Principles of Earthquake Engineering of Bridges

Part 2. Structural Analysis

R. A. Dameron, PE, David Evans and Associates, Inc., San Diego, CA
OUTLINE

- Introduction / Historical Perspective
  - Bridge Structural Analysis
  - Bridge Seismic Research
- Structural Analysis Procedures
  - Steps to follow
  - Analytical Solution Methods
  - Modeling of Components
- Example Projects
- Seismic Analysis Tutorial Example
  - Martin Luther King Viaduct
- Conclusions and Lessons Learned
INTRODUCTION / HISTORICAL PERSPECTIVE

- Distinction between “Design Analysis” and “Response Prediction Analysis”

- “Prediction Analysis” was rare prior to 1989
  - Bridge analysis mostly involved elastic and RSA techniques

- post-Loma Prieta Governor’s Board Report called for:
  - “comprehensive earthquake vulnerability analyses….of important transportation structures….using state-of-the-art methods in earthquake engineering.”

- 1990s: Caltrans conducted seismic research, bridge seismic assessments, and state wide bridge retrofitting
INTRO - cont’d

• **ULTIMATE GOAL:** CALCULATE DEMANDS and CAPACITIES

• **“DESIGN ANALYSIS”**
  – Global models to obtain member force and structure displacement demands
  – for routine projects, models are typically elastic
  – EQ simulation is typically with response spectra

• **LIMITATIONS (FOR EQ DESIGN)**
  – Member force demands often far exceed capacity (but are reduced with ductile design procedures)
  – Displacements (improved with cracked section assumptions) are approximate
  – All demands are “peak occurrence”; no info as to simultaneity, hysteretic damping, low cycle fatigue
  – Information limited on expansion joint behavior
INTRO - cont’d

• “PREDICTION ANALYSIS”
  – **Global** Analysis models with material and geometric nonlinearity
  – EQ simulation with time history input (**NTHA**)
  – **Local** Nonlinear Analysis models to assess capacity, failure mode, or local displacement history
BRIDGE ANALYSIS CHALLENGES

San Diego - Coronado Bay Bridge

Principles of Earthquake Engineering for Bridges

Dameron
...different issues for new vs. old bridges

Proposed new East Spans of SFOBB
EVOLUTION OF “PREDICTION ANALYSIS”

• Essential Bridges; Importance of knowing actual behavior

• Perf. Criteria: “Allowing Significant Damage”
  – especially for retrofitting older bridges

• Need for more accurate predictions of:
  – Dynamic character of response
  – Displacements & low cycle fatigue

• Seismic device technology
  – nonlinear dampers; iso bearings

• New, Major Bridges: Elastic Perf. Criteria
BRIDGE SEISMIC RESEARCH

• Extensive research in the 1990s
  – on seismic performance of bridge components
  – retrofitting measures
  – devices: bearings and dampers

• Much of this was initiated/funded by Caltrans - extensive literature/data now available from reports by…
  – UCSD, UCB, UCI, UCD, UNR, USC, and many other universities
PHYSICAL TESTING OF CORONADO PILES

Fig. B.7 Pier 5 Deformed Shape

Fig. B.4 Prototype Pile
Fig. B-17 Extent of Spalling of Cover Concrete at $\mu_4$
TYPICAL HYSTERESIS TESTS

Good ductility and energy absorption

Poor ductility and semi-brittle failure

Budek, Benzoni, Priestley: “Experimental Investigation of Ductility of In-Ground Hinges in Solid and Hollow Prestressed Piles”
STRUCTURAL ANALYSIS PROCEDURES

• Steps to follow

• Analytical Solution Methods
  – Response Spectrum Analysis (RSA)
  – Nonlinear Time History Analysis (NTHA)

• Modeling of Components
Steps to follow (especially for evaluating & retrofitting existing bridges)

Survey As-Built Structure

Evaluate Component Capacities
- Member Classification
- Component Strength & Ductility Analyses
- Frame Static Pushover Analyses

Perform Seismic Demand Analyses
- Local & Semi-Global Models
- Foundation Representation
- Response Spectrum Analyses
- Nonlinear Time History Analyses

Assess Vulnerability
- Deformation Based Criteria
- Component Demand / Capacity Ratios
- System Drift & Stability Limits

Adequate Performance?

Design Retrofit Solution where needed

Yes

No

Produce Final Retrofit Concept Details, Cost Estimates, and Final Report

by permission from Parsons Transp. Group
Dameron
RSA METHODS

- Sometimes models analyzed frame by frame
- Elastic modeling of members and foundations
- Expansion Joints addressed with “Tension” and “Compression” Models
- Foundations represented with Mass, Stiffness, and Damping Matrices
- (shown in more detail later with an example)
NTHA METHODS - Solution Procedure

- NTHA now available in most FE programs
- Most common formulation:
  - direct time integration using Newmark or other method
  - Equilibrium iteration; similar to a static problem
  - Choice of time step appropriate to structure and EQ input
- Need to conduct an eigenvalue study first
  - for time step selection
  - damping selection
  - QA/QC of the model
- Superstructures can often be modeled elastically
- Linear studies are always recommended prior to introducing nonlinearities
Unique Issues for some Bridge Tower Fdns.

- Stiffness matrices for battered pile groups can have negative off-diagonal terms.

- For NTHA, complex pile groups usually require Nonlinear Pushover Models with detailed representation of Cross-Sections and P-y Springs to accurately simulate group behavior AND predict Plastic Hinge Formation.
NTHA Methods – cont’d
A Typical Challenge – Pile Modeling

- P/C OR R/C M-Φ ELEMENT
- HORIZONTAL “P-Y” SPRINGS (MODEL NONLINEAR STIFFNESS AND RADIATION DAMPING)
- VERTICAL “Q-U” SPRING
NTHA cont’d - Pile (and column) Modeling

P-Y Curves derived from various programs
NTHA cont’d
M-Φ Curves Varying with Axial Load

Curves Derived from $M$-$\Phi$ Analysis Program for Different Axial Loads

Principles of Earthquake Engineering for Bridges

Dameron
NTHA METHODS - Damping

• Rayleigh Damping still most widely used
• Need capability to apply selectively to element groups
• Typical values (% of critical):
  – Welded steel 2-3%
  – Prestr. Concr. <1/2 yield 2-3%
  – R/C < 1/2 yield 3-5%
  – R/C with signif. cracking 5-7%
  – Foundations 10%

• Need to verify that…
  – damping is not double counted in element groups with significant hysteresis
  – Rayleigh damping is realistic (because of velocity reference frame)

• Advancements in fdn. modeling, e.g. radiation damping
Nonlinear FE Analysis - Component Modeling

- Requires proven ability to predict
  - nonlinear behaviors, hysteresis, energy absorption
  - degradation and local “failures”
- Ultimately, most important test for selection of program and modeling method
- Often requires specialized expertise and
  - special elements and material laws not normally used
  - key decisions in element layout / nodal geometry
- Difficult to find special research elements implemented in general purpose FE programs
NTHA Project Examples:
San Diego-Coronado Bridge

- 8,000’ structure with a 90° curve
- Steel girder superstructure; concrete substructure
- P/S concr. piles supporting marine footings
- Consultant team:
- Analytical studies (Vulnerability Study) performed by ANATECH and OPAC, et al
- Retrofit Design performed by T Y Lin / Earth Tech
Coronado Piles and Piers

Principles of Earthquake Engineering for Bridges

Dameron
NTHA Tower Modeling

- Elasto-Plastic Isolation Bearings
- Joint
- Nonlinear Col. Hinge
- Elastic Superstructure
- Dampers $F = CV^{1.0}$
- Nonlinear Contact Springs or restrainers
- Explicit Pile Elements
- Ground Node

Nonlinear Col. Hinge (M-$\Phi$ behavior coupled to axial force)
Modeling of Isolation Bearings

Superposition of Material Models

Elastic-Plastic Material

Nonlinear-Elastic Material

Shear Force (kips)

Bearing Displacement (inches)
Principles of Earthquake Engineering for Bridges

Dameron
Coronado Bridge Analysis - Highlights

• NTHA tailored to the bridge, the seismic hazard, the retrofit solution, and to the performance criteria

• Key nonlinearities (typical of many large bridges):
  – Joint opening / closing
  – Pile hinging and SFSI
  – Column hinging and P-\(\Delta\) effects
  – isolation bearings and dampers

• Laboratory component testing used to improve / verify
  – hysteretic models of piles and columns
  – failure criteria of piles and columns
  – reliability of seismic devices

• Fault rupture also evaluated
  – by combining static offsets with NTHA
Brooklyn-Queens Expressway

- Unique three-level (1948) concrete cantilevers
- Pile supported retaining walls
- Vital transportation link
- Consultant team:
  - Analytical studies of concrete structures by ANATECH
  - Project Lead: Parsons Transp. Group

by permission from Parsons Transp. Group
BQE Location Map

Principles of Earthquake Engineering for Bridges

by permission from Parsons Transp. Group

Dameron
BQE “CR” Structures

Principles of Earthquake Engineering for Bridges

Dameron

by permission from Parsons Transp. Group
<table>
<thead>
<tr>
<th>GOAL</th>
<th>APPROACH</th>
<th>TOOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPACITIES</td>
<td>CODE FORMULAE</td>
<td>SPREADSHEETS</td>
</tr>
<tr>
<td>- STRENGTH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPACITIES</td>
<td>DETAILED LOCAL</td>
<td>ANACAP / ABAQUS</td>
</tr>
<tr>
<td>DISPL / DUCTILITY</td>
<td>CYCLIC PUSHOVER</td>
<td></td>
</tr>
<tr>
<td>DYNAMIC BEH. ISSUES – SFSI, KI</td>
<td>SSI MODELS</td>
<td>ANACAP / ABAQUS</td>
</tr>
<tr>
<td>“ ”</td>
<td>SEMI-GLOBAL MODELS</td>
<td>ADINA</td>
</tr>
<tr>
<td>SPATIAL VARYING</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEMANDS</td>
<td>RSA &amp; LTHA, SEMI-GLOBAL MODELS</td>
<td>SAP-2000</td>
</tr>
<tr>
<td>MOMENT / SHEAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEMANDS</td>
<td>NTHA, LOCAL MODELS</td>
<td>ANACAP / ABAQUS</td>
</tr>
<tr>
<td>DISPLACEMENTS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Final Configuration for Applying Equivalent Uniform Motion

Outline of continuum mesh (Rebar modeled explicitly)

Shell model mesh for 3D Semi-global Models

Outline of continuum mesh (Rebar modeled explicitly)

Soil/Fdn springs with "gapping" Derived by Earth Mechanics

Stiffness Matrix Derived by Earth Mechanics

Transverse motion applied to all soil nodes

Vertical motion applied to all soil nodes

Longitudinal motion applied only to global shell model
Expected Damage to Wall

Shear Failure of Roadway Slab
BQE - Time History Response of Three Levels

Principles of Earthquake Engineering for Bridges  Dameron
Nonlinear Analysis of Components
Example: New Tacoma Narrows Br.

- Suspension structure, parallel to existing bridge, with hollow concrete tower legs
- Engineering team and global NTH analysts: Parsons Transp./HNTB JV;
- Local FE Modeling by David Evans Associates (using ANACAP-U lic. from ANATECH)
- Example of local FE analysis combined with NTHA to confirm seismic performance
FE Modeling of Tower Legs of New Tacoma Narrows

Displacements Applied in Longitudinal Direction at Elev 150'

Displacements Applied in Transverse Direction at Elev 79'

Nonlinear Concrete with Rebar Sub elements

Elastic Concrete

Bottom of Elastic Concrete Elements Fixed

Tower Section

14'-0"
Modeling of Reinforcement
Figure 27. Longitudinal Cyclic Analysis - Vertical Strain Contours at Rotational Ductility = +2.0
Axial Load = -45000 kips
Contours of Vertical Strain - Weak Axis Push

Compression Side  Tension Side  NA Location
Elev. 29.5'

Principles of Earthquake Engineering for Bridges  Dameron
Tacoma Narrows / Tower Section Analysis
Axial Load vs Transverse Rotational Ductility Demands

Principles of Earthquake Engineering for Bridges

Dameron
Martin Luther King Viaduct
Portland, OR

• Bridge Facts
  – Replacement of existing 1936 structure.
  – Total length of bridge, 340 meters
  – 12 Spans, 3 CIP/PT Box Girder Spans and 9 PC/PT Box Beam with CIP Deck Spans
  – Railroad right-of-way restrictions require highly skewed bents.

• Performed by David Evans and Assoc. for ODOT
Martin Luther King Viaduct

- **Analysis Details - Foundation Modeling**
  - Challenging soil conditions
  - Core samples revealed up to 20M thick layer of sawmill waste
  - LPILE was used to develop nonlinear lateral pile response
  - Several iterations performed to determine final tangent stiffness

---

<table>
<thead>
<tr>
<th>Elevation (meters)</th>
<th>KSOIL</th>
<th>$y'$ (kN/m$^3$)</th>
<th>$\phi'$ (deg)</th>
<th>C (kN/m$^2$)</th>
<th>k (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.38</td>
<td>4</td>
<td>18.07</td>
<td>34</td>
<td>---</td>
<td>24,430</td>
</tr>
<tr>
<td>13.01</td>
<td>4</td>
<td>15.71</td>
<td>30</td>
<td>---</td>
<td>8,790</td>
</tr>
<tr>
<td>Silty Clay Fill</td>
<td>3</td>
<td>9.43</td>
<td>*</td>
<td>---</td>
<td>*</td>
</tr>
<tr>
<td>7.98</td>
<td>1.19</td>
<td>*</td>
<td>---</td>
<td>---</td>
<td>*</td>
</tr>
<tr>
<td>Woodwaste</td>
<td>1.20</td>
<td>9.83</td>
<td>36</td>
<td>---</td>
<td>16,300</td>
</tr>
<tr>
<td>Silty Gravel</td>
<td>4</td>
<td>11.40</td>
<td>38</td>
<td>---</td>
<td>33,900</td>
</tr>
<tr>
<td>At depth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Use Custom Woodwaste PY Curves
Martin Luther King Viaduct

- **Analysis Details - Bridge Modeling**
  - Grillage model was developed using RM-2004.
Martin Luther King Viaduct

- **Analysis Details - Bridge Modeling**
  - Sections were defined in geometric pre-processor using CAD type interface with variations in girder depth, thicknesses, etc. as a function of bridge stationing.
Martin Luther King Viaduct

- Analysis Details - Bridge Modeling
  - Springs represent bearing pads at expansion joints and abutments
Martin Luther King Viaduct

- Analysis Details – Bent Modeling

Principles of Earthquake Engineering for Bridges
Martin Luther King Viaduct

- **Analysis Details - Seismic Modeling**
  - Frequency Analysis
  - Determine Mass Participation and Mode Shapes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency X (Hz)</th>
<th>Mass Participation X</th>
<th>Mass Participation Y</th>
<th>Mass Participation Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.091</td>
<td>27.30</td>
<td>1.65</td>
<td>1.24</td>
</tr>
<tr>
<td>2</td>
<td>2.282</td>
<td>52.57</td>
<td>1.30</td>
<td>1.41</td>
</tr>
<tr>
<td>3</td>
<td>2.727</td>
<td>0.05</td>
<td>0.25</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>2.815</td>
<td>0.49</td>
<td>4.50</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>3.010</td>
<td>3.33</td>
<td>0.14</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>3.171</td>
<td>0.37</td>
<td>0.84</td>
<td>2.19</td>
</tr>
<tr>
<td>7</td>
<td>3.466</td>
<td>0.13</td>
<td>0.01</td>
<td>0.18</td>
</tr>
<tr>
<td>8</td>
<td>3.515</td>
<td>0.64</td>
<td>0.48</td>
<td>0.93</td>
</tr>
<tr>
<td>9</td>
<td>3.650</td>
<td>1.35</td>
<td>0.00</td>
<td>25.42</td>
</tr>
<tr>
<td>10</td>
<td>3.688</td>
<td>0.01</td>
<td>0.03</td>
<td>21.85</td>
</tr>
<tr>
<td>90</td>
<td>11.994</td>
<td>0.00</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>91</td>
<td>12.035</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>92</td>
<td>12.080</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>93</td>
<td>12.107</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>94</td>
<td>12.116</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>95</td>
<td>12.173</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>96</td>
<td>12.205</td>
<td>0.00</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>97</td>
<td>12.208</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>98</td>
<td>12.216</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>99</td>
<td>12.249</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>100</td>
<td>12.252</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td><strong>TOTAL</strong></td>
<td><strong>95.06</strong></td>
<td><strong>50.45</strong></td>
<td><strong>91.24</strong></td>
</tr>
</tbody>
</table>
Martin Luther King Viaduct

• **Analysis Details - Seismic Modeling**
  – Site specific response spectra
Conclusions & Lessons Learned

• Modeling decisions: balance additional insights gained versus increasing complexity, cost, and uncertainties

• We always recommend a stepwise approach:
  – Linear, including eigenvalues, for model checking (RSA can generally be used in cases governed by a force-based criteria)
  – Add geometric nonlinearities of contact opening/closing and P-Δ effects
  – Add nonlinear seismic devices
  – Add material nonlinearities where demands dictate they are needed

• Some basic nonlinear procedures and elements have proven reliability
Conclusions, cont’d: Limitations on Analysis

- Lack of reliable damage models
  - especially for concrete: cover spalling, rebar buckling, shear
  - but also for steel local buckling
  - need experimental validation for acceptance
- Continued conflict between structural, geotechnical engineers, and seismologists; too much engineering effort applied to aspects which
  - have little influence on the final structure design
  - incorporate more detail than is warranted by the source info
- Codes need to resolve issue of multiple ground motions
- NTHA should continue to be augmented by linear dynamic and nonlinear static pushover methods
Acknowledgements
We wish to thank:

• California Dept. of Transp., Washington Dept. of Transp., New York State Dept. of Transp.: project owners and sponsors
• T Y Lin / Earth Tech (JMI); Parsons Transportation; PTG/HNTB JV: project design engineers and project leads for the Coronado, BQE, and Tacoma Narrows projects, respectively
• UC San Diego, Professors Seible and Priestley: Coronado pile testing and other information
• ANATECH Corp.: nonlinear analysis for the Coronado and BQE projects; authors of ANACAP program
• David Evans and Associates: nonlinear analysis for the New Tacoma Narrows tower leg evaluation and MLK project
• Mr. Brian Hansen: analyst for the Coronado, BQE, and MLK projects