collision)

<table>
<thead>
<tr>
<th>Vessel Type</th>
<th>N</th>
<th>PA</th>
<th>PG</th>
<th>PC</th>
<th>PF</th>
<th>Growth Factor</th>
<th>AF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total AF All Vessels

Pier 1

+ (PLUS)

Pier 2

+ (PLUS)

Pier 3 + Pier 4 + Pier 5 … etc. = Sum of All Pier AF’s
Once the input data has been developed and the risk analysis tables have been generated, the program can be used several ways:

- If the ultimate resistance strength of the piers has been computed (ex. an existing bridge), you can solve for $AF$ and determine if it meets the risk acceptance criteria
- You can back-solve the ultimate pier strength needed for each pier (ex. a new bridge) by setting the $AF$ for each pier to the risk acceptance criteria
- The strength of setting up the analysis in this manner is the ability to ask “what if …” questions
  - Different pier locations, span lengths, etc.
Bridge Protection Alternatives

- AASHTO Code
  - Substructure Provisions
  - Concrete & Steel Design
  - Physical Protection Systems
    - Fenders
    - Pile supported systems
    - Dolphins
    - Islands
    - Floating structures
  - Movable Bridges
  - Motorist Warning Systems
  - Aids-to-Navigation
Bridge Protection Examples

- Design Bridge for Full Impact Force
- Fender Systems
- Pile-Supported Structures
- Protection Islands
Newport Bridge
Crossing Narragansett Bay, Rhode Island (1981)

- 31,800 DWT tanker hits main tower of suspension bridge at approximately 6 knots
- Minor damage to bridge pier
- Vessel bow crushed in 11 feet
• Piers designed to withstand vessel impact forces (50,000 kips)
Throgs Neck Bridge
Crossing the East River, New York City

- Steel Framed Fender System
Concrete fenders used around perimeter of piers
- Piers also designed to withstand barge impact forces
Tappan Zee Bridge over Hudson River
Tarrytown, New York

Vessel Collision Design of Highway Bridges
Pile Supported Structure System
Orinoco River Bridge
Venezuela

- Pile Supported Structure System
Dames Point Bridge
Jacksonville, Florida
Sunshine Skyway Bridge
Tampa Bay, Florida

Figure 4: Section thru Main Pier Island.

<table>
<thead>
<tr>
<th>STONE CLASSES</th>
<th>TYPE</th>
<th>AVG. WT. (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

Vessel Collision Design of Highway Bridges
Sunshine Skyway Bridge
Tampa Bay, Florida

Vessel Collision Design of Highway Bridges
Dames Point Bridge
Jacksonville, Florida
Arthur Ravenel Jr. Bridge
Crossing the Cooper River, Charleston, SC

Vessel Collision Design of Highway Bridges
Sidney Lanier Bridge
Crossing the Brunswick River, Brunswick, GA
Vessel Collision Summary

• Let’s Learn From The Past

• Bridges Over Navigable Waterways Need:
  – Better Planning
  – Longer Spans
  – Stronger Piers
  – Better Protection
  – Better ATN

• Vessel Collision Requirements are now Mandatory under LRFD Bridge Design Code

• Engineering Judgment and Specialized Skills are Required to Design Pier Protection Systems
  – Plastic / Non-Elastic / Sacrificial Structures
Final Thoughts

• Extreme Events will Usually Control the Design of Most Major Bridges
  – Vessel Collision
  – Earthquakes
  – Storm Surge & Waves (Post Hurricane Katrina / Sandy Damage)
  – Scour from Extreme Flood Events

• Terrorist Attacks (Post 9/11 World)
  – Hijacked Vessel Used as a Weapon Against Landmark Bridges & Critical Transportation Links
  – Confidential Studies Conducted by DOT’s

• Design of New Bridges for One Extreme Event Usually Improves the Performance Response to Other Extreme Events
THANK YOU FOR PARTICIPATING!

Vessel Collision Design of Highway Bridges