# Whence and Whither Seismic Design?

## Past and Future Perspectives on Bridge Seismic Design

BergerABAM

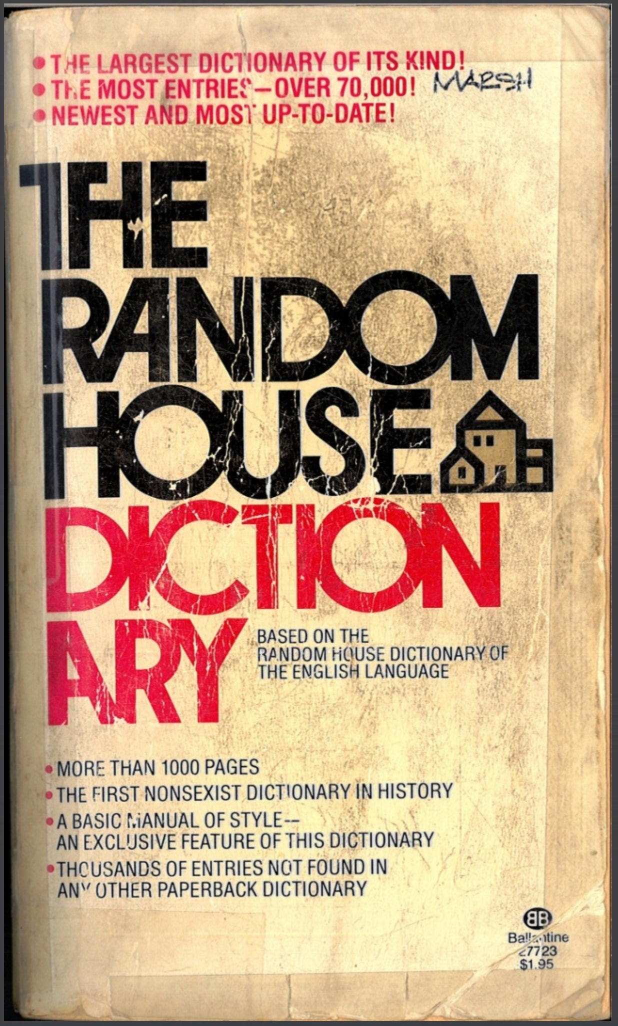
Lee Marsh, PhD, PE Principal

September 6, 2013

Western Bridge Engineers' Seminar, Bellevue, WA

# What's Up with the Title?

- Whence – from what place?
- Whither – to what place?



# Presentation Purpose

- Historical perspective on earthquake and bridge engineering – simplicity and struggle
- Take stock of where we are and where we may be headed
- While broad in scope, by no means complete
- Borrows heavily from those who have gone before, to whom we owe a debt of gratitude

# Beginnings of Plate Tectonics - Continental Drift Postulated, But No Mechanism – 1756

Lilienthal, Professor of Theology at Konigsberg, Germany in 1756 notes "fit" of continents – biblical catastrophism


Global Tectonics, Kearey and Vine, 1990

# 1811-12 New Madrid Earthquakes, Mid-America

USGS Bulletin 494 originally published in 1912, first comprehensive scientific account of the hundreds of tremors felt during 1811-12.


FIGURE 1.—Map showing the extent of earthquake disturbances in the New Madrid area in 1811-12. For additional records of the direction of vibrations see table, page 41.

Fuller, 1912

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# 1906 – San Francisco Earthquake and Subsequent Fire

Steinbrugge Collection UCB EERC

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# 1907 - California

Following 1906 San Francisco earthquake,

UC Berkeley professor Charles Derleth says:

"An attempt to calculate earthquake stress is futile. Such calculations could lead to no practical conclusions of value"

1907 ASCE Transactions

Gustave Eiffel suggests an equivalent wind load to use for seismic design

# Major Continental US
# Pacific Coast Earthquakes – 1700, 1857, 1906

# Dec 28, 1908 Messina, Italy

Large earthquake devastates Messina.

83,000 deaths

Special committee recommends static design force:

$$F = CW$$

Lateral force is recognized as a dynamic force, and recommendations given for distribution of force based on deformations (0.08g and 0.13g).

# Milne, Sano, Naito, and Suyehiro - The Japanese School

- 1880s – John Milne co-invents first seismograph and demonstrates SDOF oscillators, which form basis of response spectrum
- 1910s Riko Sano – Introduces seismic ratio: lateral to vertical force, 0.1 was used
- 1914 Tachu Naito – Receives 14cm (5 ½ in.) pocket slide rule, and the lack of precision reminds him of the degree of approximation in seismic calculations
- 1920s – Kyoji Suyehiro publishes a paper on a vibration analyzer with 13 different SDOF oscillators

Reitherman, 2012

# 1923 - Great Kanto Earthquake, Japan "M=7.9"
# Fire in Kyobashi District of Tokyo


Property of Special Collections, University of Washington Libraries. Photo Coll 8

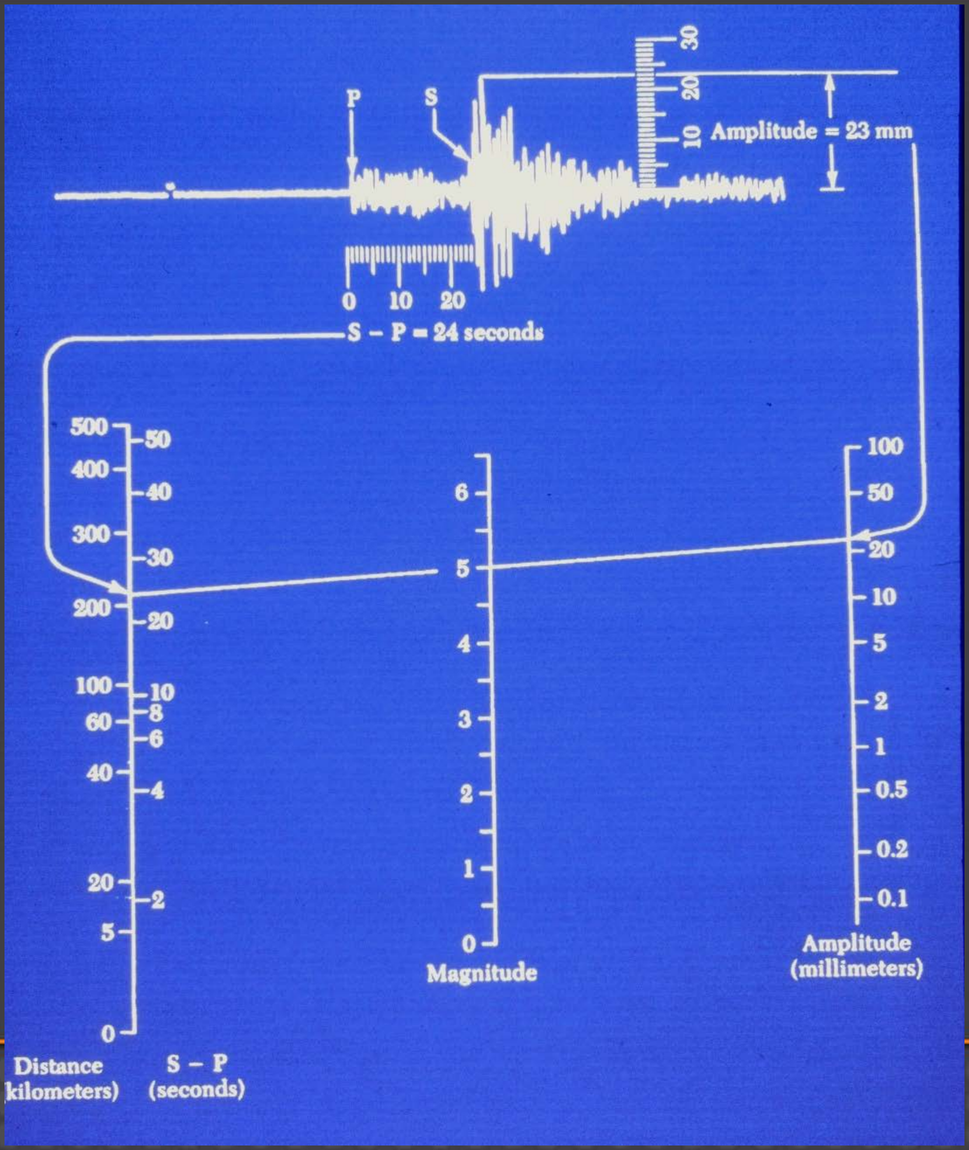
# 1933 – Long Beach Earthquake, CA "M6.2" Prompts Passage of the Field Act by the State

First strong motions recorded, 0.30g

For design,
LA adopts 0.08g

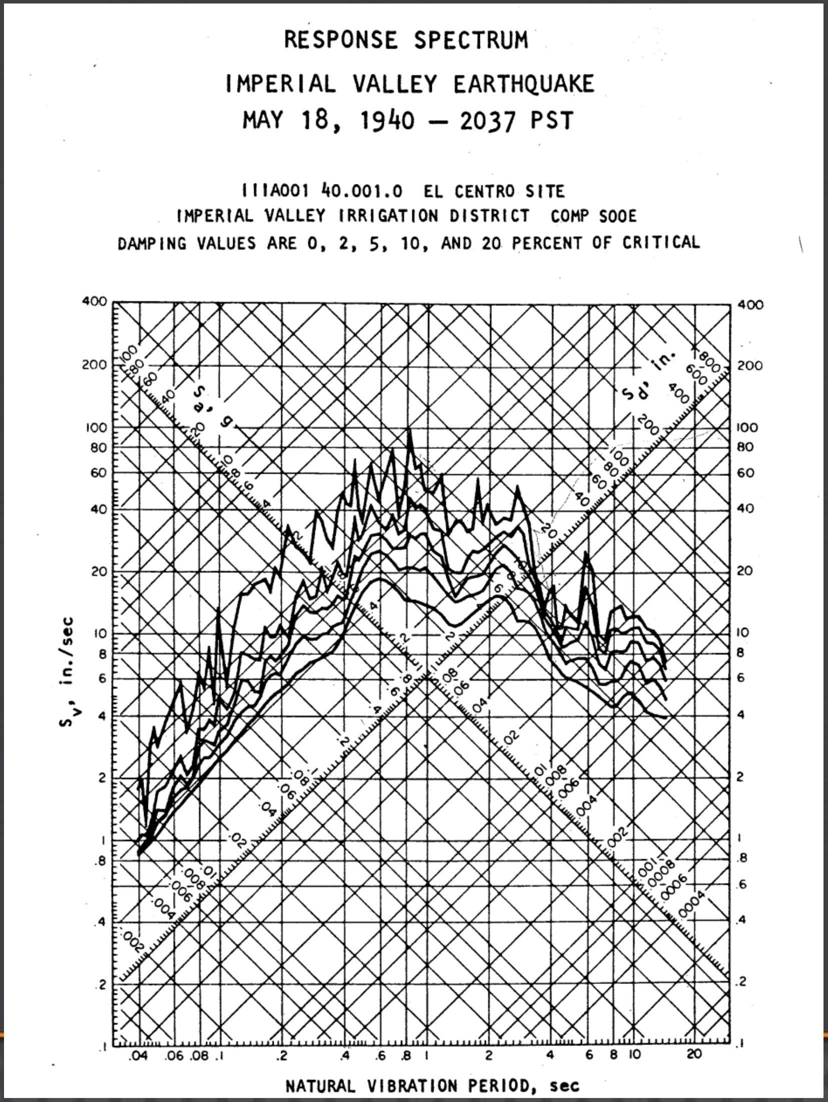
URM prohibited

# 1935 Charles Richter Develops Magnitude for Comparison of Southern CA Earthquakes




Bolt, 1978

# Response Spectrum – 1938 – 1940s

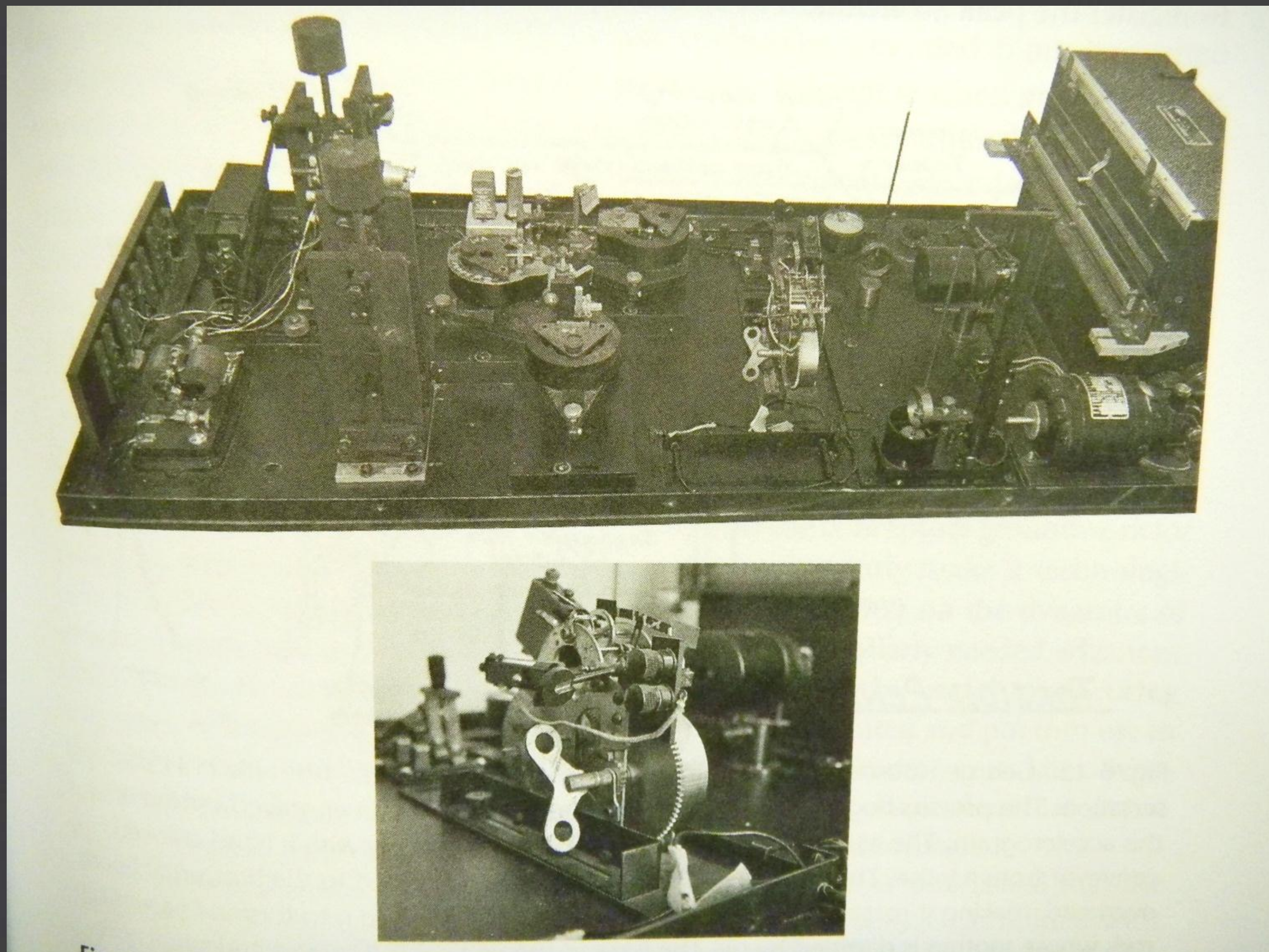



The concept is introduced by Maurice Biot of Caltech, and George Housner develops response spectra into a "central idea in the field" of earthquake engineering.

Selected Earthquake Engineering Papers of George W. Housner, ASCE 1990

Anderson (Naeim Ed.), 1989

# Instrument that Recorded “El Centro” – 1940  M6.7



# 1940s - Analysis of Strong-Motion Earthquake Records with the Electric Analog "Computor"

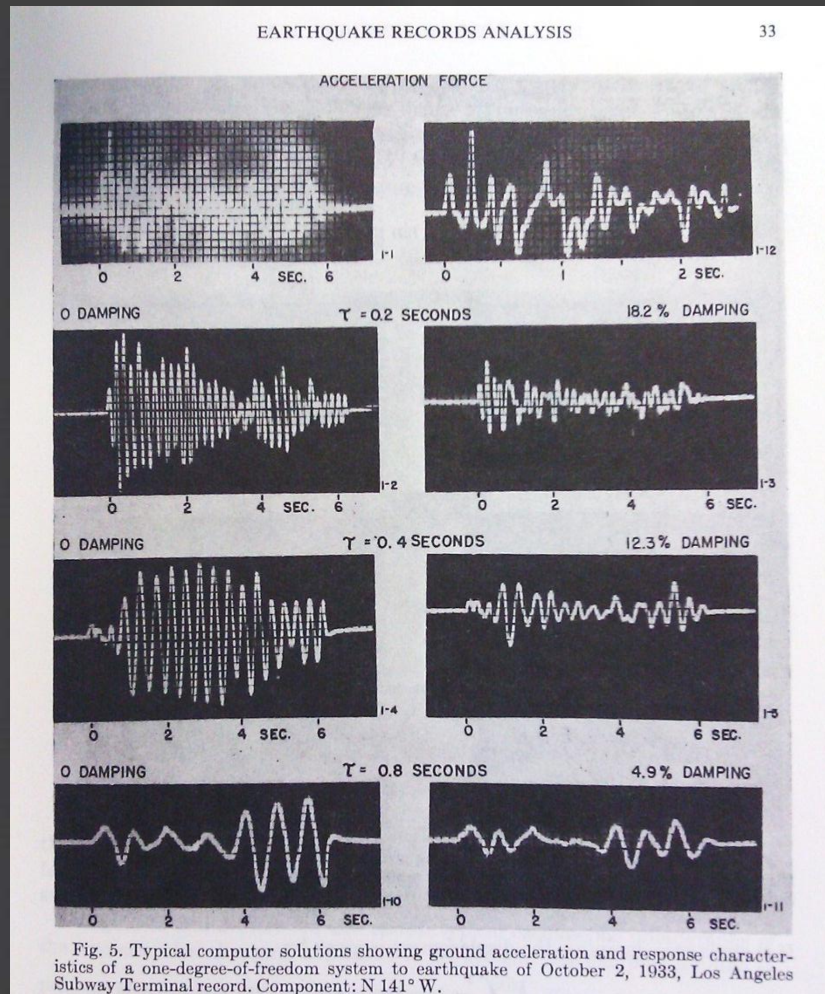
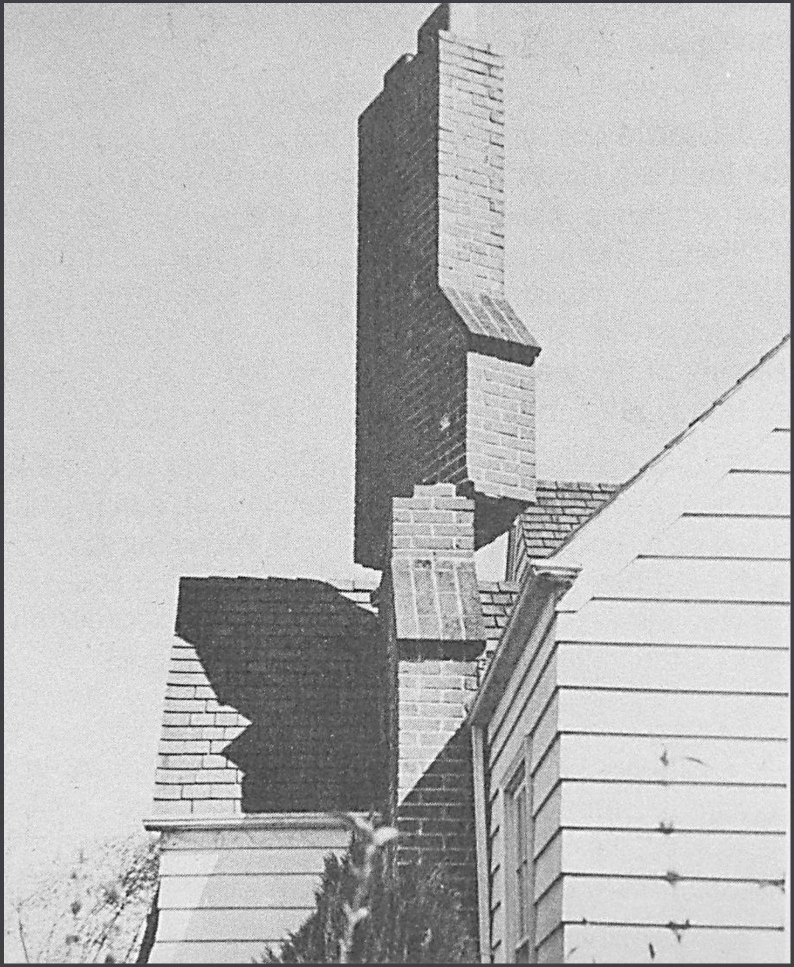

EARTHQUAKE RECORDS ANALYSIS 33



Fig. 5. Typical computor solutions showing ground acceleration and response characteristics of a one-degree-of-freedom system to earthquake of October 2, 1933, Los Angeles Subway Terminal record. Component: N 141° W.

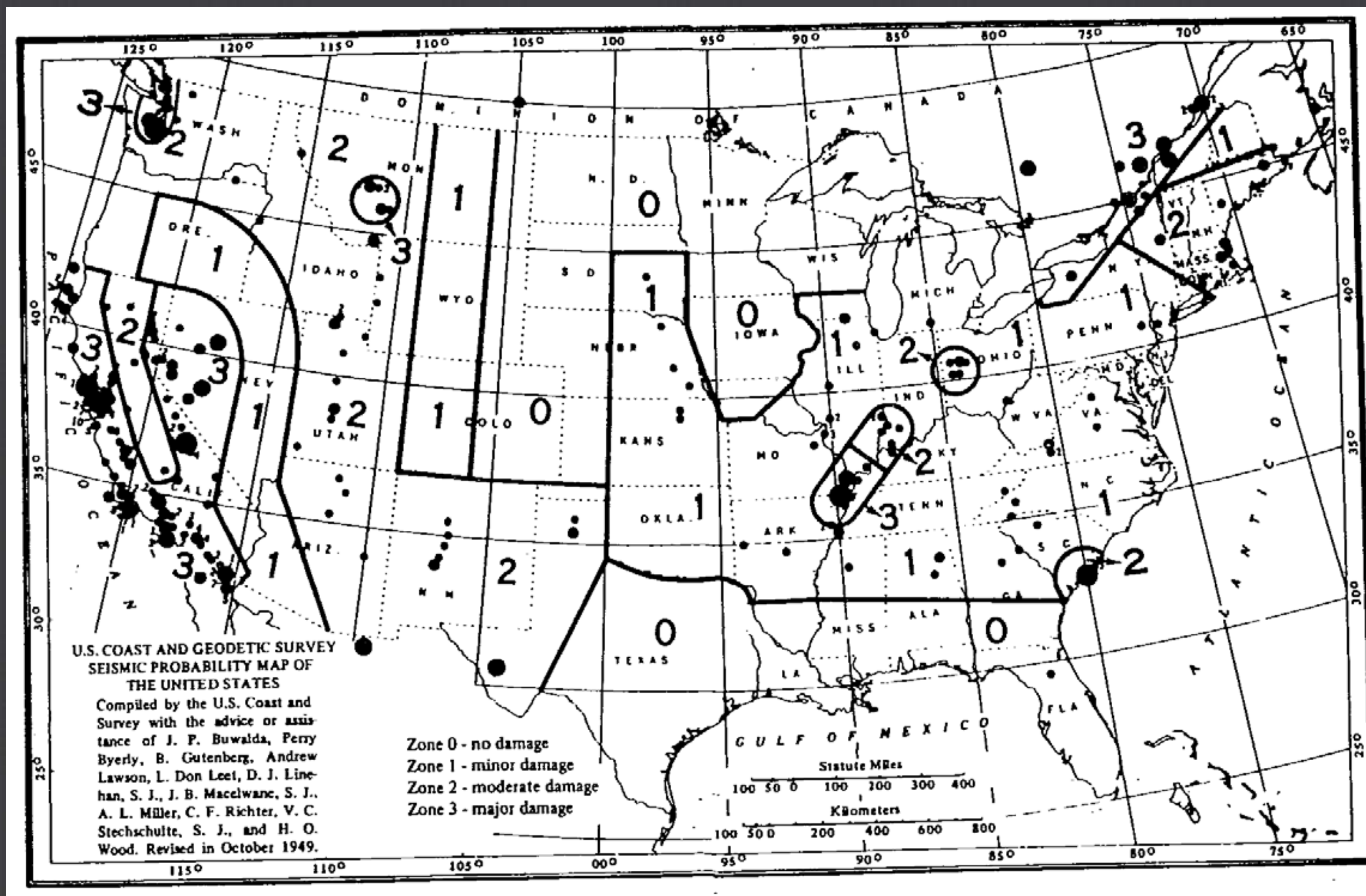
Housner and McCann, 1949 BSSA

# 1949 - Olympia Earthquake, WA – M7.1



Noson, et.al., 1988 (original photo Edwards, 1951)

# 1949 UBC Seismic Zone Map
# Historical Earthquake Locations




Algermissen, 1983, EERI Monograph Series

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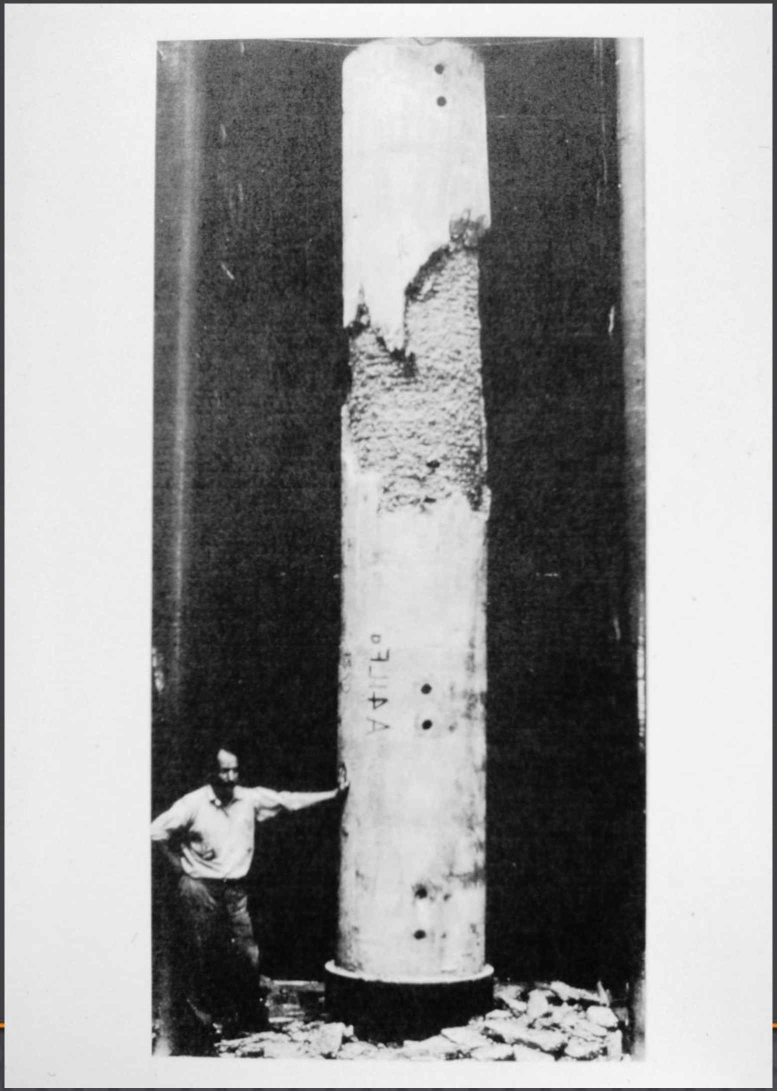
# Strength Design – 1930s – 1950s

Development of strength design methods systematically explores and quantifies inelastic capacity of structural elements



Ferguson, 1979

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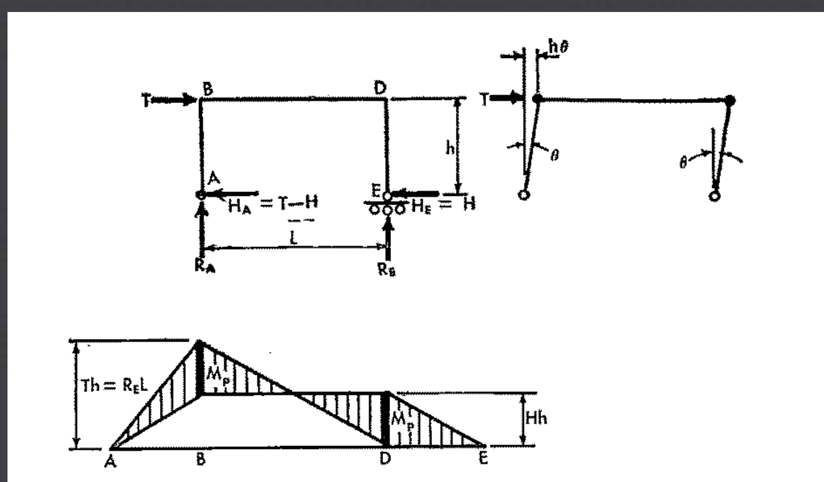
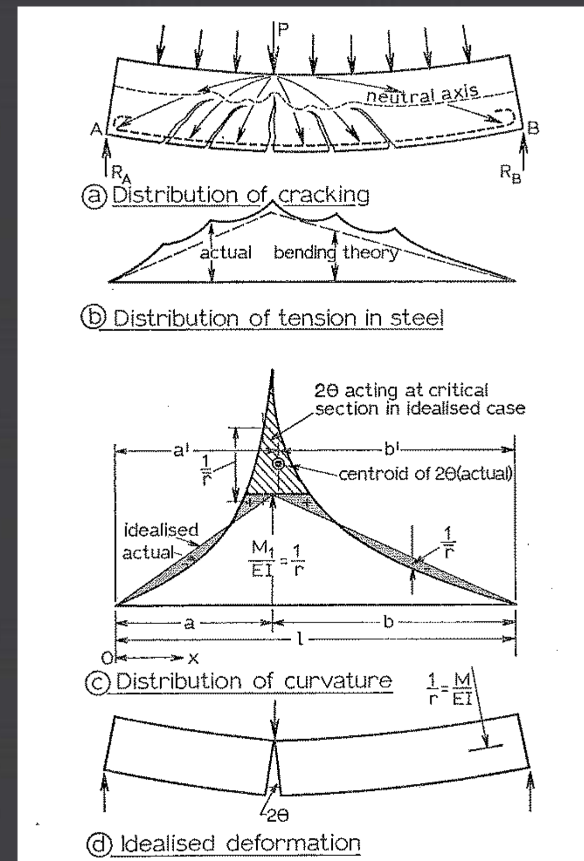
# Plastic Design for Gravity Loading – 1950s

- Lynn S. Beedle, Lehigh University, *Plastic Design of Steel Frames* and AISC – Part 2
- A.L.L. Baker, Reinforced Concrete in UK




AISC

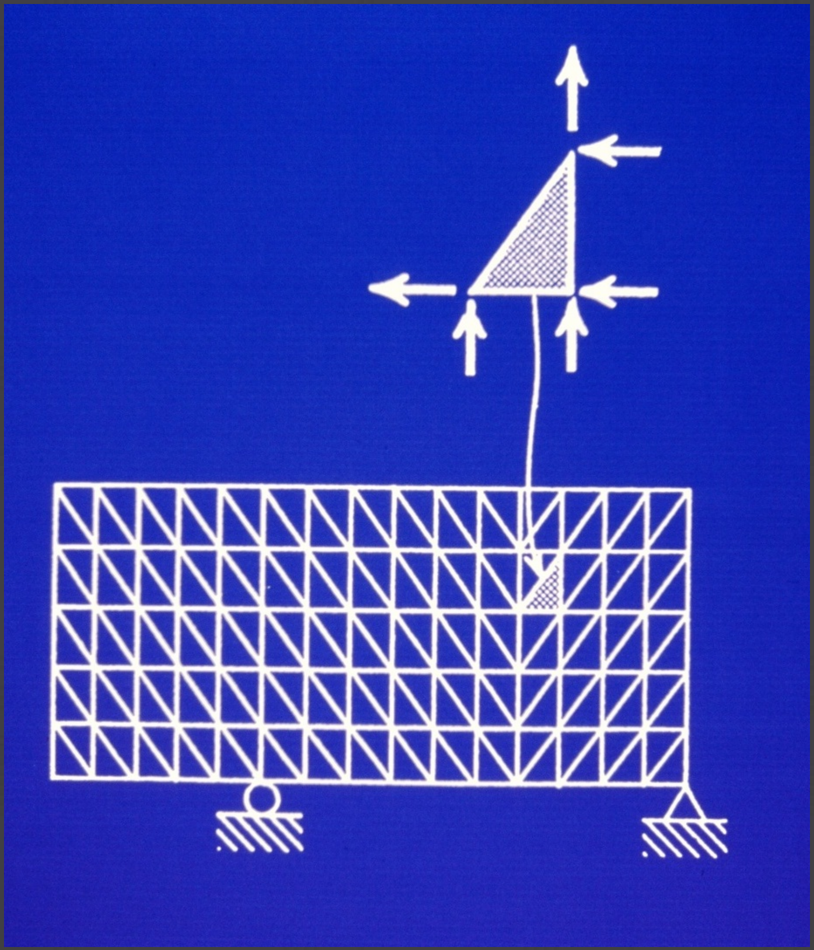



Baker

# Finite Element Method – 1956

Ray W. Clough and others develop the method at Boeing in the mid-1950s

He coins the term "finite elements" in 1960



Ray Clough Lecture Univ. of WA, 1989

# Sea Floor Mapping Revelations - 1950s

Efforts to map the sea floor provide a key piece to plate tectonic theory – spreading.

Bolt, 1978

# Estimating Inelastic SDOF Displacements from Elastic Analysis - 1960

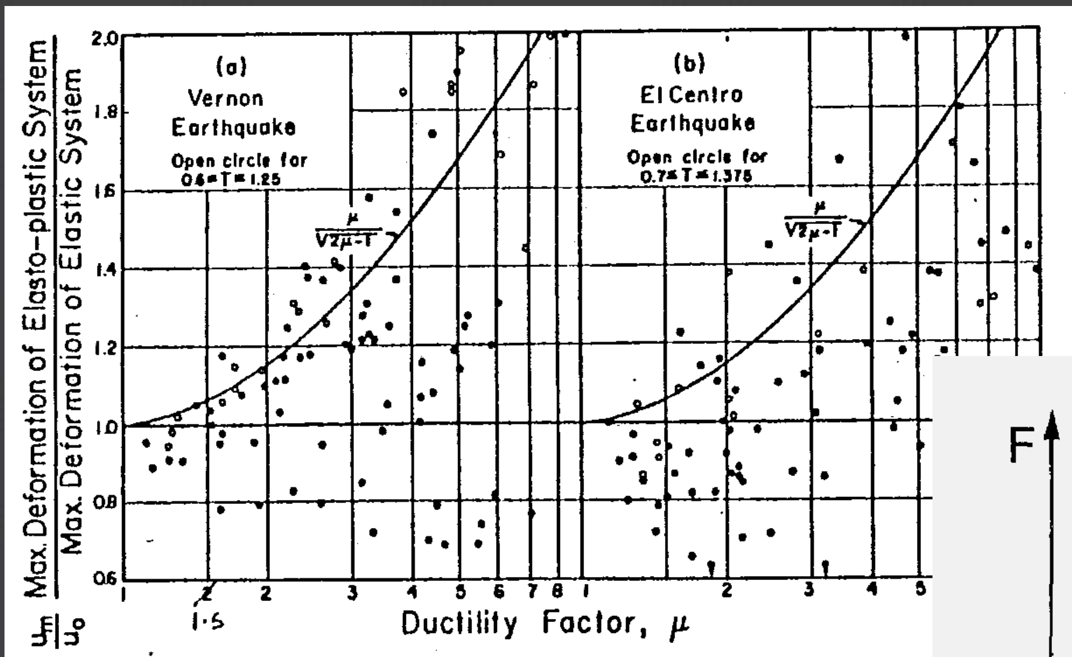
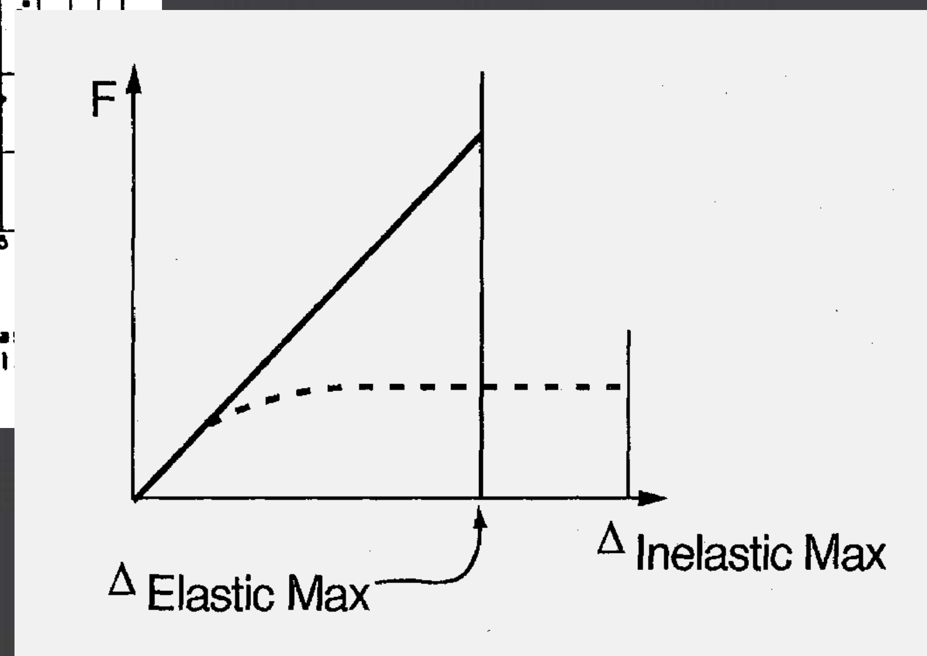



Fig. 7 Comparison of Maximum Relative Displacements of Ela
Plastic and Elastic Systems as a Function of Ductil
Factor -- Systems with 10 Percent Critical Damping




Newmark and Veletsos, 2WCEE 1960

# Nuclear Industry Contributes to Seismic Design Methodology - 1950s-1970s

San Onofre
Nuclear
Generating Station
Unit 1
1968 - 1992

Southern Cal Edison, 2005

# 1964 - Niigata Japan M=7.5
# Liquefaction/Lateral Spreading Damage

Showa Bridge ,Niigata

# 1964 – Prince William Sound Earthquake, AK  $M_w$9.2
# Tectonic Uplift

USGS Website

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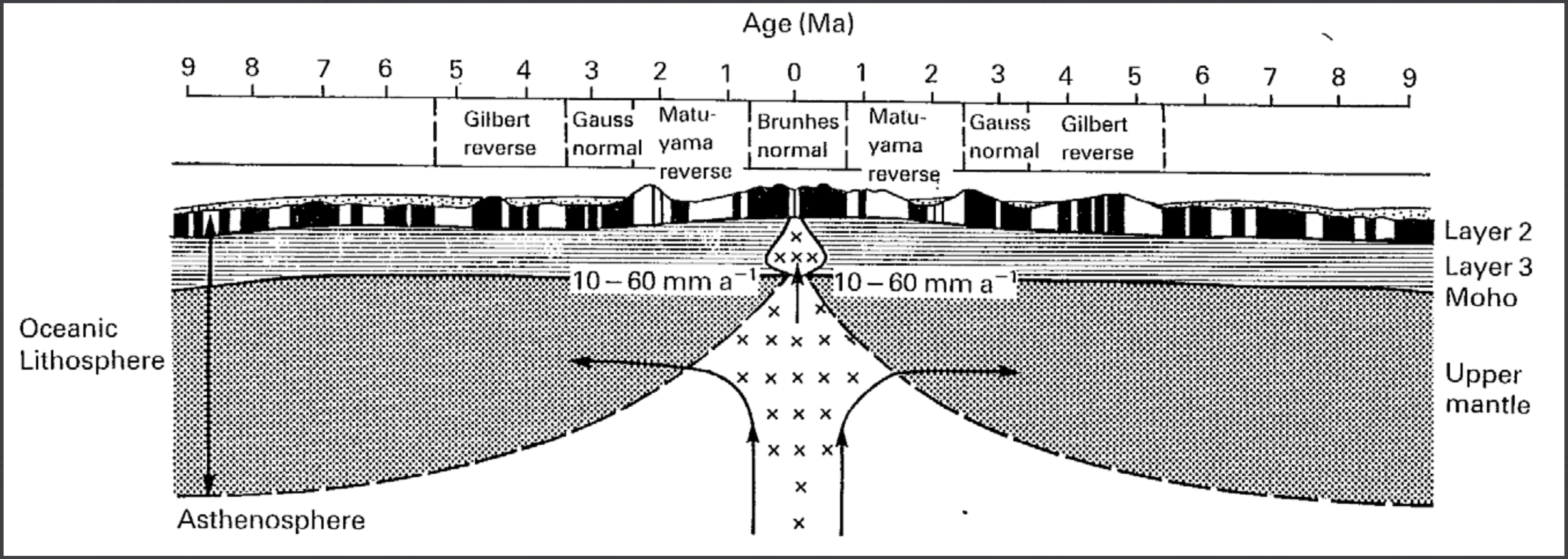
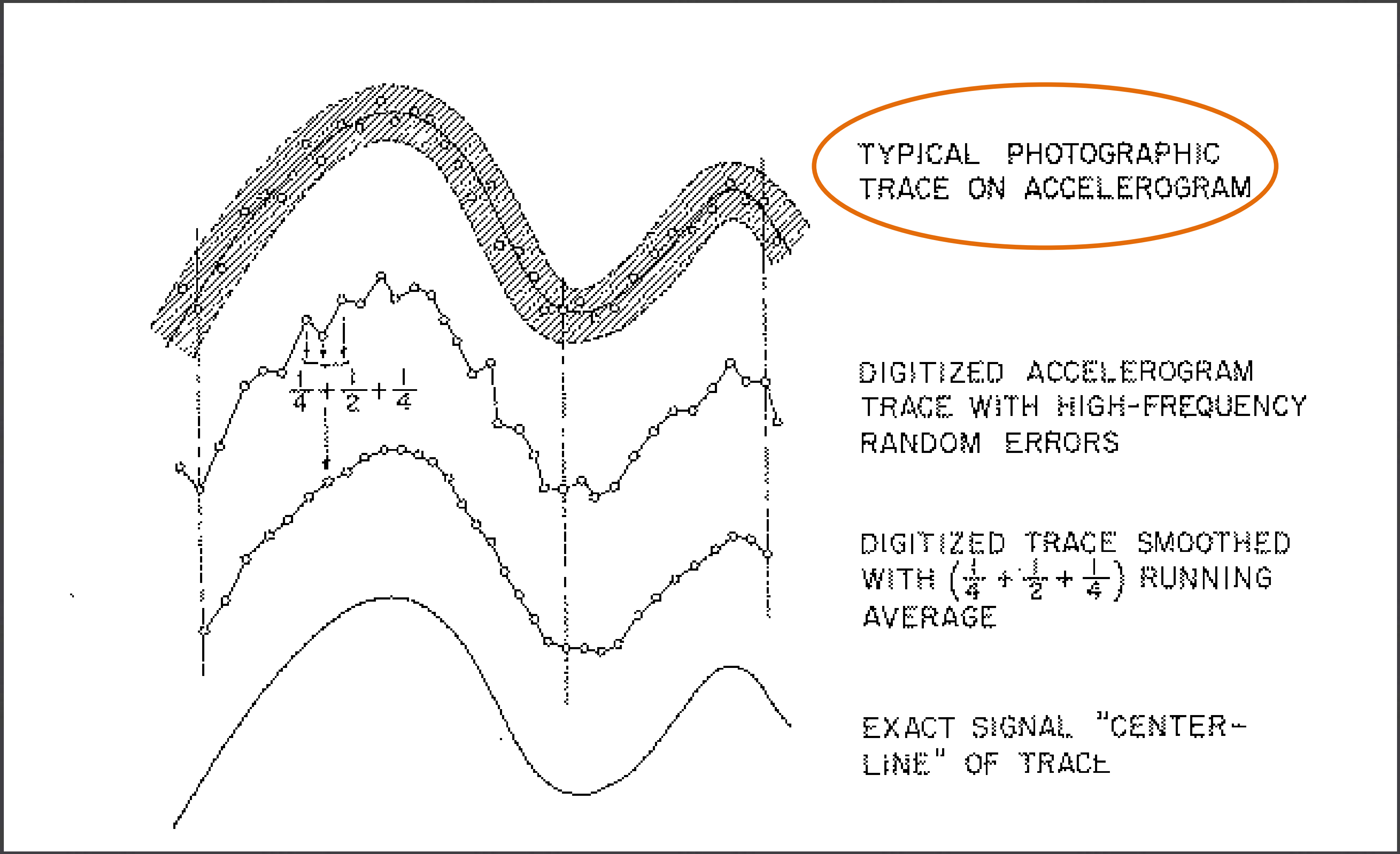
# Sea Floor Spreading
# Geomagnetic Reversals – 1960s

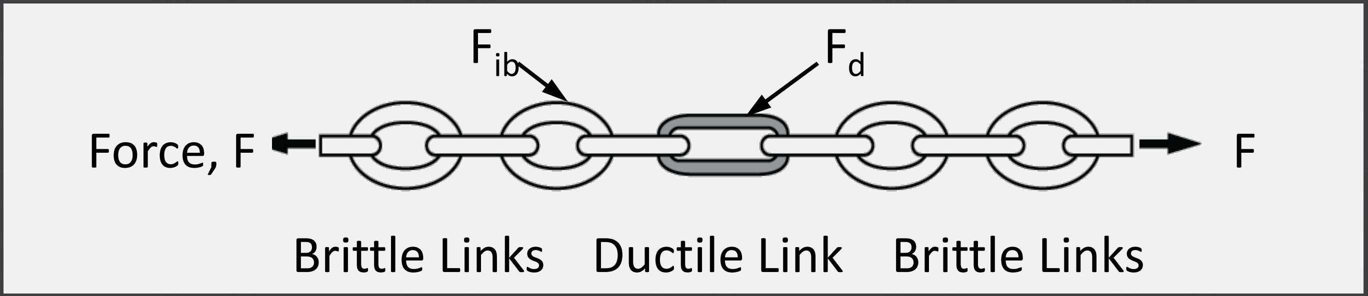
One of the last bits of evidence that establishes plate tectonic theory

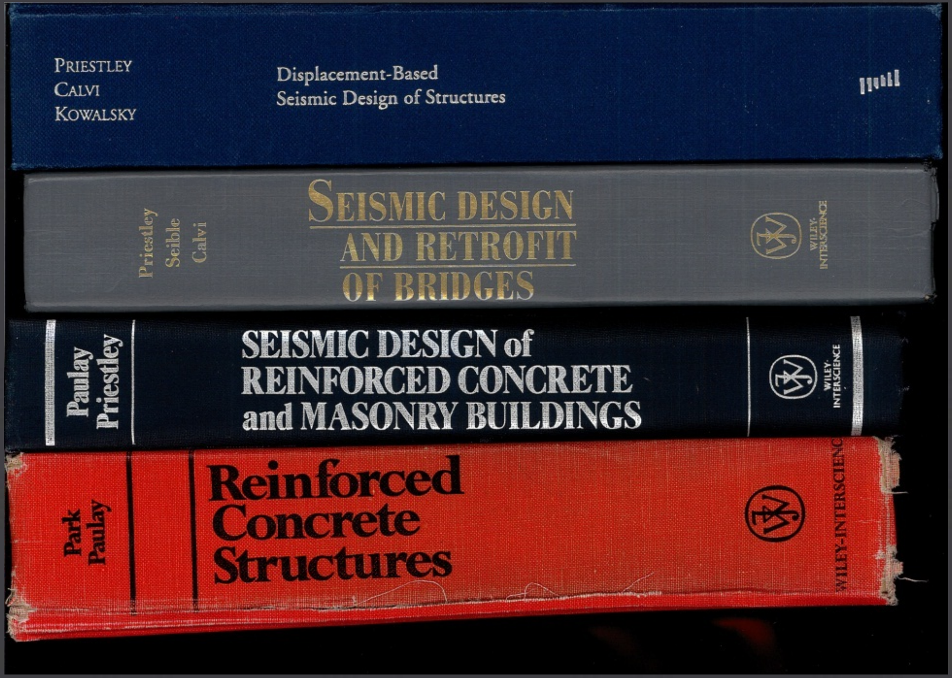


# Hand Digitization of Accelerograms! – 1950s-1970s



# Capacity Design is Formally Defined -1969




Hollings (1969), Park, Paulay, Priestley, et.al. (1975, 1992, 1996, 2007)

# 1971 - San Fernando Earthquake, CA M=6.5
# Seminal Event for Bridge Seismic Design

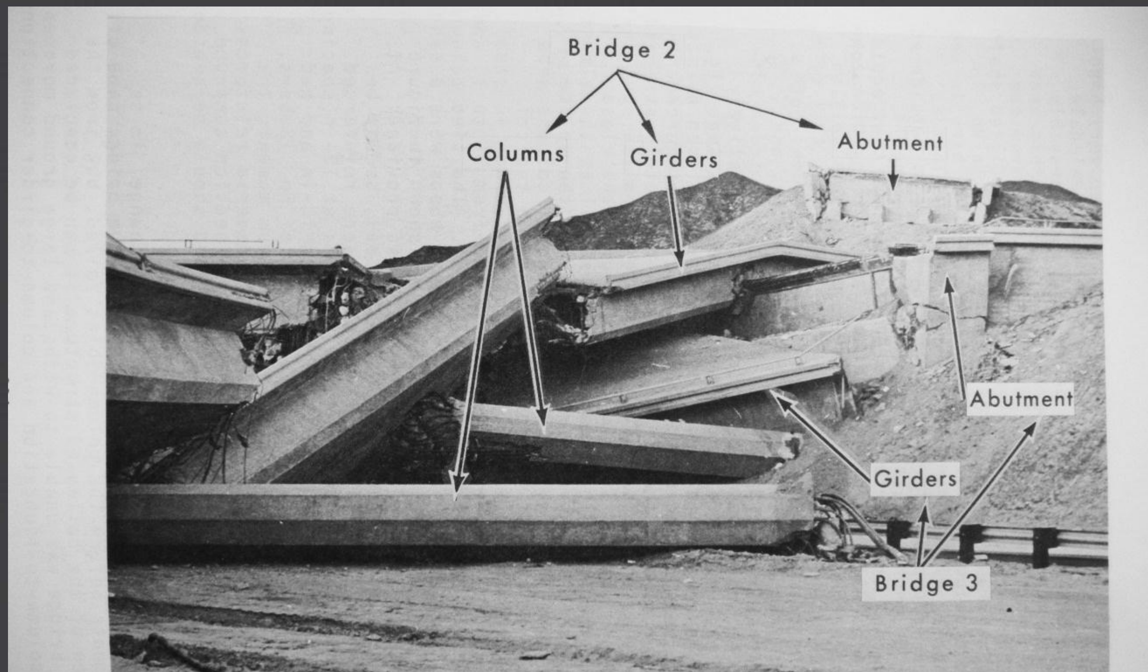
Dropped Spans
New Bridges

5/210 Interchange
San Fernando Earthquake
February 11, 1971

# 1971 San Fernando, CA
# Detailing Problems

5/210 Interchange
San Fernando Earthquake
February 11, 1971

# Highly Valuable Reconnaissance Reports from 1971 San Fernando EQ



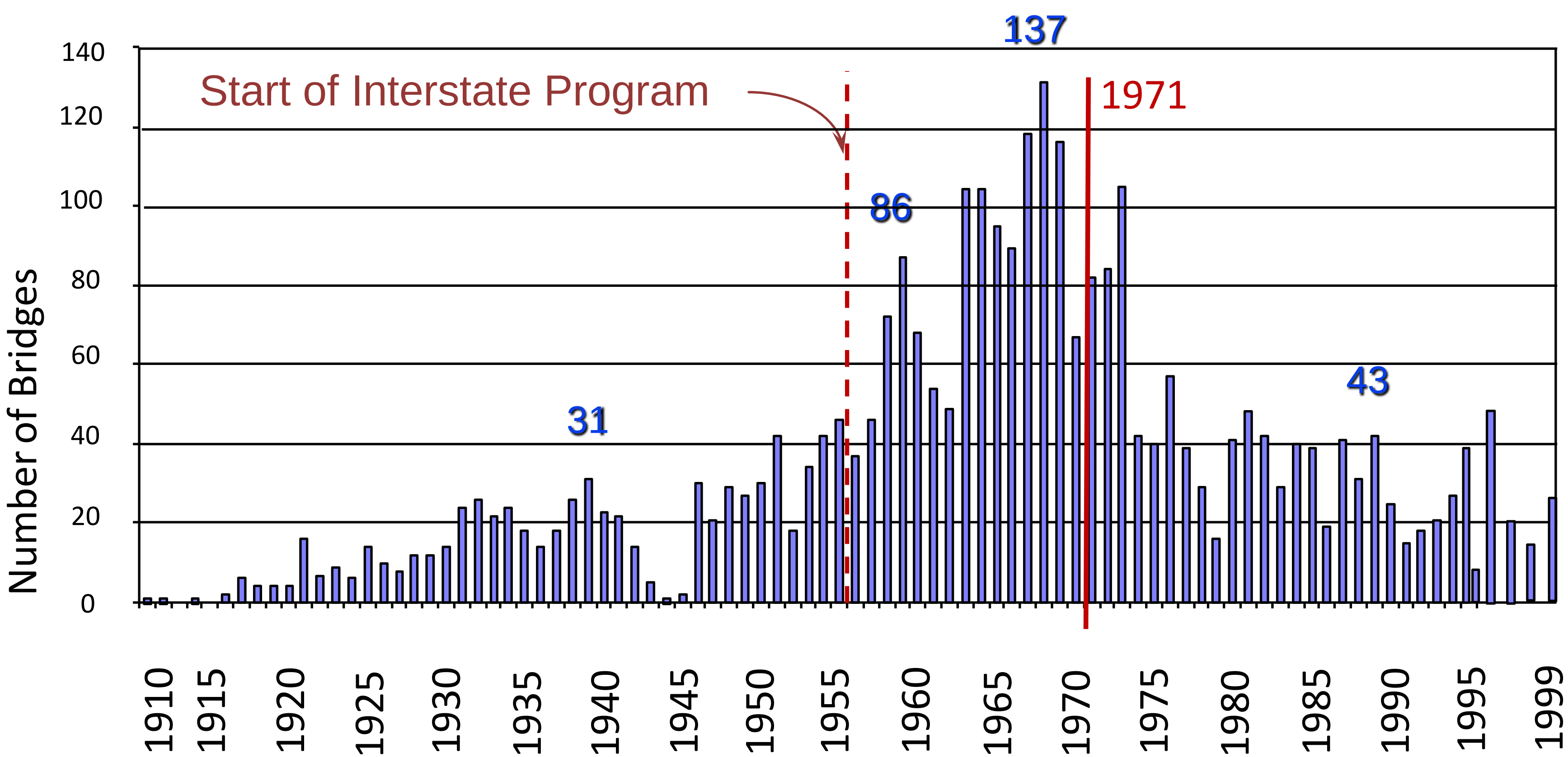


CalTech, 1971; NBS, 1971)

# Earthquake Damage in Folk Art -1972


1972 Doobie Brothers Album Cover Shot at 5/14 Interchange San Fernando, CA

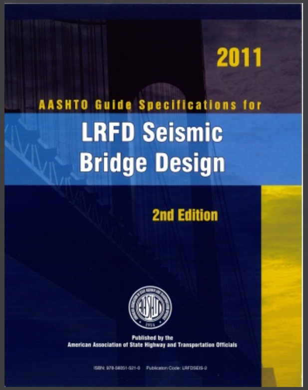
# 1910-2000 One State's Construction History



# "Phase I Retrofits" – Restrainers / Support Length – 1970s and 1980s

# Timeline - Seismic Specifications - 1975-Today

- 1975 – Interim: modified Caltrans provisions
- 1981 - ATC-6 *Seismic Design Guidelines for Highway Bridges* (Pub. No.: FHWA/RD-81/081)
- 1983 – FHWA/ATC-6 adopted as Guide Specs
- 1990 – Guide Specs adopted into Std Specs as *Division I-A*
- 1994 – First edition LRFD *Bridge Design Specs*
- *2009 – Guide Specs for LRFD Seismic Bridge Design* (published)

# Seismic Isolation - 1974: South Rangitikei River, New Zealand

Rocking/Stepping Columns
Railway Bridge

Buckle, et. al. MCEER

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# Probabilistic Seismic Hazard Map -1976

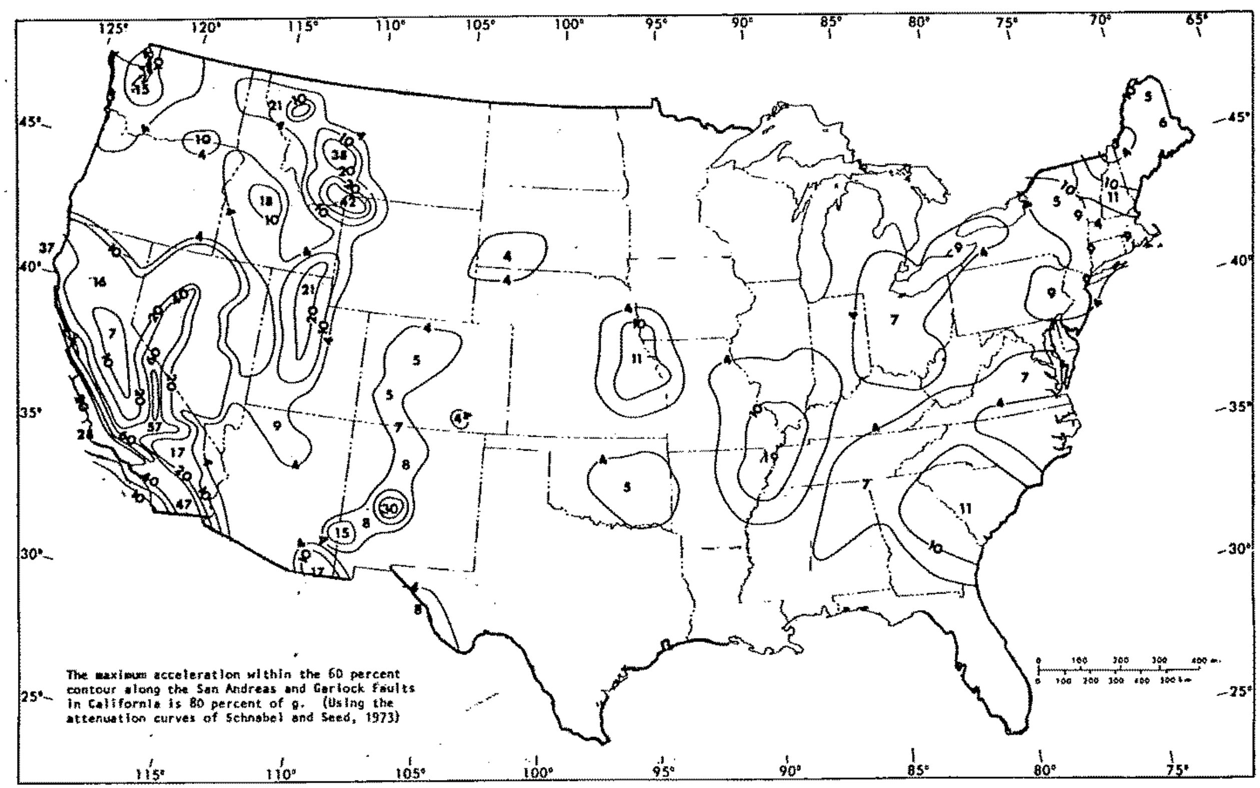
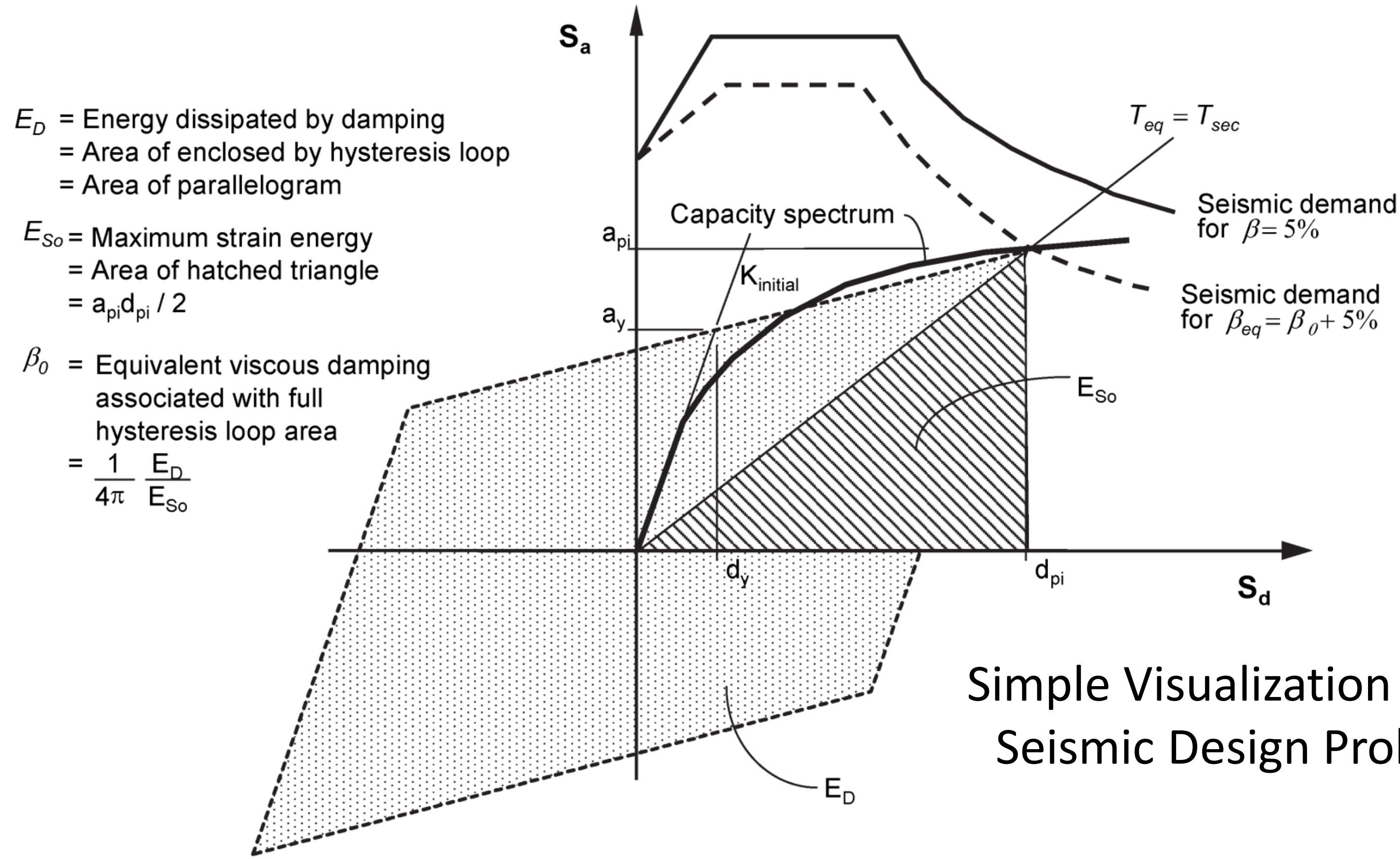


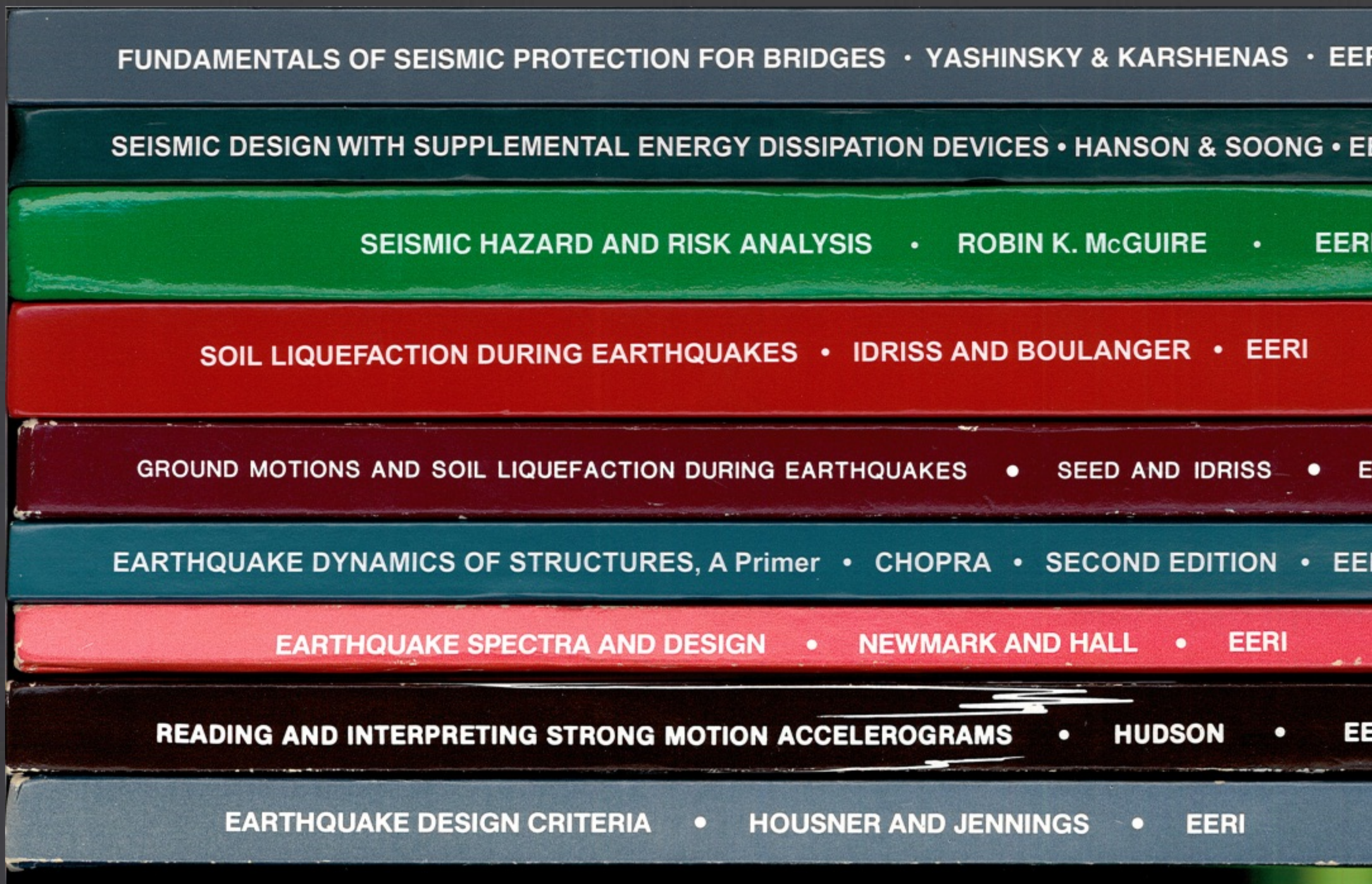

*Figure 47.* Probabilistic ground acceleration map of the conterminous United States, 50 year exposure time, 10 percent chance of exceedance, contours are percent of g (Algermissen and Perkins, 1976, Ref. 169).

# Capacity Spectrum Method – 1970s



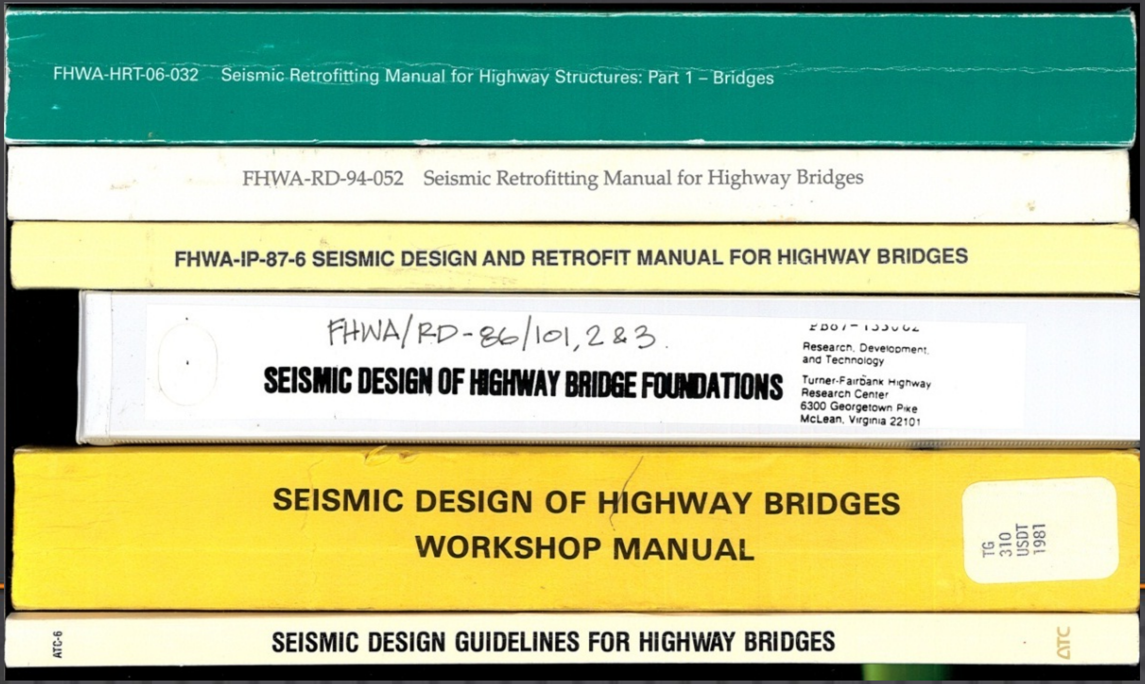

Simple Visualization of the Seismic Design Problem

# EERI Monograph Series – 1979 to 2008
# Cross-Discipline Summaries



# FHWA Dissemination of Information

- ATC 6, 1981 and ATC 6-2, 1984
- FHWA/NHI Training
- Recommended Practice
- Retrofit Manuals, 1987,1994, 2006



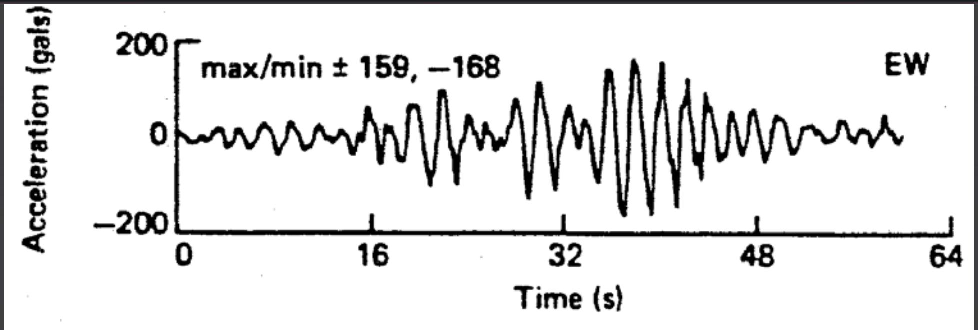

ATC, FHWA

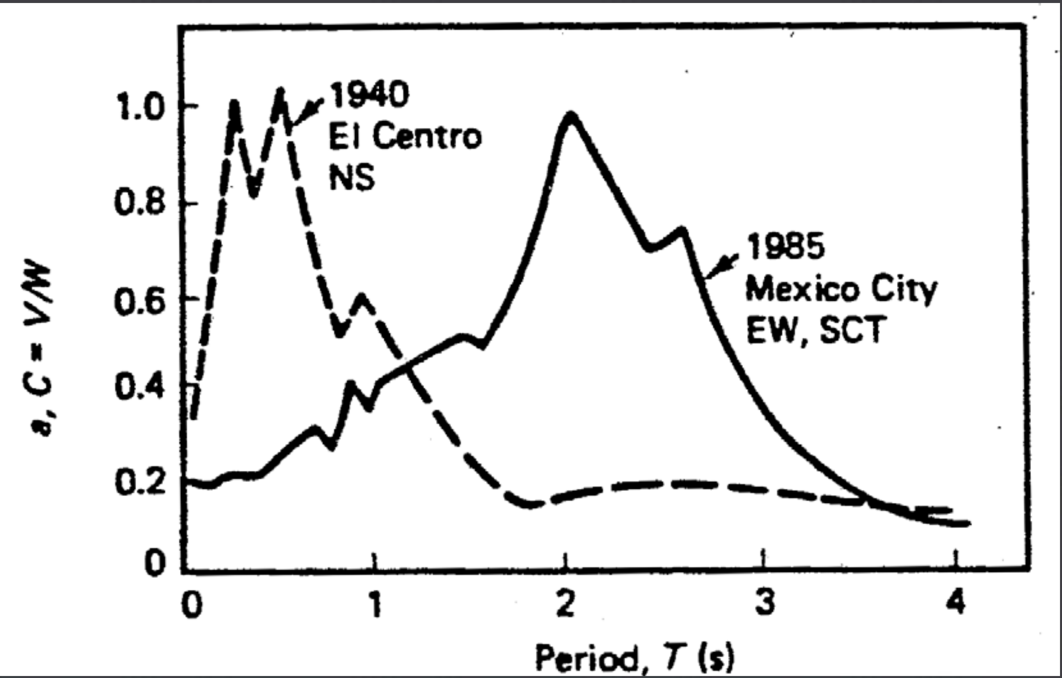
# 1985 Michoacan Earthquake, Mexico M8.1
# Soft Soil Amplification Effects

Earthquake 350 km from Mexico City, Ancient Filled-in Lake, Rock PGA = 0.04g & Lake Bed PGA = 0.16g with strong 2 sec content

Leads to Soil Profile Type IV

And emphasizes importance of site-specific ground motion response analysis




Popov, 1986

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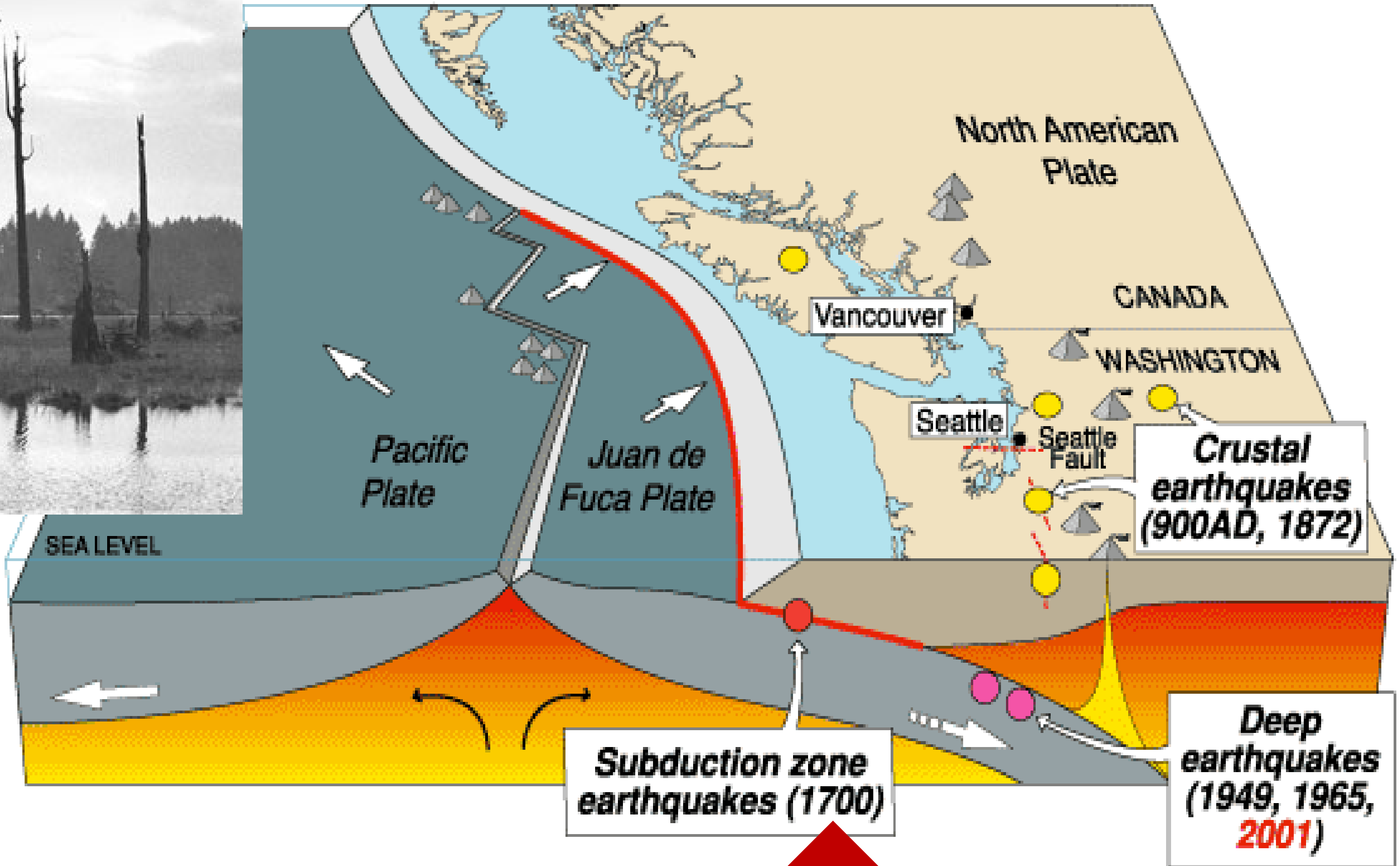
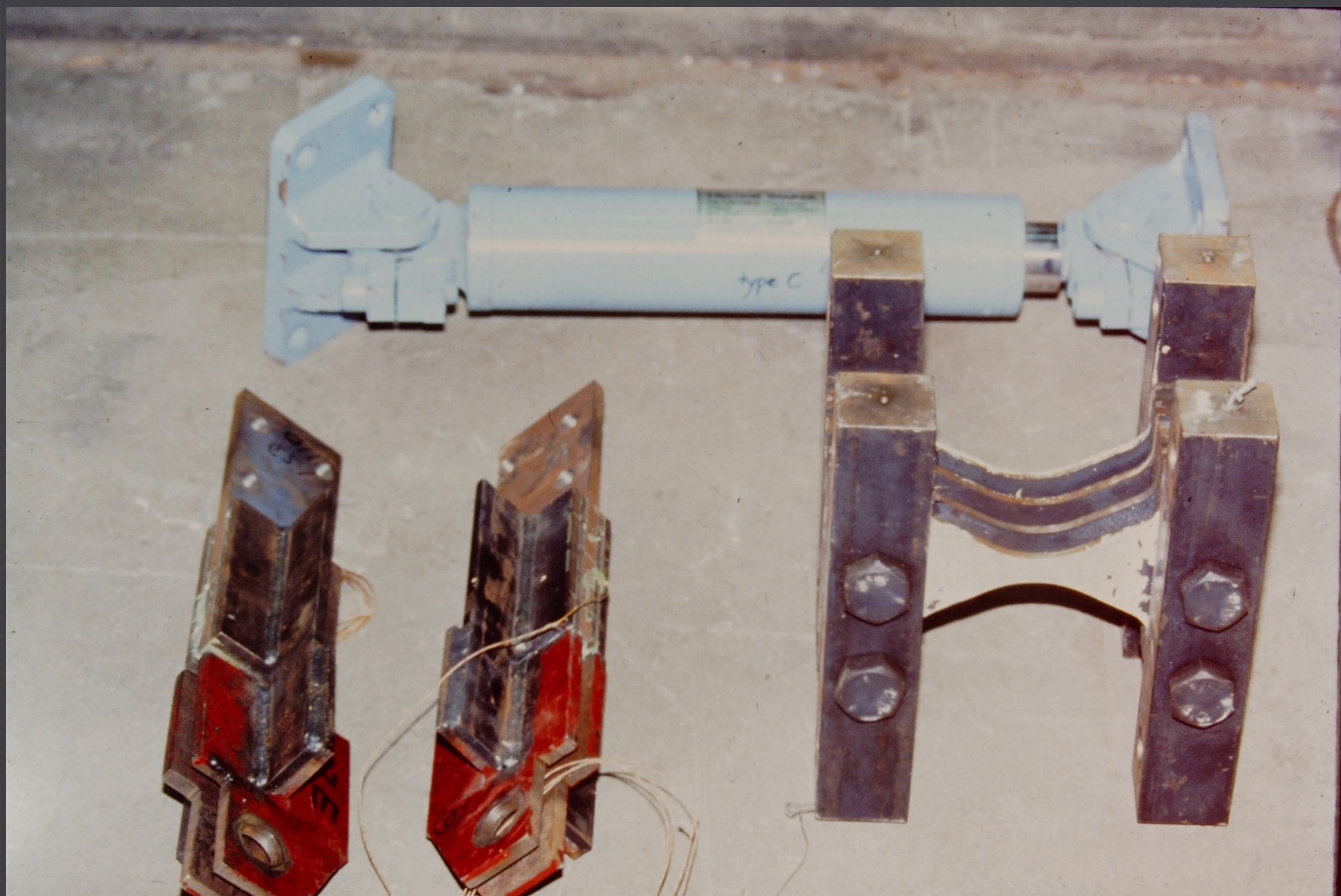
# Seismic Isolation – 1985:
# US 101 Sierra Point Overhead, CA

Survived 1989 Loma Prieta EQ
Undamaged, PGA = 0.09g

# Cascadia Subduction Zone – 1980s – 1990s



# Damper Technology Emerges – 1980s – 90s



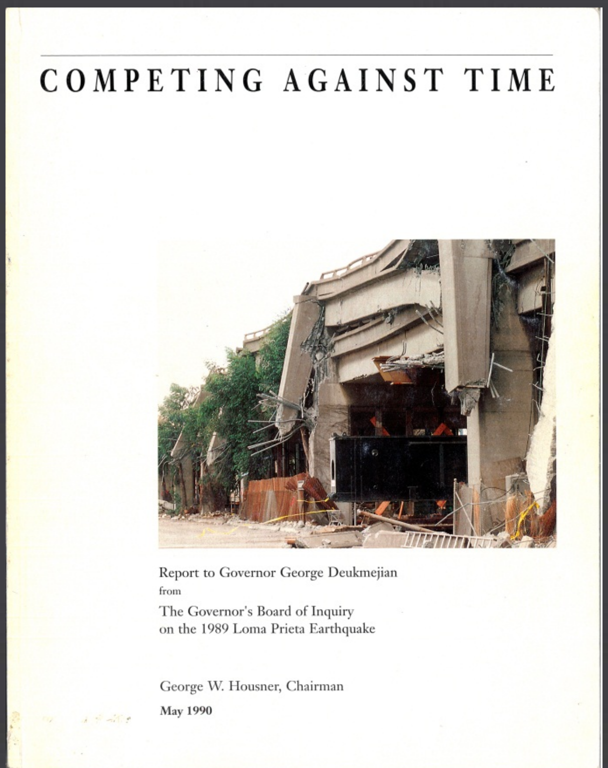
# 1989 – Loma Prieta Earthquake, CA  M=7.1
# I-880 Nimitz Freeway Viaduct Collapse

EERI Slide Collection

# 1989 – Loma Prieta – Closure Span
# San Francisco- Oakland Bay Bridge

East Spans San Francisco  - Oakland Bay Bridge

# In the Wake of the 1989 Loma Prieta Event
# Governor's Board of Inquiry




**Governor**

- Seismically Safe Structures & Importance
- Priority to Seismic Safety
- Seismic Safety Commission to Report

**Caltrans**

- Plan, Schedule, Resources, including retrofit
- Seismic Advisory Board
- Meet Governor's Safety Standards
- Specific Structure Requirements

**Other Agencies**

- Adopt Same Policies as Caltrans
- Comprehensive Vulnerability Assessments
- Rigorous Professional Development in Agencies

EERI and State of California, 1990

# Substructure Retrofit – 1990 to Today

First, single column bents
Then, multiple column bents

# Thomas Paulay – 1993 4th Mallet-Milne Lecture

Institute of Civil Engineers, London, England

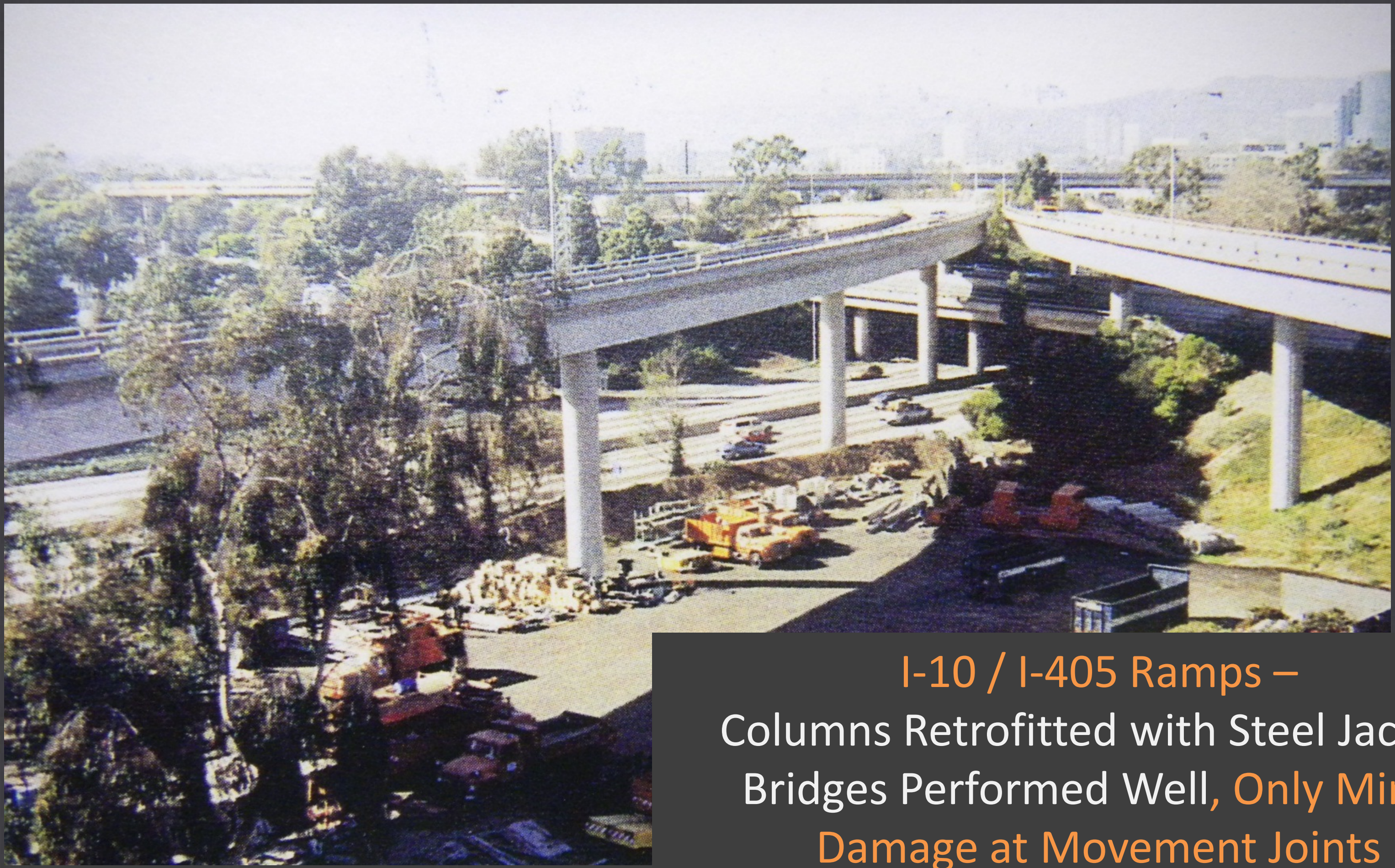
‘ the design engineer’s goal should be to make the structure have “tolerance with respect to the inevitable crudeness of predicting earthquake-imposed displacements” ‘

# 1994 Northridge Earthquake, CA   M=6.7
# Non-Retrofitted Structures

Mission Gothic Undercrossing
I-118 Simi Valley – San Fernando Freeway

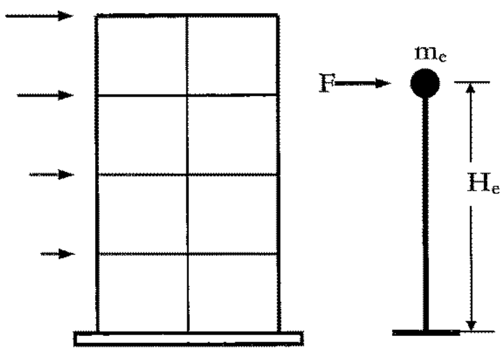
Caltrans

# 1994 Northridge, CA – Retrofitted Structures

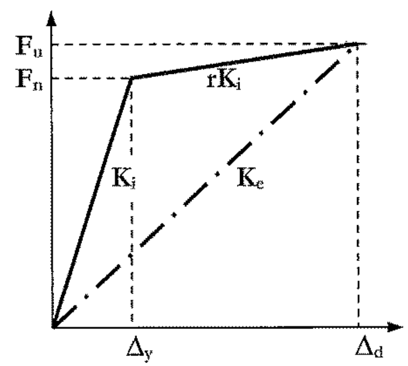


I-10 / I-405 Ramps –
Columns Retrofitted with Steel Jackets
Bridges Performed Well, Only Minor Damage at Movement Joints

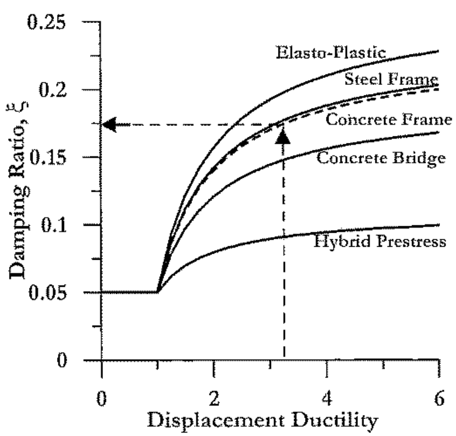
# Direct Displacement-Based Design (DDBD) – 1990s



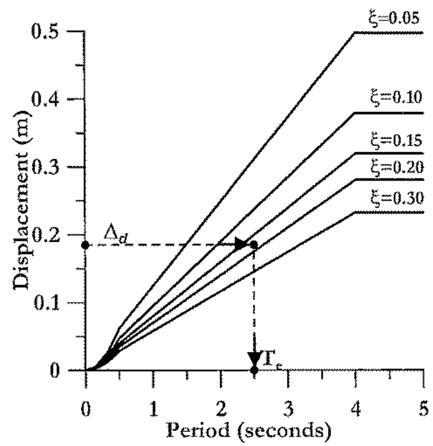

(a) SDOF Simulation



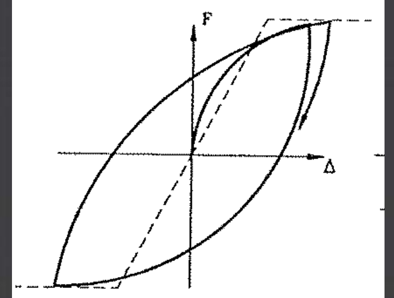

(b) Effective Stiffness $K_e$



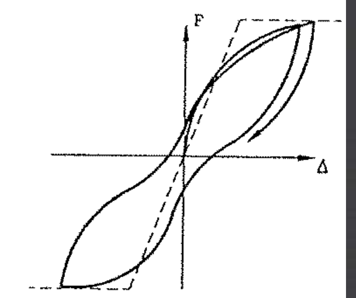

(c) Equivalent damping vs. ductility




(d) Design Displacement Spectra




(b) Reinforced Concrete Frame Response




(d) Bridge Column with High Axial Load

Priestley, Calvi, Kowalsky, 2007

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# Progression of Analysis/Demand Methods

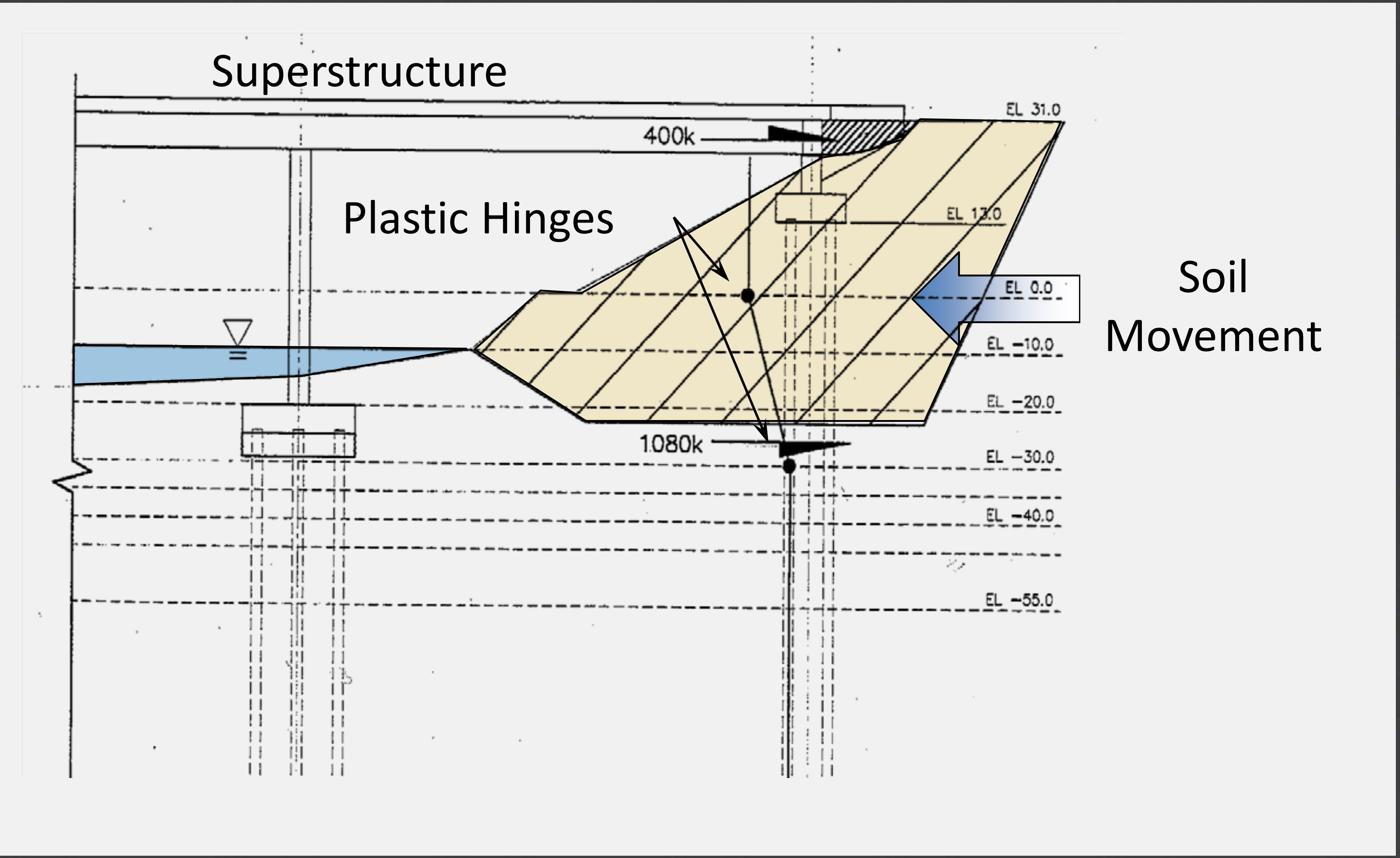
- Static, fraction of weight
- Pseudo static with amplification: soil & period
- Single-mode method
- Multi-mode method
- Capacity-spectrum method
- Direct Displacement-Based Design
- Response History

# AASHTO Design Methodologies

- **Force-Based Methods**
  - All early methods
  - ATC 6/Guide Spec
  - Division I-A
  - LRFD Provisions
- **Displacement-Based Methods**
  - Caltrans SDC
  - Guide Specs for LRFD Seismic Design

Both Methods Based on Capacity Design Principles, They Are Just Different Approaches

# Design for Liquefaction and Geotechnical Hazards – 1990s



# Seismic Isolation - 2000:
# I-680 Benecia-Martinez, CA

Seismic Isolation as part of a seismic retrofit of 1962-era I-680 southbound bridge

Buckle, et. al. MCEER

# 2011 Great East Japan Earthquake $M_w = 9.0$
# Tsunami Damage Utatsu O-hashi

# Large-Scale Shake-Table Testing of Complete Bridges


Buckle, University of Nevada - Reno

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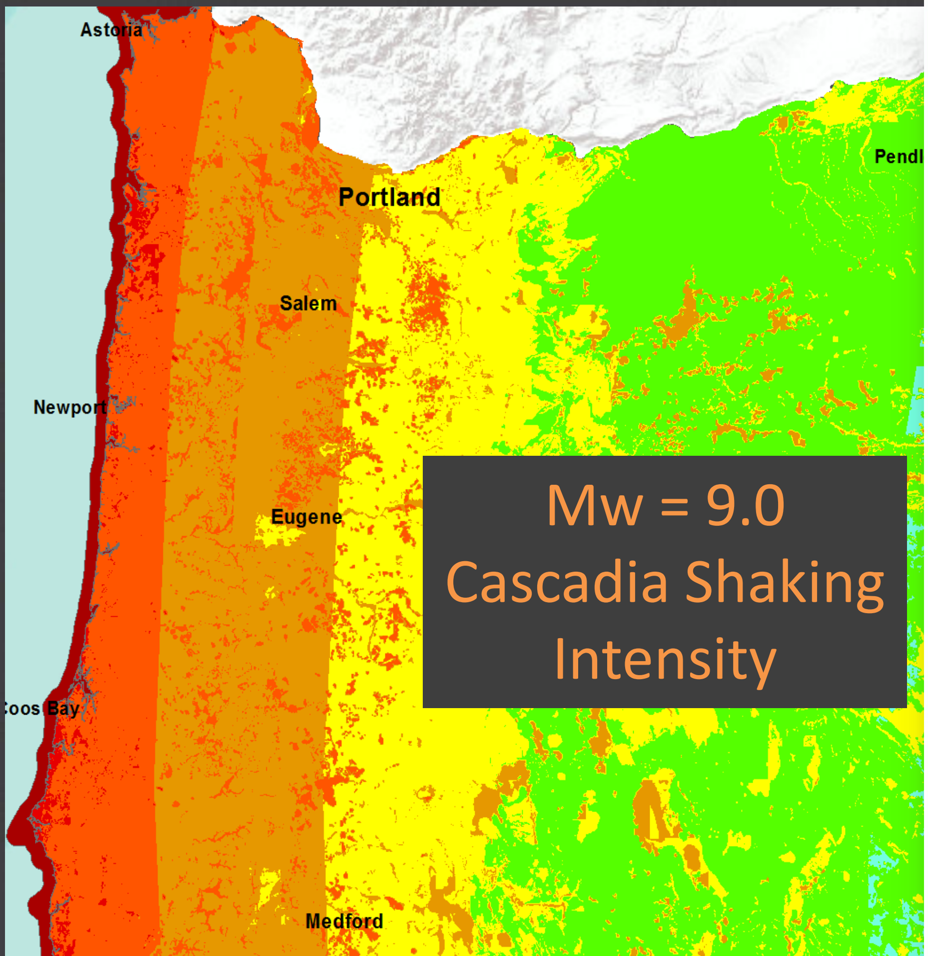
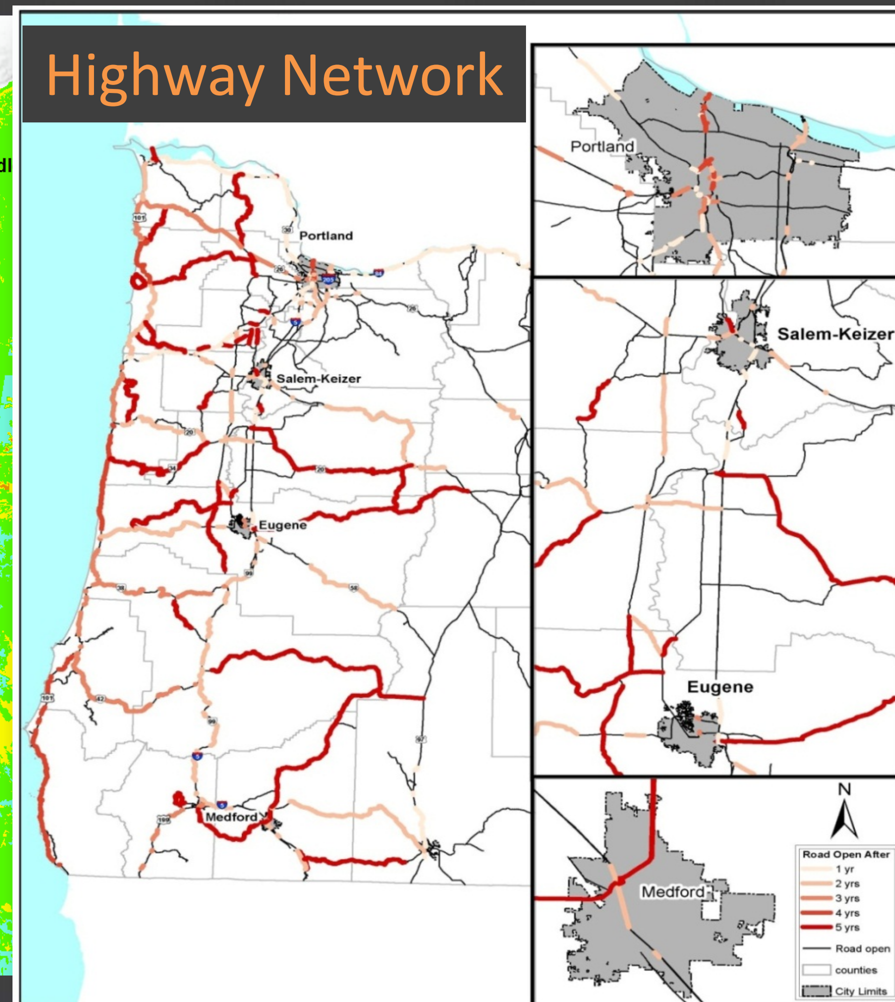
# Shake-Table Testing of Complete Bridges with Vehicles (Scale Trucks)


Buckle, University of Nevada - Reno

BergerABAM

# Transportation System-Level Planning for Extreme Events




Albert Nako, ODOT, 2013

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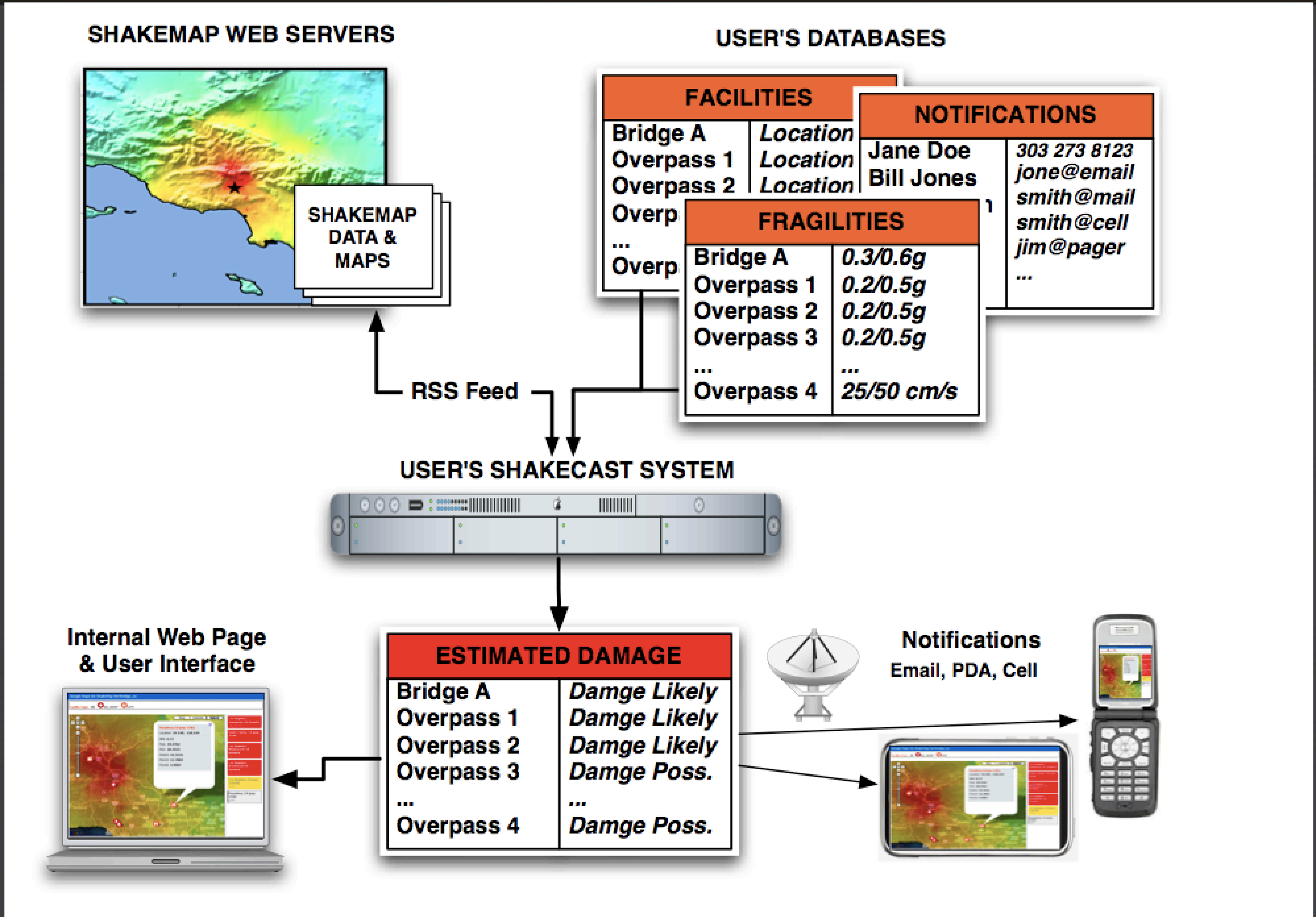
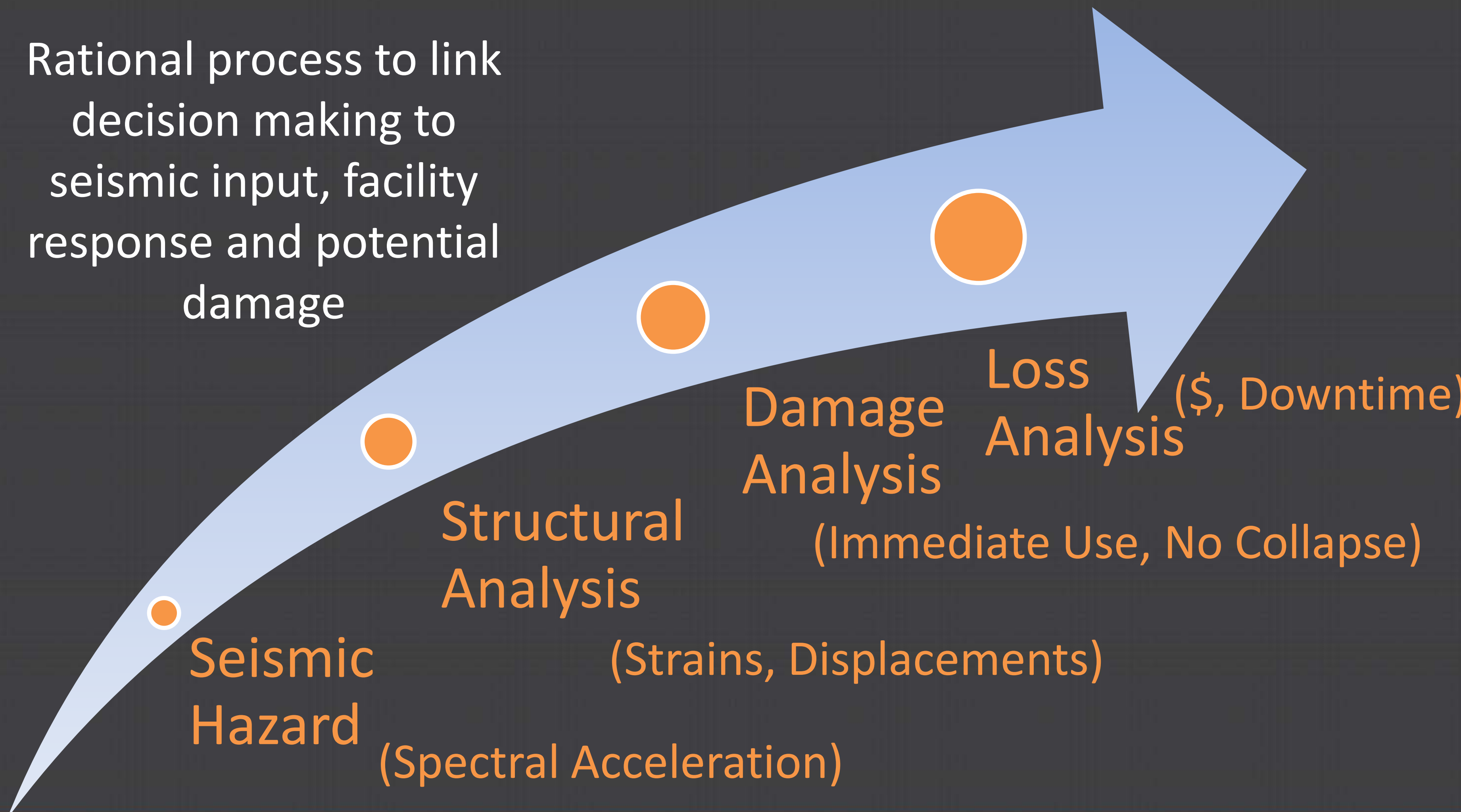
# Shake Map and Shake Cast Tools Facilitating Dispatch of Inspection Teams

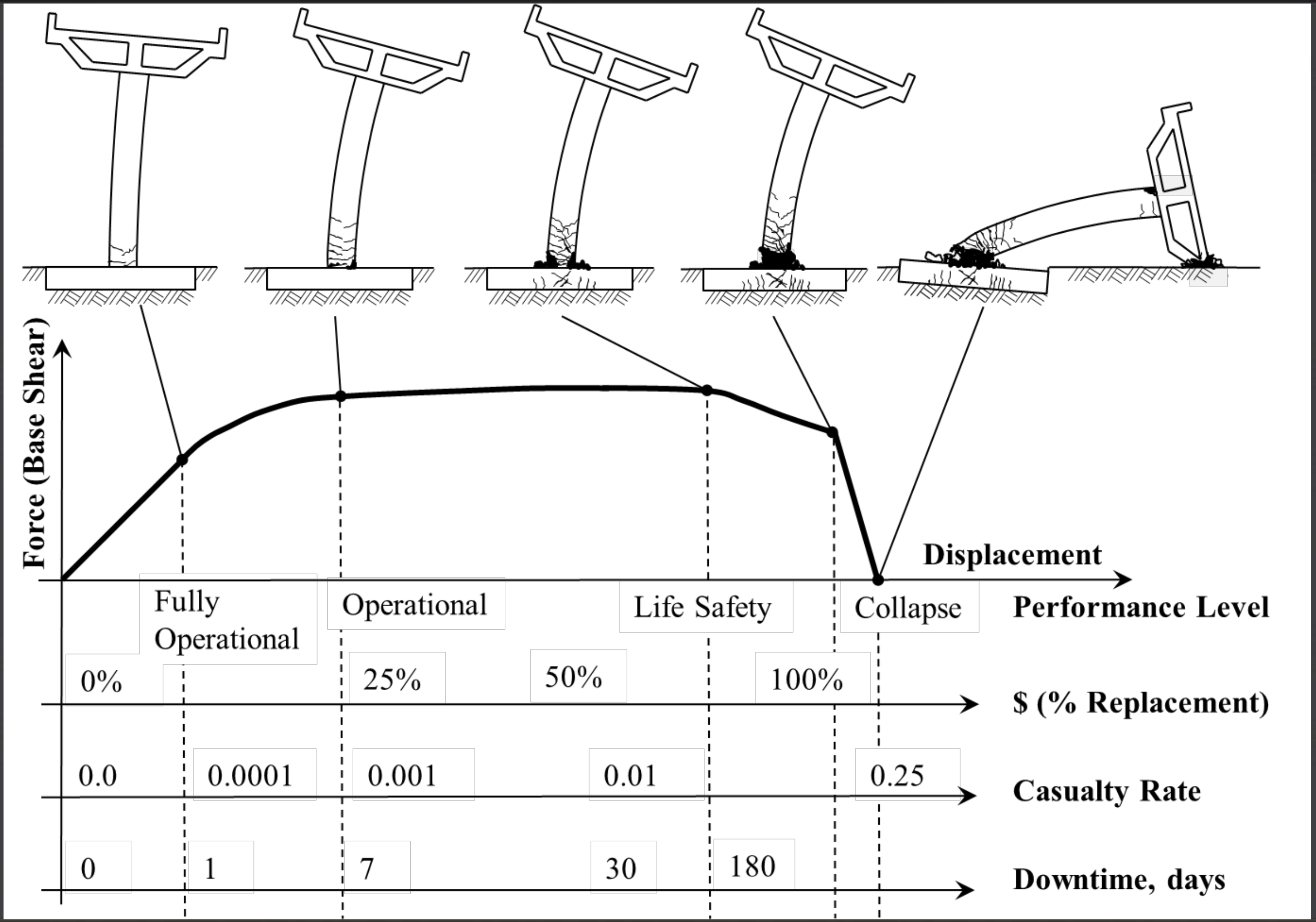


# Performance-Based Seismic Design

Rational process to link decision making to seismic input, facility response and potential damage

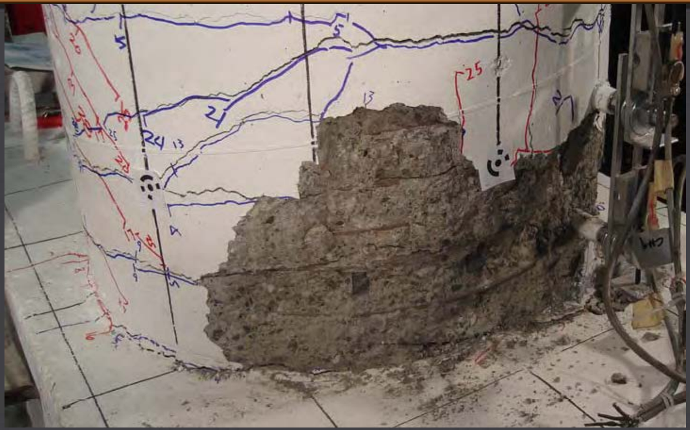


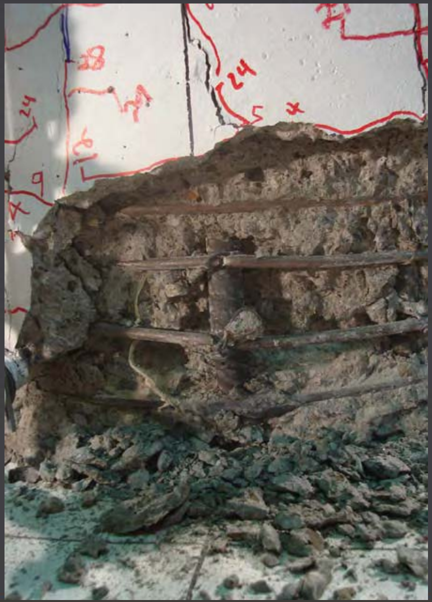
# Relationship of Seismic Response to Outcome




NCHRP 440 / Moehle & Deierlein, 2004

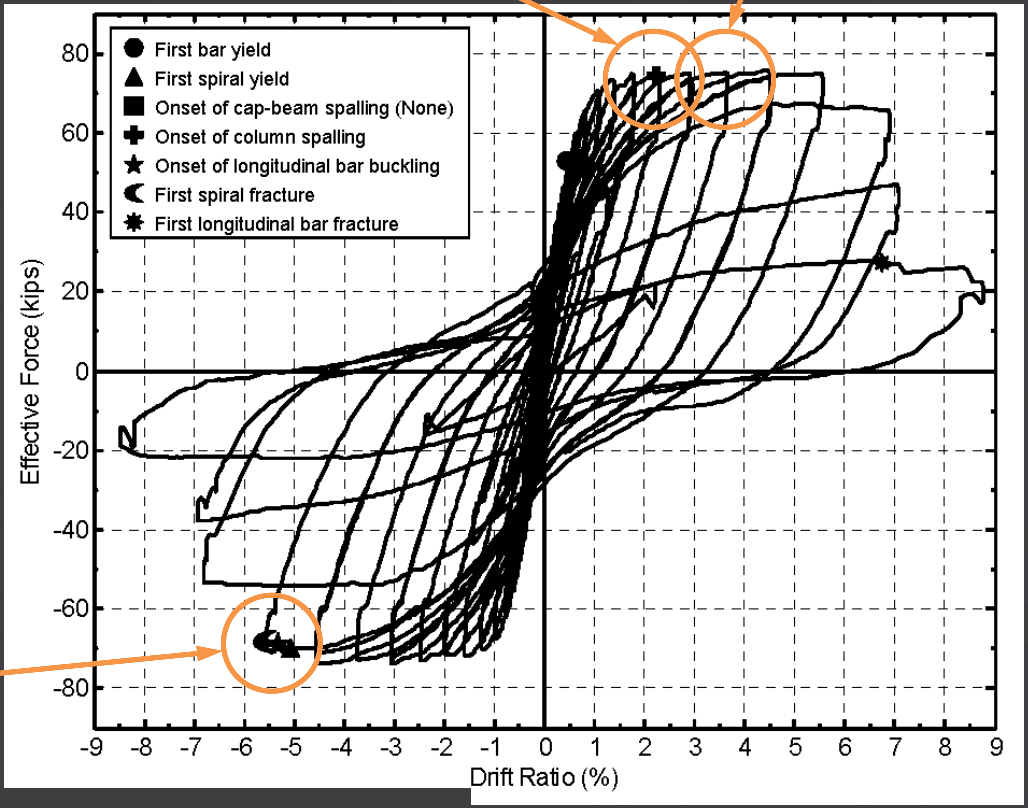
# Visual Catalogs from Cyclic Testing





Spalling Condition at 3.7% Drift

Spalling Onset 2.2% Drift




Bar Buckling & Spiral Fracture 5.6% Drift

Caltrans, PEER, and UCSD

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# ASCE 7-05 vs 7-10 Seismic Maps

- ASCE 7-05: “Seismic-Hazard Maps … with 2% Probability of Exceedance” (ground motion)

- ASCE 7-10 “target risk of structural collapse equal to 1% in 50 years based upon a generic structural fragility” *Risk-Targeted*

# Performance-Based Project Specific Criteria - 2005


**Ravenel Bridge**

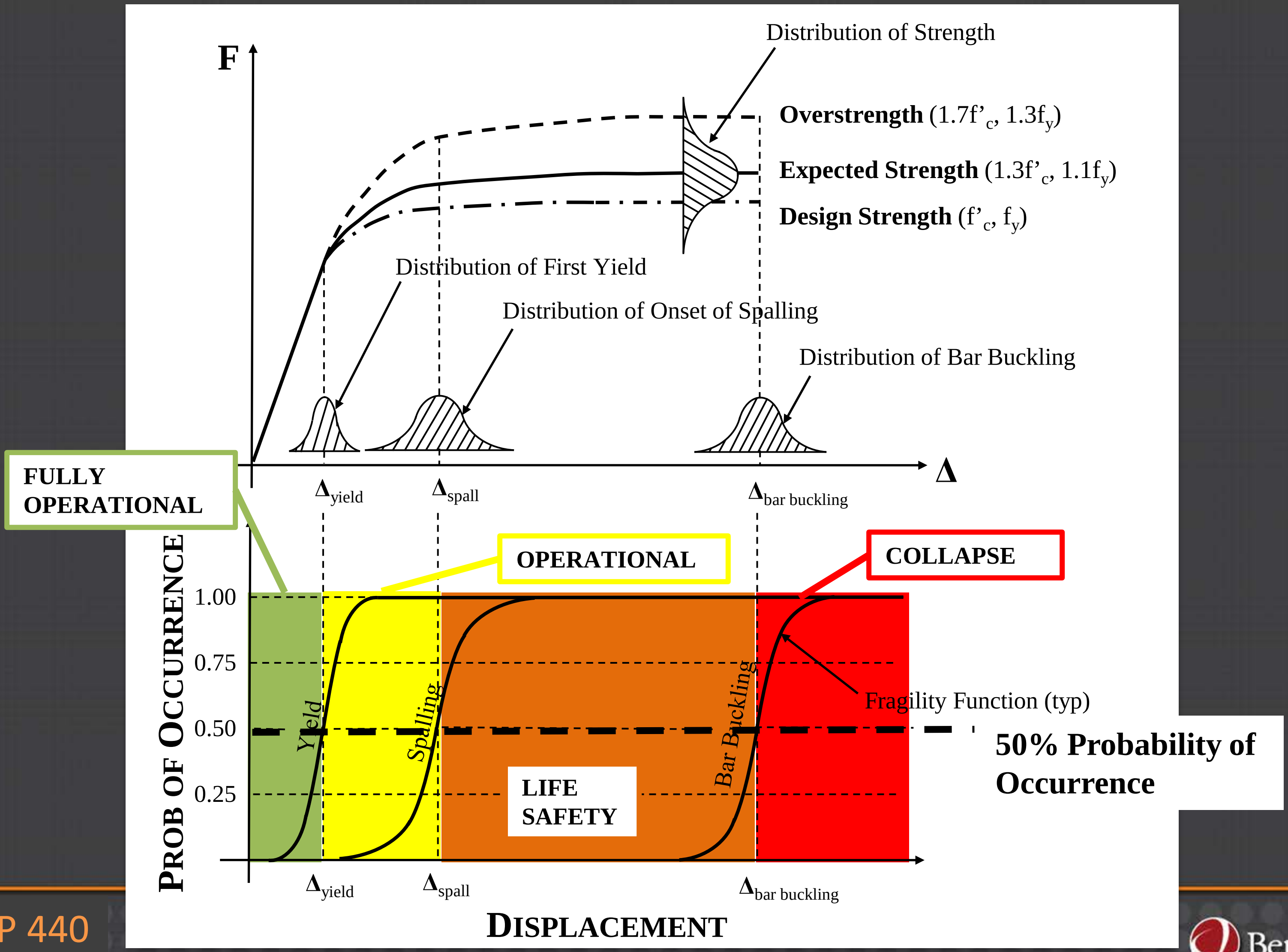
Charleston, SC

| Earthquake | Return Period | Performance | Damage |
|---|---|---|---|
| Lower Level | 500-yr | Immediate | Minimal |
| Upper Level | 2,500-yr | Functional | Repairable |

# Combined Performance, Damage, and Hazard Data

| | | | | | | |
|---|---|---|---|---|---|---|
| **Damage Descriptors** | **Damage Level** | I | II | III | IV | V |
| | **Classification** | None | Minor | Moderate | Life Safety | Near Collapse |
| | **Damage Description** | None | Minimal | Repairable | Significant | Near Collapse |
| | **Physical Description (RC Elements)** | Hairline cracks | First yield of tensile reinforcement | Onset of spalling | Wide cracks extended spalling | Bar buckling bar fracture confined concrete crushing |
| | **Displacement Ductility** | $\mu_\Delta \leq 1$ | | $\mu_\Delta = 2$ | $\mu_\Delta = 4$ to 6 | $\mu_\Delta = 8$ to 12 |
| **Repair** | **Reparability** | None/no interruption | Minor repair/ no closure | Repair/limited closure | Repair/weeks to months closure | Replacement |
| **Performance Descriptors** | **Availability** | Immediate Open to All Traffic | | Open to Emergency Vehicles Only | | Closed |
| | **Performance Level** | Fully Operational | | Operational | Life Safety | Collapse |
| | **Retrofit Manual** | PL3 | | PL2 | PL1 | N/A |

# Probabilistic Basis for Defining Performance Level



# Integral Bent/Superstructure Connection System

Precast Bent System – Highways for LIFE

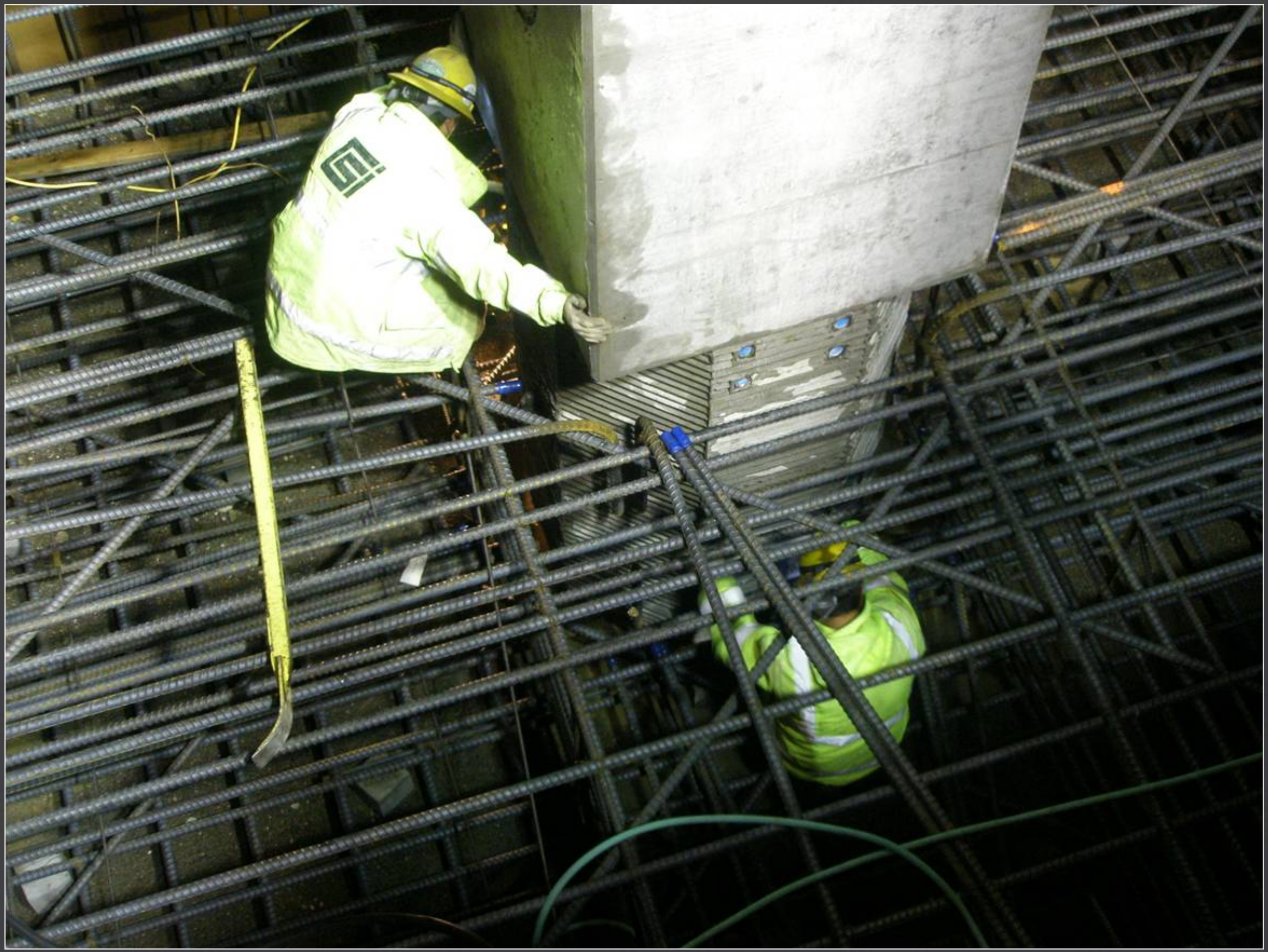
Conventional CIP Integral Connection with Precast Superstructure - WSDOT

# Integral Bent/Superstructure Connection System

Caltrans - San Mateo Bridge

# Precast Columns in High Seismic Areas

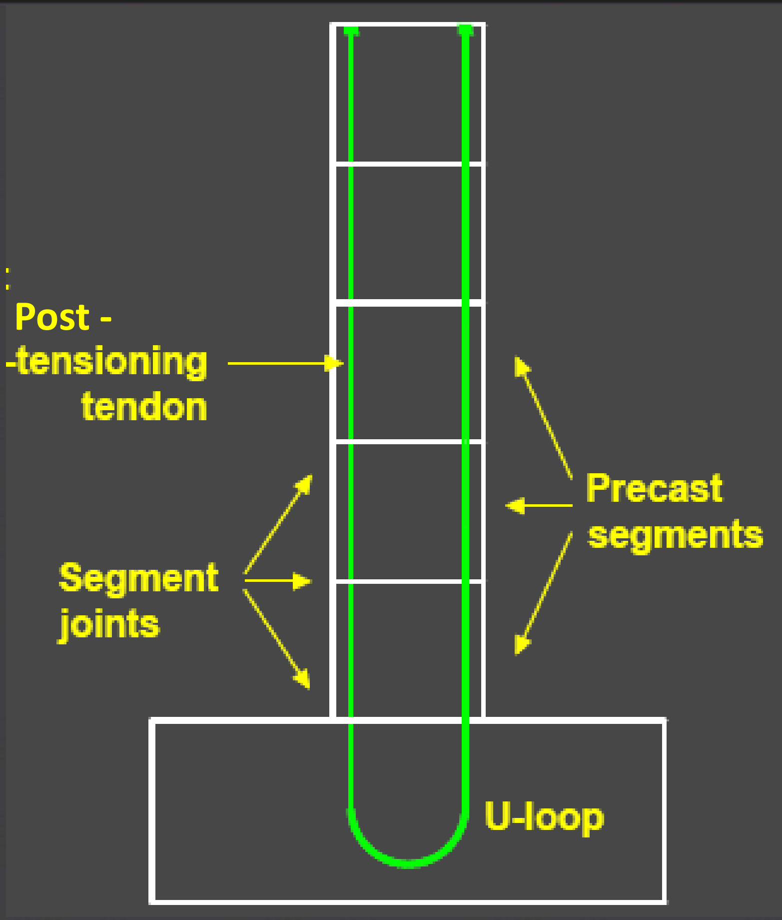
Precast Column with Cast-in-Place Footing



# Replaceable Plastic Hinge Zone Components

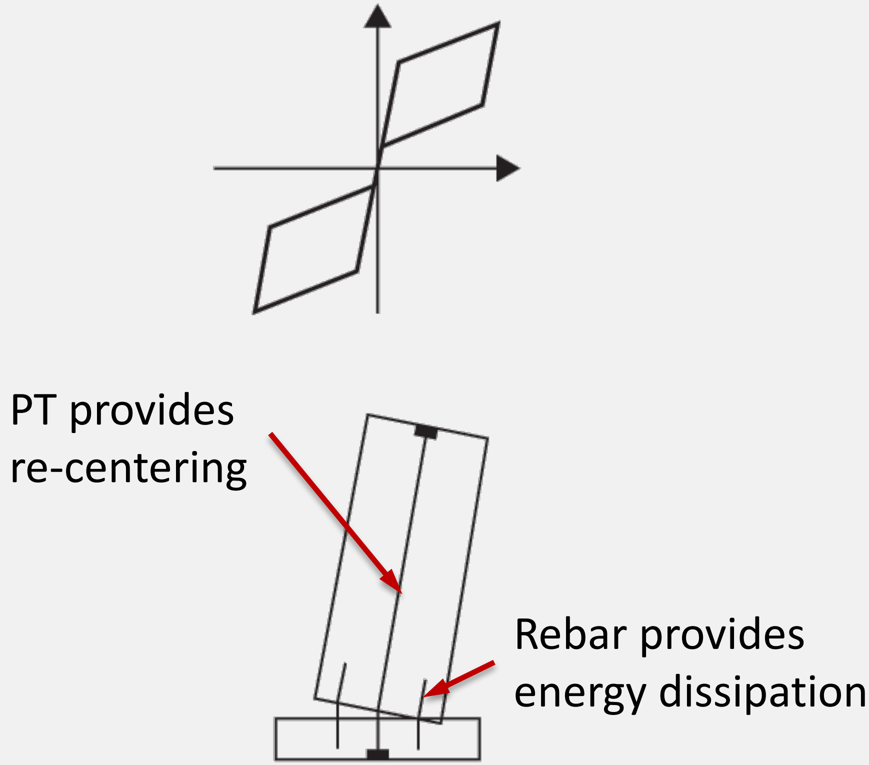
Caltrans'
Next
Generation
Bridge
Testing

# Hybrid Connections / Systems

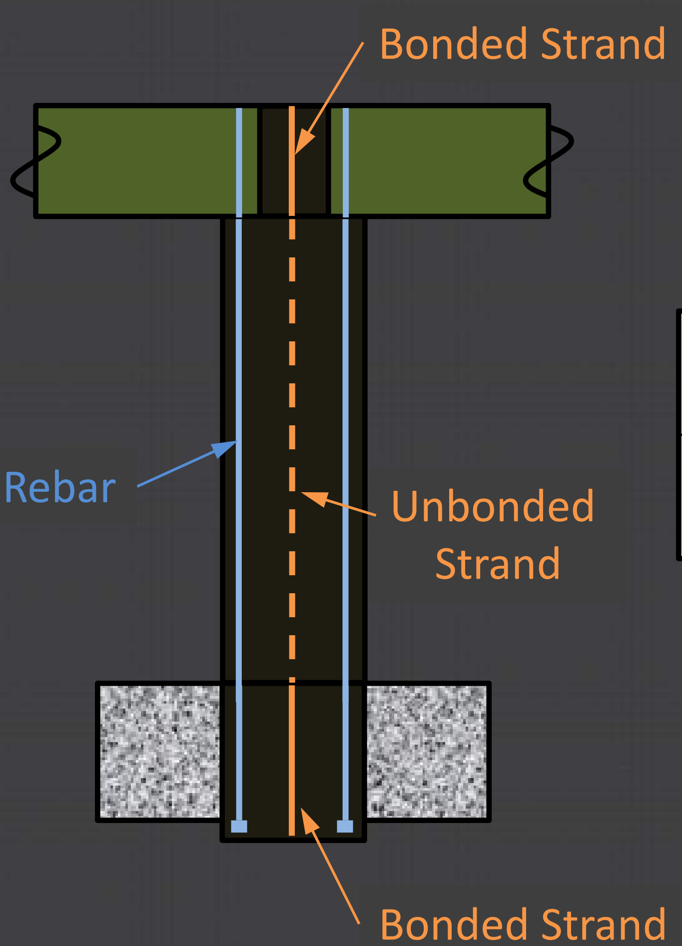



Force – Displacement

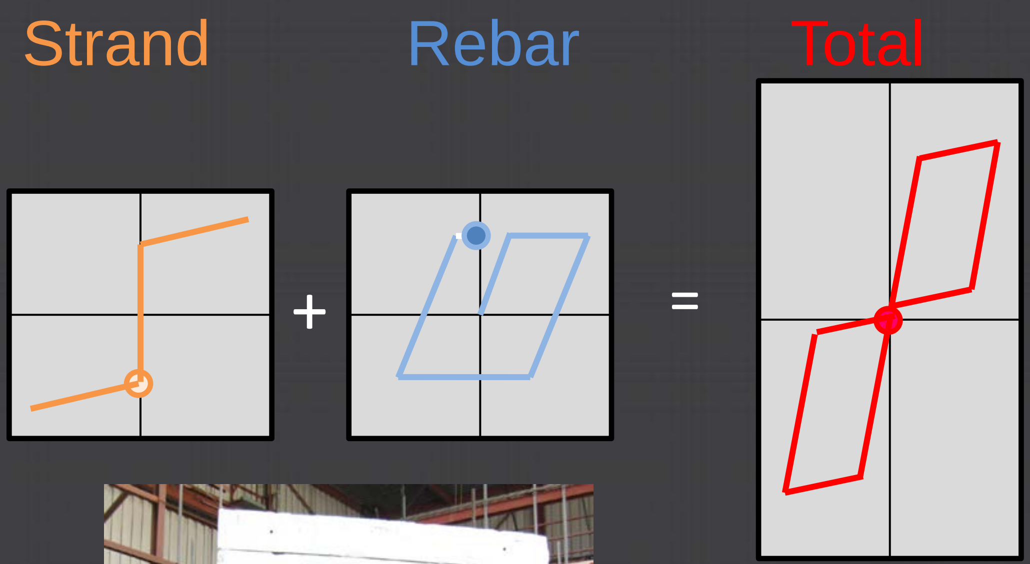
Energy Dissipation & Re-centering



# Pretensioned Precast Column



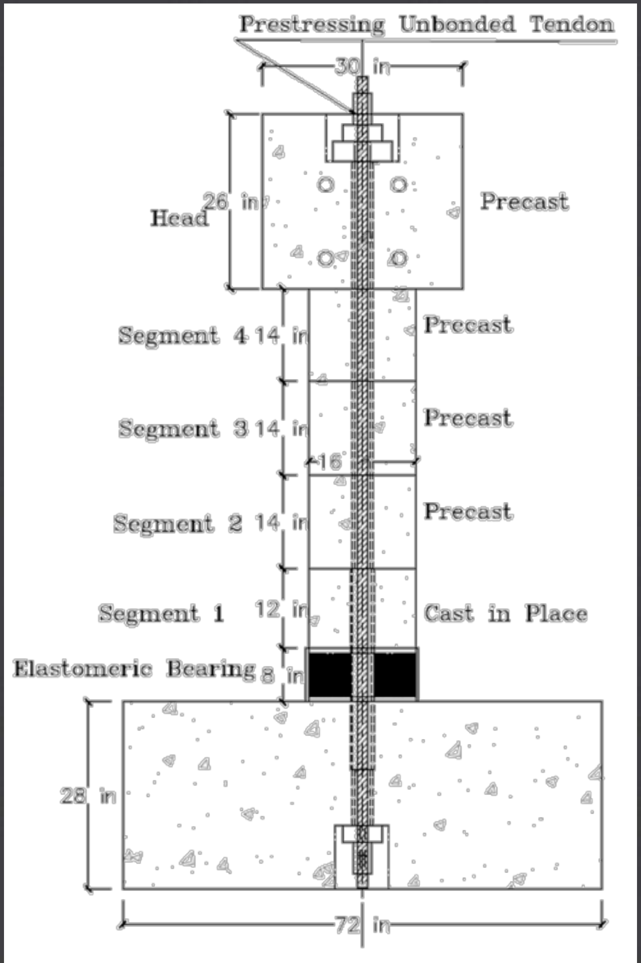

## Moment-Rotation

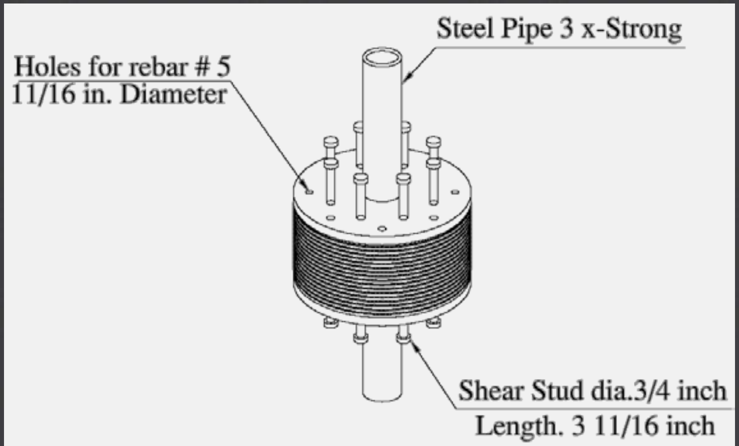




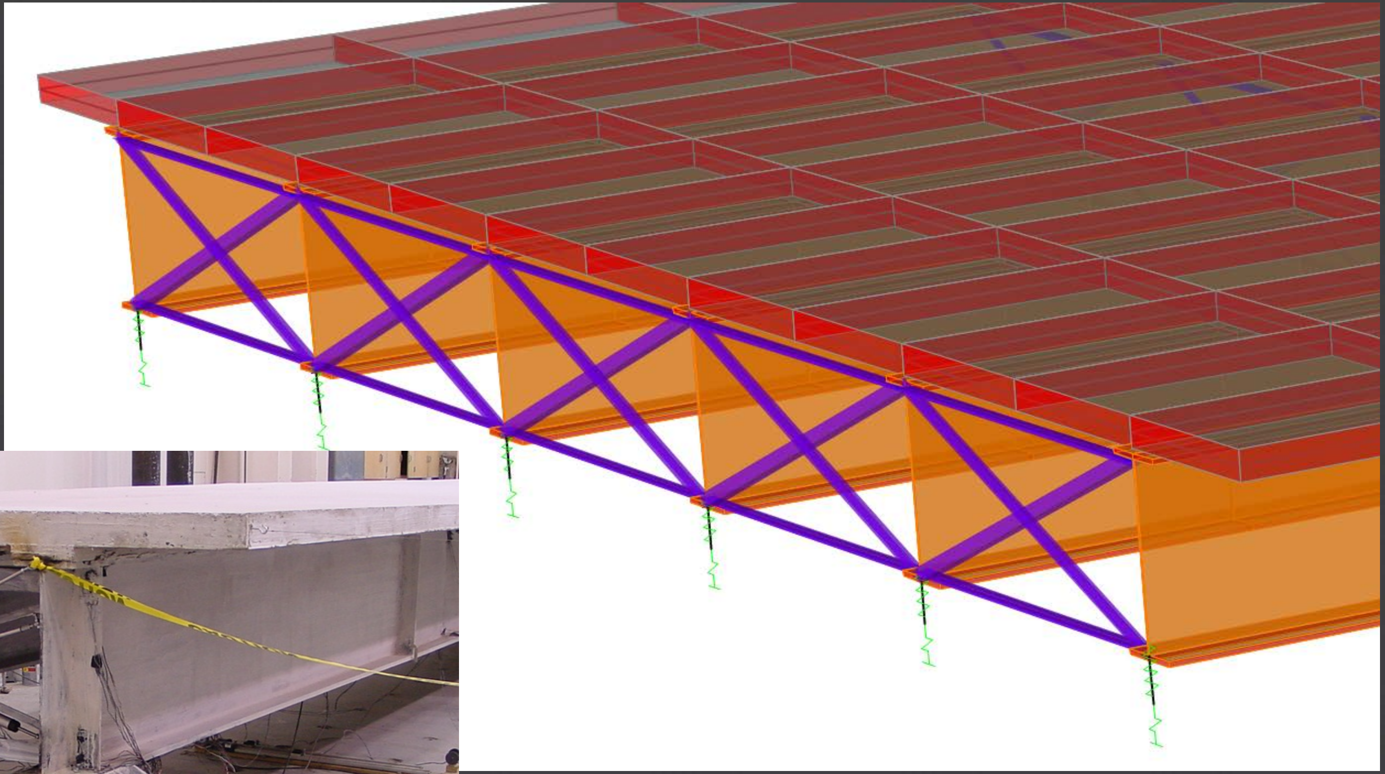
Shake Table Test

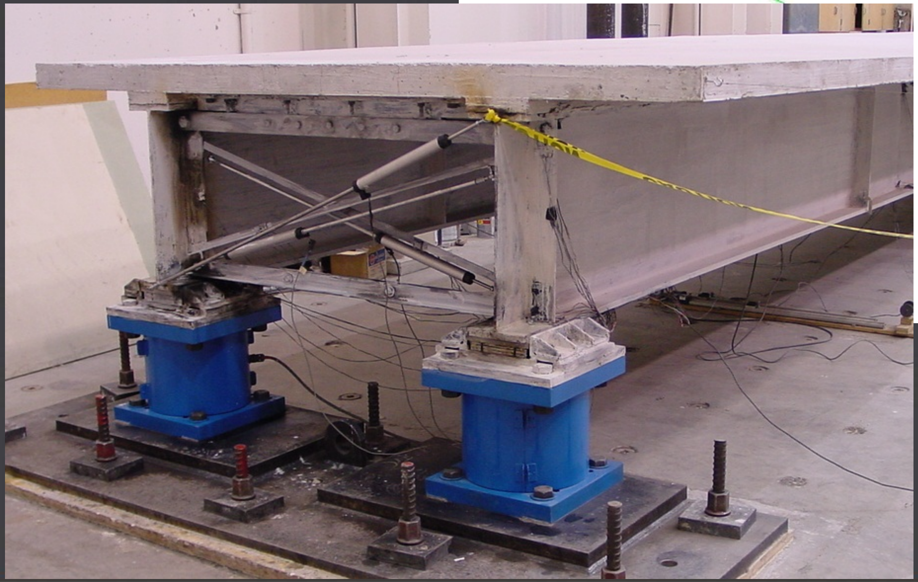
# Emerging Technology Connections



# Use of Ductile Cross Frames in Bridges





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# Technology Readiness Level (TRL)

## Conceptual Example

| Technology Readiness Level (TRL) | | % of development complete | | | |
|---|---|---|---|---|---|
| TRL | Description | 0-25 | 25-50 | 50-75 | 75-100 |
| 1 | Concept exists | | | | |
| 2 | Static strength predictable | | | | infill |
| 3 | Non-seismic deployment | | | | " |
| 4 | Analyzed for seismic loading | | | | " |
| 5 | Seismic testing of components | | catch-up required | | |
| 6 | Seismic testing of subassemblies | | " | | |
| 7 | Design & construction guidelines | | | | |
| 8 | Deployment in seismic area | | | | |
| 9 | Adequate performance in EQ | | advancement | | |

TRL Concept Developed by NASA

# The Progression of Engineering – Past 100 Years of the Automobile

1913 Ford Model T Roadster
(The year mass production is introduced)

2013 Ford Shelby GT500

# The Progression of Engineering – Past 100 Years of Bridges

1911 Index, WA
North Fork Skykomish River

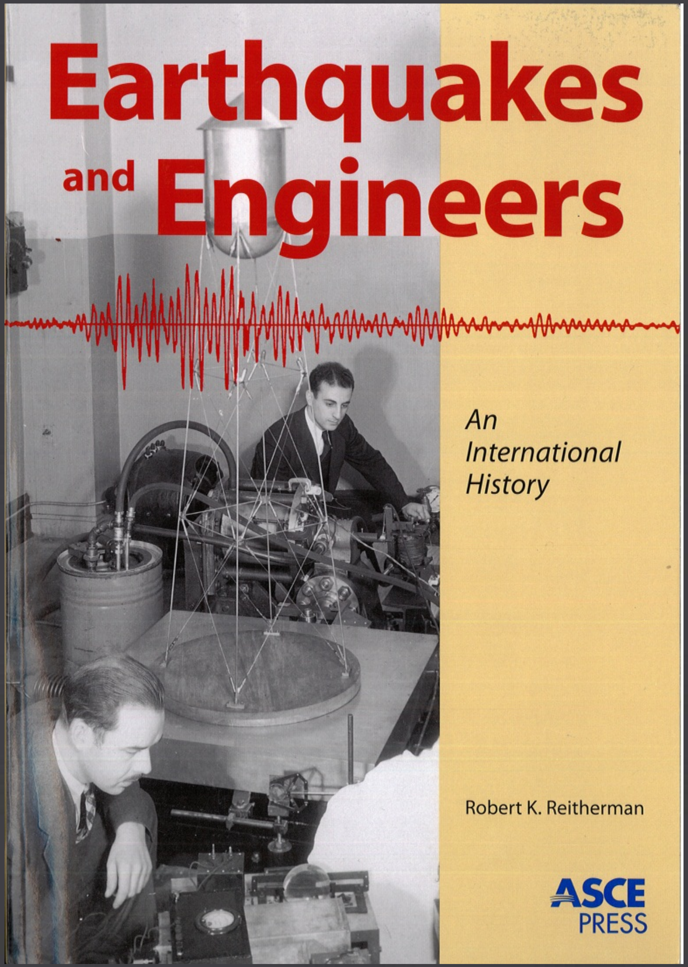
2009 Clallum Co, WA
Elwha River Bridge
Replacement

Univ. of WA, Lee Picket Collection and BergerABAM

# How Does It Look From Here?
# Where Might Advancement Occur?

| | |
|---|---|
| S | • Simplicity |
| E | • Economy and Efficiency |
| I | • Innovation and Improvement |
| S | • Safety |
| M | • Materials and Manufacturing (PBES) |
| I | • Involvement |
| C | • Capability (Performance) |

# Thank You!

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