National Science Foundation
WHERE DISCOVERIES BEGIN

University of California at San Diego
NHERI
Natural Hazards Engineering Research Infrastructure

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

Bridge Engineering

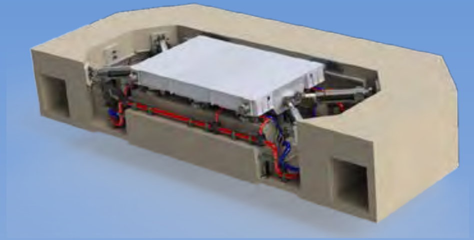
State of Practice and Potential Research Needs

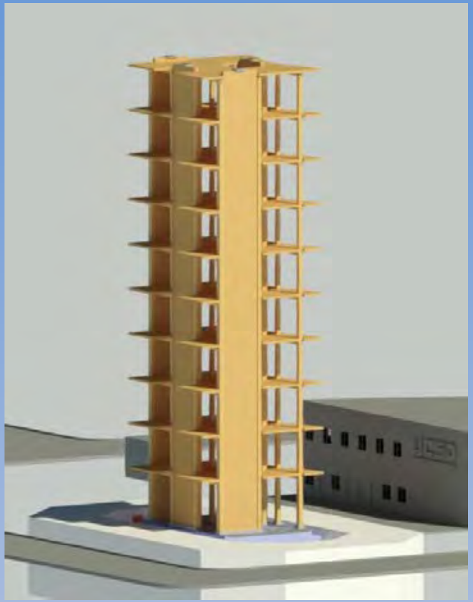
Anthony V. Sánchez, PhD, PE

SYSTRA IBT

Joint Academia-Industry NHERI Workshop
NHERI@UC San Diego

September 21-22, 2020
University of California, San Diego





Anthony V. Sánchez, PhD, PE

Curriculum Vitae

Education

1989-1991, Field Engineer-Bridge Construction, Raisch Company, San Jose, CA

1989, Loma Prieta earthquake

1991, BS Civil Engineering, UC Berkeley
- Materials, J.W. Morris (NAE)
- Fluid Mechanics, H.W. Shen (NAE)
- Transportation, A.D. May (NAE)
- Statics, R.L. Taylor (NAE)
- Struct. Analysis, A.C. Scordelis (NAE)
- RC Design, V.V. Bertero (NAE)

1995, MS Structural Engineering, UC San Diego

1998, PhD Structural Engineering, UC San Diego
- Frieder Seible (NAE)
- M.J. Nigel Priestley (ONZM)

Industry

1998-1999, Bridge Engineer, Athalye Consulting Engineers

1999-2010, Bridge Engineer, T.Y. Lin International
- Man-Chung Tang (NAE)
- David Goodyear (NAE)

2010-2019, Bridge Services Manager, Moffatt & Nichol

2019-Present, Principal Engineer, SYSTRA IBT
- Daniel Tassin (NAE)

Teaching

2009-Present, Lecturer, UC San Diego
- SE-213, Bridge Design

NHERI = Natural Hazards Engineering Research Infrastructure

An NSF sponsored program to support engineering research for the better understanding and mitigation of natural hazards.

Natural hazards to bridges…

1. **Earth** (quakes)
2. **Wind** (hurricanes)
3. **Fire** (wild fires, droughts, climate change)
4. **Water** (flooding, scour, sea level rise, tsunamis)

1. State of the Art Bridge Technologies

- CIP and PC segmental
- Cable-stayed
- Advanced construction methods (temporary stays, launched bridges)
- Example bridges

2. Natural Hazards

- Wind
- Floods
- Seismic

3. Research Needs

Bridge Basics – Structural Forms

Arch

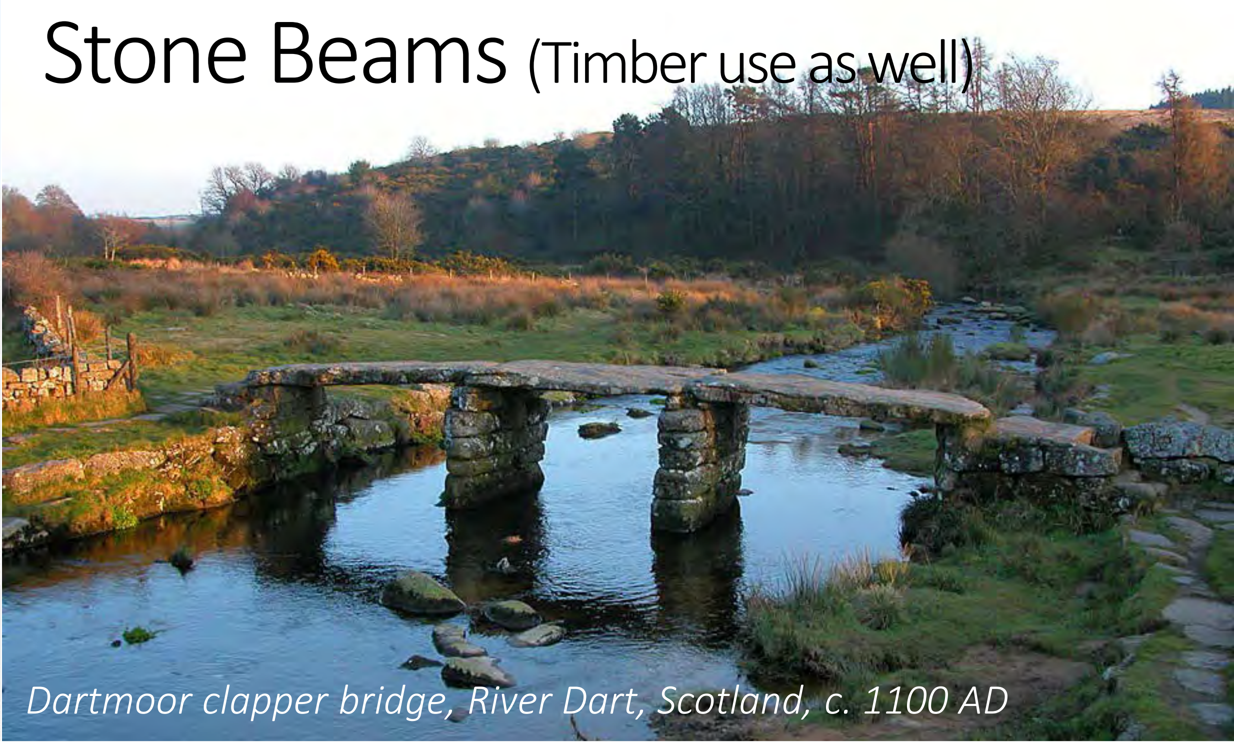
Beam

Cable

Stone Arches

Roman aqueduct, Gard River, France, c. 40-60 AD

Stone Beams (Timber use as well)



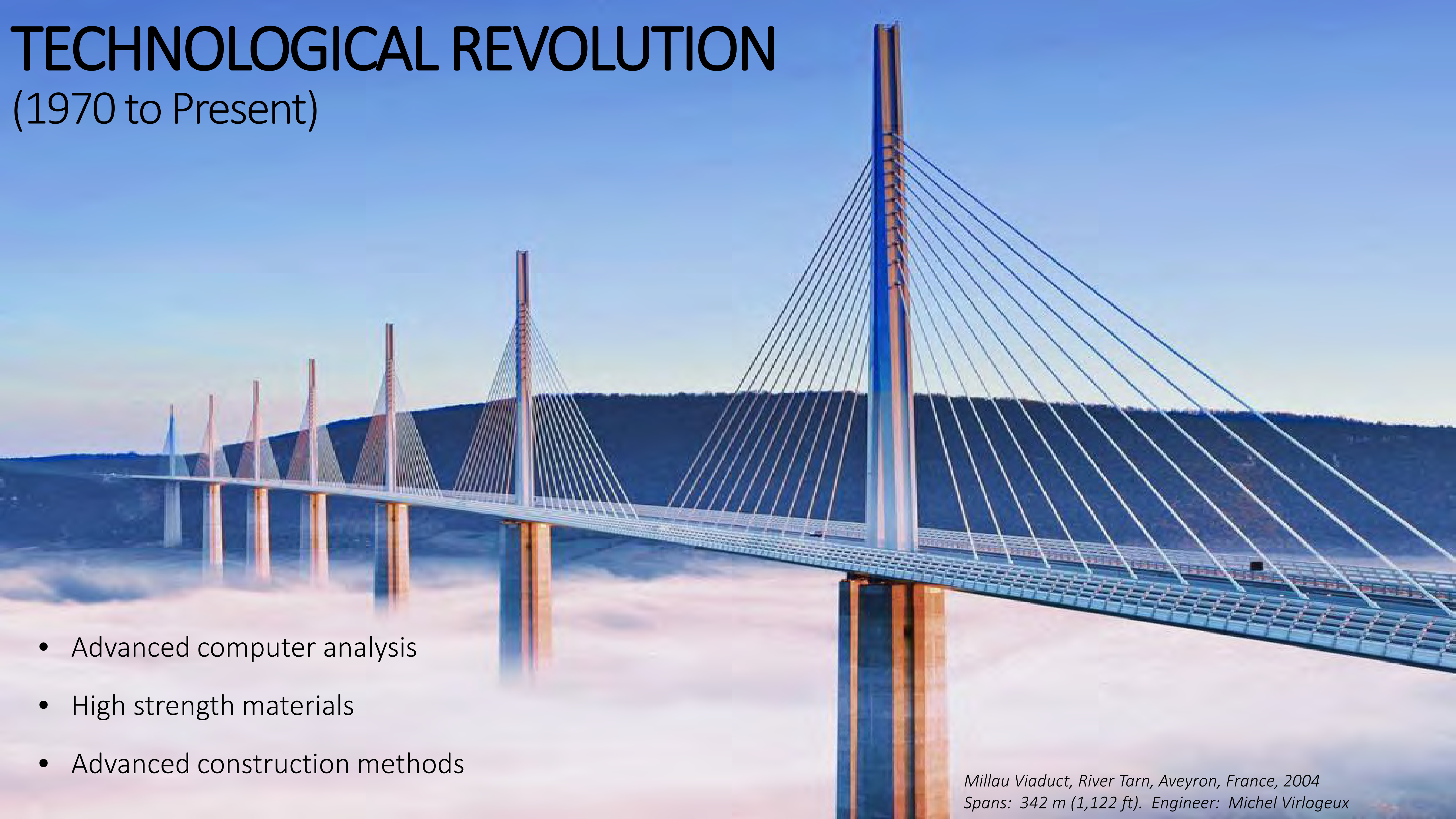
Dartmoor clapper bridge, River Dart, Scotland, c. 1100 AD

Hemp Cables

Inca rope bridge, Andes Mountains

TECHNOLOGICAL REVOLUTION

(1970 to Present)



- Advanced computer analysis
- High strength materials
- Advanced construction methods

Millau Viaduct, River Tarn, Aveyron, France, 2004
Spans: 342 m (1,122 ft). Engineer: Michel Virlogeux

1980’s – Segmental Girders

Linn Cove Viaduct, Blue Ridge Mountains, NC, Figg & Muller, 1982
First PC Segmental Bridge in US. L = 1,243 ft, Main spans 180 ft. Curved alignment, 200 ft radii.

Jean Muller, 1925-2005

Freyssinet
Compenon Benard
Figg & Muller
J. Muller International

1990’s Advanced Analysis

Sacramento River Trail Bridge
Redding, CA, 1990
Main span = 418 ft
Depth 15 in.

Jiří Stráský, b. 1946
1991 Founder Stráský, Hutsy and Partners
Brno, Czech Republic

1990’s and 2000’s – Modern Cable-Stayed Bridges

Atlantic Bridge, 3rd Crossing of the Panama Canal, 2018

L = 10,108 ft, Main Span = 1,738 ft, Design Engineer Systra-IBT

Daniel Tassin, b. 1948

International Bridge Technologies

2000's Advanced Construction Technology – Temporary Stay Cables

Hoover Dam Bypass Bridge, AZ-NV, 2010
Main span = 1,060 ft, Height = 900 ft

David Goodyear, b. 1949
1987 Founder DGES
1996-2018 T.Y. Lin International
Olympia Washington, USA

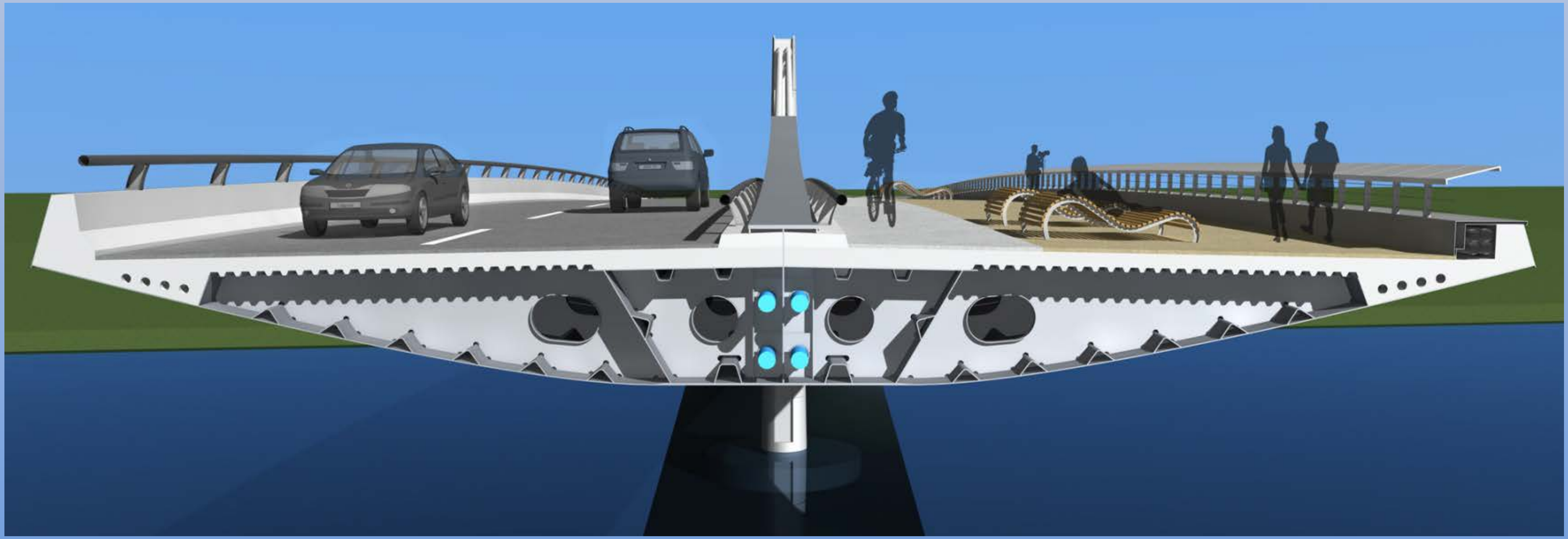
Historical Development: *Three solutions to the same problem*

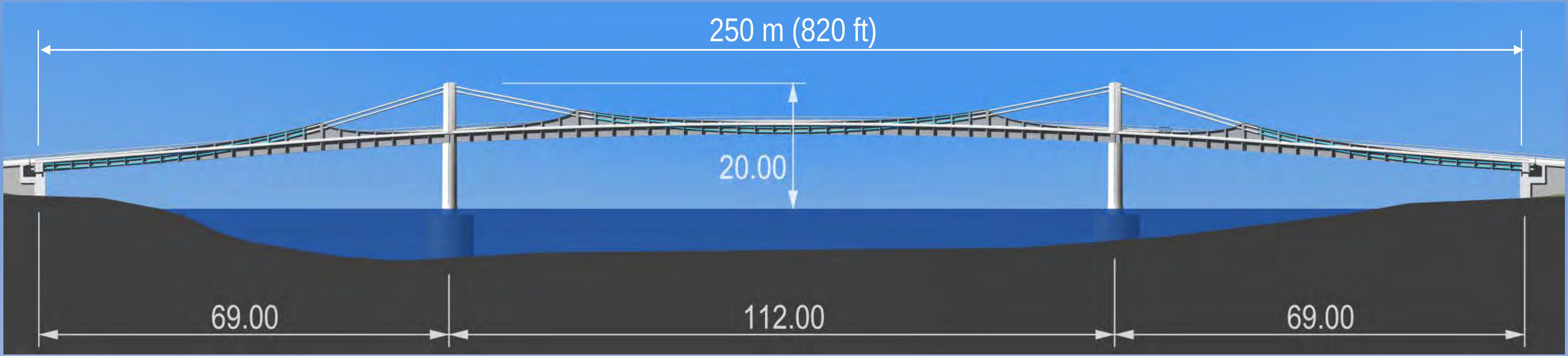
Firth of Forth Bridges, Edinburgh, Scotland

CASE STUDY –

Rio Ebro Bridge

Deltebre-San Jaume D'Enveja, Spain, 2011





Rio Ebro Bridge, Spain

SHP
www.shp.eu

Rio Ebro Bridge, Spain

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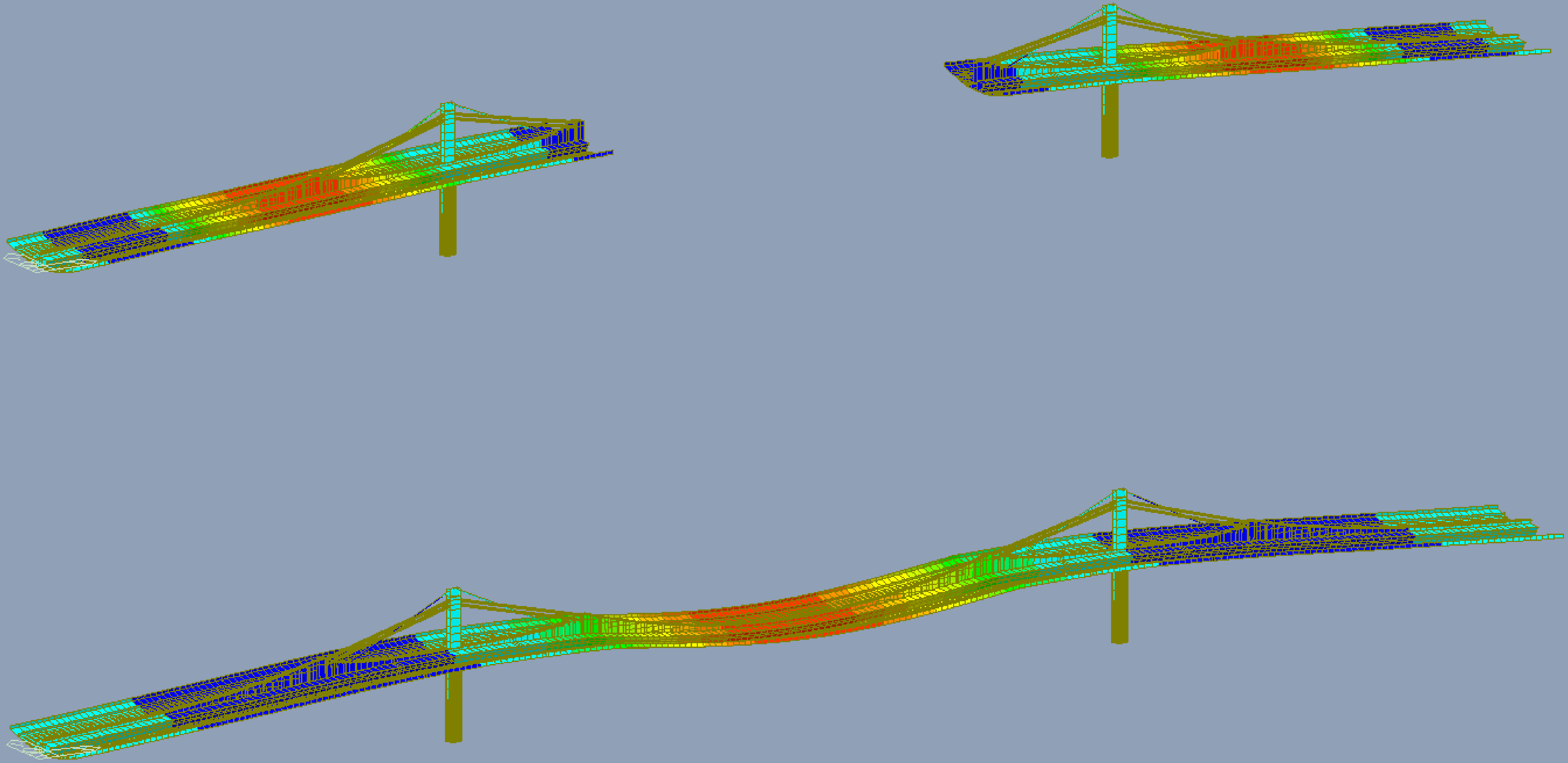

Rio Ebro Bridge, Spain

www.shp.eu

Rio Ebro Bridge, Spain

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Bridge Loads

AASHTO LRFD + CA Amendments

Permanent Loads

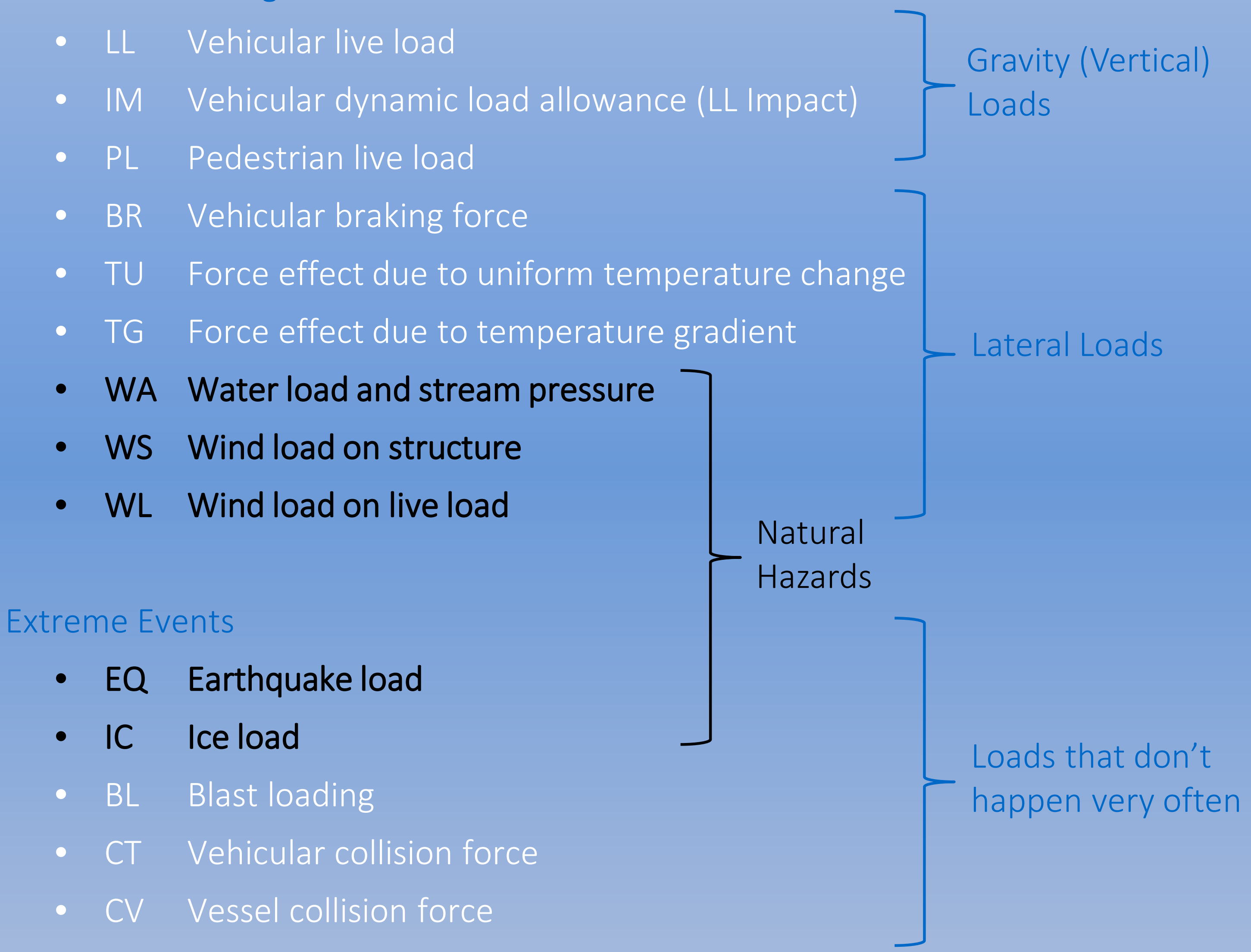
LRFD 3.3.2

Always on structure, occur in all limit states

- DC Dead load of structural components
- DW Dead load of wearing surfaces and utilities
- EH Horizontal earth pressure
- EV Vertical earth pressure
- EL Locked in force effects due to construction
- PS Secondary forces from post tensioning
- CR Force effect due to creep (concrete)
- SR Force effect due to shrinkage (concrete)

Transient Loads

LRFD 3.3.2



Service and Strength Limit States

- LL Vehicular live load
- IM Vehicular dynamic load allowance (LL Impact)
- PL Pedestrian live load
- BR Vehicular braking force
- TU Force effect due to uniform temperature change
- TG Force effect due to temperature gradient
- WA Water load and stream pressure
- WS Wind load on structure
- WL Wind load on live load

Extreme Events

- EQ Earthquake load
- IC Ice load
- BL Blast loading
- CT Vehicular collision force
- CV Vessel collision force

Wind Loads (WS, WL)

AASHTO LRFD 3.8 (Through 7th Ed, 2016)

- WS = wind on structure
- WL = wind on live load

Apply at the Strength Limit State:

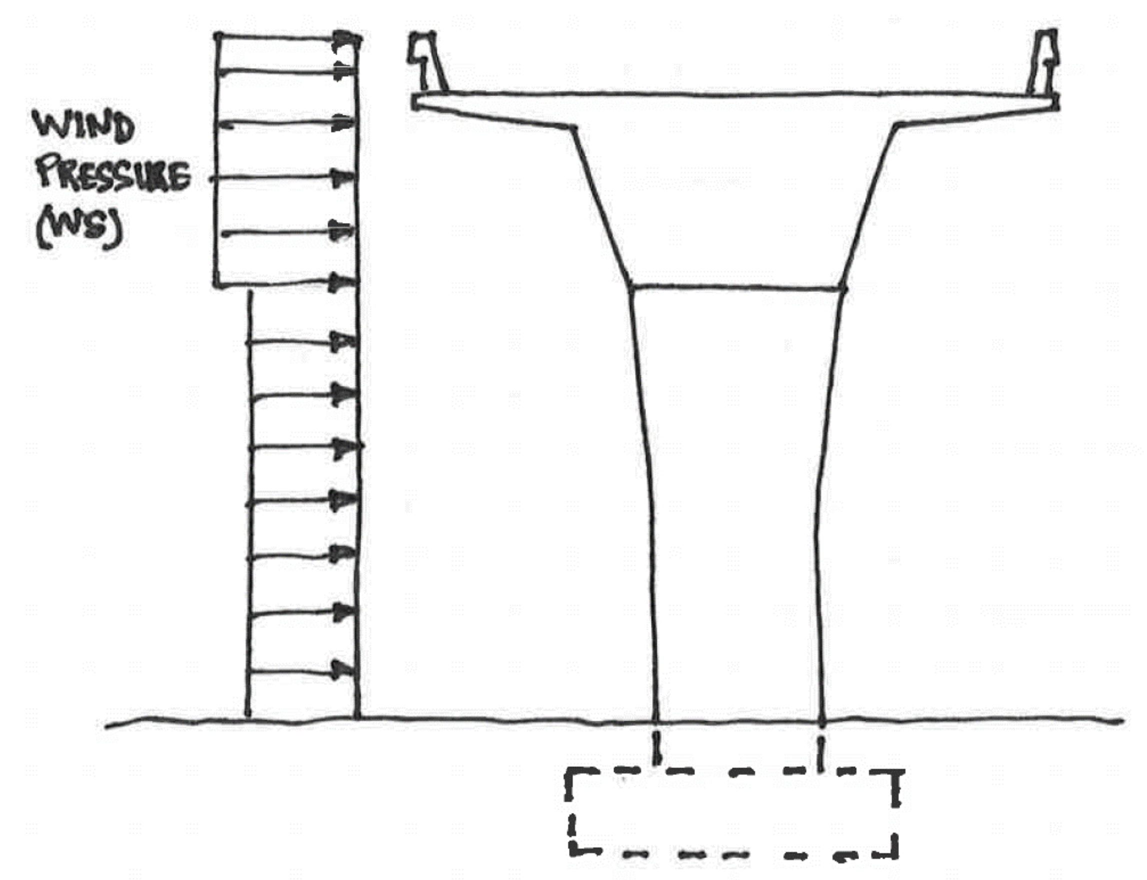
Strength I (live load, no wind) =	1.75 (LL+IM) + 0.0 WS + 0.0 WL
Str. III (high winds, no LL) =	0.0 (LL+IM) + 1.4 WS + 0.0 WL
Str. V (55 mph wind, some LL) =	1.35 (LL+IM) + 0.4 WS + 1.0 WL

For standard bridges, apply static wind pressure per LRFD 3.8.1

- Base wind velocity, V_B = 100 mph
- Design wind velocity V_{DZ} may be different based site conditions
- V_{DZ} should be adjusted for components >30 ft above ground or water
- Wind pressure:

= 50 psf * $(V_{DZ}/V_B)^2$ on girders (3.8.1.2.1)

= 40 psf * $(V_{DZ}/V_B)^2$ on columns (3.8.1.2.3)



Wind Loads

Long-span bridges:

- Wind can affect superstructure (dynamic instability)
- Special wind tunnel testing and dynamic analysis is required

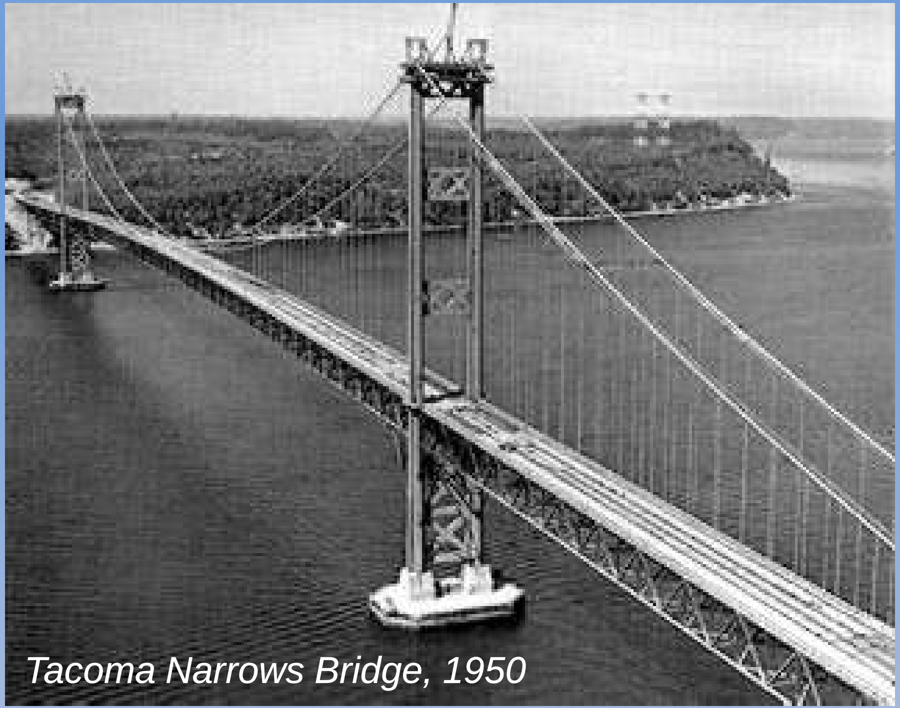
Tacoma Narrows Bridge, 1940

- Opened July 1940
- Collapsed Nov 1940, 40 mph wind
- 2800 ft main span
- 8 ft deep plate girder, d/s = 0.0029, very flexible

Tacoma Narrows Bridge, 1950

- First use of wind tunnel testing and aerodynamic theory
- Stiffening truss, 40 ft deep, ~600 times stiffer for bending
- Open truss, catches less wind
- Open steel deck

Tacoma Narrows Bridge, 1940



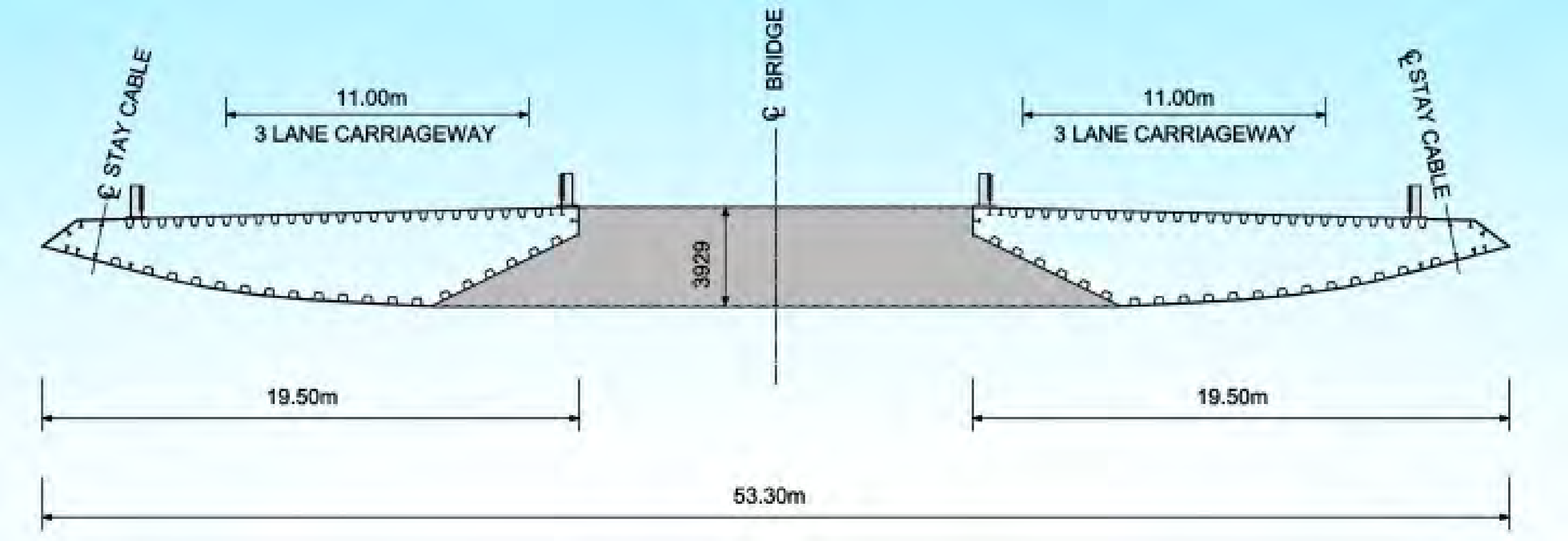
Tacoma Narrows Bridge, 1950

Wind Loads

Long Span Bridges in the 21st Century:

- Better understanding of aerodynamic principals
- Wind tunnel testing and dynamic analysis
- Aerodynamic shapes

Carquinez Suspension Bridge, California, 2003



Stonecutters Cable-Stayed Bridge, Hong Kong, 2004

Floods

- Water loads (WA) LRFD 3.7
- Debris Impact
- Scour

Scour

No. 1 cause of bridge failures in USA

Degradation Scour:

- Erosion of stream bed due to transportation of material downstream

Contraction Scour:

- Occurs at bridges where waterway is constricted flow velocity increases

General Scour =
Degradation + Contraction Scour

Local Pier Scour:

- Caused by turbulence around pier

Earthquake Loads (EQ)

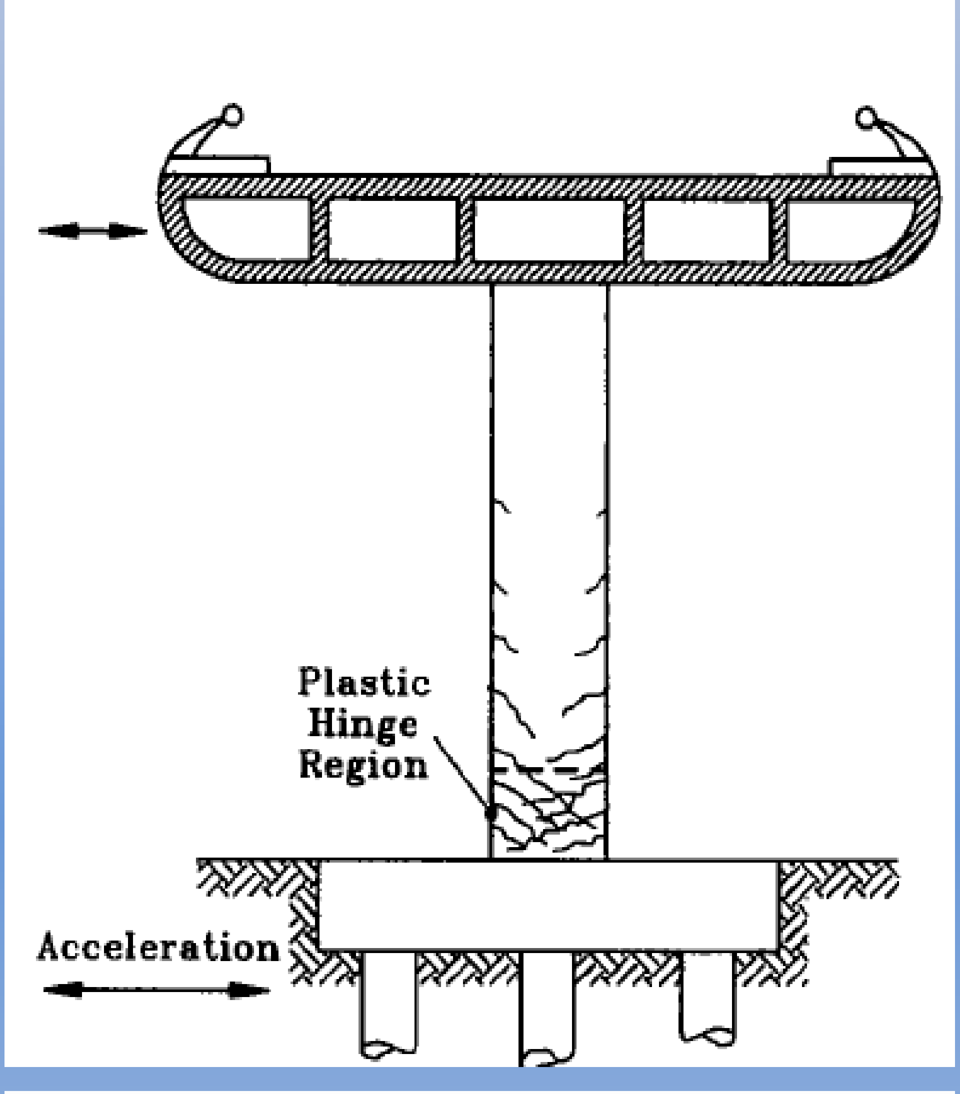
AASHTO LRFD 3.10 In California use SDC

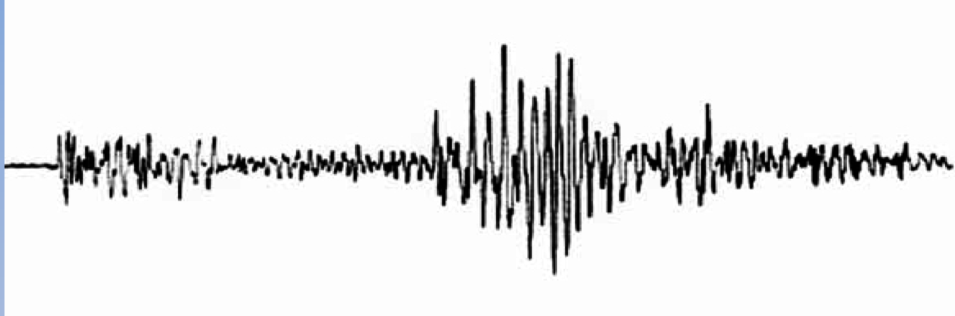
Seismic Shaking / Inertial Loading:

- Ground acceleration causes bridge to vibrate
- Superstructure moves relevant to the ground
- F = m*a. Acceleration depends on mass and stiffness.
- $T = 2\pi\sqrt{m/k} = 0.32\sqrt{W/k}$

Other Seismic Issues:

- Liquefaction
- Lateral spreading at abutments
- Fault rupture



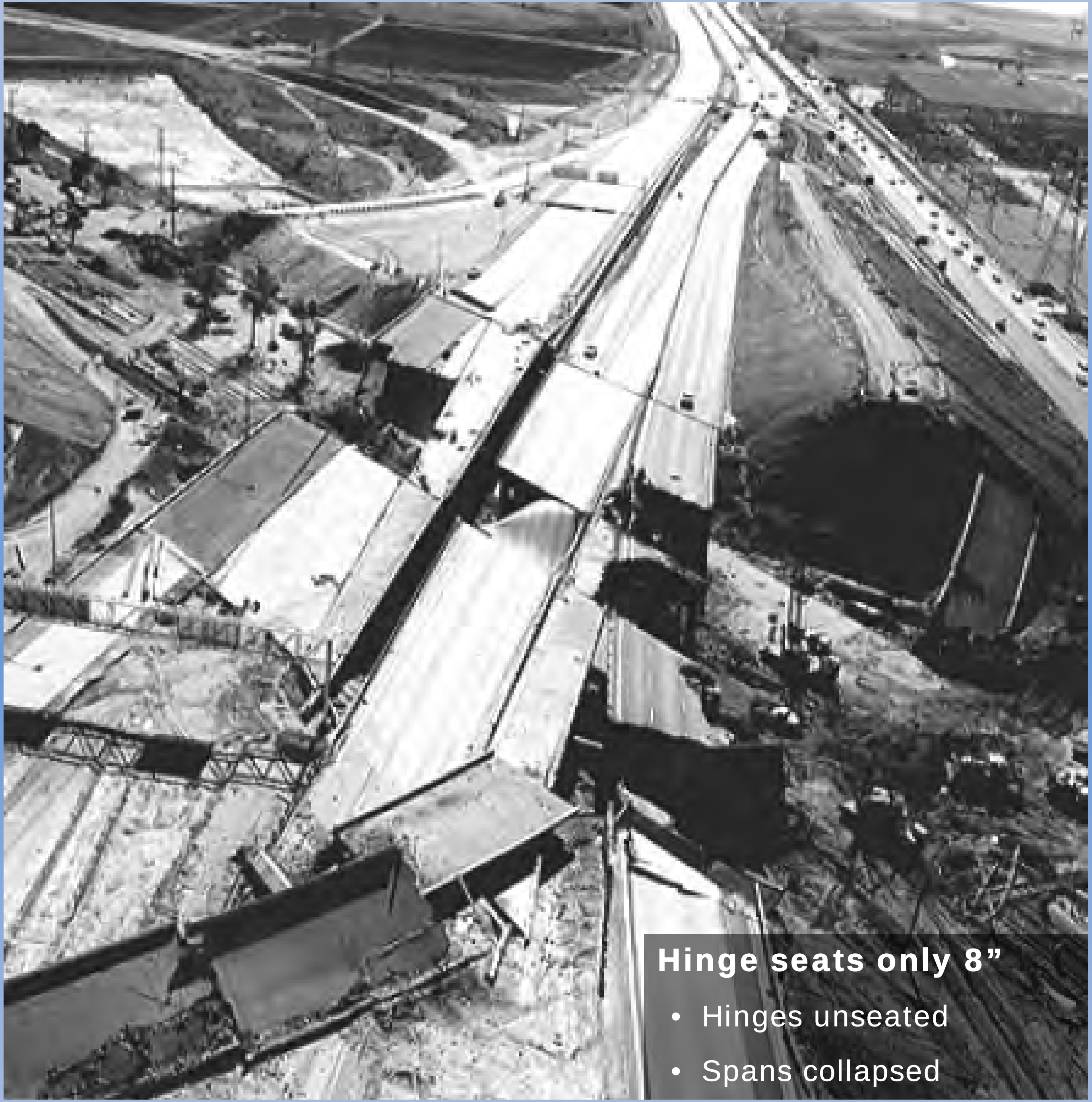


San Fernando
1971

M6.6
Epicenter 26 mi NW of LA

Not enough horizontal reinforcement in columns:

- Column hoops, #4 @ 12”
- Column failures
- Shear failures
- Plastic hinge failures



Hinge seats only 8”

- Hinges unseated
- Spans collapsed

Loma Prieta 1989

M6.9
Epicenter 10 mi NE of Santa Cruz

SF-Oakland Bay Bridge

- Span un-seated
- Bridge closed for weeks

Cypress Street Viaduct, I-880, Oakland

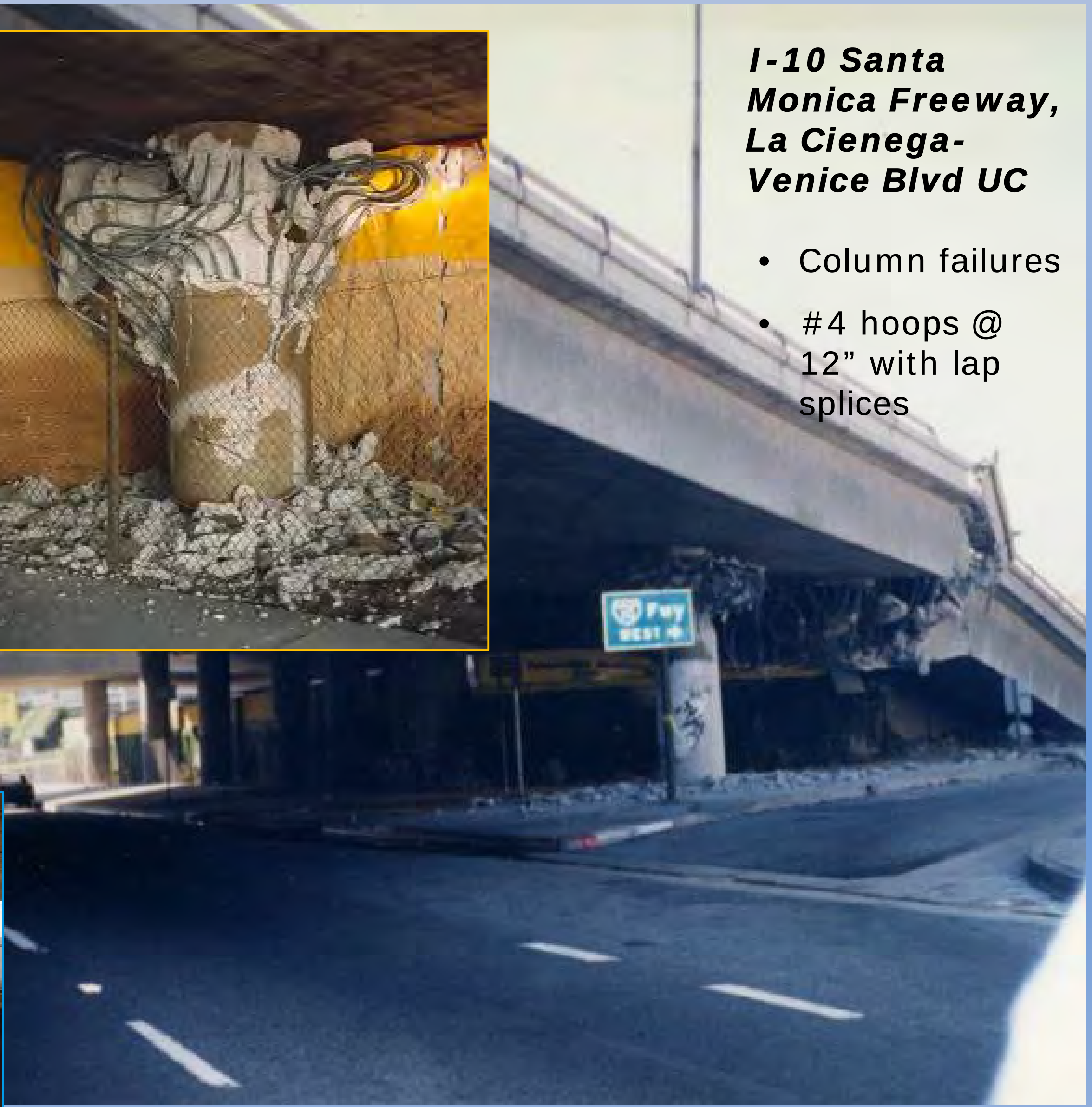
- 1.6-mile double deck viaduct
- Built in 1950
- Seismic design conformed to codes of the day
- Poor detailing of connections
- Not enough horizontal reinforcement in columns

Northridge 1994

M6.7
Epicenter 20 mi NW of LA

SR-118 Simi Valley, Mission & Gothic Undercrossing

- Flared column failures

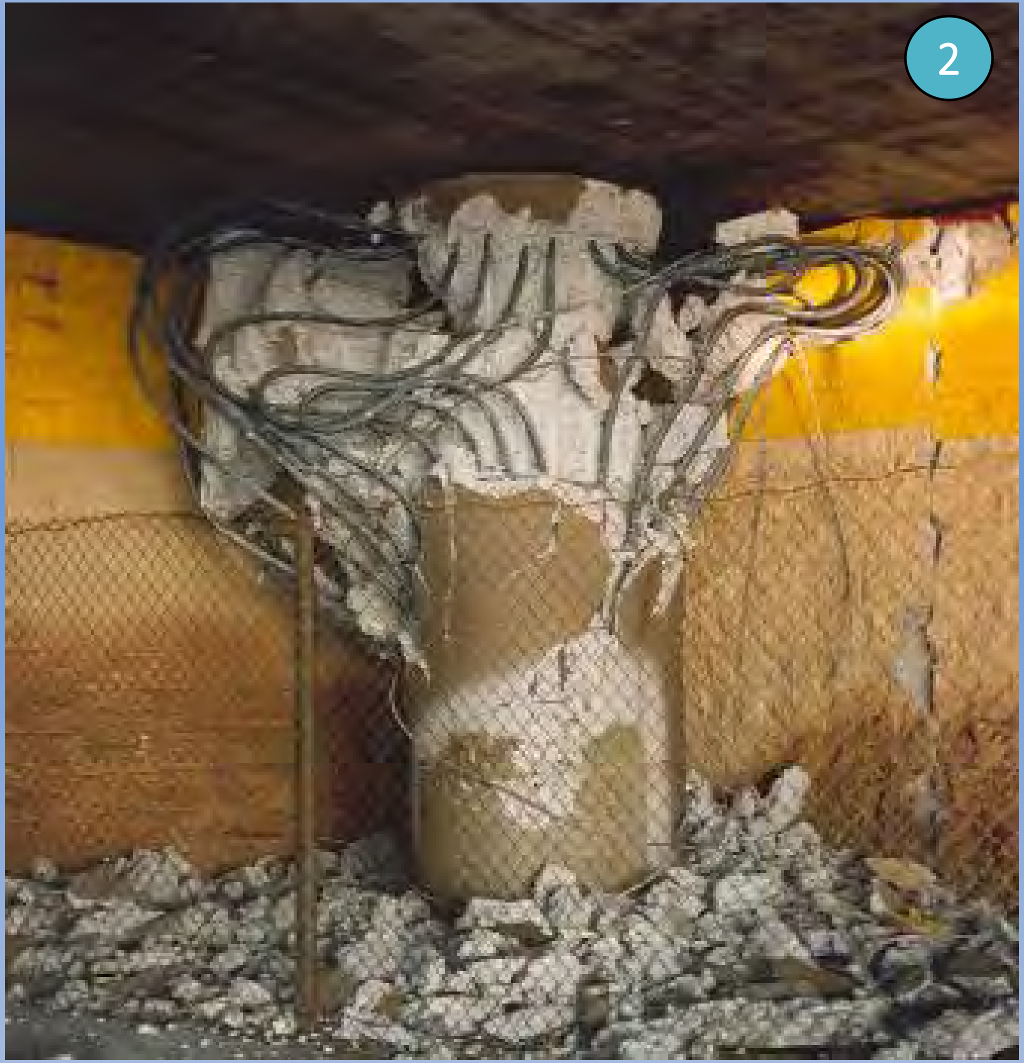


I-10 Santa Monica Freeway, La Cienega-Venice Blvd UC

- Column failures
- #4 hoops @ 12” with lap splices

Seismic Failure Modes

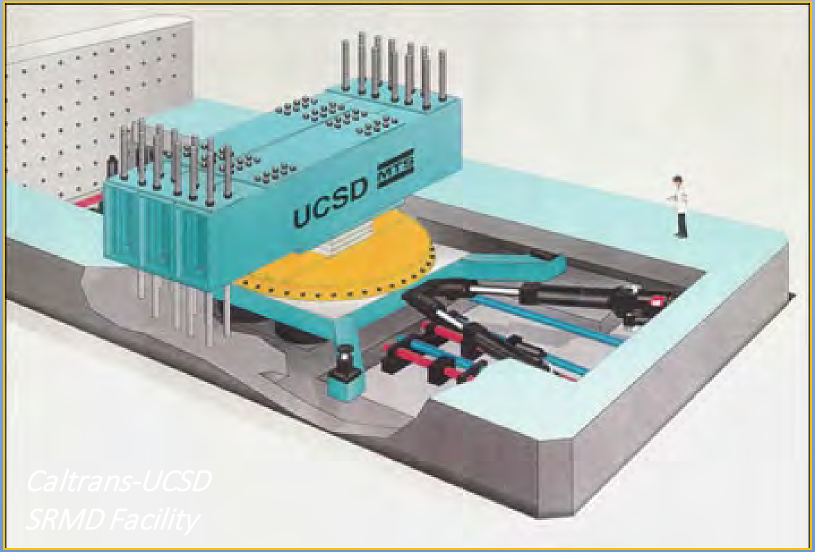
1. Unseating of expansion joints
2. Column failures
3. Poor detailing of bridge joints



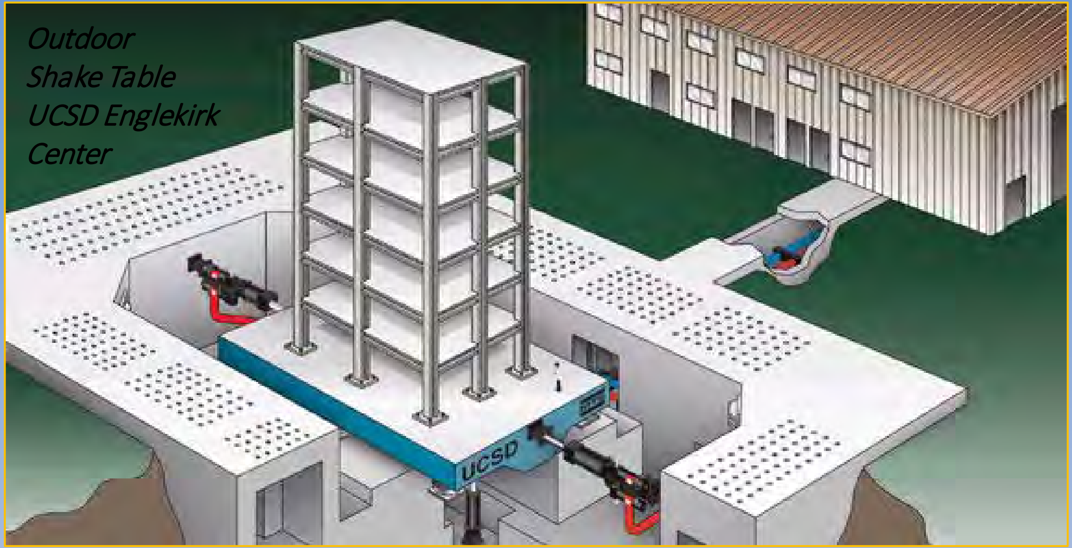
Seismic Labs at UCSD

UC San Diego
JACOBS SCHOOL OF ENGINEERING

- **Structural Systems Lab, 1986**
  (50’ high x 30’ wide strong wall, full-scale 5-storey buildings)
- Loma Prieta Earthquake, 1989
- Northridge Earthquake, 1994
- **Structural Components Lab, 1994**
  (30’ high x 62’ wide strong wall)
- **Composite Structures Lab, 1994**
  (30’ high x 18’ wide strong wall)
- **Caltrans SRMD Test Facility, 1999**
  (6 DOF table, full-scale tests of bearings and dampers)
- **Englekirk Center, 2005**
  (Outdoor shake table, soil-structure interaction testing)



*Caltrans-UCSD
SRMD Facility*



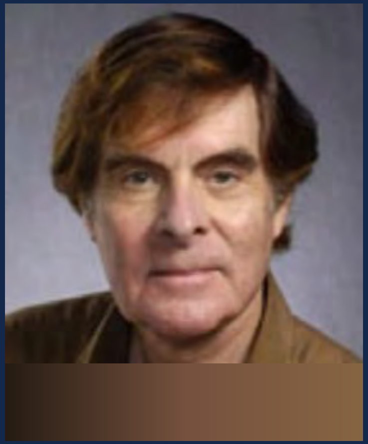
*Outdoor
Shake Table
UCSD Englekirk
Center*

Seismic Research at UCSD

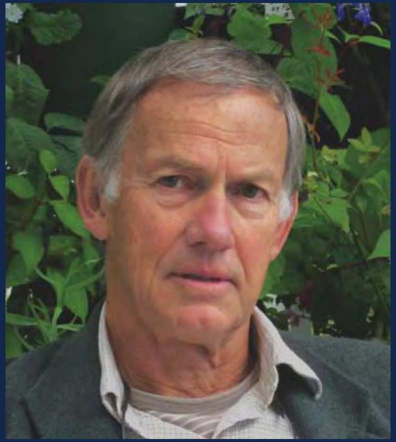
Innovations

1. Column ductility
2. Simple and effective seismic analysis and assessment methods
3. Column retrofit with steel jackets
4. Seismic design of beam-column joints (joint shear)
5. Seismic design of PC/PS systems
6. Proof testing of large-scale bridge and building systems
7. Research changed the way we do seismic design around the world

Founders of the Department of Structural Engineering at UC San Diego


Distinguished Prof. Emeritus
Gilbert Hegemier

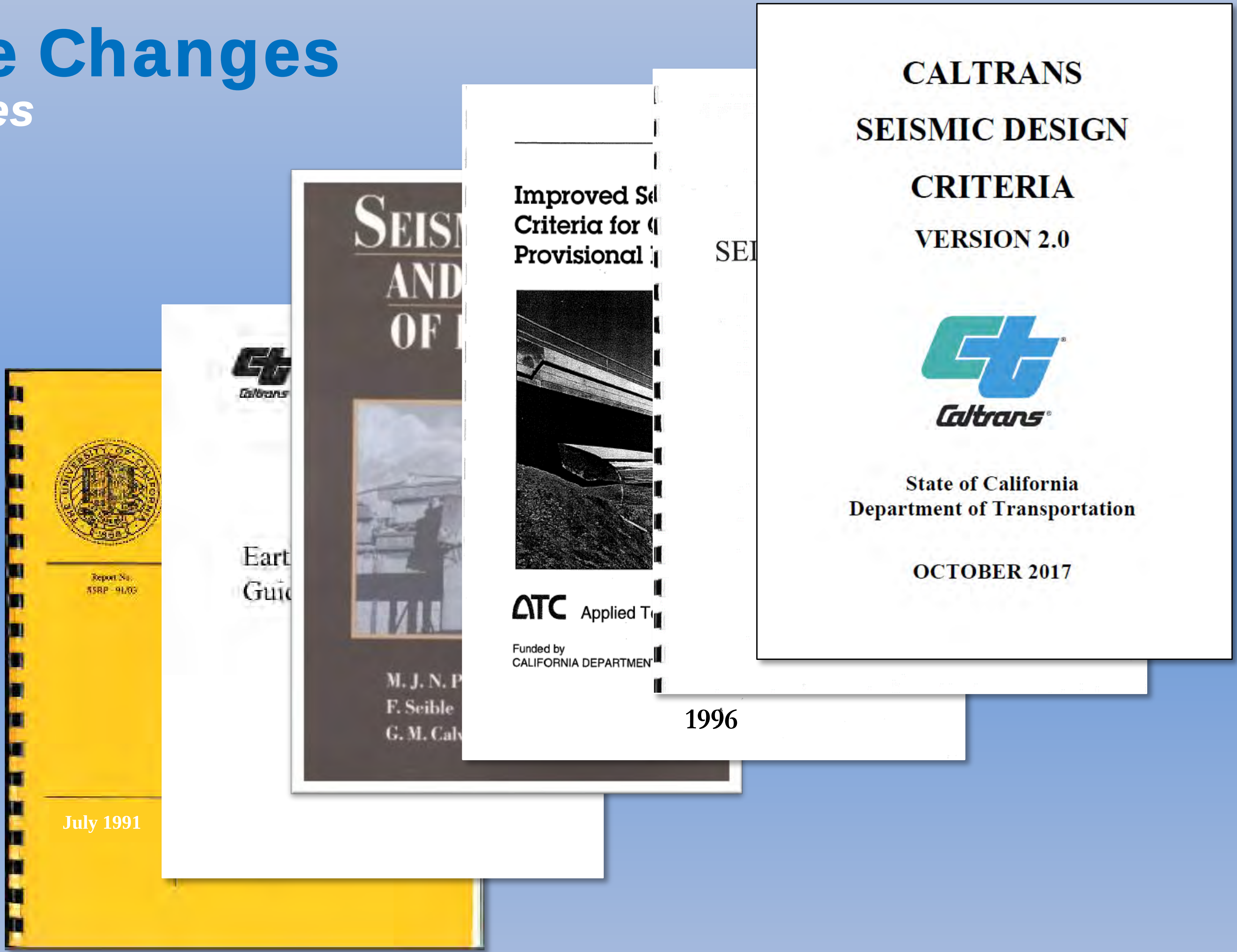

Distinguished Prof. Emeritus
Frieder Seible


Late Distinguished Prof. Emeritus
MJ Nigel Priestley


Distinguished Prof. Emeritus
J. Enrique Luco

Seismic Code Changes
for California Bridges

1. **Design for larger seismic shaking**
2. **Displacement based approach**
3. **Capacity design principles**
   - Allow columns to hinge
   - Limits internal forces and protects other components
   - Design bridge for the maximum internal force the column hinges can produce



CALTRANS

SEISMIC DESIGN

CRITERIA

VERSION 2.0

Caltrans

State of California
Department of Transportation

OCTOBER 2017

Performance Criteria

Ordinary Bridges

- Damage allowed but only in ends of columns (ductile areas)
- Superstructure and foundations remain undamaged
- Does not need to remain open after design level (1000-yr) earthquake

Important Bridges

- Enhanced performance and reduced damage:
  - Small (500-yr) earthquake – No damage
  - Medium (1000-yr) earthquake – Minimal damage, remain open
  - Large (2500-yr) earthquake – Moderate damage, no collapse

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3. Research Needs

Recent and On-Going Bridge Research

Seismic

Abutments, Foundations and Soils:

1. Bridge foundations allowed to uplift during earthquakes (UC Berkeley, 2015)
2. Non-linear lateral performance of skewed abutments (UNR, 2016)
3. Methods for soil structure interaction analysis (UCLA, 2017)
4. Methods for seismic analysis and design of retaining walls (UCLA, 2018)
5. action of MSE abutments with superstructures (UC San Diego, 2018)
6. Liquefaction and lateral spreading (UC San Diego, 2019)
7. Liquefaction induced down-drag on piles (UC Davis, 2020)
8. Fault displacement hazards (UCLA, 2020)

Columns and Substructures:

1. Ductile behavior of RC arch ribs (UC Berkeley, 2018)

Superstructures:

1. Seismic performance of superstructures in ABC (UNR, 2017)

Analysis Methods:

1. NL time history accuracy focused on column ductility (OSU, 2020)
2. Second order effects for slender RC columns (PEER, 2020)

Reinforcing Details:

1. High strength rebar in earthquake resistant bridges (UC San Diego, 2019)
2. Grade 80 rebar in plastic hinges (NC State, 2020)

Isolation and Dampers:

1. Concave friction isolators (UC San Diego, 2020)

Assessment and Monitoring:

1. Next generation monitoring of California bridges (Iowa State, 2019)
2. Bridge rapid assessment for extreme events (PEER, 2020)
3. Statistical variation of seismic damage index (PEER, 2020)

Recent and On-Going Bridge Research

Other Topics

Accelerated Bridge Construction:

1. Abutment systems for Accelerated Bridge Construction (Iowa State, 2020)
2. Alternative substructures for Accelerated Bridge Constr (Iowa State,2020)
3. Bridge systems for Accelerated Bridge Construction (UNR, 2020)
4. Ultra High Performance Concrete for Accel. Br. Constr. (UNR, 2020)
5. Recovery columns for Accelerated Bridge Construction (UC San Diego, 2020)
6. Effective ABC methods for abutment design and constr. (PEER, 2020)

Prestressed and Precast Girders:

1. PT box girder general anchorage zone reinforcing (UNR, 2018)
2. Shear capacity in CIP/PS girders (UC Davis, 2020)
3. Shear strengthening of existing concrete girders (UC Davis, 2020)
4. Precast system connection durability (UC Irvine, 2020)

Bridge Decks:

1. Deck overlays for PT box girders using UHPC (Iowa State, 2020)
2. Deck design loads and analysis (Auburn Univ., 2020)
3. Refined bridge deck design and analysis (PEER, 2020)

Temperature and Shrinkage

1. Controlling temperature and shrinkage cracks in bridge decks (UC Davis, 2017)

Foundations:

1. Permanent steel casings installation methods (PEER, 2020)

Steel Trusses:

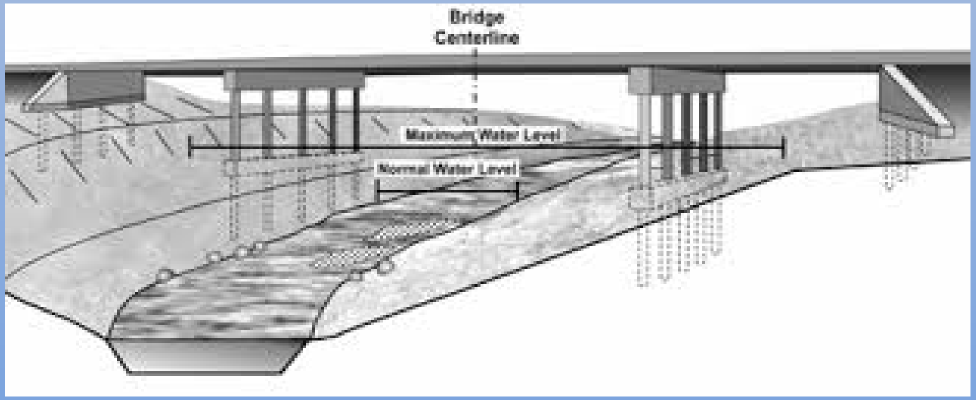
1. Eccentricity in truss analysis (UC San Diego, 2020)

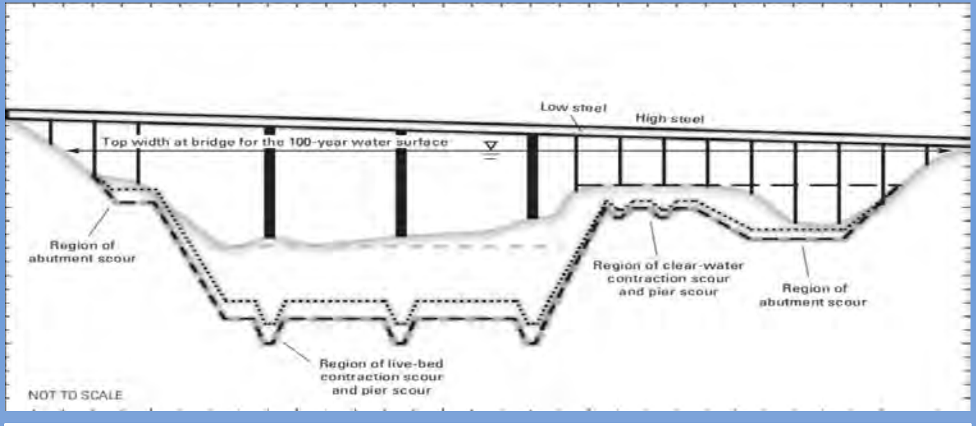
Potential Research Topics – Floods & Scour

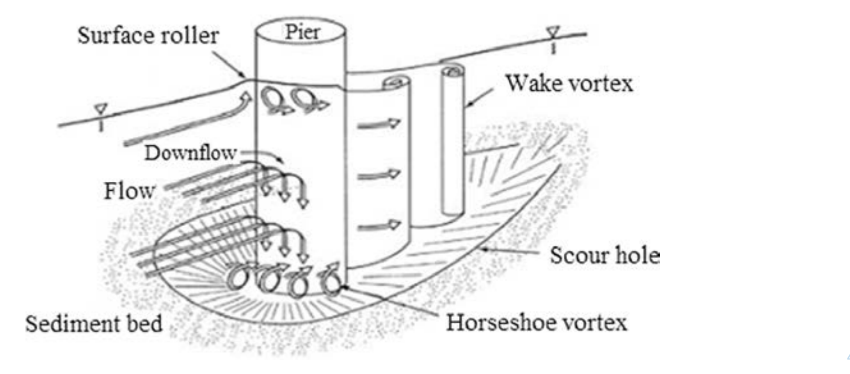
Issue: Current methods to evaluate scour (FHWA HEC-18) sometimes predict scour depths that seem unreasonable large

Research Needs:

1. Better methods to assess scour – produce more realistic and reliable scour depths
2. Practical methods to streamline pier shapes to reduce turbulence and scour depths
3. Fenders or other hydraulic devices to reduce turbulence and scour depths
4. Improvements to FHWA HEC-23 to reduce bridge scour





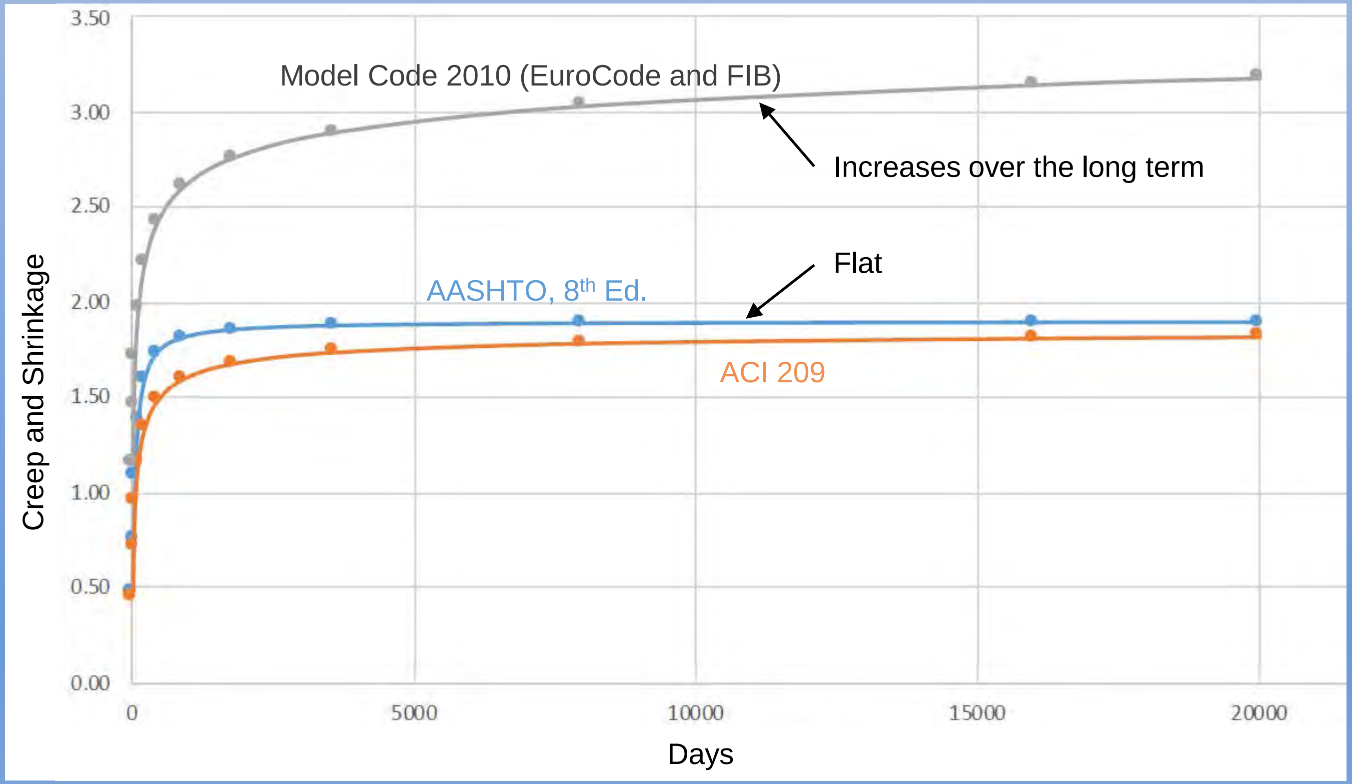


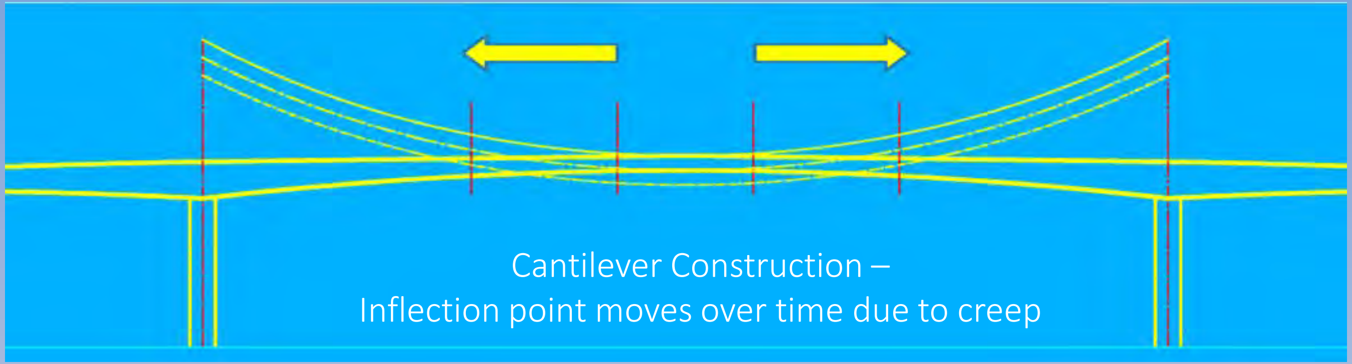
AASHTO and ACI Code Creep Issue

D. Goodyear, 2020 ©

AASHTO material model for creep and shrinkage is inconsistent with research, and presents ill-advised (unconservative) recommendations for design of cast-in-place segmental bridges.

1. Large error in mean creep values (magnitude and form)
2. Misrepresentation of form – missing long term ascension in MC2010 (B_3/B_4) when using the asymptotic form of AASHTO/ACI
3. Ignores empirical evidence: AASHTO/ACI do not adequately forecast creep during CIP bridge service life (Bazant, et al papers over recent decades and West Seattle Bridge)
4. Omitting large variance in creep and shrinkage effects in design (effectively basing LRFD design for creep on b=0.0) is unconservative and inconsistent with the reliability basis for AASHTO LRFD load factors

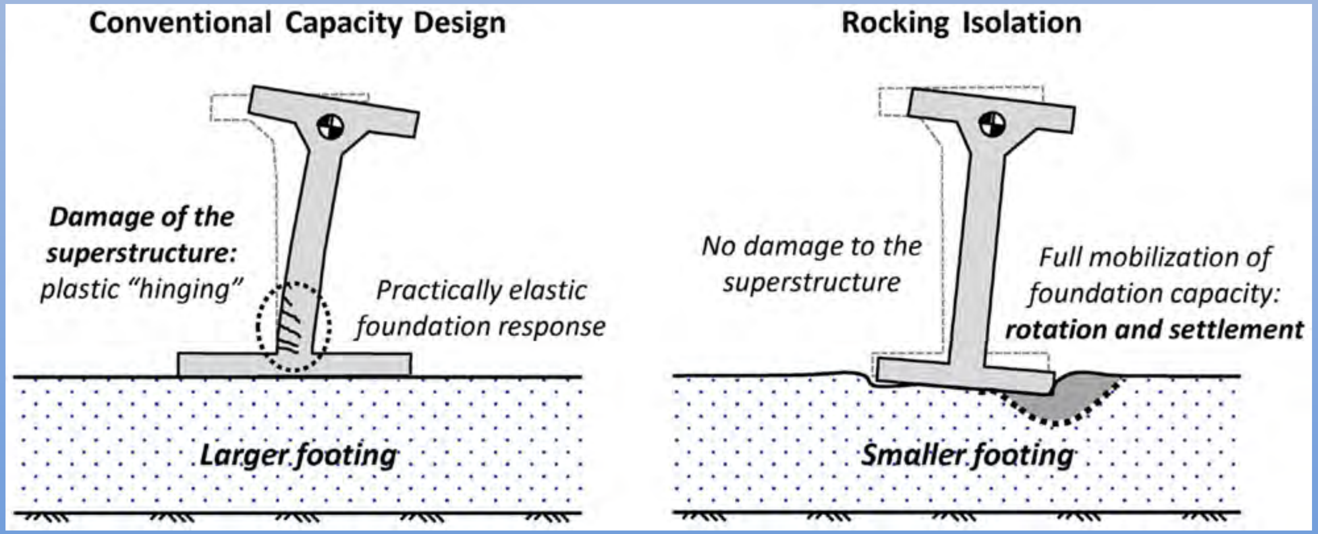



Cantilever Construction –
Inflection point moves over time due to creep

Potential Research Topics – Seismic

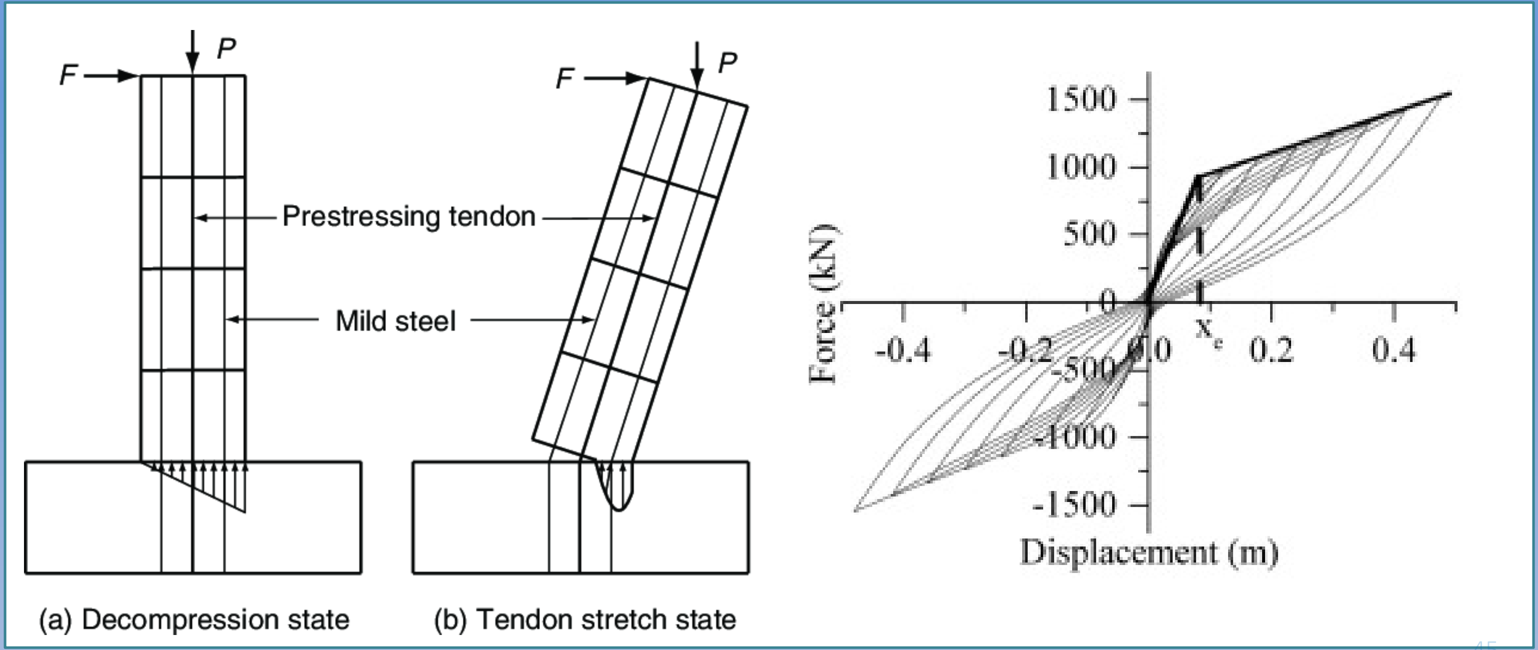
Ductile design: collapse prevention → save lives → damage (replace bridge) → Expensive $$$

Nonlinear elastic design: collapse prevention → save lives → less damage (minor repairs) → Saves $$$



Research Needs:

1. Foundation rocking (dissipate energy, reduce damage)
2. Unbonded prestressing in columns (nonlinear elastic design)
3. Shake table proof testing



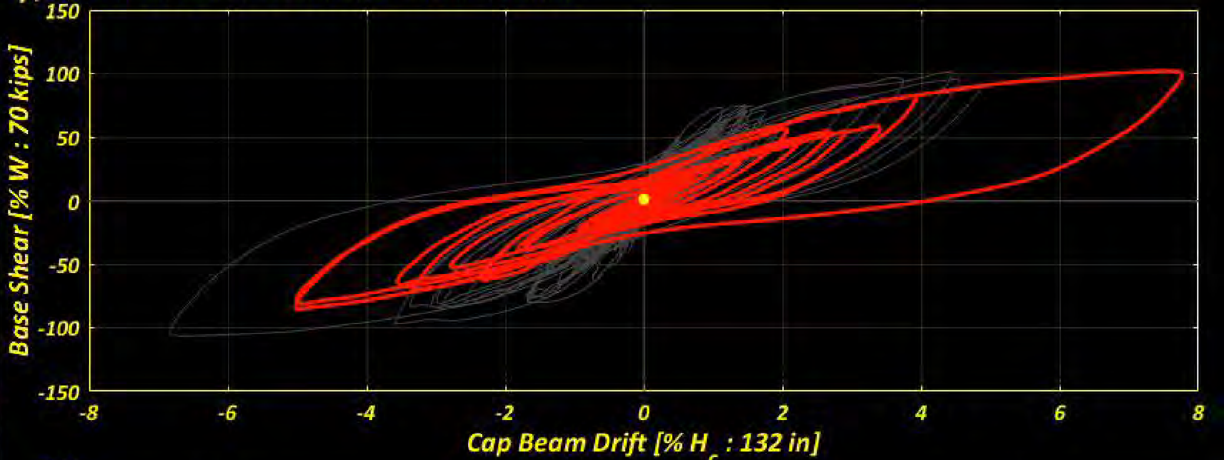
(a) Decompression state

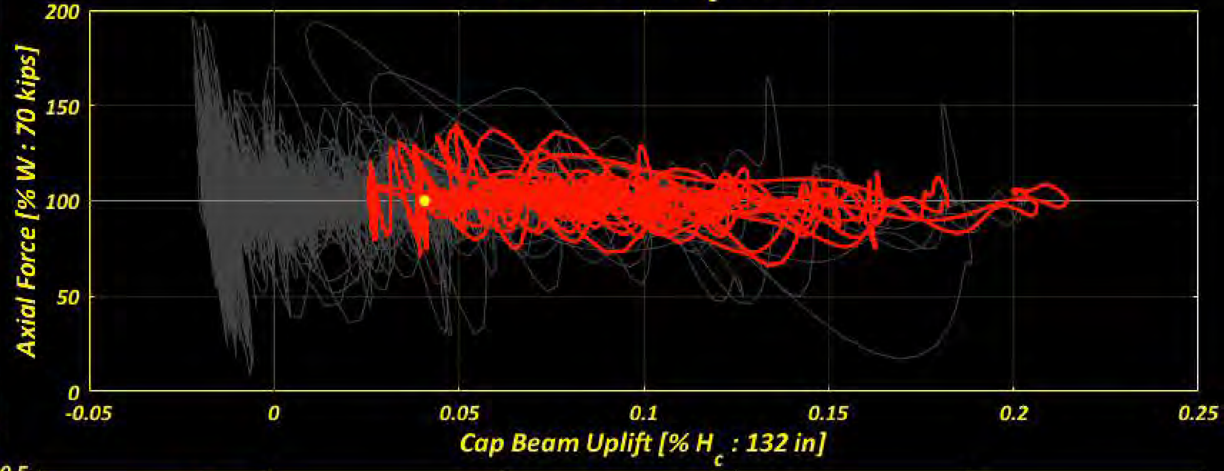
(b) Tendon stretch state

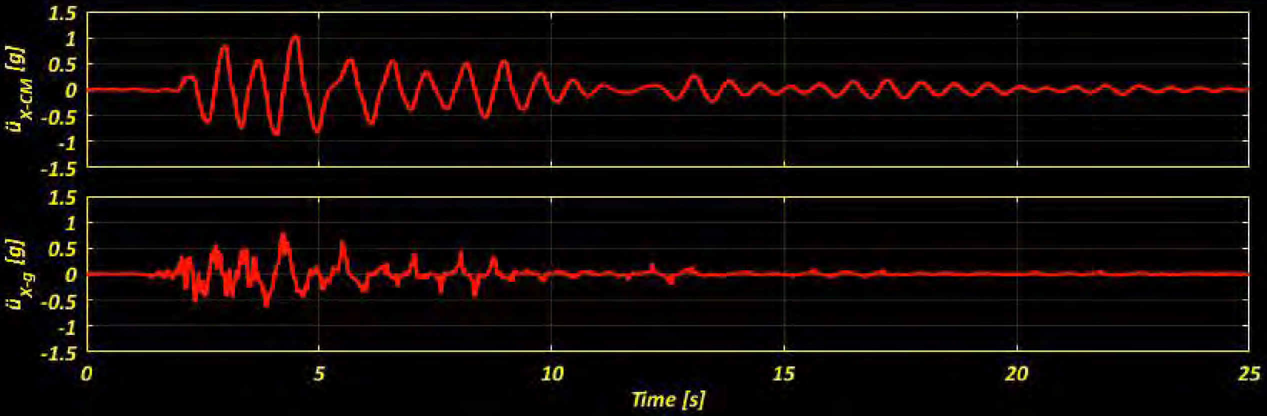
PEER
UC San Diego
Berkeley
UNIVERSITY OF CALIFORNIA

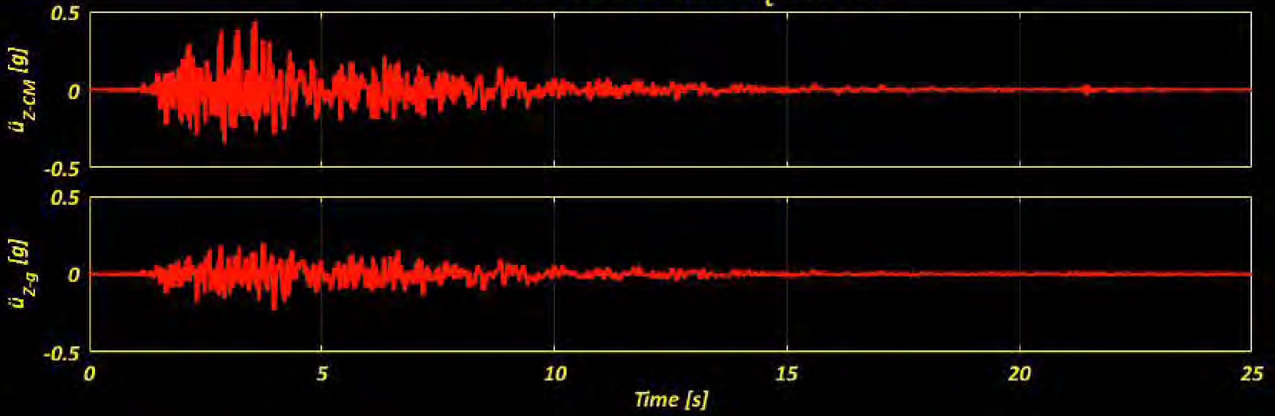
EQ09 : Kobe Earthquake (1992), Takatori Station x 90%

https://youtu.be/C6ifQxdEqmw









Reliability and Robustness

Needed Code Improvements

1. Update AASHTO **fracture critical members for steel bridges** to address toughness of contemporary materials (requirements are 30 years out of date, even with newer internally redundant guide specs).

2. Include **strain aging for bent steel plates** (covered in the Euro Code but not so well in AASHTO).

3. Topics related to **system 'robustness' for concrete and steel bridges** – an extrapolation of redundancy that affects how the Code deals with reliability.

4. More rational **reliability considerations for both concrete and steel**


I35W Bridge, Minneapolis, MN, 2007


FIU Bridge, Miami, FL, 2018


Ponte Morandi, Genoa, Italy, 2018

Reliability and Robustness

Needed Code Improvements

5. Improved understanding of **fatigue in steel members**
6. Improved **grouting provisions** for post tensioned tendons
7. Improved **durability of bridge decks** – high performance concrete and ultra
8. Better understanding of the **limitations of lightweight concrete**

Lightweight concrete deck, I-5 Stockton Channel Viaduct, Stockton, CA 2017

Fatigue cracks in steel braces, I-5 Stockton Channel Viaduct, Stockton, CA 2017