Seismic Design and Retrofit
Detailing Fundamentals

Reginald DesRoches
Professor and Associate Chair
Georgia Institute of Technology
Learning Outcomes:

- List the types of detailing that increase a bridge's displacement capacity.
- List the types of detailing to enhance a bridge's ductility.
- For displacement-based design, explain the relationship between the SDC, expected concrete strain, and required detailing.
- List typical retrofit details along with their seismic performance benefit.
Presentation Outline

- Vulnerabilities of Typical Bridges
- Seismic Detailing Fundamentals
  - Support Length
  - Detailing for Ductility
    - Columns
    - Footings
- Seismic Retrofit Fundamentals
  - Superstructure
    - Seat Extenders, Restrainers, Shear Keys, Stoppers
  - Substructure
    - Column Jacketing, Bent Cap
- Isolation
- Application of Fragility Curves for Seismic Retrofit
Vulnerabilities of Typical Bridges

- Superstructure
  - Brittle Steel Bearings
  - Inadequate Seat Widths

- Columns
  - Insufficient Lap Splices
  - Inadequate Transverse Reinforcement
    - Limited ductility
    - Low shear strength

- Footings with Inadequate Reinforcement

- Liquefiable Soils Common
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Unseating at Expansion Joints

Northridge Earthquake 1994
Superstructure Expansion Joint

Pre-1971 Typical Expansion Joint
6-inch hinge seat width

Post-1971 Typical Expansion Joint
24 inch hinge seat width
Minimum Seat Width – SDC A

\[ N = (4 + \Delta_{ot} + 0.20H_h) \left( \frac{1 + S_k^2}{4000} \right) > 12" \]

- \(\Delta_{ot}\) = movement due to pre-stress shortening, creep, shrinkage, and thermal expansion.
- \(H_h\) = Largest column height w/in flexible frame (clear height – ft).
- \(S_k\) = angle of skew of support (degrees)
Minimum Seat Width – SDC B, C, D

\[ N = (4 + \Delta_{ot} + 1.65\Delta_{eq}) \frac{(1 + S_k^2)}{4000} (\text{in}) > 12'' \]

- \( \Delta_{ot} \) = movement due to prestress shortening, creep, shrinkage, and thermal expansion.
- \( \Delta_{eq} \) = seismic displacement demand of long period frame on one side of exp joint.
- \( S_k \) = angle of skew of support (degrees)
Minimum Seat Width – N
Minimum Seat Width – N

\[ \Delta_{ot} = \Delta_{p/s} + \Delta_{cr+sh} + \Delta_{temp} \]

*Hinge within a span*

*Expansion joint or end of bridge deck*

Seat ≥ 12 in.
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Improved Bridge Seismic Details

Column Vulnerabilities

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Non-ductile details have four main structural problems:

1- Lack of Confinement. (#4 @ 12” ties)
2- Inadequate Lap Splice at the Base of the Column
3- No footing Top Steel Rebar Mat
4- Inadequate Rebar Development into the Superstructure
New Column Details

Ductility/Confinement/Continuity

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Effect of Confinement

- Old Columns: Vertical rods and 1/2" steel hoops on 12" centers. During quake, columns collapse under lateral motion.
- New Columns: Continuous 3/4" steel spirals on 3" centers supported by vertical rods.

Retrofitted Column with Steel Casing
Tied vs. Spiral Columns

- Second maximum load
- Shell spalls
- Spiral breaks
- Spiral column
- Tied column

Axial shortening (in.)

Load
Compression Reinforcement

\[ \frac{M_n}{f'_c bh^2} \]

- \( \rho' = 0 \)
- \( \rho' = 0.5 \rho \)
- \( \rho' = \rho \)

- \( f'_c = 4000 \text{ psi} \)
- \( f_y = 60000 \text{ psi} \)
- \( \rho = A_s / lb \) = 0.03
- \( \rho_b = 0.0285 \)

\( \phi h \) (%) vs. \( \phi h \) (%)

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6 NSC Charleston 2008
Confinement (SDC B, C and D)

- All longitudinal bars should be enclosed by hoops or spirals.
  - #3 for # 9 longitudinal bars or smaller
  - #5 for #10 longitudinal bars or larger
  - #5 for bundled bars
- The spacing of hoops or ties shall not exceed the least dimension of the compression member or 12 inches
Confinement (SDC C and D)

- Hoops and ties shall be arranged with corner ties having minimum 135 degree angles.
- No longitudinal bars shall be further than 6 inches clear on each side along the tie.
- Ties shall be located vertically not more than half a tie spacing above the footing or other support and not more than half a tie spacing below the lowest horizontal reinforcement in the supported member.
Requirements for Ductile Design

- Maximum axial load shall not be greater than $0.20f'_{ce}A_g$.
- Area of longitudinal reinforcement for compression members shall not exceed $0.04A_g$.
- Minimum Longitudinal Reinforcement
  - $0.007A_g$ for columns in SDC B, C
  - $0.01A_g$ for columns in SDC C, D
  - $0.0025$ for Pier Walls in SDC B, C
  - $0.005$ for Pier Walls in SDC D
Inadequate Lap Splice

Splicing of Longitudinal Reinforcement in Columns (SDC C or D)

- Splicing of longitudinal reinforcement shall be outside of plastic hinging zone for SDC C and D.

- For SDC D, mechanical couplers must be used for splicing.
Development Length (SDC C and D)

- Column longitudinal reinforcement shall be extended into footings and cap beams as close as possible to opposite face of footing or cap beam.

- Minimum anchorage length into cap beams should be $24d_{bl}$. 

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Confinement (SDC C and D)

- The maximum spacing for lateral reinforcement in the plastic end region shall not exceed the smallest of the following:
  - 1/5 least dimension (Columns),
  - 6 times the nominal diameter of longitudinal reinforcement
  - 6 inches for single hoop
Confinement (SDC C and D)

- The lateral reinforcement shall extend into footing to the beginning of the longitudinal bar bend above the bottom mat.

- The longitudinal steel shall extend a distance to ensure adequate development for plastic hinge into bent cap.
Problems with Flared Columns

- Strong flare creates shorter, stiffer column
- Failure at the base of the flare is not desirable and does not agree with the design assumptions
Improved Bridge Seismic Details

- Ductility
- Confinement
- Continuity
- Flare isolation
Improved Bridge Seismic Details
Flared Columns

FLARE COLUMN DETAILS-1

Dimension to be determined by Engineer

Mechanical Couplers (see Note 5)

Transverse Flare Reinforcement (see Note 3)

Longitudinal Flare Reinforcement (see Note 2)

Flare Gap (see Note 1)

Soffit

Construction Joint (Location optional)

Column

Superstructure

Parabolic Flare

Limits of Flare Reinforcement

Transverse Flare Reinforcement (see Note 3)

Mechanical Couplers (see Note 5)
Improved Footing Details

20 #5 (D16) Legs

#6 Hoops @ 3.00"
(D19 @ 76)

30"
(762mm)

Extra External Stirrups: #5 @ 10"
(D16 @ 254mm) Each Way
for 30"
(762mm) Ring Around Column

(b) 50% Column bars bent out

2 #11 (D36) Horizontal Shear Bars 18’ (5486mm)
Long Each Way

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Seismic Technologies for Extreme Loads
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Seismic Technologies for Extreme Loads
Seat Extenders

- Goal: Provide additional support length
- Relatively inexpensive and easy
- Consider out-of-phase motion to determine seat extender length
Seat Extenders – Box Girder Bridges

(b) devices for support following unseating at internal movement joints
Seat Extenders – Simply Supported Bridges
Seat Extenders – Simply Supported Bridges – Steel Bracket
Seat Extenders – Simply Supported Bridges – Steel Bracket
Seat Extenders - Steel Beams
Restrainer Cables and Bars

- Goal: Limit movement at hinge or support adjacent girders should unseating occur
- Relatively inexpensive and easy
- Consider out of phase motion to determine restrainer size and length
Restrainer Cables and Bars—Design Procedure

DesRoches and Fenves, 2000
Restrainers - Design Procedure

\[ D_{eq} = \sqrt{D_1^2 + D_2^2 + 2\rho_{12} D_1 D_2} \]

\[ K_{r(j+1)} = K_{r(j)} + (K_{meff} + K_{r(j)}) \left( \frac{D_{eq(j)} - D_r}{D_{eq(j)}} \right) \]

\[ K_{eff} = \frac{1}{\mu} K \]

\[ 1 - 0.95 \frac{1}{\sqrt{\mu}} - 0.05 \sqrt{\mu} \]

\[ \xi_{eff} = \xi + \frac{1}{\pi} \]

DesRoches and Fenves, 2000
## Restrainers– Multi-Step Procedure

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
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</table>
| 1    | Calculate the maximum restrainer deflection, $D_r$  
$D_r = D_y + D_s$, where $D_y =$ yield displacement, and $D_s =$ restrainer slack |
| 2    | Estimate $D_{eq_o}$, the maximum relative hinge displacement without restrainers, where $D_{eq_o} = \sqrt{D_{1_o}^2 + D_{2_o}^2 - 2\rho_{12}D_{1_o}D_{2_o}}$  
If $D_{eq_o} < D_r$, use the minimum number of restrainers |
| 3    | Determine the restrainer stiffness required to reduce $D_{eq_o}$ to target  
$K_r = \frac{K_{m_eff}(D_{eq_o} - D_r)}{D_{eq}}$ where $K_{m_eff} = \frac{K_{1_eff}K_{2_eff}}{K_{1_eff} + K_{2_eff}}$ |
| 4    | Perform 2 DOF modal analysis to determine $D_{eq}$ using CQC combination rule. $D_{eq} = \sqrt{D_{1}^2 + D_{2}^2 + 2\rho_{12}D_{1}D_{2}}$  
If $D_{eq} > D_r$ continue to step 4, else  
Stop - use $K_r$  
$N_r = K_rD_r/(f_yA_r)$ |
| 5    | Calculate Restrainer stiffness, $K_r$  
where $K_{r_{i+1}} = K_{r_{i}} + (K_{m_eff} + K_{r_{i}})\frac{(D_{eq} - D_r)}{D_{eq}}$ |
Restrainers– Single Step Procedure

STEP 1 and STEP 2 (same as iterative procedure)

\[ K_r = K_{eff, mod} \left[ 0.50 + \frac{0.50 - \eta^2}{\eta} \right] \]

\[ K_{eff, mod} = \frac{K_1 K_2}{\mu(K_1 + K_2)} \]

\[ \eta = \frac{D_r}{D_{eq,0}} \]

\[ N_r = \frac{K_r D_r}{f_y A_r} \]
Restrainer Cables and Bars—Properties and Models

Stress

\[ E = 69000 \text{ MPa} \]

\[ \sigma_y = 1210 \text{ MPa} \]

Slack

Strain

Elongation - mm

Load - kips

Gage lengths = 114 in.
Restrainer Cables – Box Girder Bridges

Note: Access may be gained from either the deck or soffit (bottom side), but not both.
Restrainer Cables – Simply Supported Bridges

Cables Looped Over Bent-Cap

Straight Cables
Restrainer Cables – Simply Supported Bridges

Simply Supported Concrete Girder Bridge

Connection Details

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Seismic Technologies for Extreme Loads
Restrainer Cables – Simply Supported Bridges

Simply Supported Steel Girder Bridge

Connection Details
Restrainer Cables – Simply Supported Bridges

Connection Details

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Seismic Technologies for Extreme Loads
Restrainer Bars – Simply Supported Bridges
Restrainer Bars – Simply Supported Bridges
Restrainers – Vertical Tie Downs
Bumpers or Stoppers

- Goal: Limit movement at hinge or support adjacent girders
- Relatively inexpensive and easy
Bumpers or Stoppers
Shear Keys and Keeper Plates

- Limit transverse displacement of deck relative to bent beam
- Designed with shear friction approach based on Priestley et al. (1999)

\[ V_{sk} = \phi_s \mu A_s f_y \]

- Limited \( V_{sk} < \frac{1}{2} V_{col} \)
Damage due to transverse movement

0.31m
Shear Keys and Keeper Plates

- Failsafe Load Path for Bearing
- Load May Not Be Even Due to Construction Tolerances (Unbuttoning)
- Design to Fail in Ductile Manner

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Seismic Technologies for Extreme Loads
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Seismic Retrofitting Fundamentals – Substructure “Detailing for Ductility”
Columns

- Goal: Improve
  - Shear strength, deformation
  - Ductility capacity
  - Lap Splice.

- Approaches include:
  - Steel Jacket
  - Concrete Jacket
  - Pre-stressed High Strength Cables
  - Composite Jackets
**Column Steel Jacketing**

- Confinement of plastic hinge region
  - Increased compressive strength and ultimate strain
  - Enhanced ductility capacity
- Improved bond transfer and lap splice performance
- Increased shear strength
Steel Jacketed Column

Pre 1971 Column

Steel Jacketed Column

"As-Built" Column with a Lap Splice

Retrofit Column with Steel Casing
Modeling of Steel Jacketed Column

- Increased compressive strength and ultimate strain in confined concrete
- 20-40% increase in column stiffness for full height jacket (testing by Priestley et al.)
Steel Jacket Retrofit
Concrete Overlay Jacket

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Seismic Technologies for Extreme Loads
Column Wrap - Composites

- Low Installation Cost
- Lightweight
Cable Column Wrap
Bent Caps

- Goal: Improve
  - Shear strength
  - Ductility capacity
  - Flexural Strength

- Approaches include:
  - Steel Jacket
  - Concrete Jacket
  - Pre-stressed High Strength Cables
Bent Cap Retrofit - Prestressing

Connection Details

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Bent Cap Retrofit - Prestressing

Connection Details
Bent Cap Retrofit – Concrete Overlay

Connection Details
Bent Cap Retrofit – Steel Jacket

Connection Details

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Seismic Technologies for Extreme Loads
Bent Cap Retrofit – Steel Plates

Connection Details

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Seismic Technologies for Extreme Loads
Seismic Retrofitting
Fundamentals - Isolation
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Isolation

- Goal
  - Replace Vulnerable Brittle Bearings
  - Protect (Isolate) Vulnerable Substructure
  - Change Vibration Mode
Vulnerable Bearings

Damage to steel and elastomeric bearings
Seismic Response Modification Devices (SRMD)

- Isolation Devices used to reduce forces transmitted to the substructure system
- Damping Devices used to reduce displacements
Seismic Response Modification Devices (SRMD)

- Isolation Devices used to reduce forces transmitted to the substructure system
- Damping Devices used to reduce displacements
Isolation - Basics

- Period, $T$
- Acceleration response spectrum: $S_a$
- Displacement response spectrum: $S_d$

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Seismic Technologies for Extreme Loads
Effect of Damping

- Lower damping
- Higher damping

Acceleration response spectrum

Displacement response spectrum
Types of SRMDs

- Isolation Devices
  - Elastomeric Bearings
  - Lead-rubber bearings
  - Friction Pendulum Bearings
  - Sliding Bearings

- Damping Devices
  - Hysteretic Dampers (Lead Bar)
  - Fluid Viscous Damping
  - Visco-elastic Damper
Isolation – Types

Elastomeric  Sliding  Friction Pendulum
Elastomeric Bearings

Elastomeric Bearing

Lead Filled Elastomeric Bearing
Friction Pendulum Bearings

Friction – Pendulum Isolation Bearing
Friction Pendulum Bearing
Fluid Viscous Damper & Lock-up Device

Dampers

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Bridge Fragility Curves

Fragility = \( P[D \geq ds | IM = y] \)

- Expert Opinion
- Empirical
- Analytical
  - Non-linear time history approach

\[ p_f = P\left[ \frac{D}{C} \geq 1 \right] \]

Very few studies developing fragilities for retrofitted bridges
Bridge Vulnerability

Given Seismic Event

What is the probable bridge performance over a range of potential EQ intensities?
Bridge Fragility Curves

MSSS Steel

![Bridge Fragility Curves Diagram](Image)
Bridge Fragility Curves - Comparisons

Nine Bridge Classes Considered
Typical Bridge Classes & Retrofits

- MSC-Concrete - 6.5%
- MSC-Steel - 13.2%
- MSSS-Concrete - 18.9%
- MSSS-Slab - 6.1%
- MSSS-Steel - 11.3%
- SS-Concrete - 13.9%
- SS-Steel - 11.2%
- Other Materials - 4.6%
- Other Construction - 7%

Total - 163,448 Bridges
11 - States

Steel Jacket
Shear Key
Restrainer Cable
Elastomeric Bearing
Seat Extender

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Seismic Technologies for Extreme Loads
Motivation: Probable Performance

Given Seismic Event

What is the impact of retrofit on the probable bridge performance over a range of potential EQ intensities?
Approach: Bridge Fragility Curves

- Assess bridge performance
- Evaluate & select retrofit measures
- Regional seismic risk analyses
- Performance-based retrofit

Fragility = \( P[D \geq ds | IM = y] \)
Retrofitted MSSS Steel Fragility
Applications of Retrofitted Bridge Fragility Curves

- Retrofit Selection based on Median Value Improvement
- Performance-Based Retrofit in Support of Seismic Retrofit Manual Dual-Level Evaluation
- Cost-Benefit Analyses
- Regional Seismic Risk Assessment
Performance-Based Retrofit
Performance-Based Retrofit

- Identify viable retrofit strategy based on performance objectives
  - Objective:
    - Limit slight damage (design level PGA=0.7g)
Performance-Based Retrofit

Objective:
- Limit slight damage (design level PGA=0.7g)

|         | P[Slight|PGA=0.7] |
|---------|------------|
| As-Built| 1.0        |
| RC      | 1.0        |
| EB      | 0.8        |
| SE      | 1.0        |
| SJ      | 1.0        |

MSSS Steel–Slight

PGA (g)
Performance-Based Retrofit

Identify viable retrofit strategy based on performance objectives

- **Objective:**
  - Limit slight damage (design level pga=0.7g)

- **Objective:**
  - Avoid complete damage (design level pga=0.7g)
Performance-Based Retrofit

- Identify viable retrofit strategy based on performance objectives.

Objective: Limit slight damage (design level PGA = 0.7 g)

|                | P[Complete|PGA=0.7] |
|----------------|------------|
| AB             | 0.30       |
| RC             | 0.20       |
| EB             | 0.18       |
| SE             | 0.12       |
| SJ             | 0.21       |

MSSS Steel–Complete

Graph showing P[Complete|PGA] vs. PGA (g) for different retrofit strategies (As-Built, Seat Extender, Restrainer, Steel Jacket, Elasto Brg, Shear Key, RC & SK, SE & SK), with respective values for P[Complete|PGA=0.7].
Retrofitted Bridge Fragility Curves

MSSS Concrete

P[Sligh DS | PGA]

PGA

As-Built
Steel Jacket
Elasto Brg
Restrainer
Shear Key
Seat Extender
RC & SK
SE & SK

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Seismic Technologies for Extreme Loads
Retrofitted Bridge Fragility Curves

MSSS Concrete

P[Extensive DS|PGA]

PGA

0.0 0.2 0.4 0.6 0.8 1.0

0.0 0.2 0.4 0.6 0.8 1.0

As-Built  Steel Jacket  Elasto Brg  Restrainer
Shear Key  Seat Extender  RC & SK  SE & SK

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Seismic Technologies for Extreme Loads
Retrofitted Bridge Fragility Curves

MSC Concrete

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<th>Moderate</th>
<th>Extensive</th>
<th>Complete</th>
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