More Discussion on the *AASHTO Guide Specifications for LRFD Seismic Bridge Design*

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Engineers vs. Non-Engineers

- radians and degrees
- Know the answer first
- *The world needs more engineers*

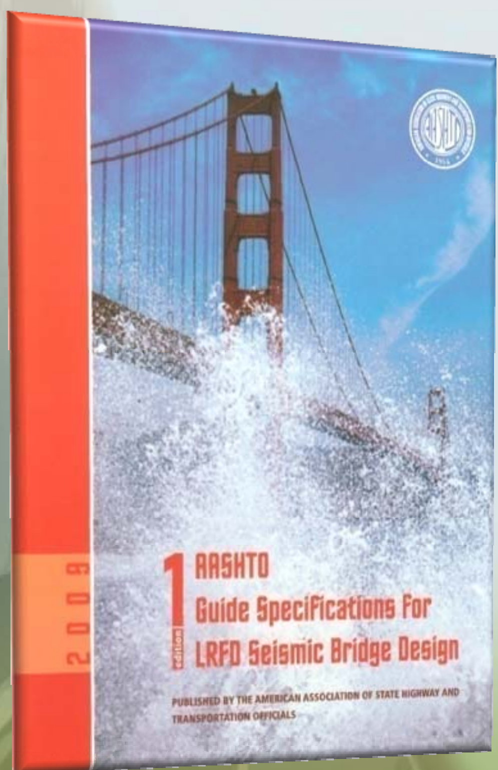
Overview

- QC / QA
  - Approximate methods
  - Displacement spectra
  - Substitute structure method

- Cold climate effects

- Detailing recommendations

Background



- March 2009 – First edition of the *AASHTO Guide Specifications for LRFD Seismic Bridge Design*
- Primarily a displacement-based approach
- A more direct, rational approach

Seismic Analysis Assumptions

- Linear, elastic model used to model non-linear, plastic bridge
- Luckily, the **displacements** calculated from the elastic model are *reasonably* close to those of the non-linear model

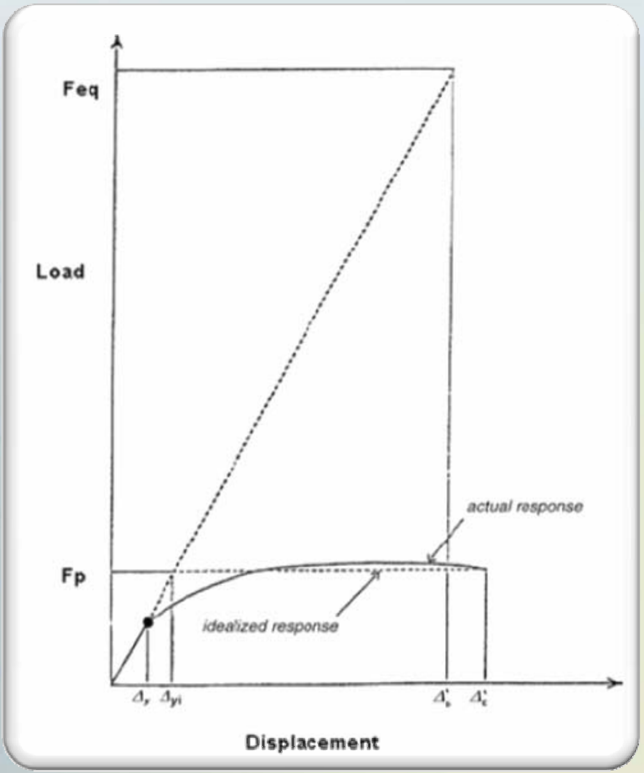


Figure C3.3-1

Reasonably close displacements…

- Displacement magnification, R_d, for short-period, in-elastic responding structures

$$R_d = \left(1 - \frac{1}{\mu_D}\right)\frac{T^*}{T} + \frac{1}{\mu_D} \geq 1.0 \quad \text{for} \quad \frac{T^*}{T} > 1.0 \qquad (4.3.3\text{-}1)$$

$$R_d = 1.0 \quad \text{for} \quad \frac{T^*}{T} \leq 1.0 \qquad (4.3.3\text{-}2)$$

in which:

$$T^* = 1.25 T_s \qquad (4.3.3\text{-}3)$$

where:

μ_D = maximum local member displacement ductility demand
= 2 for SDC B
= 3 for SDC C
= determined in accordance with Article 4.9 for SCD D. In lieu of a detailed analysis, μ_D may be taken as 6.

T_s = period determined from Article 3.4.1 (sec.)

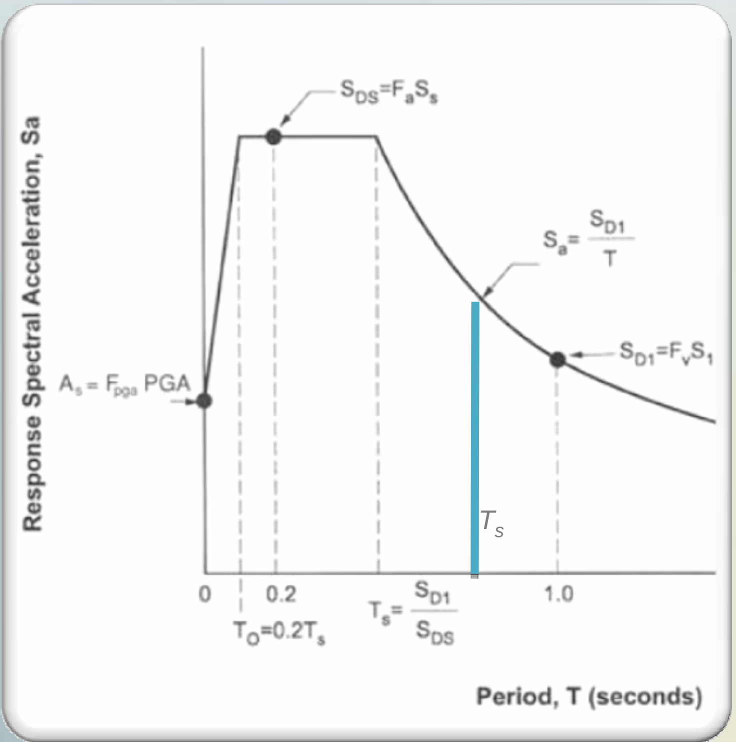
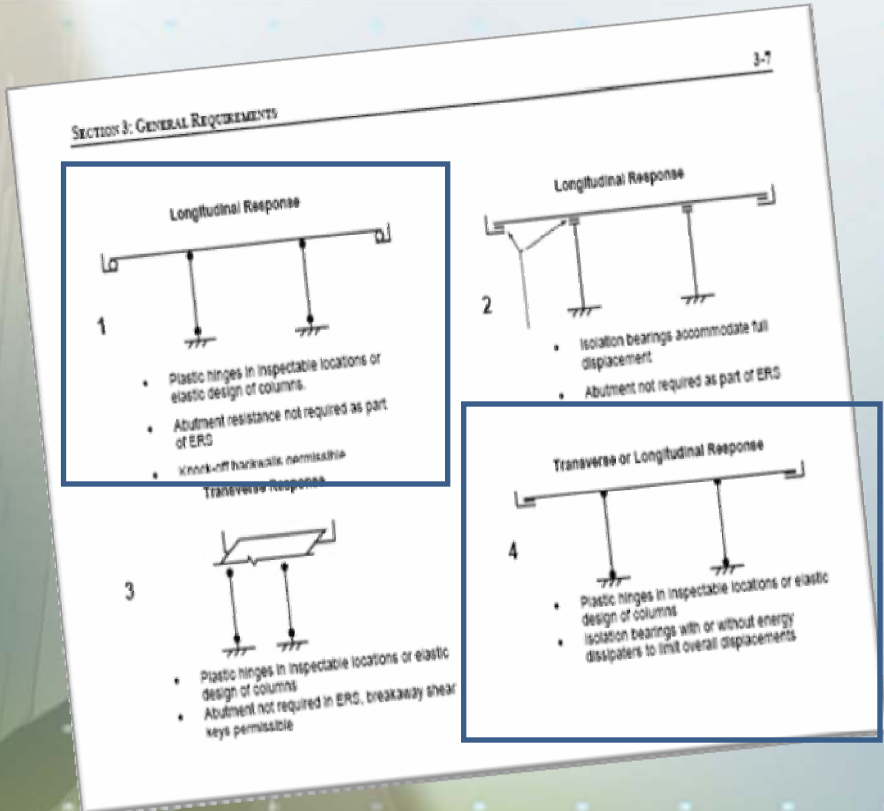


Figure 3.4.1-1

EQ Resisting Systems and Elements



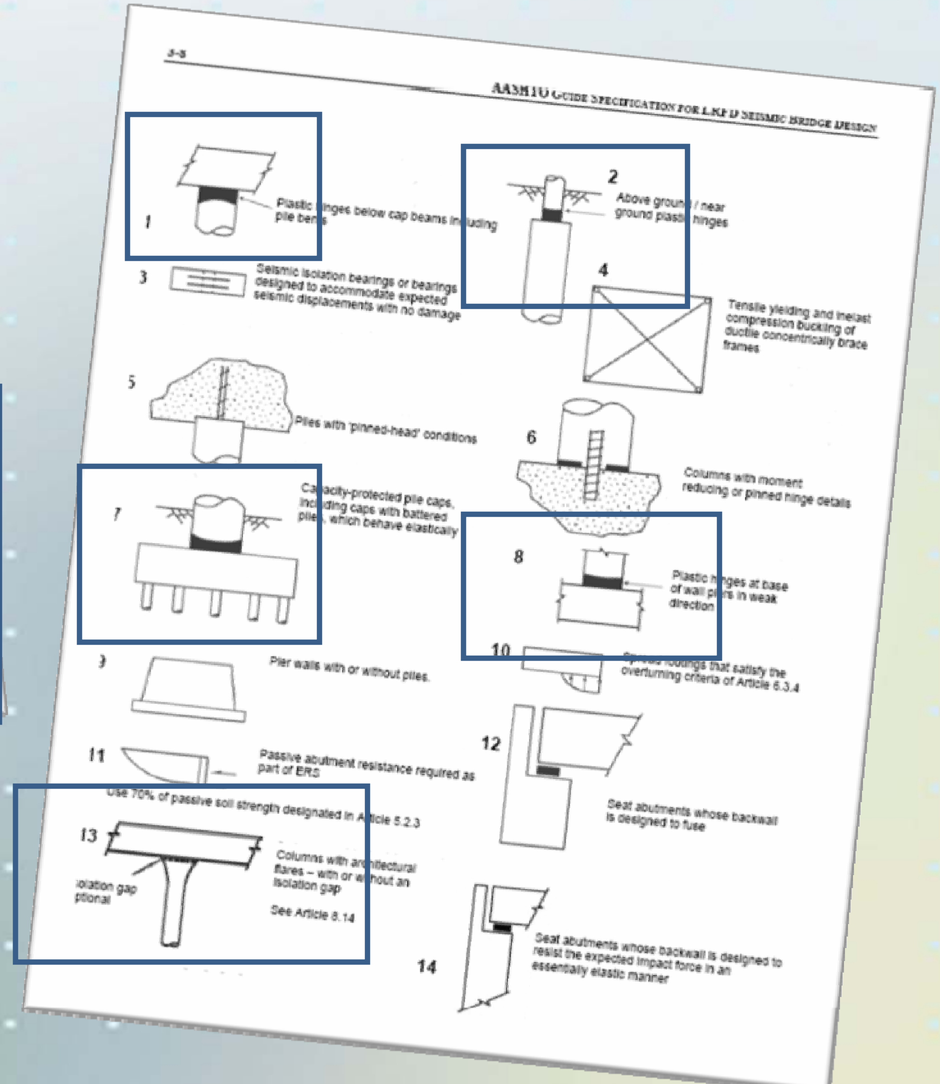
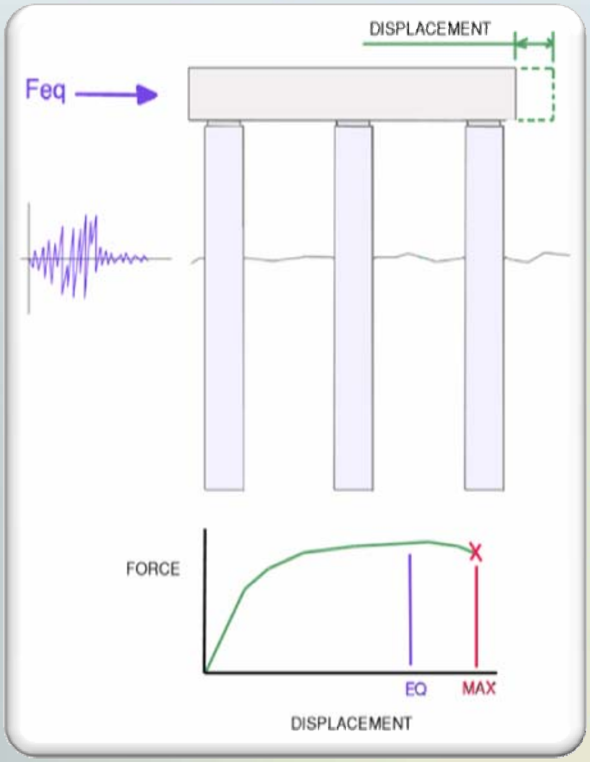


Figure 3.3-1a and b

Displacement-Based Approach

- Tools currently that allow us to explicitly compare the design displacement demand to the nominal displacement capacity

- Large plastic displacements can be achieved provided that brittle and premature failure modes can be prevented



Displacement Capacity Notation

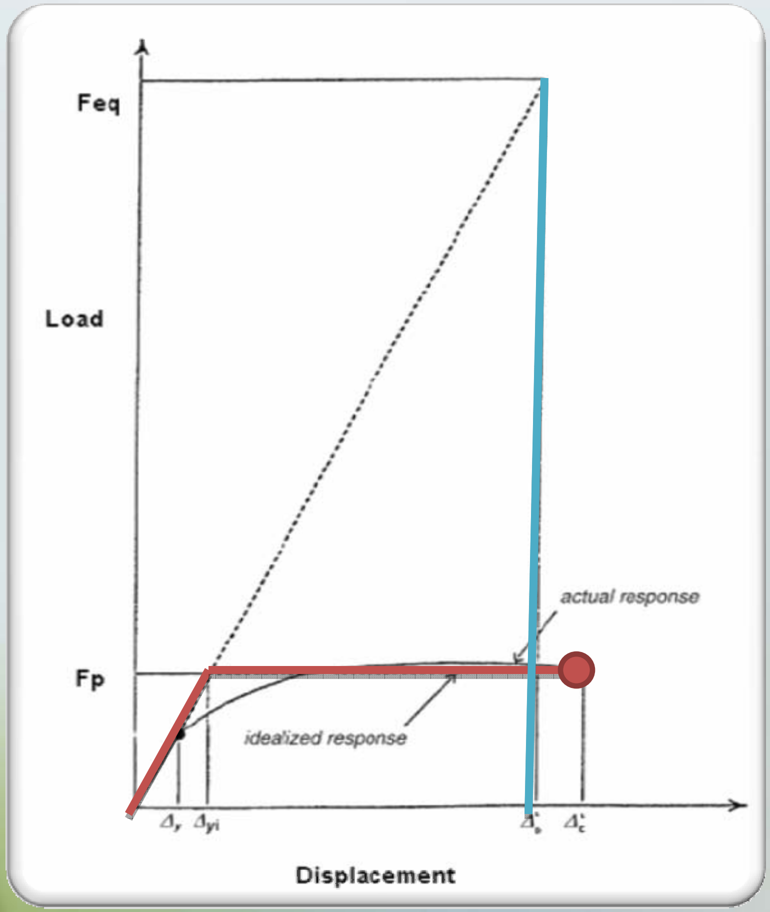


Figure C3.3-1

Displacement Capacity Calculation

- For SDC B and C, *closed-form* member displacement capacity equations are available

SDC B: $\Delta^L_C = 0.12H_o(-1.27 * ln(x) - 0.32) > 0.12H_o$

SDC C: $\Delta^L_C = 0.12H_o(-2.32 * ln(x) - 1.22) > 0.12H_o$

where:

$x = \Lambda B_o / H_o$

Λ = fixity factor, pin-fix = 1, fix-fix = 2

H_o = contraflexure to plastic hinge distance (FT)

B_o = column diameter (FT)

Displacement Capacity Calculation

- For SDC D, a pushover analysis is required and often requires the following steps:

  1.) collect geometric and material data
  2.) determine analytic plastic hinge length
  3.) generate moment-curvature relationships with axial loads (DL, DL + Overturning, DL - Overturning) usually by computer
  4.) calculate corresponding lateral load and displacement
  5.) determine Overturning forces associated with lateral load
  6.) if calculated Overturning is within 10% of assumed continue, otherwise return to step 3
  7.) compare lateral displacement demand to displacement capacity
  8.) if demand exceeds capacity, revise sections and return to step 1
  9.) complete design including capacity protection and ductile detailing

Material Properties for Push-Over

- For the SDC D, push-over analysis is required

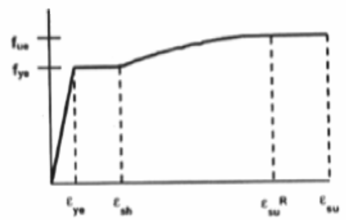


Figure 8.4.2-1 Reinforcing Steel Stress-Strain Model.

Table 8.4.2-1 Stress Properties of Reinforcing Steel Bars.

Property	Notation	Bar Size	ASTM A706	ASTM A615 Grade 60
Specified minimum yield stress (ksi)	f_y	#3 - #18	60	60
Expected yield stress (ksi)	f_{ye}	#3 - #18	68	68
Expected tensile strength (ksi)	f_{ue}	#3 - #18	95	95
Expected yield strain	ε_{ye}	#3 - #18	0.0023	0.0023
Onset of strain hardening	ε_{sh}	#3 - #8	0.0150	0.0150
		#9	0.0125	0.0125
		#10 - #11	0.0115	0.0115
		#14	0.0075	0.0075
		#18	0.0050	0.0050
Reduced ultimate tensile strain	ε_{su}^R	#4 - #10	0.090	0.060
		#11 - #18	0.060	0.040
Ultimate tensile strain	ε_{su}	#4 - #10	0.120	0.090
		#11 - #18	0.090	0.060

Table 8.4.2-1

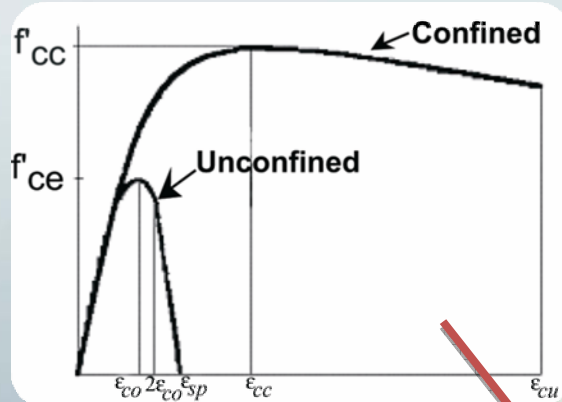


Figure 8.4.4-1

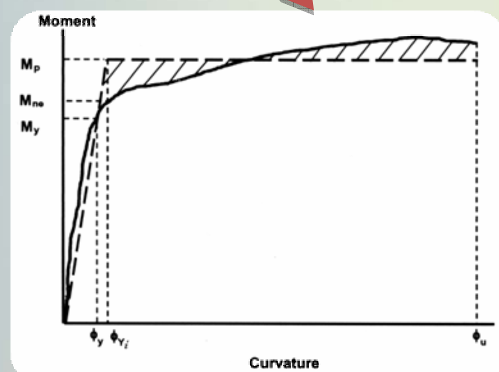


Figure 8.5-1

Displacement Capacity Check

- the use of curvature in design is uncommon
- don't have a good "feel" for curvature values
- desire a method to predict / check the computer results
- could use the closed-form equations to start but they are developed for specific target ductilities

Approximate Methods - ϕ_{yi}

- For a rough check of conventional circular reinforced concrete column sections:

$$\phi_{yi} \sim 2.25 * \varepsilon_y / 12B_o \sim 1/2300B_o$$

where:

ϕ_{yi} = idealized yield curvature (1/IN)
B_o = column diameter (FT)
ε_y = expected yield strain ~ 0.002345 (IN/IN)

Approximate Methods - Δ_{yi}

- For a rough check of conventional circular reinforced concrete column sections:

$$\Delta_{yi} \sim 1/3 * \phi_{yi} * (12H_o + 0.15 * f_{ye} * d_b)^2 \sim H_o^2/48B_o$$

where:

Δ_{yi} = idealized yield displacement (IN)

H_o = contraflexure to plastic hinge distance (FT)

d_b = diameter of longitudinal column bar (IN)

ϕ_{yi} = idealized yield curvature (1/IN)

B_o = column diameter (FT)

f_{ye} = expected yield stress (KSI)

Approximate Methods - ϕ_u

- And for a very rough check of conventional circular reinforced concrete column sections:

$$\phi_u = \min(\varepsilon_{cu}/c_c \;,\; \varepsilon_{su}^R/d\text{-}c) \sim \varepsilon_{su}^R/12B_o$$

where:

ϕ_u = ultimate curvature (1/IN)

ε_{cu} = ultimate confined concrete strain (1/IN)

ε_{su}^R = reduced ultimate tensile strain (IN/IN)

c_c = neutral axis to edge of confined core (IN)

d-c = neutral axis to extreme tension bar (IN)

B_o = column diameter (FT)

Approximate Methods - Δ_c^L

- And for a very rough check of conventional circular reinforced concrete column sections:

$$\Delta^L_C \sim \Delta_{yi} + (\phi_u - \phi_{yi})*L_p*(12H_o - L_p/2) \sim H_o^2/10B_o$$

where:

Δ^L_C = local displacement capacity (IN)

H_o = contraflexure to plastic hinge distance (FT)

L_p = analytical plastic hinge length (IN)

ϕ_u = ultimate curvature (1/IN)

ϕ_{yi} = idealized yield curvature (1/IN)

B_o = column diameter (FT)

What about Double Curvature?

- Column height, H_o, is taken from the maximum moment location to the contraflexure point
- Then add the displacement results for each part

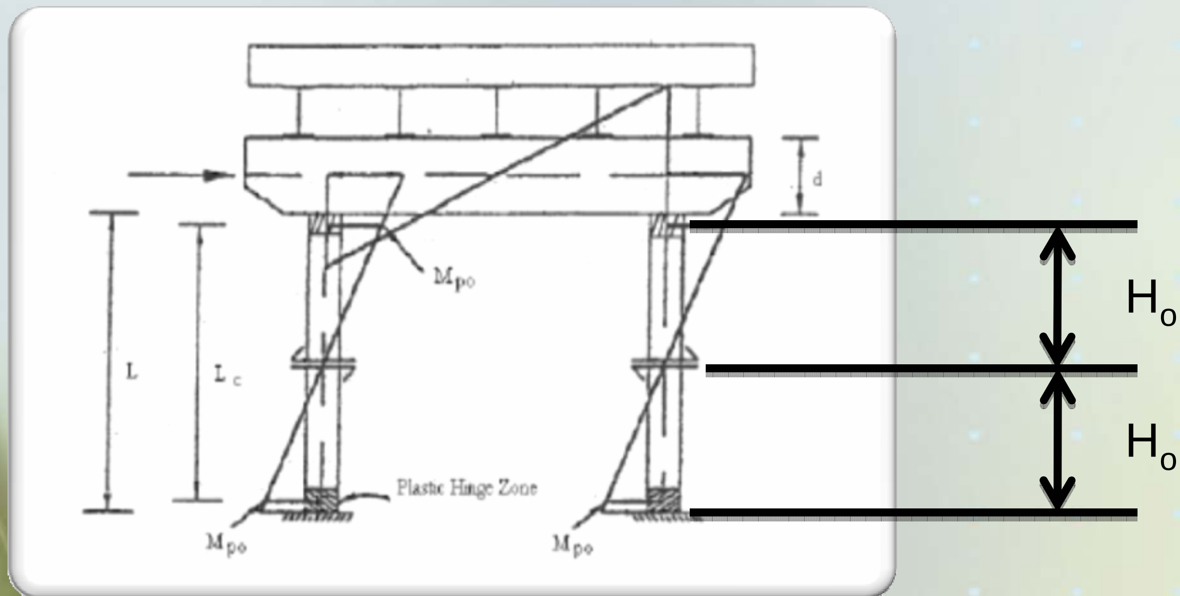
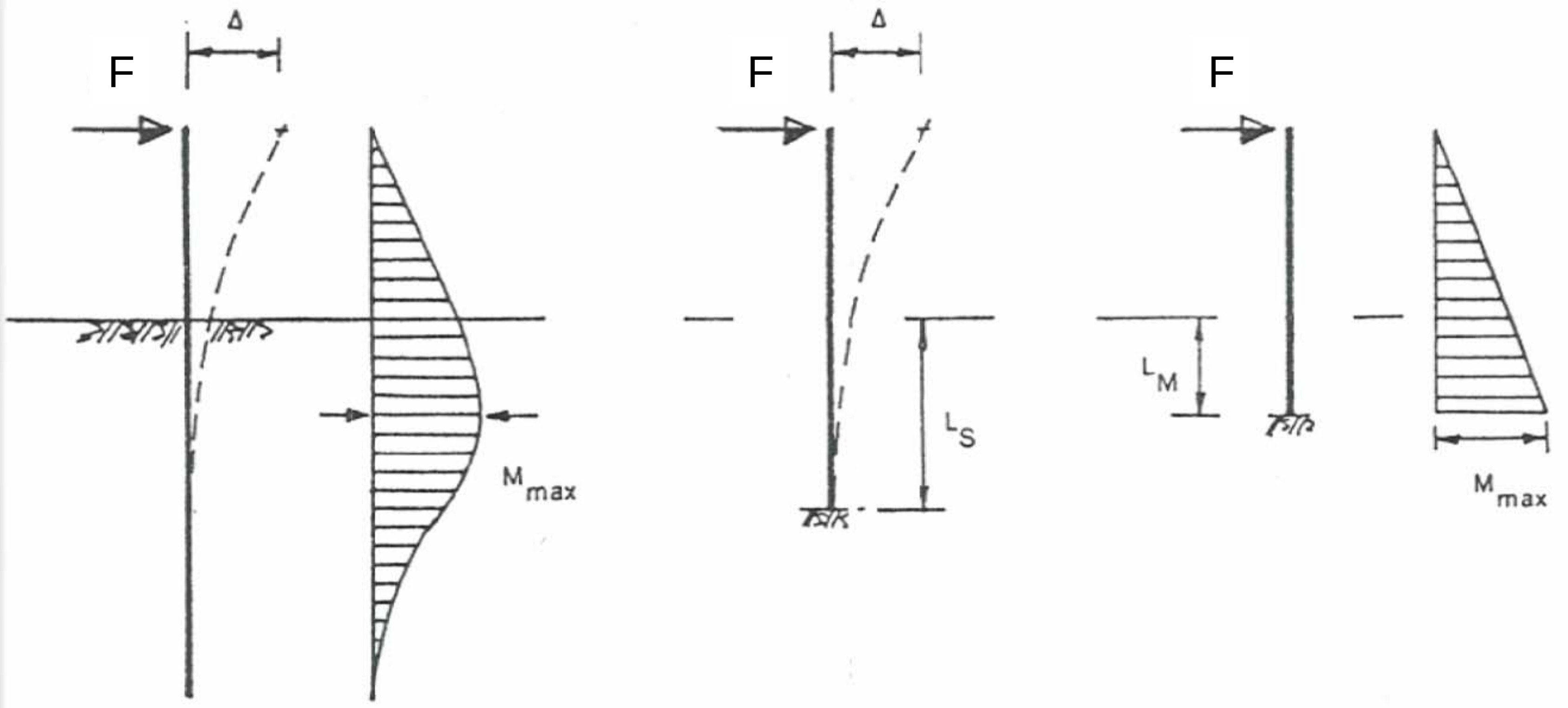


Figure 4.11.2-1

What about Pile/Shaft Extensions?

- In this case, the H_o values will not be of equal length above and below the contraflexure point
- Calculate Δ_{yi} from the point of effective fixity, L_S, for stiffness calculations (typically $3B_o < L_S < 7B_o$)
- Calculate Δ_c^L from the plastic hinge location, L_M, below the ground line (typically $1B_o < L_M < 3B_o$)

What about Pile/Shaft Extensions?



Seismic Displacement Spectra

- The use of the displacement spectra may allow for a quick check of the analysis results

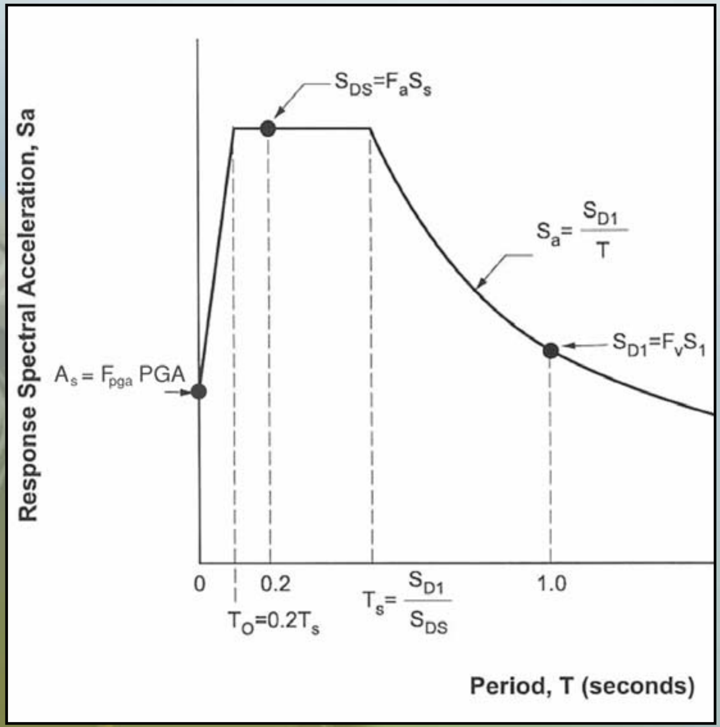
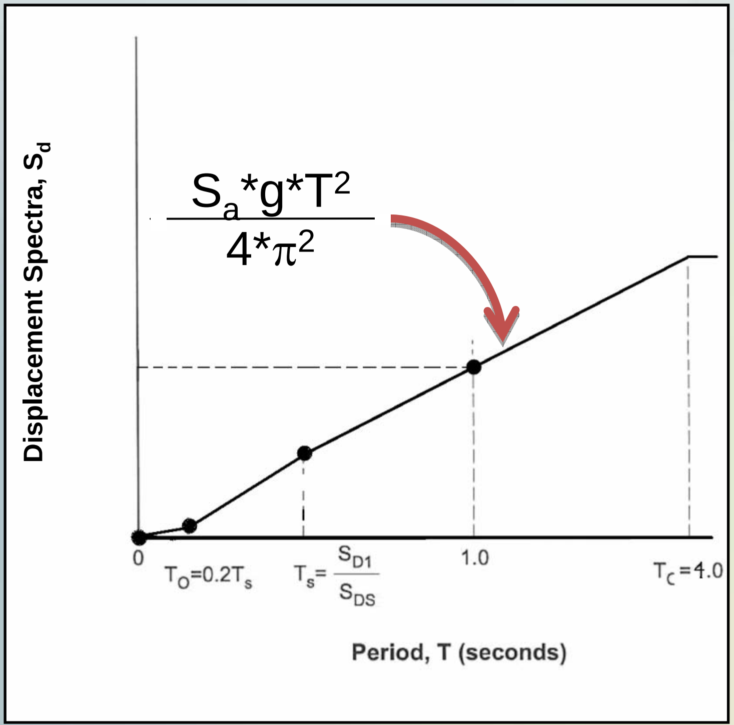


Figure 3.4.1-1



From CDROM or calculate

Seismic Displacement Spectra

Recognizing the nearly linear relationship, the EQ deflection for $T_S < T < T_C$ ca be approximated as

$$\Delta^L_D \sim 10 * S_{D1} * T$$

where:

Δ^L_D = local displacement demand (IN)
S_{D1} = $F_v * S_1$
F_v = site coefficient for S_1
S_1 = 1.0-sec. period spectral acceleration coefficient
T = period of vibration of the structure (SEC)

Substitute Structure Method

- Consider the method by which abutment soil resistance is often addressed

- An effective stiffness is used to provide the passive soil resistance in the seismic model

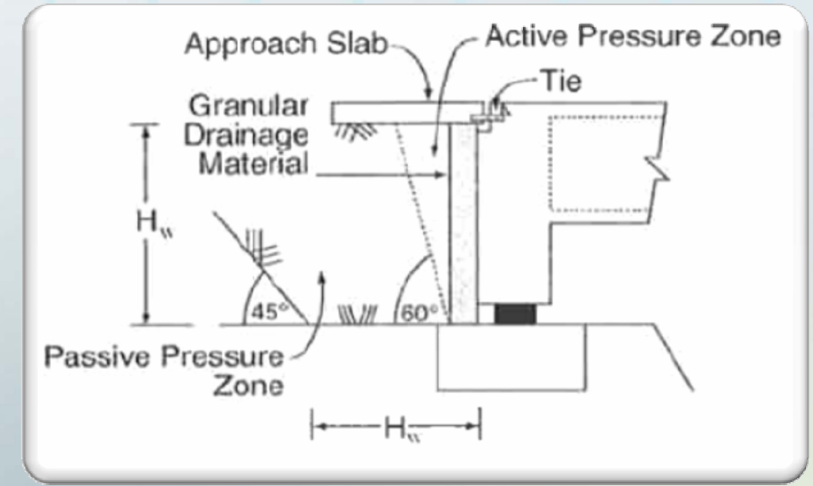


Figure 5.2.3.2-1

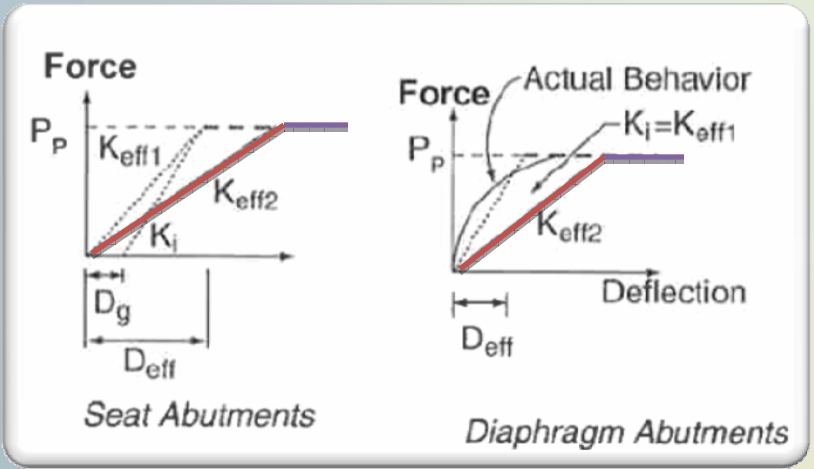


Figure 5.2.3.3-1

Substitute Structure Method

- Why not do the same thing for the entire bridge?

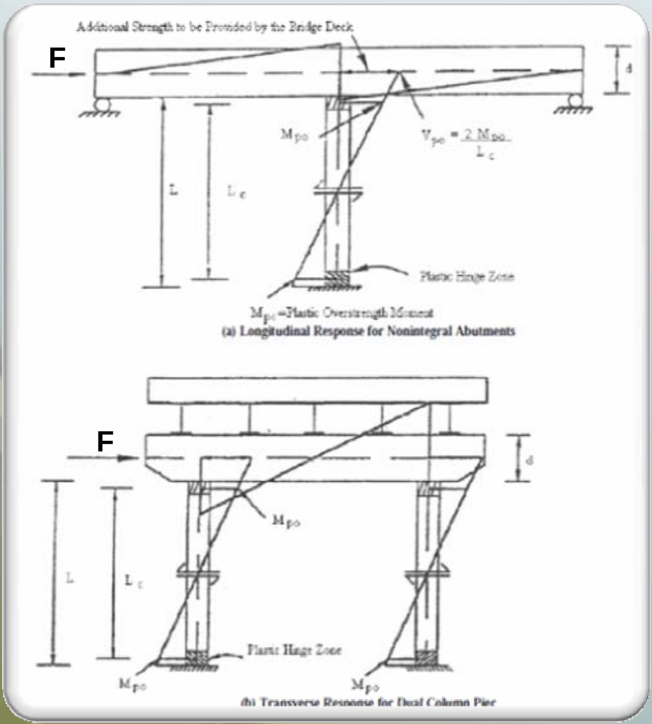


Figure 4.11.2-1a and b

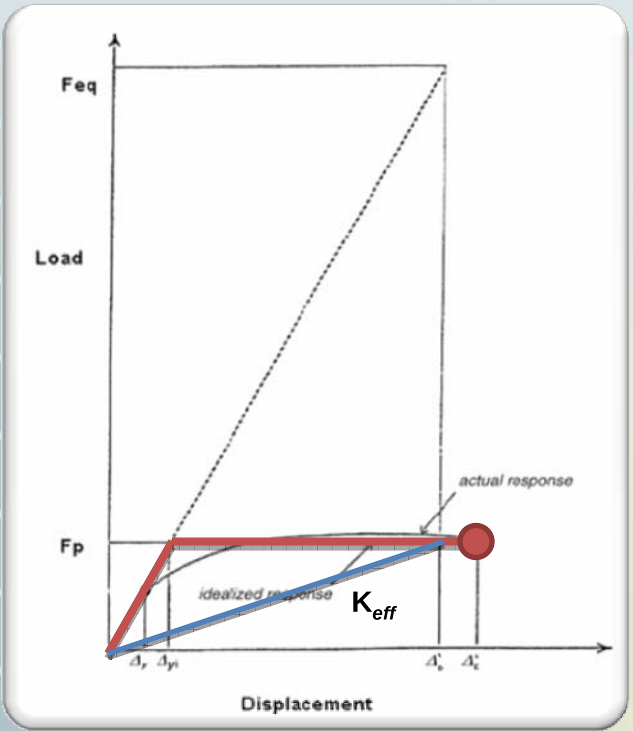


Figure C3.3-1

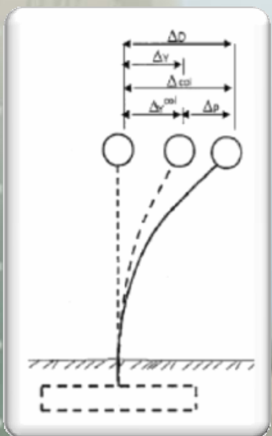
Substitute Structure Method

- Advantages
  - insensitive to initial stiffness
  - relatively easy to use
  - different methodology for QC/QA

- Disadvantages
  - *equivalent viscous damping adjustment*
  - complex geometry limitations
  - limited utilization to date

Substitute Structure - Example

- Given:



Simple SDOF bridge

$F_p = V_{po} = 1200$ KIPS

$\Delta_{yi} = 2$ IN

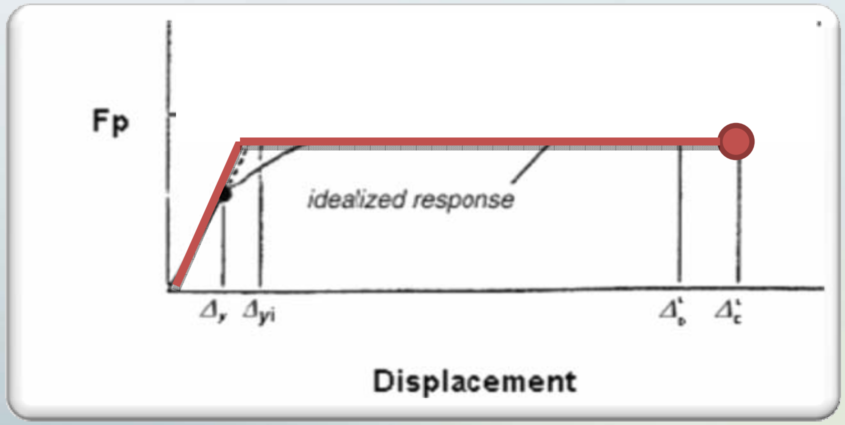
$\Delta^L_C = 10$ IN

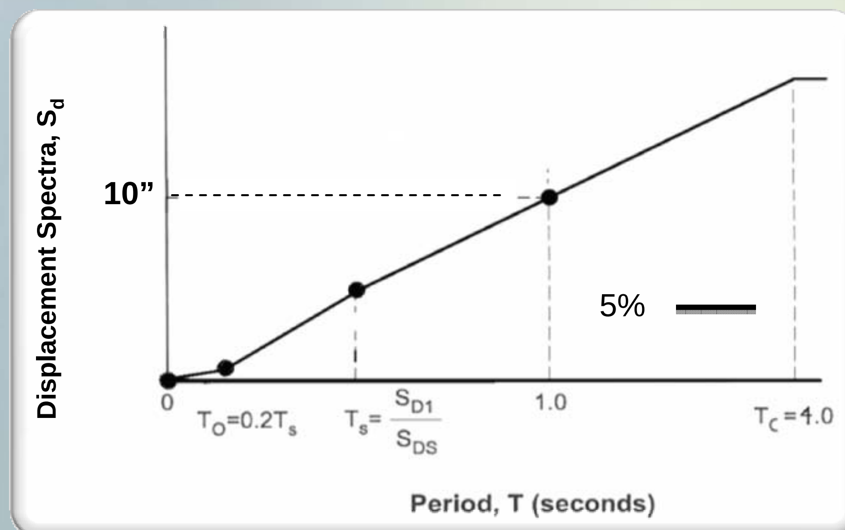
$W_{seismic} = 2500$ KIPS

For displacement spectra shown

- Find:

$\Delta^L_D = ?$





From CDROM

Substitute Structure - Example

- Solution:

try $\Delta^L_D = 8''$

and $K_{eff} = 1200K/8'' = 150K/IN$

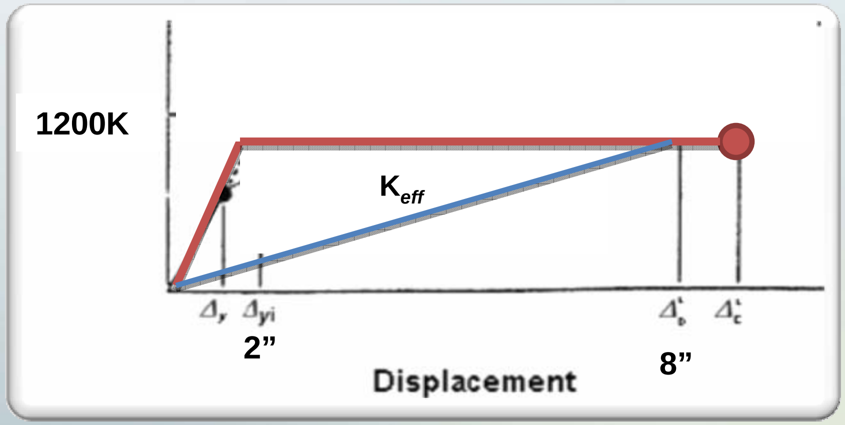
so $T_{eff} = 2\pi\sqrt{\dfrac{W_{seismic}}{g*K_{eff}}} = 1.31\ s$

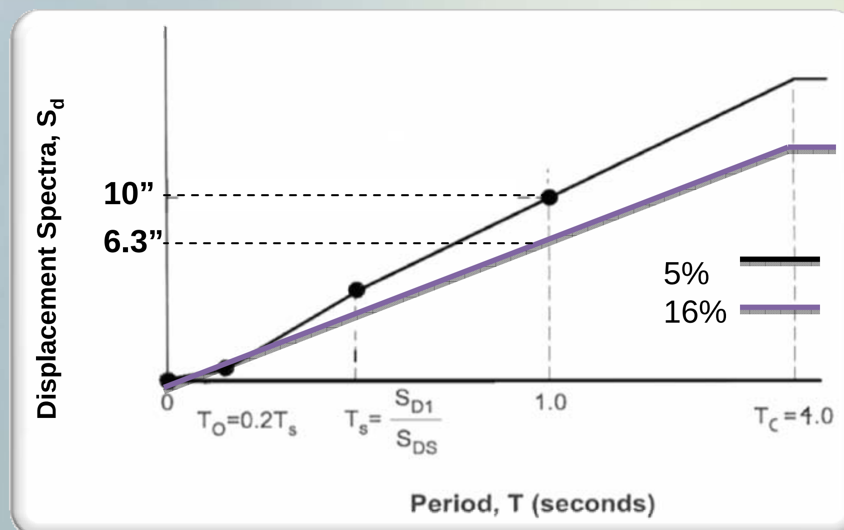
and $\mu_D = 8''/2'' = 4$

so $\xi_{eq} = 0.05 + \dfrac{4(\mu_D - 1)}{9(\pi\mu_D)} = 0.16$

and $R_D = (0.05/0.16)^{0.4} = 0.63$

then $\Delta^L_D = 10*1.31*0.63 = 8.3''$





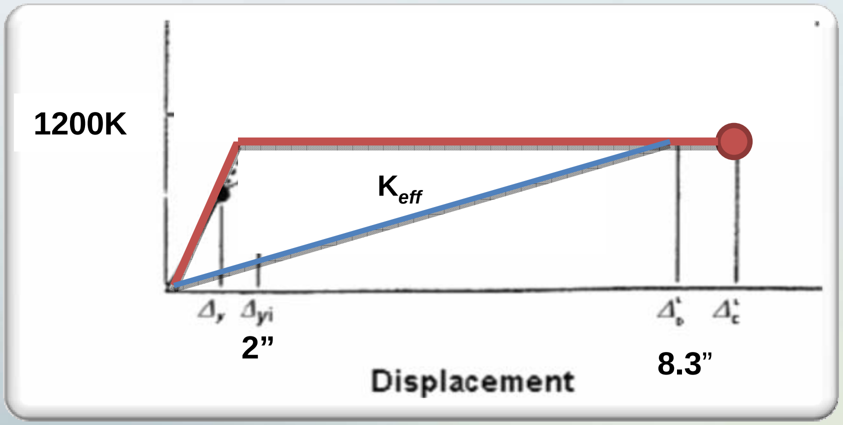
From CDROM and Eq. 4.3.2-1

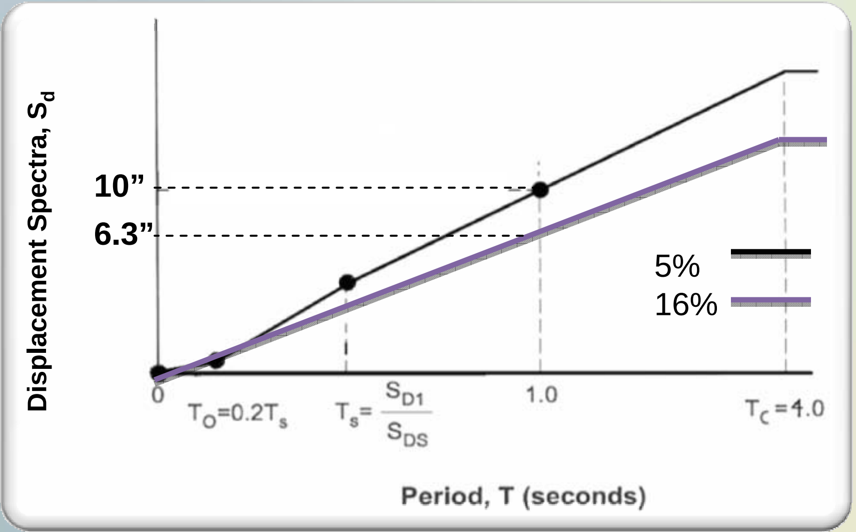
Substitute Structure - Example

- Second iteration:

try $\Delta^L_D = 8.3''$
and $K_{eff} = 145K/IN$
so $T_{eff} = 2\pi\sqrt{\dfrac{W_{seismic}}{g*K_{eff}}} = 1.33\ s$
and $\mu_D = 8.3''/2'' = 4.15$
so $\xi_{eq} = 0.05 + \dfrac{4(\mu_D-1)}{9(\pi\mu_D)} = 0.16$

and $R_D = (0.05/0.16)^{0.4} = 0.63$
then $\Delta^L_D = 10*1.33*0.63 = 8.4''$
elastic : $\Delta^L_D = 8.7''$ – good check





From CDROM and Eq. 4.3.2-1

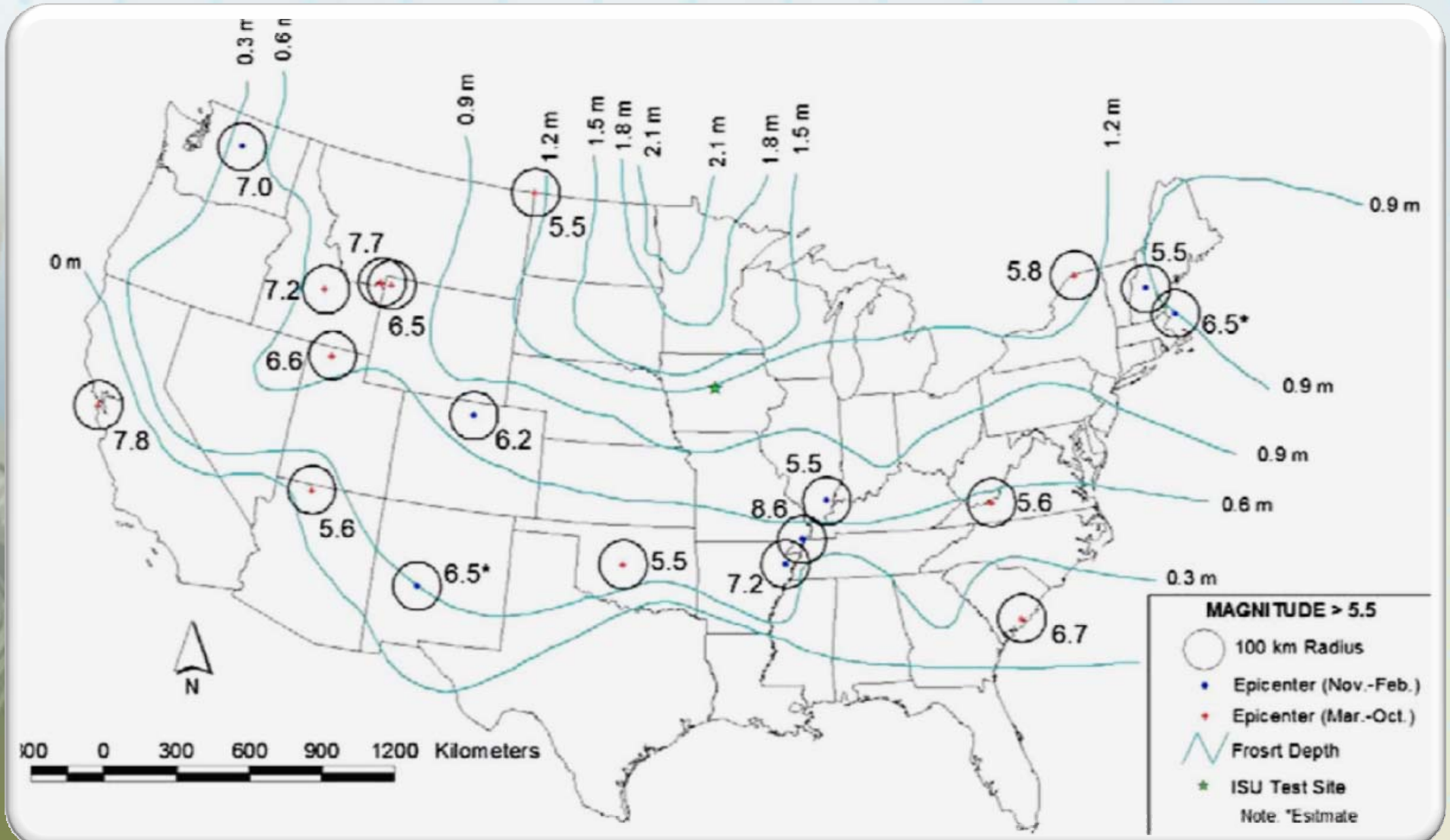
Substitute Structure - Resources

- *Alternately, change F_p by adding or subtracting steel until desired displacement demand is achieved*
- M. J. N. Priestley, G. M. Calvi, and M. J. Kowalsky, *Displacement-Based Seismic Design of Structures*, IUSS Press, Pavia, Italy, 2007.
- Direct Displacement-Based Design

Cold Climate Concerns

(Yang 2009)

Cold Climate Concerns



(Sritharan et al. 2008)

Cold Climate Concerns

- Research regarding the effects of cold climate

1.) **material mechanics** – strength increases, ductility decreases, L_p decreases*

2.) **boundary conditions** – frozen soil much stiffer then unfrozen soil

3.) **site coefficient** – not typically affected but may result in higher demands in some circumstances

Cold Climate – Material Mechanics

- No changes to reinforcing strain limits
- Increase *expected* concrete strength, f'_{ce}, by 40%
- Increase *expected* yield stress, f_{ye}, and *expected* tensile strength, f_{ue}, by 10%
- Reduce analytical plastic hinge length, L_p, by 40% *

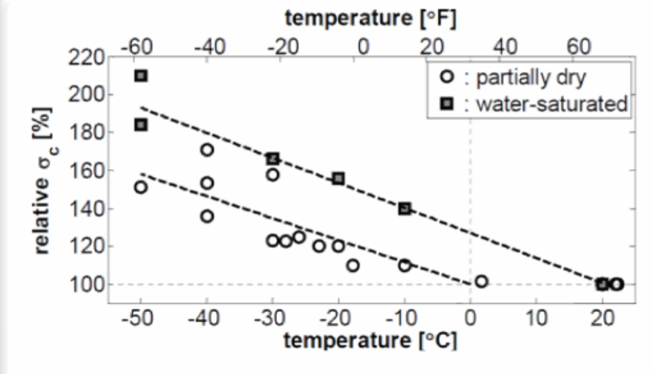


Figure 1.1. Effect of low temperatures in compressive strength of concrete

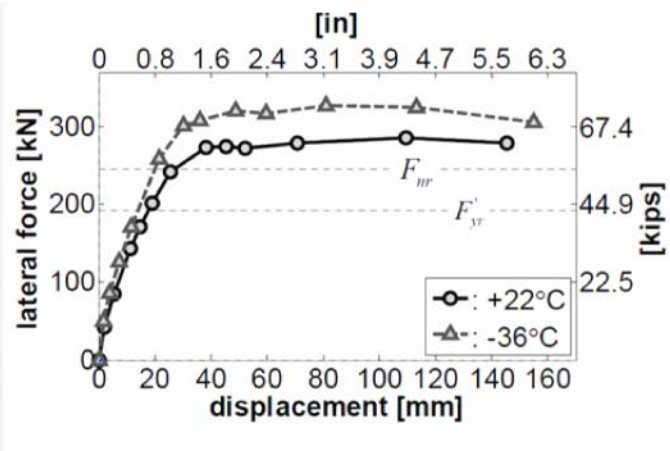


Figure 4.66 Average first cycle envelopes of FL-89C and FL-89A.

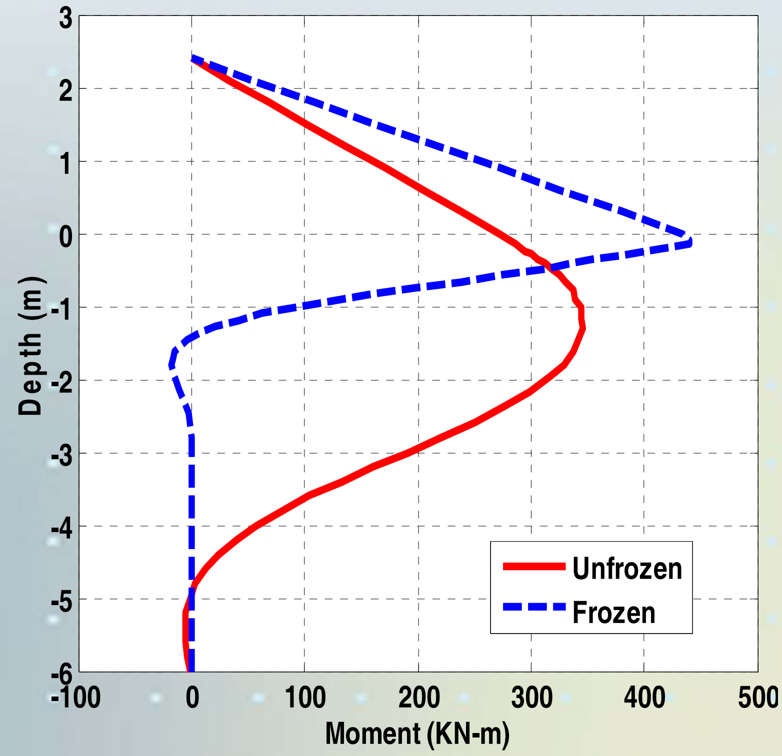
Kowalsky et al. (2008)

Cold Climate – Boundary Condition

- Frozen soil is up to 100 times more stiff than unfrozen soil
- AKDOT Rule-of-thumb:

  stiffness fixity at B_o
  plastic moment at $B_o / 2$

- Research recommendations for simplified and refined analyses are forthcoming



0.3m imposed top deflection
(Yang 2009)

Cold Climate – Site Coefficients

- Most cases the stiffer frozen soil is slightly less than the unfrozen response spectra
- For design, use envelope of unfrozen site coefficient spectra and Site Class “B” site coefficient spectra
- In some cases the response spectra can be amplified beyond un-frozen case
- Research ongoing - better recommendations are forthcoming for simplified and refined analysis

Detailing

- Distribution of reinforcing steel in pier cap beams
- Primary shear and joint shear reinforcing

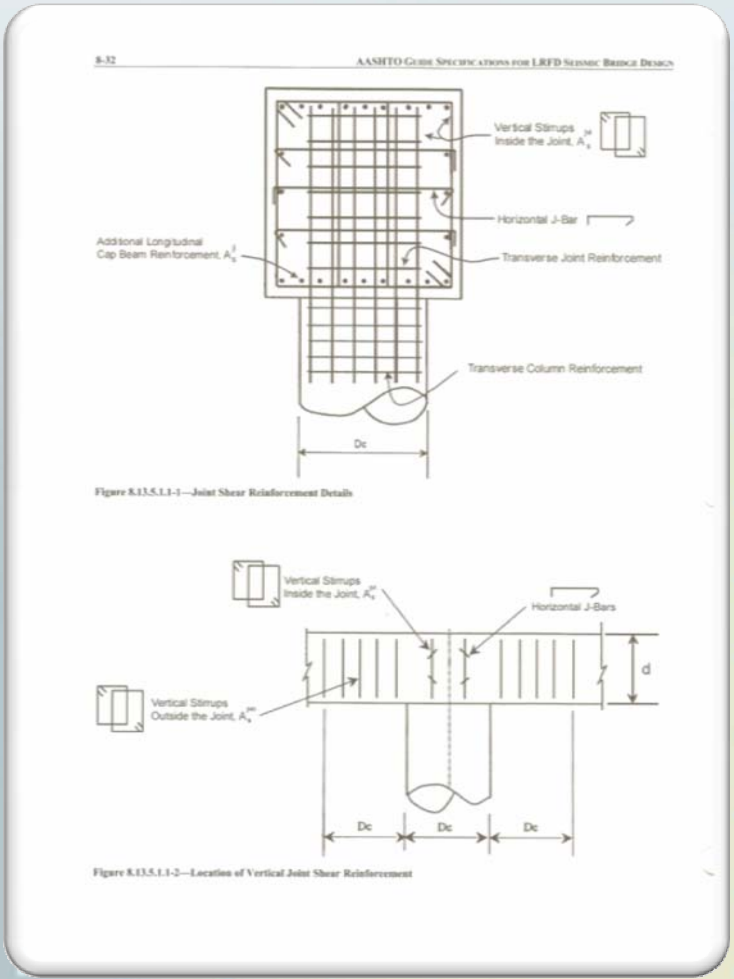
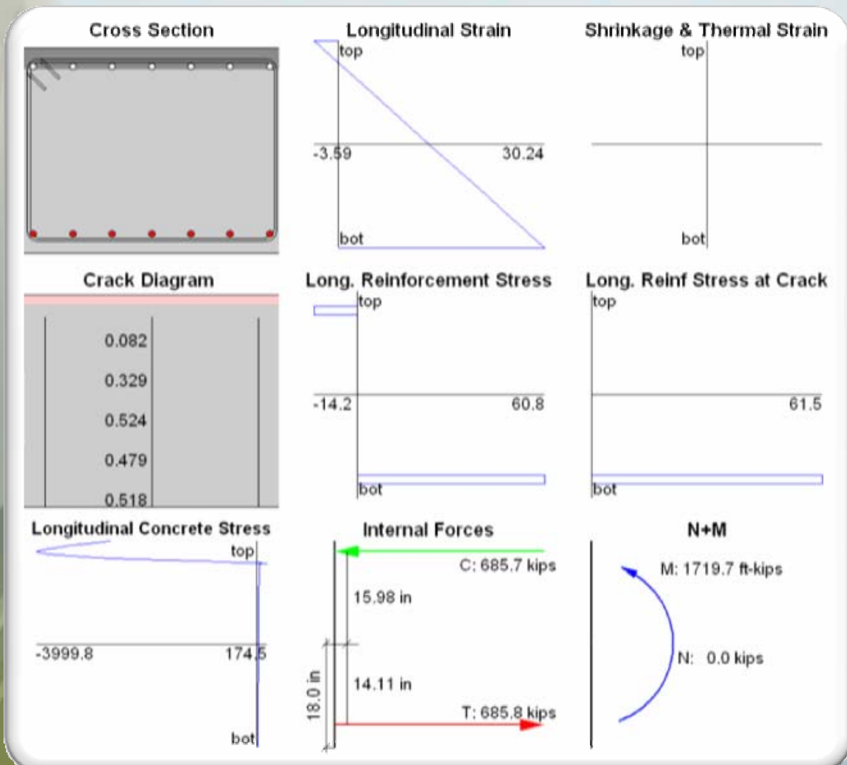
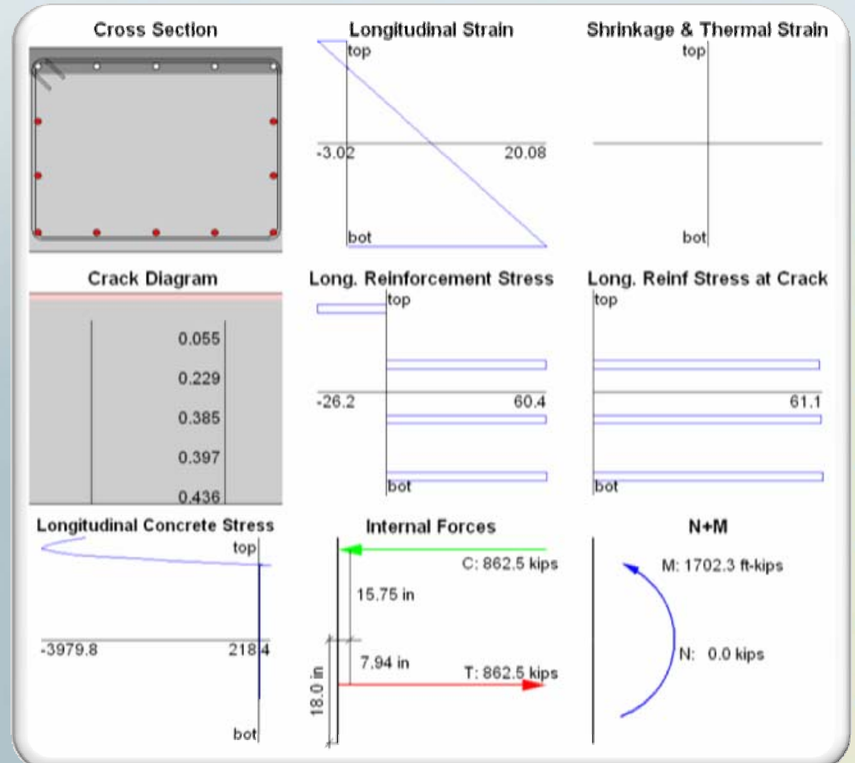


Figure 8.13.5.1.1-1 and 2

Detailing - Flexure

- Flexural steel distributed traditionally and uniformly





M_n = 1720 K-FT **M_n = 1700 K-FT**

Detailing - Shear

- Calculate conventional shear stirrup spacing, S_v, and joint shear spacing, S_j then find total shear stirrup spacing, S

$$1/S = 1/S_v + 1/S_j$$

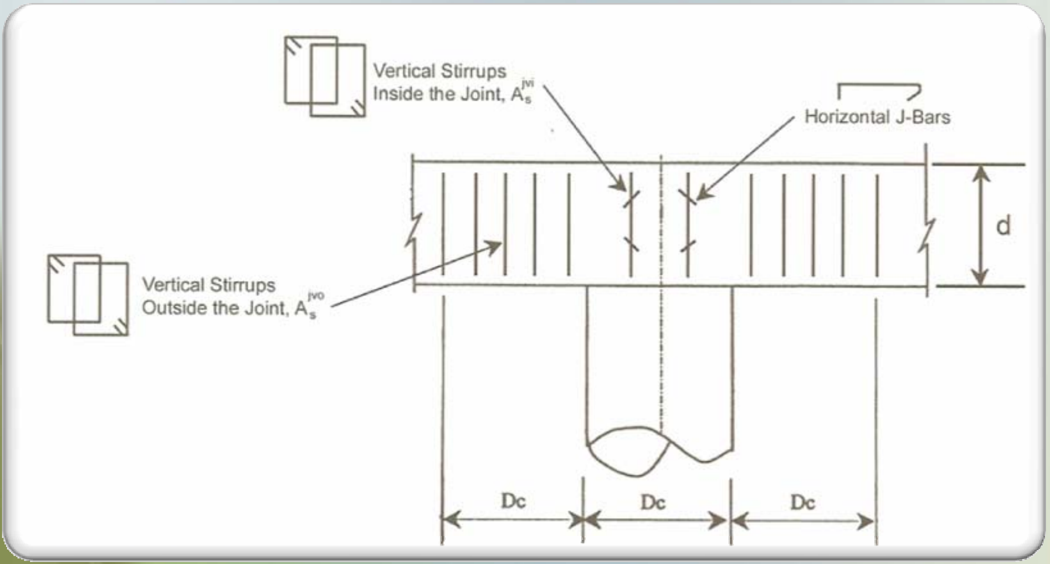


Figure 8.13.5.1.1-2

Summary

- Need for QC / QA
- Use simple tools for verifying results
- Use more than one methodology
- Consider climate effects

Thank You & Questions

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