Reinforced Concrete Failure Mechanisms

Best Practices in Dam and Levee Safety Risk Analyses

Part E – Concrete Structures

Chapter E-2

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US Army Corps of Engineers®

U.S. Department of the Interior
Bureau of Reclamation

Department of Energy
Federal Energy Regulatory Commission

TVA

Reinforced Concrete Failure Mechanisms

OUTLINE:

- Types of Structures
  - Spillway Piers
  - Navigation Lock Walls
  - Floodwalls
  - Slabs
  - Buttresses
- Factors influencing strength and stability of reinforced concrete sections
- National code requirements in the context of risk
- Considerations when determining risk analysis failure probabilities based on structural analysis results
- Typical event tree of the progression of failure

Reinforced Concrete Failure Mechanisms

OBJECTIVES:

- Get a broad overview of potential failure modes for different kinds of reinforced concrete structures
- Understand the mechanisms that affect reinforced concrete failures
- Understand how to construct an event tree to represent reinforced concrete failures
- Understand how to estimate event probabilities and probability of breach

Reinforced Concrete Failure Mechanisms

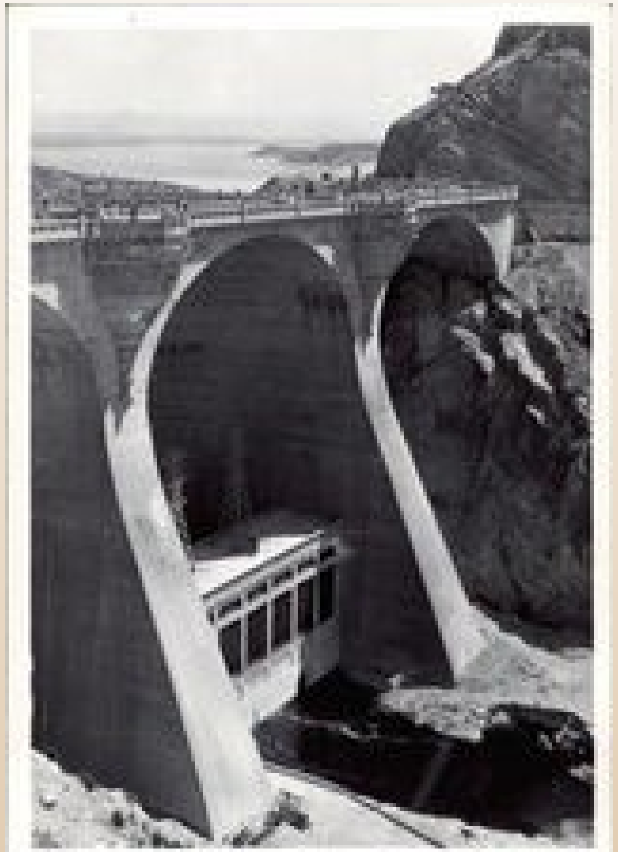
SUMMARY OF KEY CONCEPTS:

- Significant uncertainty for reinforced concrete failure mechanisms under seismic loading due to limited case histories
- Concrete and reinforcement material properties can be determined with confidence for dams and floodwalls.
- Type and duration of loading is important to understand – consider both static and earthquake loading
- Ductile and Brittle Failure mechanisms
- Seismic reinforcement details have changed dramatically over the past few decades; older concrete hydraulic structures may be more vulnerable to seismic events
- Use w/ caution modern codes when computing capacity of older reinforced concrete structures
- Typical event tree presented for reinforced concrete buttresses and piers

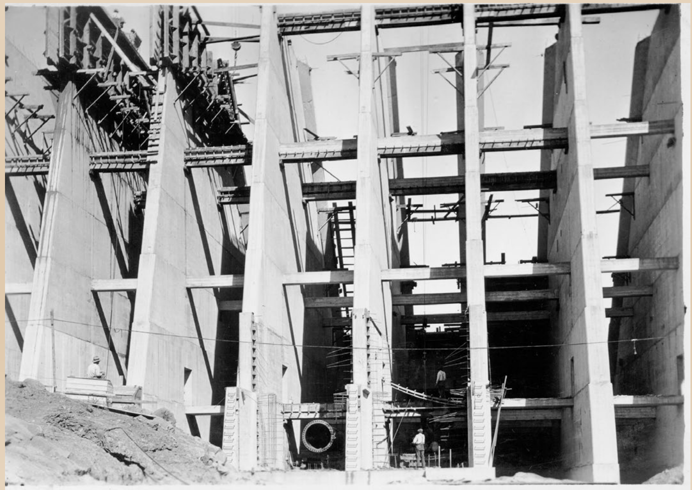
Geometry and Support Conditions – Piers and Buttresses

Spillway Gate Piers

Spillway Gate Piers

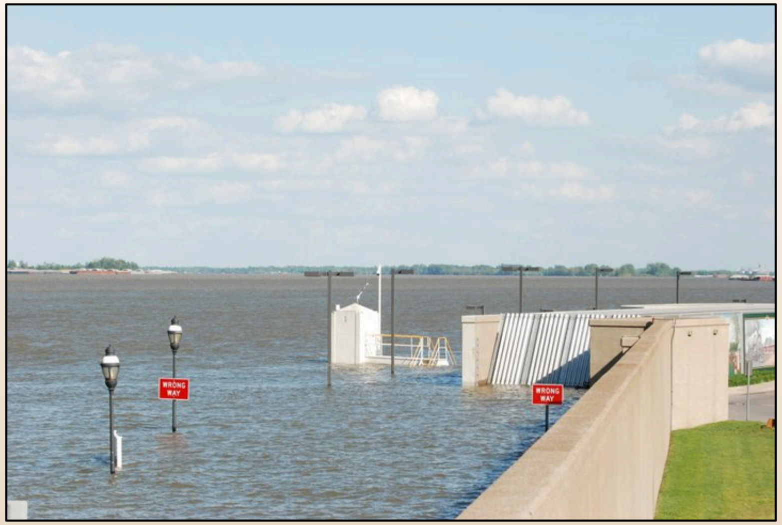


Thick Buttress Construction



Thin Buttress Construction

Geometry, Support and Loading Conditions – Floodwalls



Paducah, KY Floodwall: 2011 Ohio River Flood

New Orleans Floodwall: 2005 Katrina

Newport, KY Floodwall

Sunbury, PA Floodwall: 1972 Hurricane Agnes flood loading, Susquehanna River

Damage to Floodwall by an Aberrant Barge During Hurricane Gustav (Orleans East Parish)

Geometry, Support and Loading Conditions – Floodwalls

New Orleans Lower Ninth
Ward
Failed I-Wall:
September 2005
Hurricane Katrina

Geometry, Support and Loading Conditions – Floodwalls

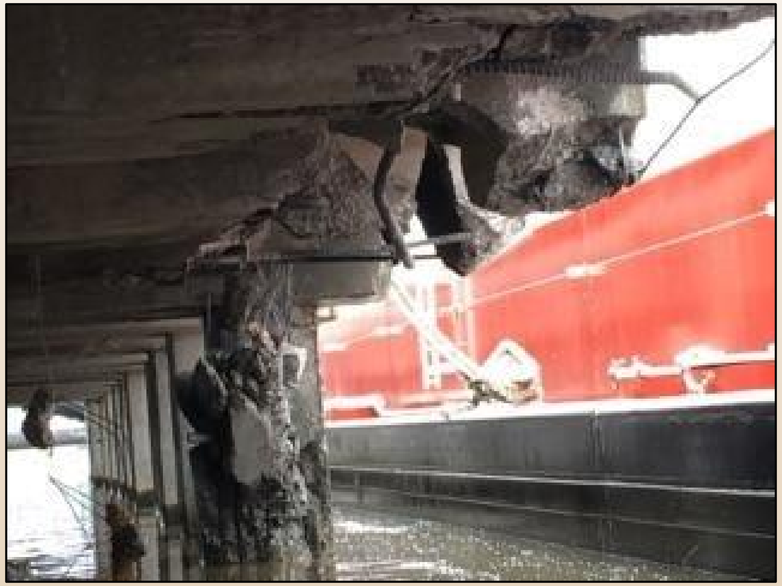
New Orleans Floodwall:
Barges against face of floodwall
2005 Katrina

St. Bernard Parish, New Orleans - Damage to top of I-Wall from a Barge:
2005 Hurricane Katrina

Damage to Floodwall by an Aberrant Barge during Hurricane Gustav, 2008
(Orleans East Parish)

Geometry, Support and Loading Conditions – Navigation Locks & Dams

Tow w/loaded coal barges



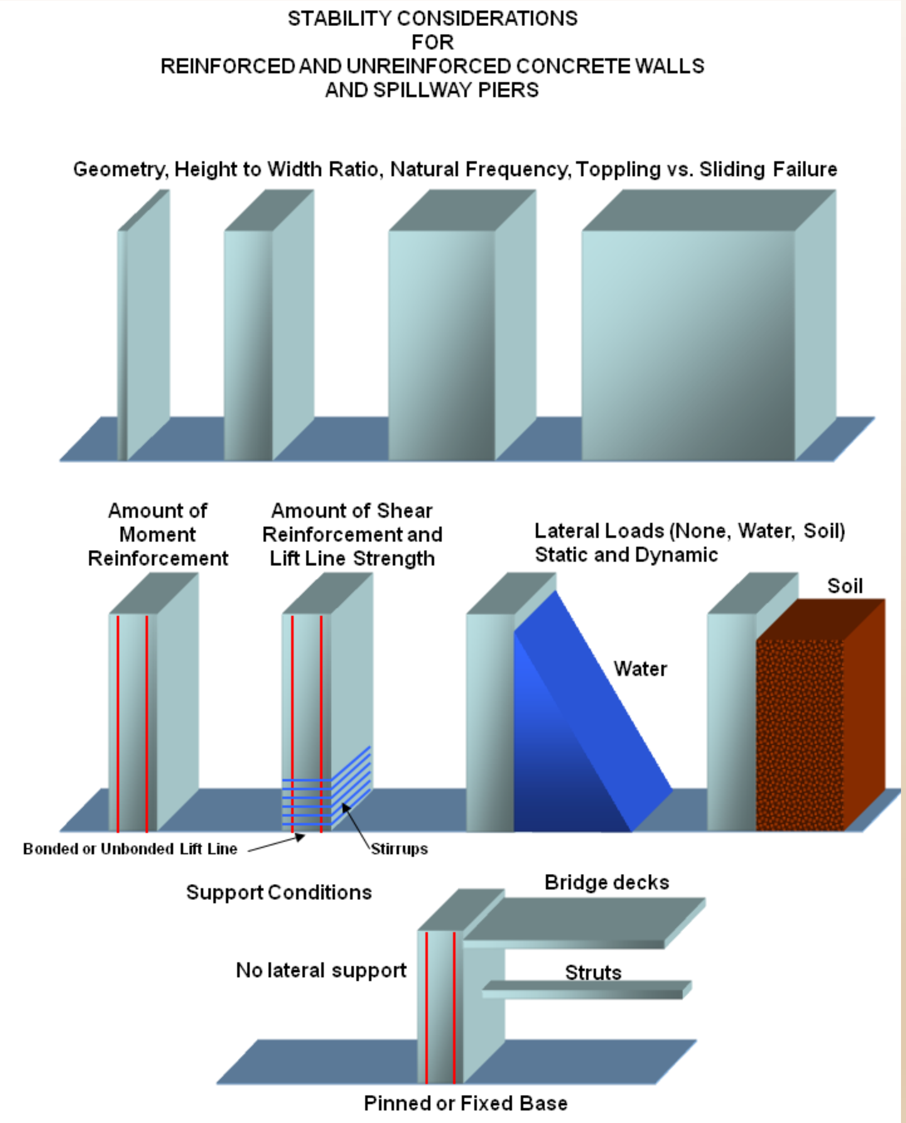
Damage from Barge Impact

Belleville L&D Barge Accident,

Mississippi
River Lock
No. 2
Barge
Impact
Guide Wall

Maxwell Dam,
Monongahela River,
November 1985

Geometry and Support Conditions



- ➢Reinforced concrete sections in hydraulic structures vary greatly in size and shape
    - ✓Spillway walls and Floodwalls can be very tall and narrow
    - ✓Spillway piers and floodwall closure abutments tend to be shorter and wider than walls
    - ✓Buttresses can vary from very thin tall sections to more stout sections
- ➢The geometry of the concrete section can have a significant impact on how the section fails
- ➢Sections with height to width ratios of 4:1 or less tend to slide more than rotate or bend while sections with height to width ratios more than 4:1 tend to bend, rotate and topple (deep beam criteria in ACI Code 318)

Geometry and Support Conditions - Spillways

Glendo Dam Chute Walls

Stampede Dam Inlet Control Structure

Stampede Dam Stilling Basin

- Examples typically not considered a reinforced concrete PFM
- Generally only consider gated spillway crest structure
- However failure could contribute to another PFM such as internal erosion through a gap that initiates between a spillway crest structure wall and the adjacent embankment

Geometry and Support Conditions

- Structures have definite, signature dynamic characteristics
- The geometry greatly affects the natural frequency of the reinforced concrete member
- The natural frequency of the member decreases as the height to width ratio increases.
- The natural frequency becomes smaller as a reinforced concrete structure is damaged due to earthquake shaking

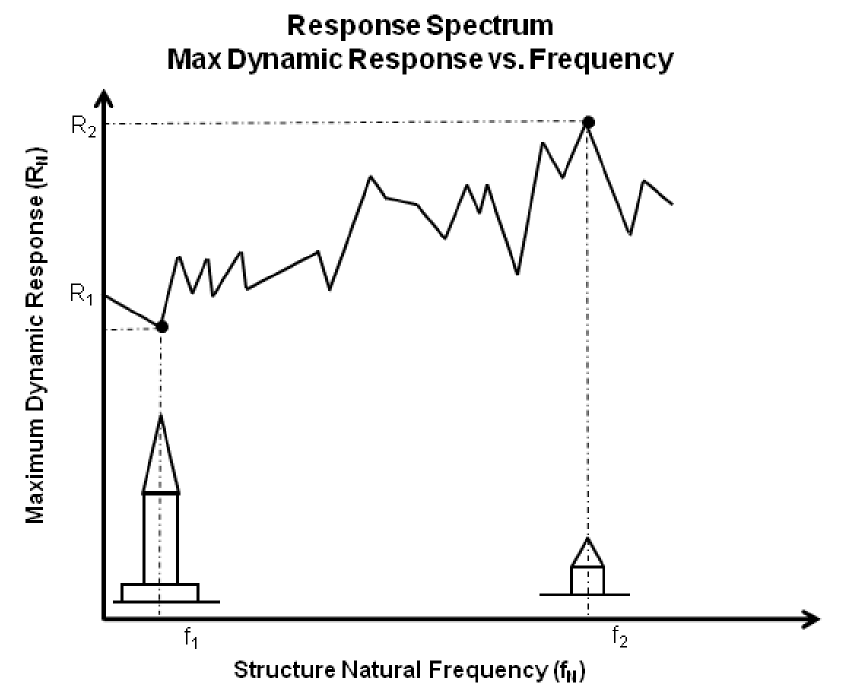
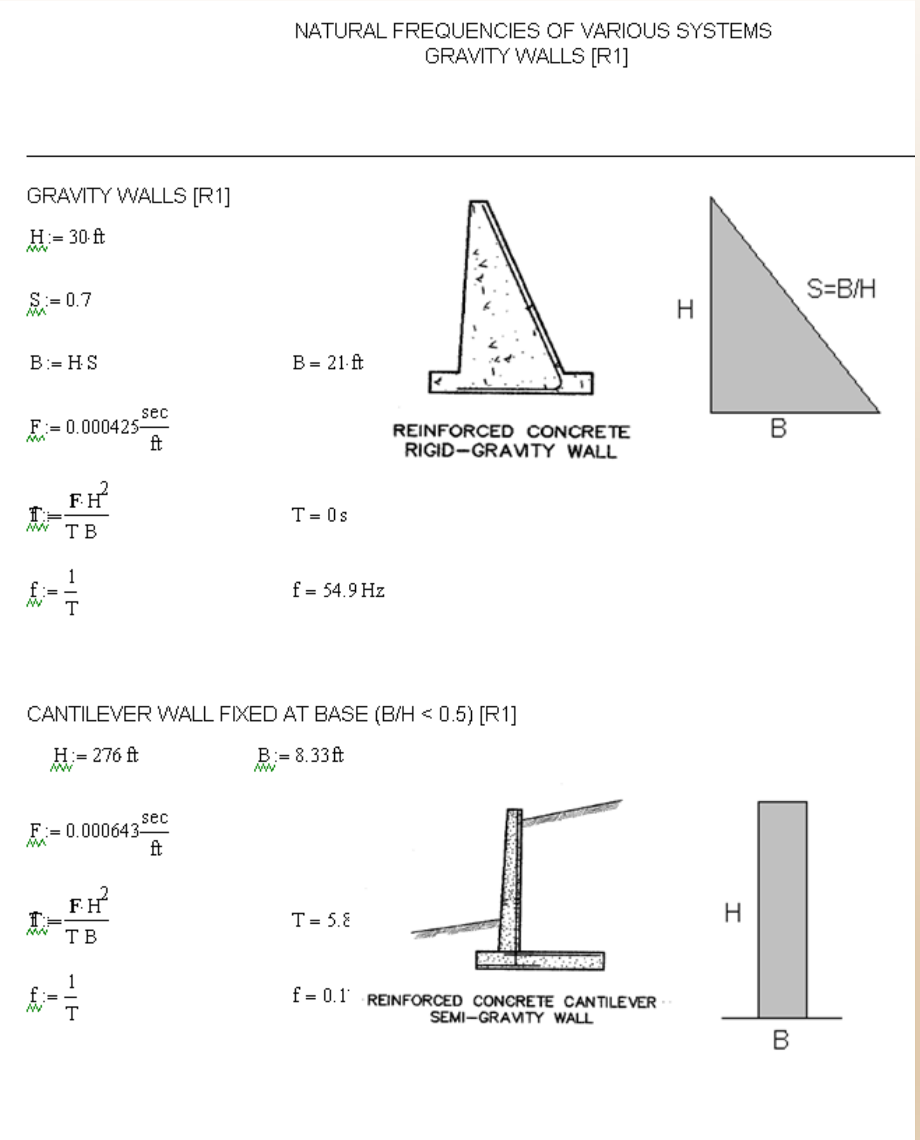


Figure modified from ASCE *Seismic Design and Performance of Building Structures*, 2008

Geometry and Support Conditions



NATURAL FREQUENCIES OF VARIOUS SYSTEMS
GRAVITY WALLS [R1]

GRAVITY WALLS [R1]

$H := 30 \cdot ft$

$S := 0.7$

$B := H \cdot S$ $\quad B = 21 \cdot ft$

$F := 0.000425 \frac{sec}{ft}$

$T := \frac{\mathbf{F} \cdot H^2}{T\,B}$ $\quad T = 0\,s$

$f := \frac{1}{T}$ $\quad f = 54.9\,Hz$

REINFORCED CONCRETE
RIGID–GRAVITY WALL

CANTILEVER WALL FIXED AT BASE (B/H < 0.5) [R1]

$H := 276\,ft$ $\quad B := 8.33\,ft$

$F := 0.000643 \frac{sec}{ft}$

$T := \frac{\mathbf{F} \cdot H^2}{T\,B}$ $\quad T = 5.8$

$f := \frac{1}{T}$ $\quad f = 0.1$

REINFORCED CONCRETE CANTILEVER
SEMI–GRAVITY WALL

- ➢ Structural response to seismic loading will be different for sections:
  - ✓ on rock foundations compared to soil foundations
  - ✓ founded on the top of a dam where ground motions are generally amplified

Reinforcement Material Properties

- Material properties of reinforcement directly contribute to strength of the concrete section. While the modulus of elasticity of steel is fairly consistent at 29,000 ksi, yield strength of reinforcement depends:

Steel Grade	Min. Yield	Ultimate	Years	
			From	To
33	33,000	55,000	1911	1966
40	40,000	70,000	1911	present
50	50,000	80,000	1911	present
60	60,000	90,000	1959	present
70	70,000	80,000	1959	present
75[1]	75,000	100,000	1959	present

[1] Excludes the years from 1966 through 1987

- Historical reinforcement availability and yield properties can be found in CRSI Engineering Data Report No. 48 and ASCE 41 Seismic Rehabilitation of Existing Buildings.
- The shear strength of the reinforcement is typically taken as the yield strength.
- FEMA 356, *Pre-standard and Commentary for the Seismic Rehabilitation of Buildings*, recommends increasing these specified minimums by 125 percent for dynamic analysis

Concrete Material Properties

- Key contributors to member strength and structural response

- Required concrete properties to estimate reinforced concrete member strength and structural response include:
  - Density
  - Modulus of elasticity
  - Compressive strength
  - Tensile strength
  - Shear strength

- Standard or assumed values for concrete material properties can be used in preliminary structural evaluations (Reference ASCE 41)
  - Uncertainty
  - Unconservative results
  - Concrete coring and lab testing may be required
  - See table of “Compressive Strengths for Concrete from Different Time Frames” in Chapter E-2 “Concrete Properties Considerations”

Concrete Material Properties

➢Construction joints

✓Unbonded -> No tensile strength/reduced shear resistance

✓Often adversely located in structure

Construction joint at geometric discontinuity

Reinforcement Details

- Ductile vs. brittle failures
  - Ductile failure much better than brittle failures
  - Ductile failures occur much slower than brittle failures
  - Ductile failures provide evidence of structural distress prior to failure
  - Ductile failures allows time for repair or evacuation prior to failure
  - Shear failures tend to be more sudden (brittle) than ductile type bending or tensile failures

- Ductile sections
  - Require reinforcement design details per ACI code
  - Detailing examples
    - stirrups confine areas of damaged concrete/help maintain post-seismic structural integrity
    - $A_{s(min)} = 200 b_w d / f_y$
    - Shear strength based exclusively on V_c is okay provided $A_s \geq A_{s(min)}$ and $\rho \leq 0.75 \rho_b$
  - If a section does not meet the requirements above it doesn't mean it will fail or necessarily fail in a brittle manner.

Reinforcement Details

- Older hydraulic structures were not designed for current seismic loads
- Seismic detailing requirements have changed dramatically over the last several decades
- Insufficient embedment lengths, splice lengths or hook details can result in sudden pullout failures
- Massive hydraulic structures are typically lightly or under-reinforced and can be greatly overstressed by large earthquakes and can yield and deflect excessively
- Older concrete structures are also typically more massive and the concrete strength and mass may compensate for the lack of reinforcement detailing.

Structural System Considerations

- Structural systems that perform well during earthquakes
  - ✓Dissipate energy through inelastic deformation
  - ✓Alter dynamic properties (period shift)
  - ✓Mobilize additional strength elsewhere in the system (highly redundant)
- Hydraulic structures are generally not highly redundant
- However, retaining walls have historically performed very well during earthquakes
- Seismic loads extend beyond performance database

Analysis Results Considerations

- When evaluating D/C ratios, it is important to evaluate values representative of the structure as a whole and not just localized maxima
- A progressive failure may occur if a localized area is overstressed, but this will take time under multiple earthquake peaks if there is potential for load redistribution
- Displacement criteria should be used to evaluate inelastic behavior of reinforced concrete members
- Biggest challenge for RA team
  - ✓ Severe damage may result from many cycles of demand exceeding capacity
  - ✓ The remaining strength of the damaged section is primarily a judgment call of the RA team

Reinforcement Details Matter!

1999 Kocaeli, Turkey Earthquake

Shi-Kang Dam - 1999 Chi-Chi, Taiwan Earthquake – immediate aftermath

Type and Duration of Load

Static loads

- Examples - hydrostatic or soil pressures
- Typically act for long durations - sustained loads
- There may be no mechanism to stop or resist a section in the process of failing if the static loads exceed the capacity of the structure
- If a reinforced concrete structure is stable, the static loads *generally* have to change in some way to lead to failure
- Exceptions to latter point are in cases of advanced corrosion of reinforcement resulting in yielding and Alkali-Aggregate Reactions (AAR) leading to abnormal expansion and cracking of concrete in service.

Type and Duration of Load

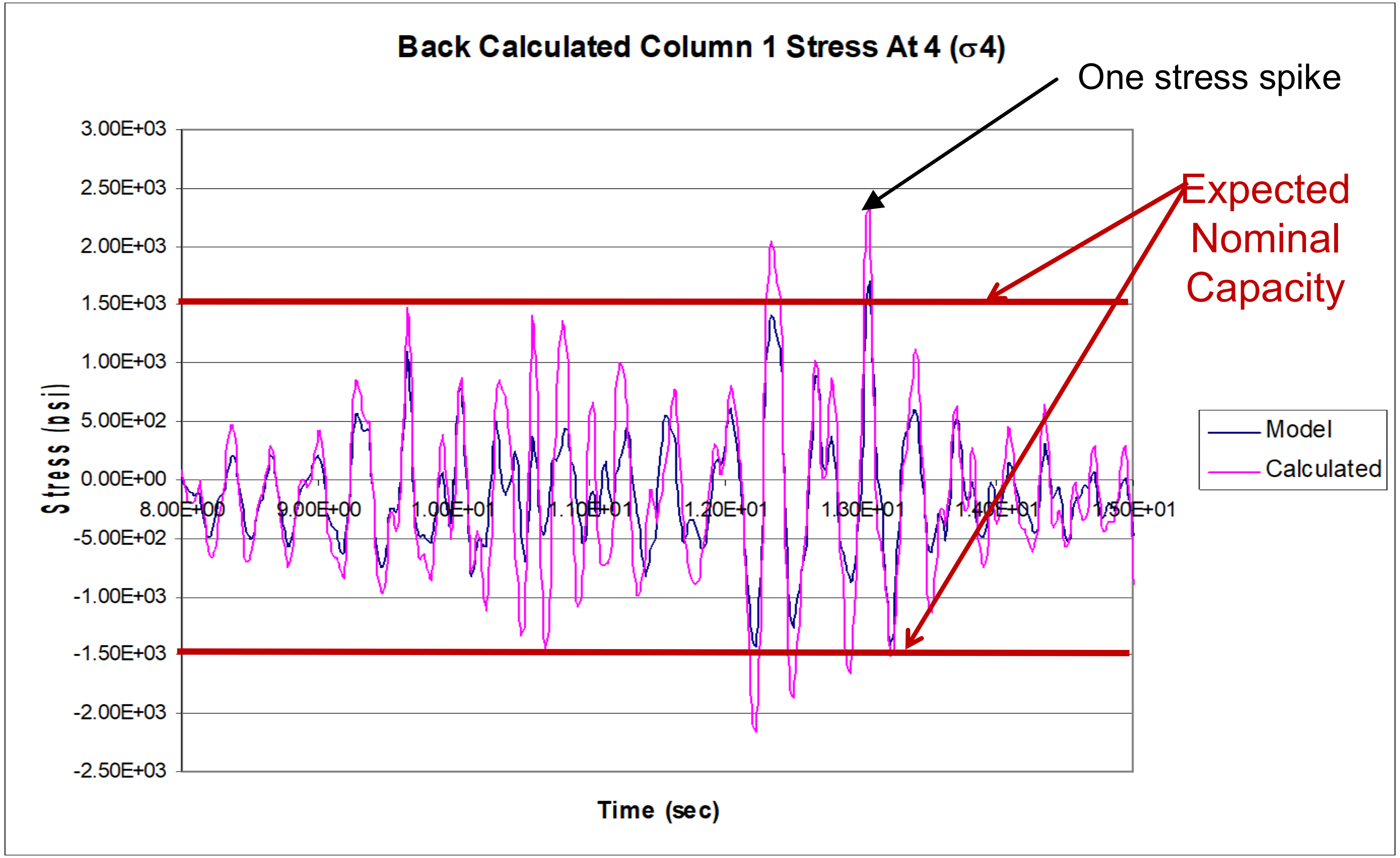
Dynamic loads - Earthquake and Barge Impact

- Earthquake loads are cyclical and change direction rapidly
- Barge Impacts are rapid and typically involve a large magnitude, highly concentrated first blow, flowed by multiple smaller impacts as the barge moves along the face of the lock wall.
- Sections may not crack through the member thickness even though the tensile capacity is exceeded for short durations
- Dynamic loads of either type may not have sufficient duration or have enough significant stress peaks to completely strain a section to failure
- As the member cracks and changes frequency, the response of the structure may change the loads and failure potential

➢Post-seismic or post barge impact stability must consider the ability of a damaged section to carry static loads

Type and Load Duration – Seismic

Comparing Results from Dynamic FEM and “Traditional” Time History Analysis



One stress spike

Expected Nominal Capacity

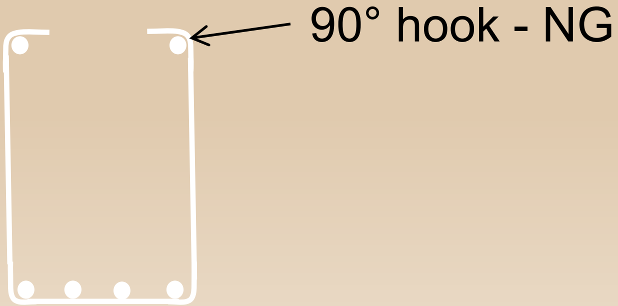
See the chapter on Concrete Properties Considerations.

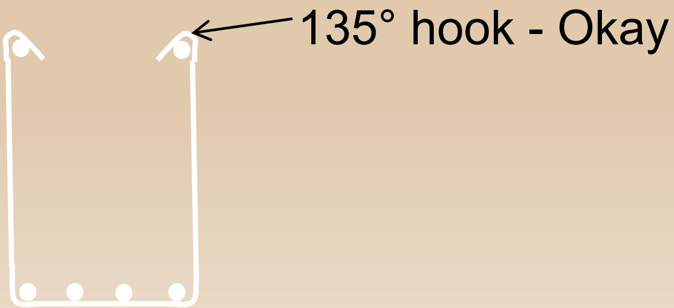
It discusses this concept in more detail and provides performance curves to be considered for seismic loading and linear elastic analyses.

Code Considerations

- Caution should be exercised when using National codes like ACI or AASHTO to compute the capacity of reinforced concrete sections.
- If a concrete structure does not meet current code requirements it does not mean the probability of failure is high.
- The sections tend to be pretty massive in concrete dams and the concrete and mass contribute to stability. The seismic hazard also could be low.
- Most codes are for new designs and assume ductile sections with adequate reinforcement details (adequate lap splices; appropriate confining reinforcement – closed ties or stirrups; and proper anchorage of ties and hooks – 135° seismic hooks)

- Consider looking at one of these references for assistance when evaluating an existing structures
  - ASCE 31 – Seismic Evaluations of Existing Buildings
  - FEMA 356, Pre-standard and Commentary for the Seismic Rehabilitation of Buildings



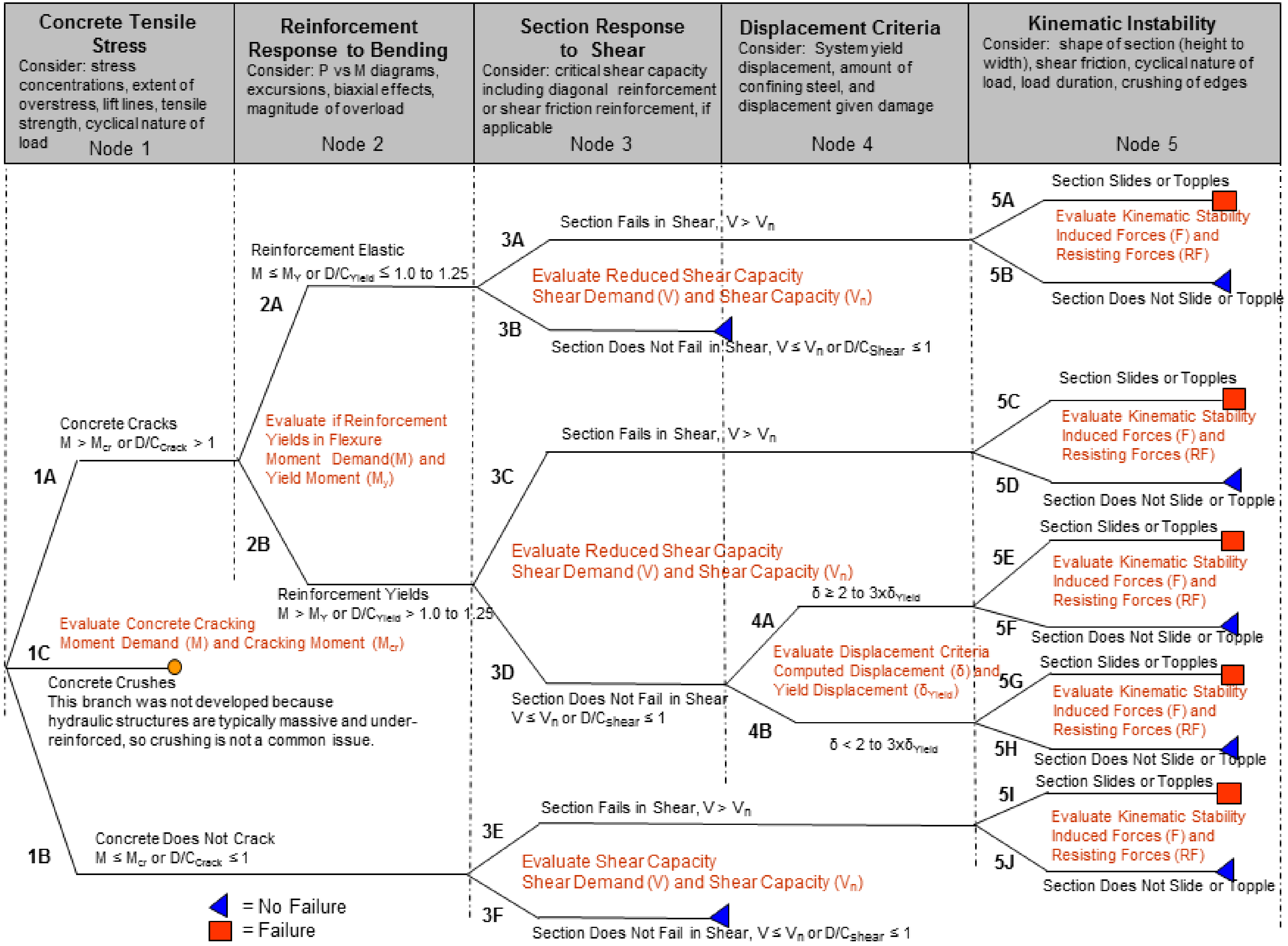


Code Considerations

- ➢Load factors and strength reduction (φ) factors
  - ✓Used for new designs to
    - ▪Address analysis and design uncertainties and assumptions (LF)
    - ▪Account for variations in materials (φ)
    - ▪Account for variations in construction (φ)
    - ▪Generally build-in factors of safety
  - ✓Do not apply for risk analyses of existing reinforced concrete structures
    - ▪Compute the demand or load on the section without load factors
    - ▪Compute the “true” or “expected” capacity of the section without φ
- ➢During the risk analyses team members should consider:
  - ✓The condition of the concrete and reinforcement
  - ✓Severity of the environment
  - ✓Deterioration due to alkali-aggregate reaction
  - ✓Evidence of freeze-thaw deterioration
  - ✓Evidence of corrosion

Typical Event Tree for Reinforced Concrete Columns, Piers, and Buttresses

Revision date: March 24, 2015



Concrete Tensile Stress	Reinforcement Response to Bending	Section Response to Shear	Displacement Criteria	Kinematic Instability
Consider: stress concentrations, extent of overstress, lift lines, tensile strength, cyclical nature of load	Consider: P vs M diagrams, excursions, biaxial effects, magnitude of overload	Consider: critical shear capacity including diagonal reinforcement or shear friction reinforcement, if applicable	Consider: System yield displacement, amount of confining steel, and displacement given damage	Consider: shape of section (height to width), shear friction, cyclical nature of load, load duration, crushing of edges
Node 1	Node 2	Node 3	Node 4	Node 5

1A Concrete Cracks $M > M_{cr}$ or $D/C_{Crack} > 1$

Evaluate if Reinforcement Yields in Flexure Moment Demand(M) and Yield Moment (M_y)

2A Reinforcement Elastic $M \leq M_Y$ or $D/C_{Yield} \leq 1.0$ to 1.25

Evaluate Reduced Shear Capacity Shear Demand (V) and Shear Capacity (V_n)

3A Section Fails in Shear, $V > V_n$

Evaluate Kinematic Stability Induced Forces (F) and Resisting Forces (RF)

5A Section Slides or Topples 🟥

5B Section Does Not Slide or Topple ◀

3B Section Does Not Fail in Shear, $V \leq V_n$ or $D/C_{Shear} \leq 1$ ◀

2B Reinforcement Yields $M > M_Y$ or $D/C_{Yield} > 1.0$ to 1.25

Evaluate Reduced Shear Capacity Shear Demand (V) and Shear Capacity (V_n)

3C Section Fails in Shear, $V > V_n$

Evaluate Kinematic Stability Induced Forces (F) and Resisting Forces (RF)

5C Section Slides or Topples 🟥

5D Section Does Not Slide or Topple ◀

3D Section Does Not Fail in Shear $V \leq V_n$ or $D/C_{shear} \leq 1$

Evaluate Displacement Criteria Computed Displacement (δ) and Yield Displacement (δ_{Yield})

4A $\delta \geq 2$ to $3x\delta_{Yield}$

Evaluate Kinematic Stability Induced Forces (F) and Resisting Forces (RF)

5E Section Slides or Topples 🟥

5F Section Does Not Slide or Topple ◀

4B $\delta < 2$ to $3x\delta_{Yield}$

Evaluate Kinematic Stability Induced Forces (F) and Resisting Forces (RF)

5G Section Slides or Topples 🟥

5H Section Does Not Slide or Topple ◀

Evaluate Concrete Cracking Moment Demand (M) and Cracking Moment (M_{cr})

1C Concrete Crushes ●

This branch was not developed because hydraulic structures are typically massive and under-reinforced, so crushing is not a common issue.

1B Concrete Does Not Crack $M \leq M_{cr}$ or $D/C_{Crack} \leq 1$

Evaluate Shear Capacity Shear Demand (V) and Shear Capacity (V_n)

3E Section Fails in Shear, $V > V_n$

Evaluate Kinematic Stability Induced Forces (F) and Resisting Forces (RF)

5I Section Slides or Topples 🟥

5J Section Does Not Slide or Topple ◀

3F Section Does Not Fail in Shear, $V \leq V_n$ or $D/C_{shear} \leq 1$ ◀

◀ = No Failure

🟥 = Failure

Figure 10-9 – Example Event Tree for Failure of a Reinforced Concrete Member

Event 1 – Concrete Stress

Cracking moment criteria - compare moment demand (M) to cracking moment capacity (M_{CR})

✓$M \leq M_{cr}$

where:

$M_{cr} = f_t I_g / y_t$ (modified ACI Eq. 9-9)

f_t = concrete tensile strength per Chapter 20

I_g = moment of inertia of the gross concrete section

y_t = distance from the section centroid to the extreme tension fiber

✓ Tensile stresses from axial loads compared to f_t

✓ Concrete crushing due to compressive stresses is unusual

Event 2 – Reinforcement Response to Bending

Yield moment criteria - compare moment demand (M) to yield moment capacity (M_y)

- ✓$M \leq M_y$
- ✓$M_n \leq M_y \leq M_{pr}$

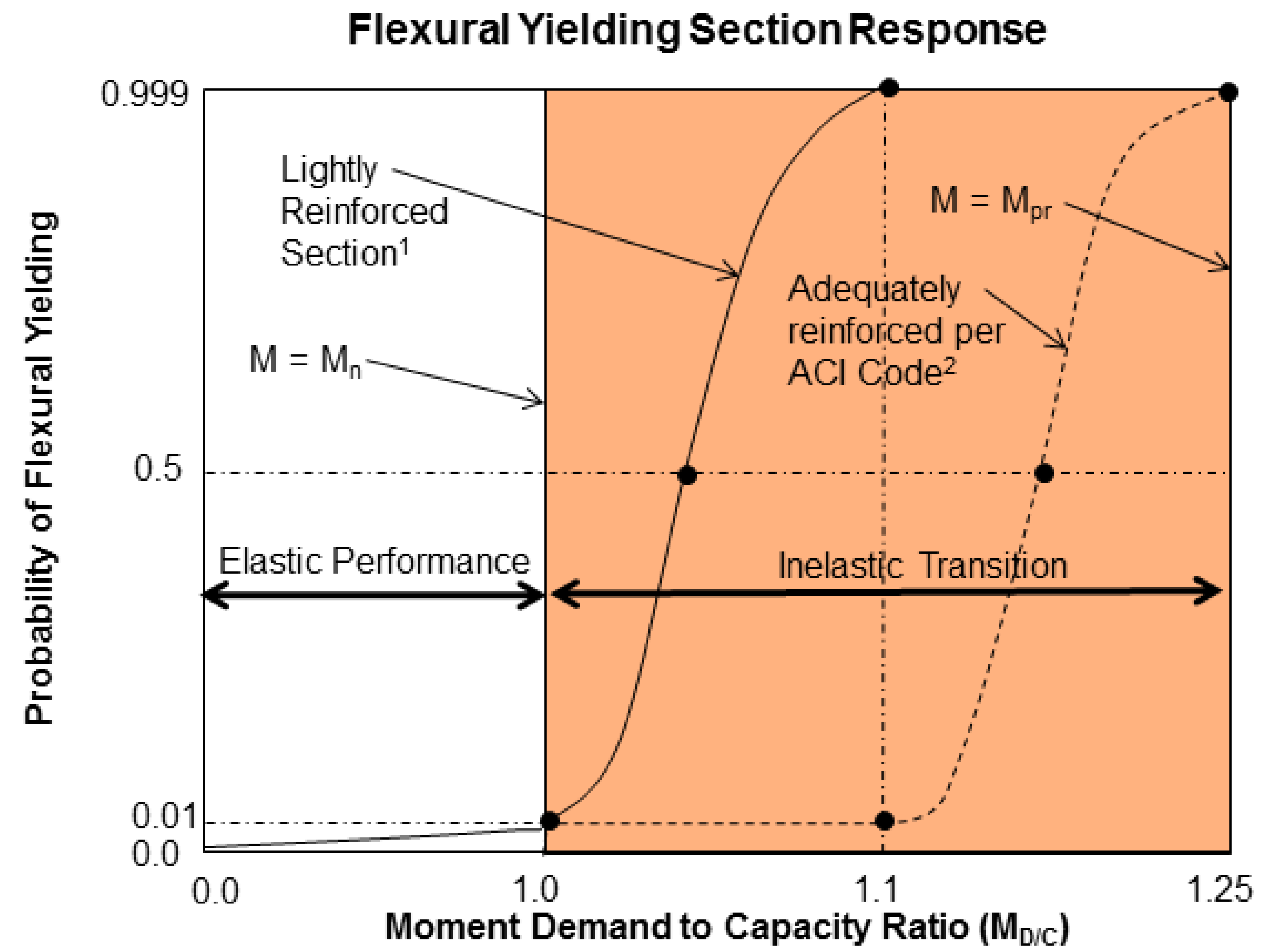
where:

M_y = section yield moment

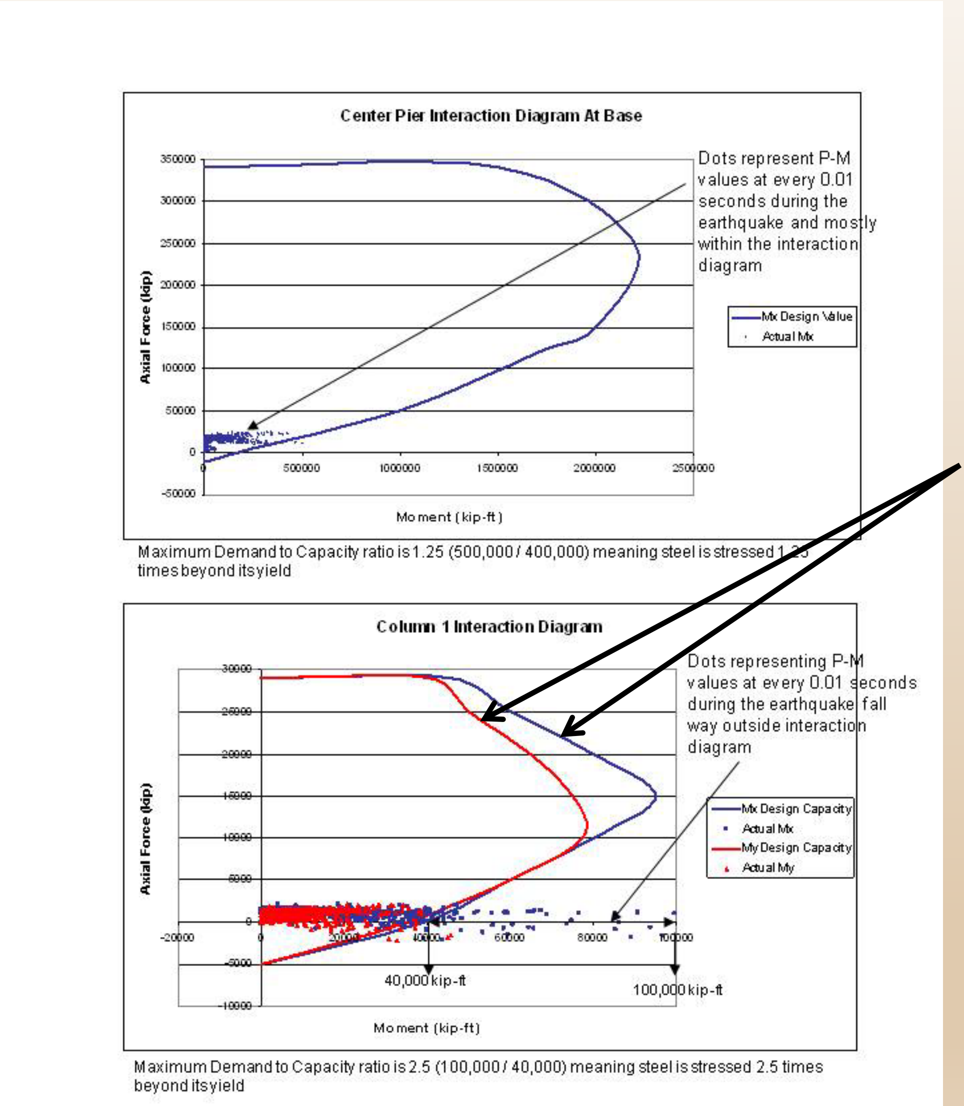
$M_n = A_s f_y (d - a/2)$ = nominal moment capacity

$M_{pr} = A_s (1.25 f_y)\,(d - a/2)$ = probable moment strength at plastic hinging

Event 2 – Reinforcement Response to Bending



Event 2 – Reinforcement Response to Bending



Center Pier Interaction Diagram At Base

Dots represent P-M values at every 0.01 seconds during the earthquake and mostly within the interaction diagram

Maximum Demand to Capacity ratio is 1.25 (500,000 / 400,000) meaning steel is stressed 1.25 times beyond its yield

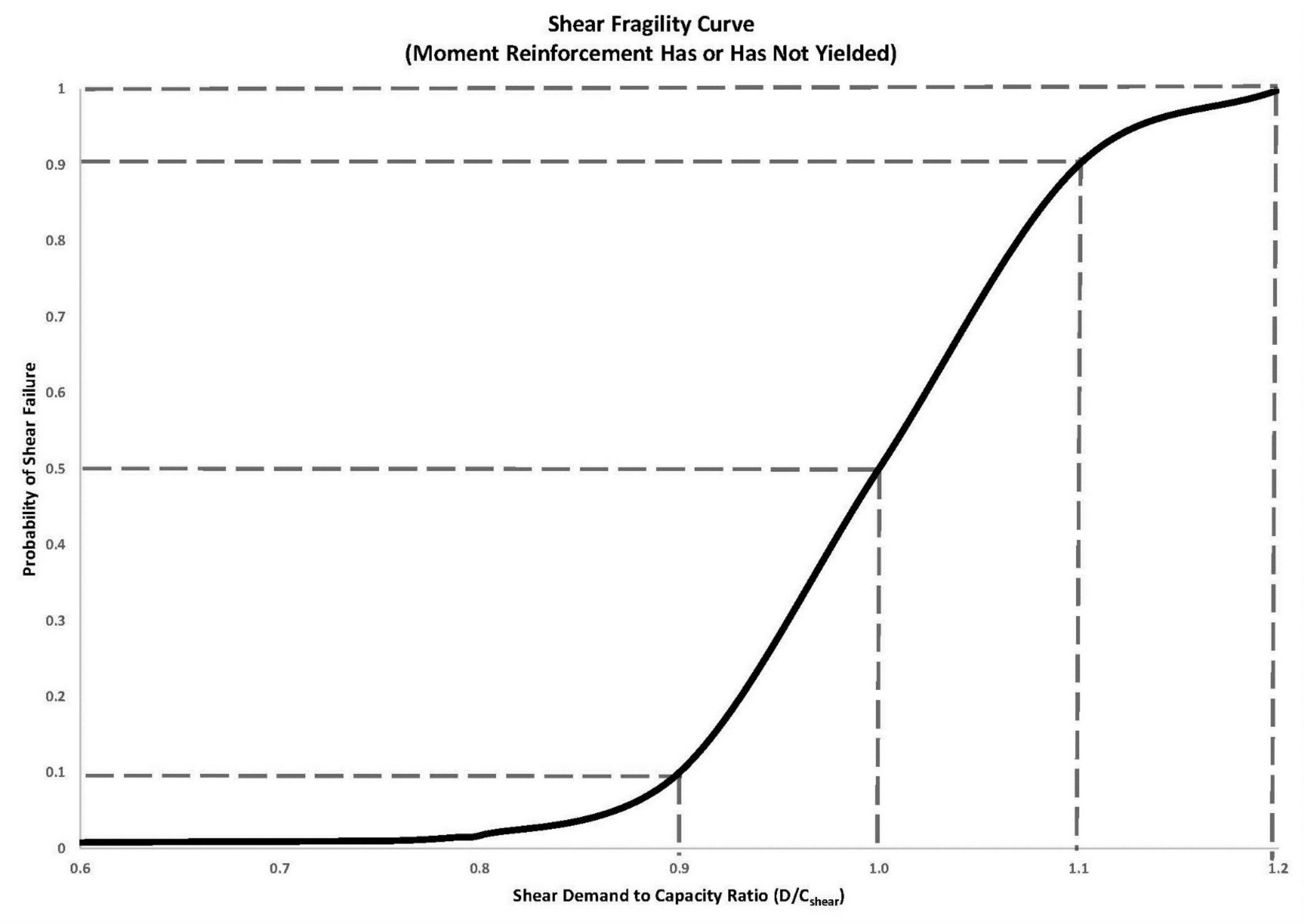
Column 1 Interaction Diagram

Dots representing P-M values at every 0.01 seconds during the earthquake fall way outside interaction diagram

Maximum Demand to Capacity ratio is 2.5 (100,000 / 40,000) meaning steel is stressed 2.5 times beyond its yield

spColumn – interaction diagrams for member subjected to both axial load and flexure

Event 3 - Section Response to Shear



Response curve more representative of lightly or unreinforced sections - shear reinforcement will add ductility

For slender members (>4H:1W)
$V_n = V_c + V_s$

- V_c = concrete shear strength
- V_s = reinforcement shear strength

Shear friction reinforcement
- Need to consider type of shear failure when evaluating shear capacity – diagonal crack or horizontal crack
- Should be supplemental to primary flexural reinforcement

Event 3 - Section Response to Shear

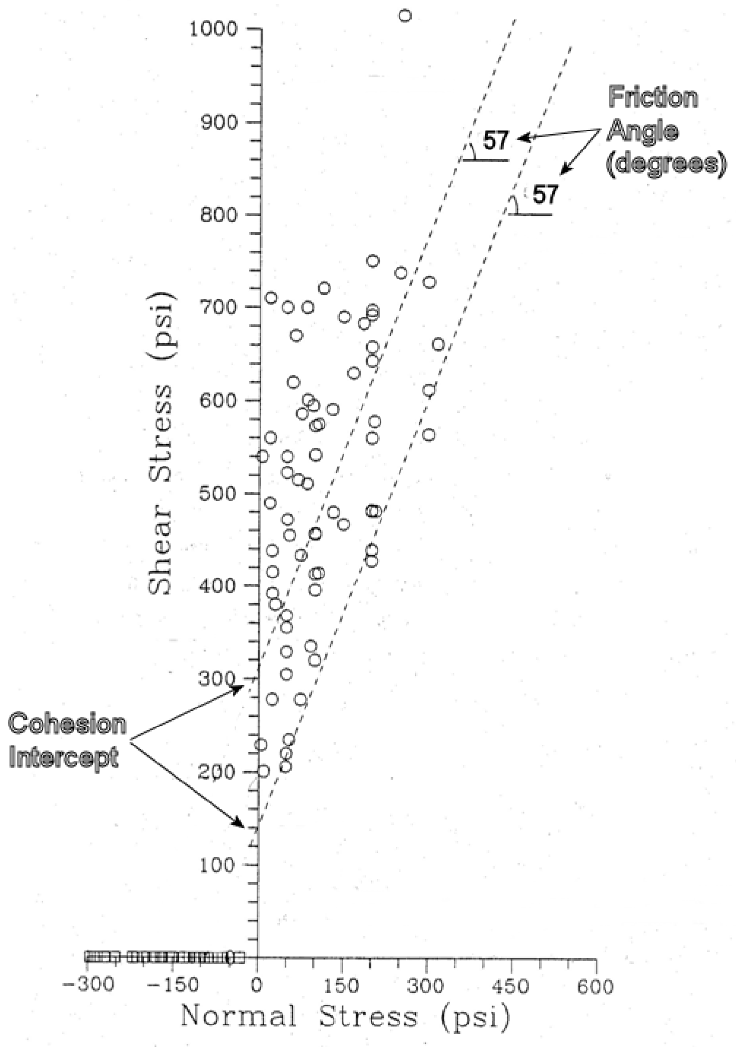
- Sliding

$$SF = (N - U)\mu + CA$$

where:
SF = Shear resistance
N = Normal force on the sliding plane
U = Uplift forces along sliding plane
μ = Friction coefficient (tangent of the friction angle)
C = Cohesion (or apparent cohesion)
A = Area of slide surface

Event 3 - Section Response to Shear

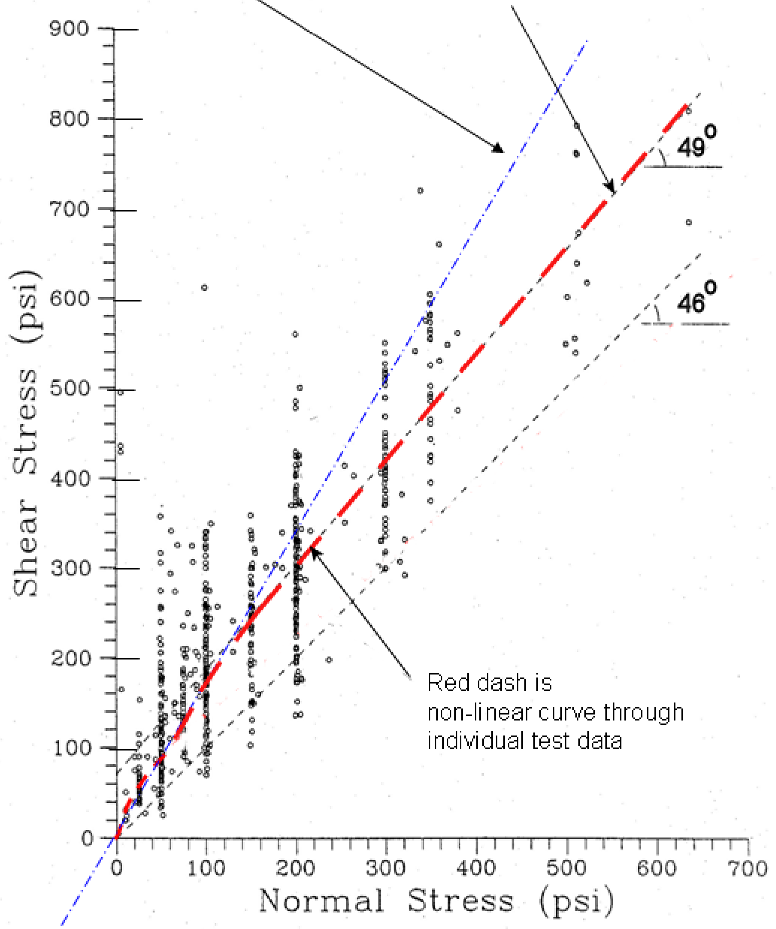
Bonded Lift Line or Construction Joint



Peak Shear Strength of Concrete-Lift Joints

This straight line approximates non-linear curve at low normal stress
Apparent Cohesion = 0
Friction = 60 degrees

This straight line approximates non-linear curve at high normal stress
Apparent Cohesion = 70 lb/in^2
Friction = 49 degrees



Red dash is
non-linear curve through
individual test data

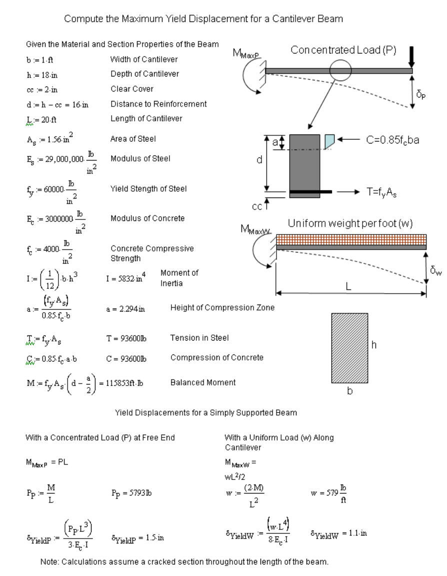
Unbonded Lift Line or Construction Joint

Sliding Friction Shear Strength of Concrete-Lift Joints (Unbonded joints)

Event 4 - Displacement Criteria

- Based on research at the University of Illinois at Champagne-Urbana by Mete Sozen
- Considers nonlinear behavior of section within structural system
- Determine nonlinear displacements in reinforced concrete system
- Structure may be viable if: $\delta / \delta_{yield} \leq 2$ to 3

Event 4 - Displacement Criteria



Compute the Maximum Yield Displacement for a Cantilever Beam

Given the Material and Section Properties of the Beam

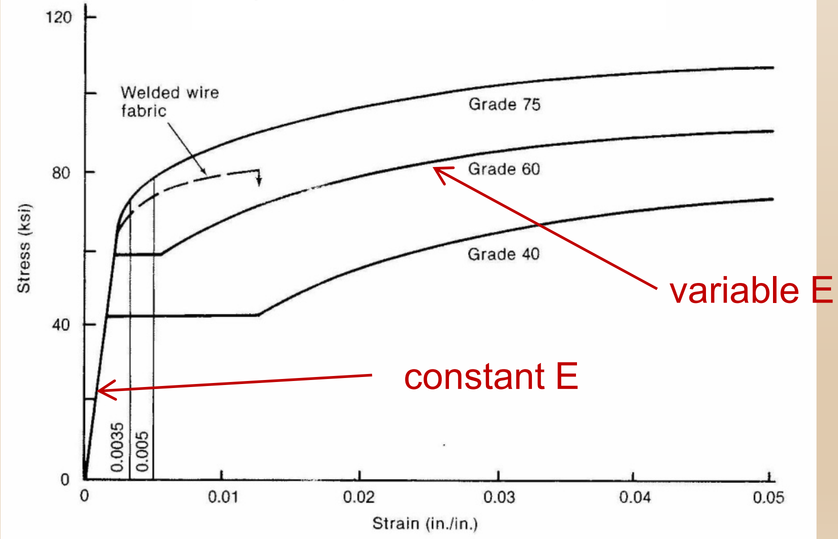
$b := 1\cdot ft$		Width of Cantilever
$h := 18\cdot in$		Depth of Cantilever
$cc := 2\cdot in$		Clear Cover
$d := h - cc = 16\cdot in$		Distance to Reinforcement
$L := 20\cdot ft$		Length of Cantilever
$A_s := 1.56\cdot in^2$		Area of Steel
$E_s := 29{,}000{,}000\cdot \frac{lb}{in^2}$		Modulus of Steel
$f_y := 60000\cdot \frac{lb}{in^2}$		Yield Stength of Steel
$E_c := 3000000\cdot \frac{lb}{in^2}$		Modulus of Concrete
$f_c := 4000\cdot \frac{lb}{in^2}$		Concrete Compressive Strength
$I := \left(\frac{1}{12}\right)\cdot b\cdot h^3$	$I = 5832\cdot in^4$	Moment of Inertia
$a := \frac{(f_y\cdot A_s)}{0.85\cdot f_c\cdot b}$	$a = 2.294\, in$	Height of Compression Zone
$T := f_y\cdot A_s$	$T = 93600\, lb$	Tension in Steel
$C := 0.85\cdot f_c\cdot a\cdot b$	$C = 93600\, lb$	Compression of Concrete
$M := f_y\cdot A_s\cdot\left(d - \frac{a}{2}\right) = 115853\, ft\cdot lb$		Balanced Moment

Yield Displacements for a Simply Supported Beam

With a Concentrated Load (P) at Free End		With a Uniform Load (w) Along Cantilever	
$M_{MaxP} = PL$		$M_{MaxW} = wL^2/2$	
$P_P := \frac{M}{L}$	$P_P = 5793\, lb$	$w := \frac{(2\cdot M)}{L^2}$	$w = 579\, \frac{lb}{ft}$
$\delta_{YieldP} := \frac{(P_P\cdot L^3)}{3\cdot E_c\cdot I}$	$\delta_{YieldP} = 1.5\cdot in$	$\delta_{YieldW} := \frac{(w\cdot L^4)}{8\cdot E_c\cdot I}$	$\delta_{YieldW} = 1.1\cdot in$

Note: Calculations assume a cracked section throughout the length of the beam.

Figure 10-20 – Example Yield Deflection Calculation for a Simple Cantilever Beam



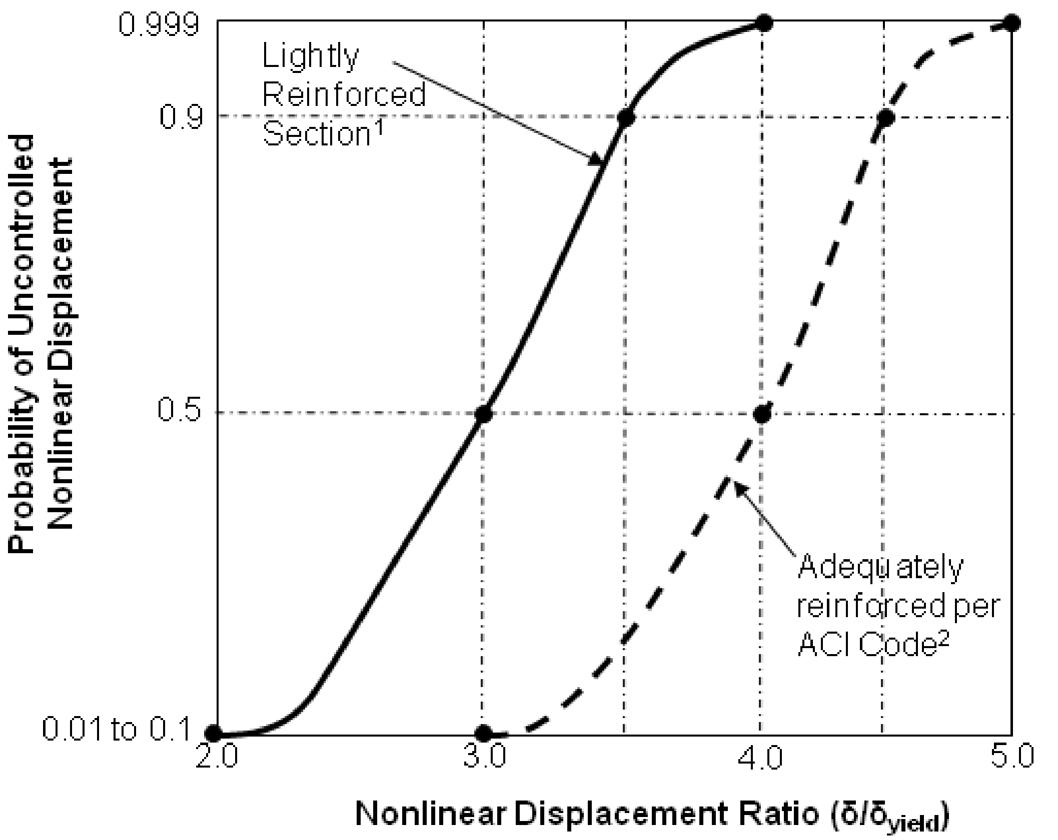
variable E

constant E

- δ_{yield} calculation
  - ✓Straightforward – constant E
  - ✓ Actual yield deflections will likely be larger since moment of inertia will be that for a cracked section (method is conservative)
- δ calculation
  - ✓Not so easy – variable E
  - ✓ Non-linear FEA most accurate approach
  - ✓Simplified approach use ⅓ to ½ E_c
  - ✓System secondary (P-δ) analysis

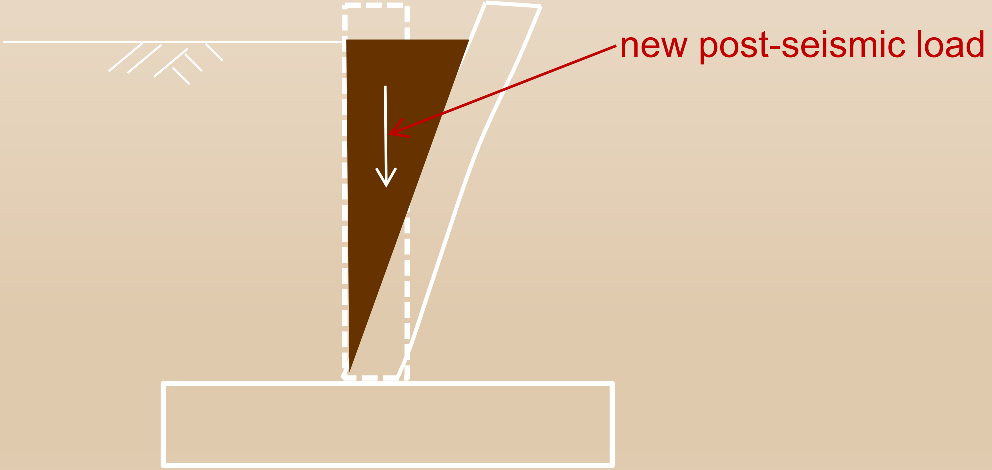
Event 4 - Displacement Criteria

Uncontrolled Nonlinear Displacement System Response (No Shear Failure)



Event 5 - Kinematic Instability

- Three cases to consider
  - ✓ Independent concrete block separated from structure by shear failure (sliding)
  - ✓ Uncontrolled displacement of yielded member (toppling)
  - ✓ Post-seismic instability of yielded member



Takeaway Points

- Failure mechanisms for various types of reinforced concrete structures are generally well understood, but there is significant uncertainty under seismic loading due to limited case histories.
- Many failures have been well documented on navigation structures, mostly resulting from barge impact.
- Virtually no failures of floodwalls or spillway walls have been documented that were the result of structural failures under expected design static or seismic loads.
- Concrete and reinforcement material properties are generally well understood but there may be limited information about in situ properties making risk analysis challenging.
- Type and Duration of Loading is important to understand – consider both static and dynamic (earthquake and barge impact) loading
- Consider both Ductile and Brittle Failure mechanisms
- Seismic reinforcement details have changed dramatically over the past few decades; older concrete hydraulic structures may be more susceptible to brittle failures under seismic loading, but most are pretty robust and probably are not more vulnerable in general
- Modern design codes should be used with care when computing capacity of older reinforced concrete structures