AASHTO Provisions for Loss of Prestress: Explained

(AASHTO 5.9.5)

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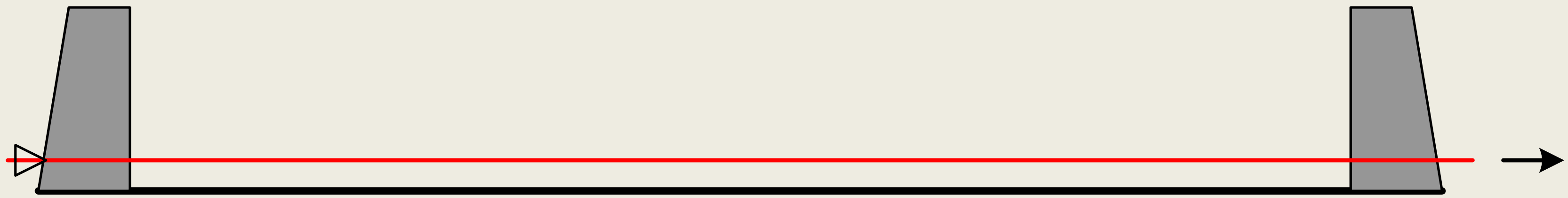
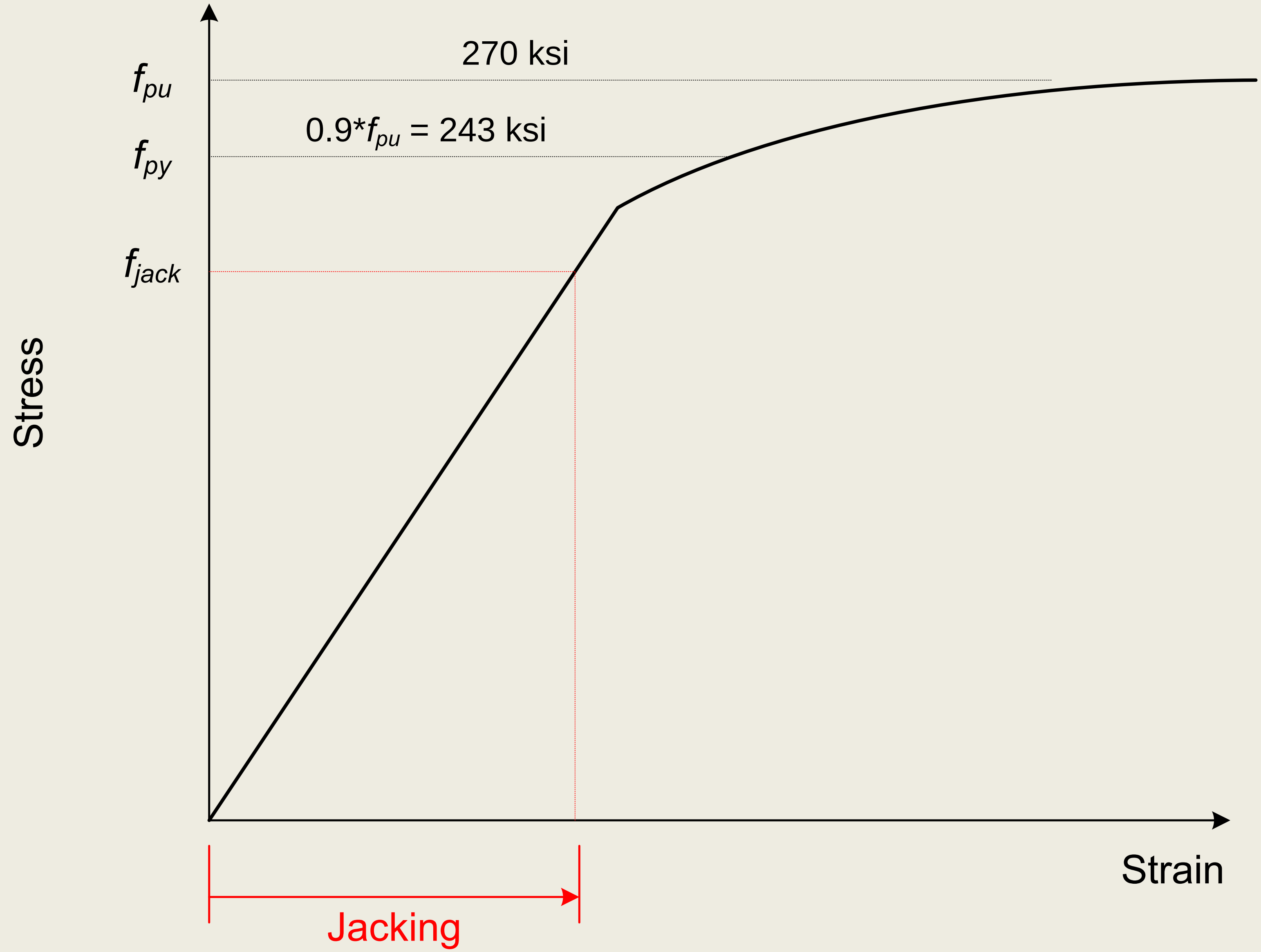
Developed by Brian Swartz for the ABCD Susquehanna Technical Conference, 2013

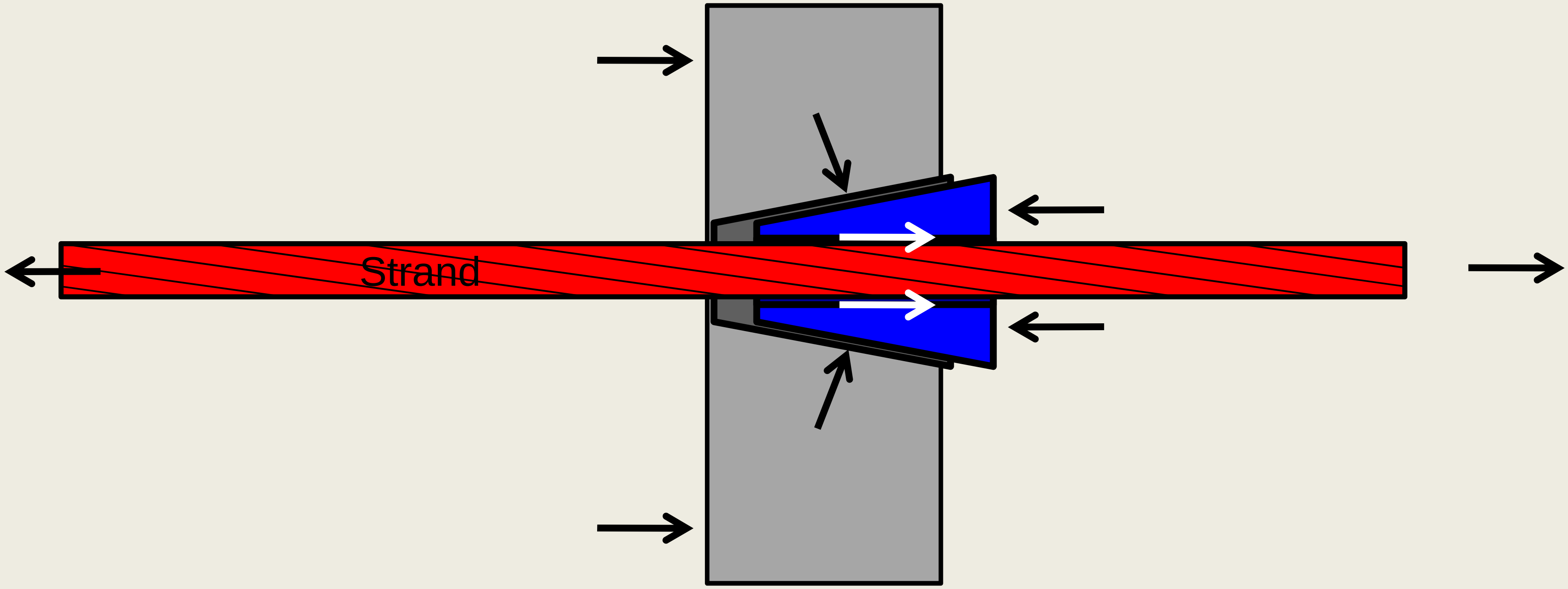
Construction Timeline: Tension Strands



P/S Steel Properties: Stress vs. Strain (Grade 270)



Construction Timeline: Anchorage Seating



P/S Steel Properties: Relaxation

- Loss of stress in a stressed material held at constant length
- Recall: Creep = Change in length of a material under constant stress
- Most significant factors: f_{pi}/f_{py} and time

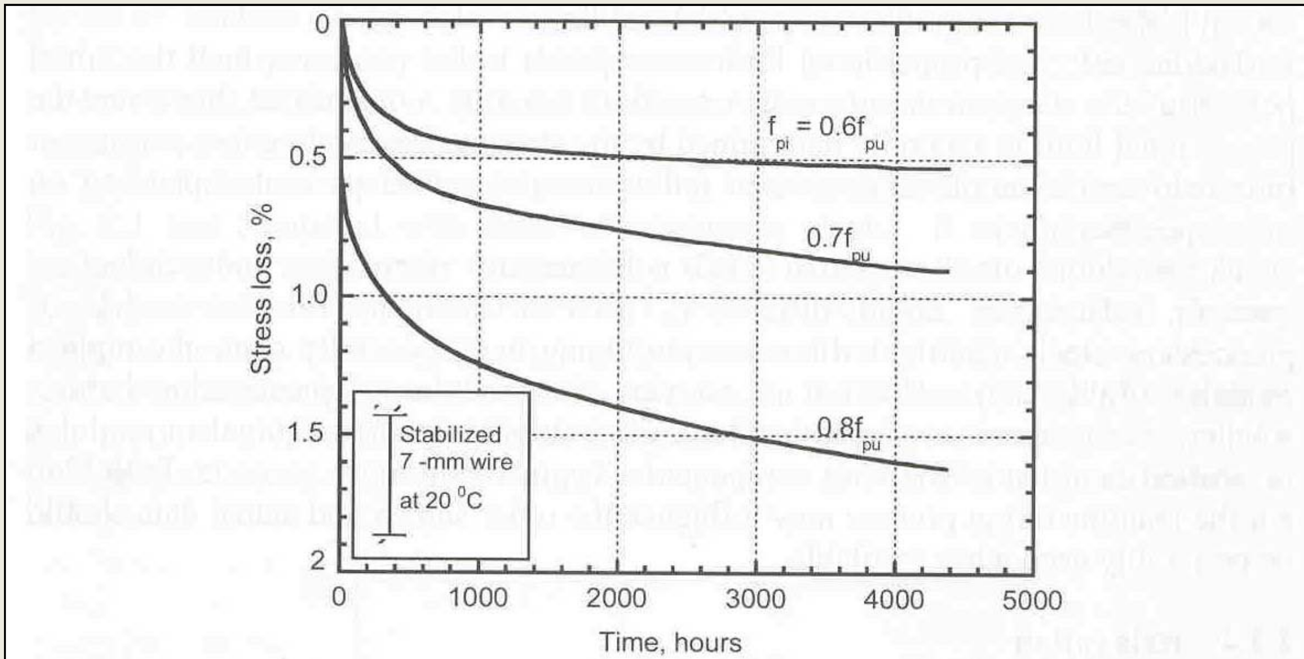
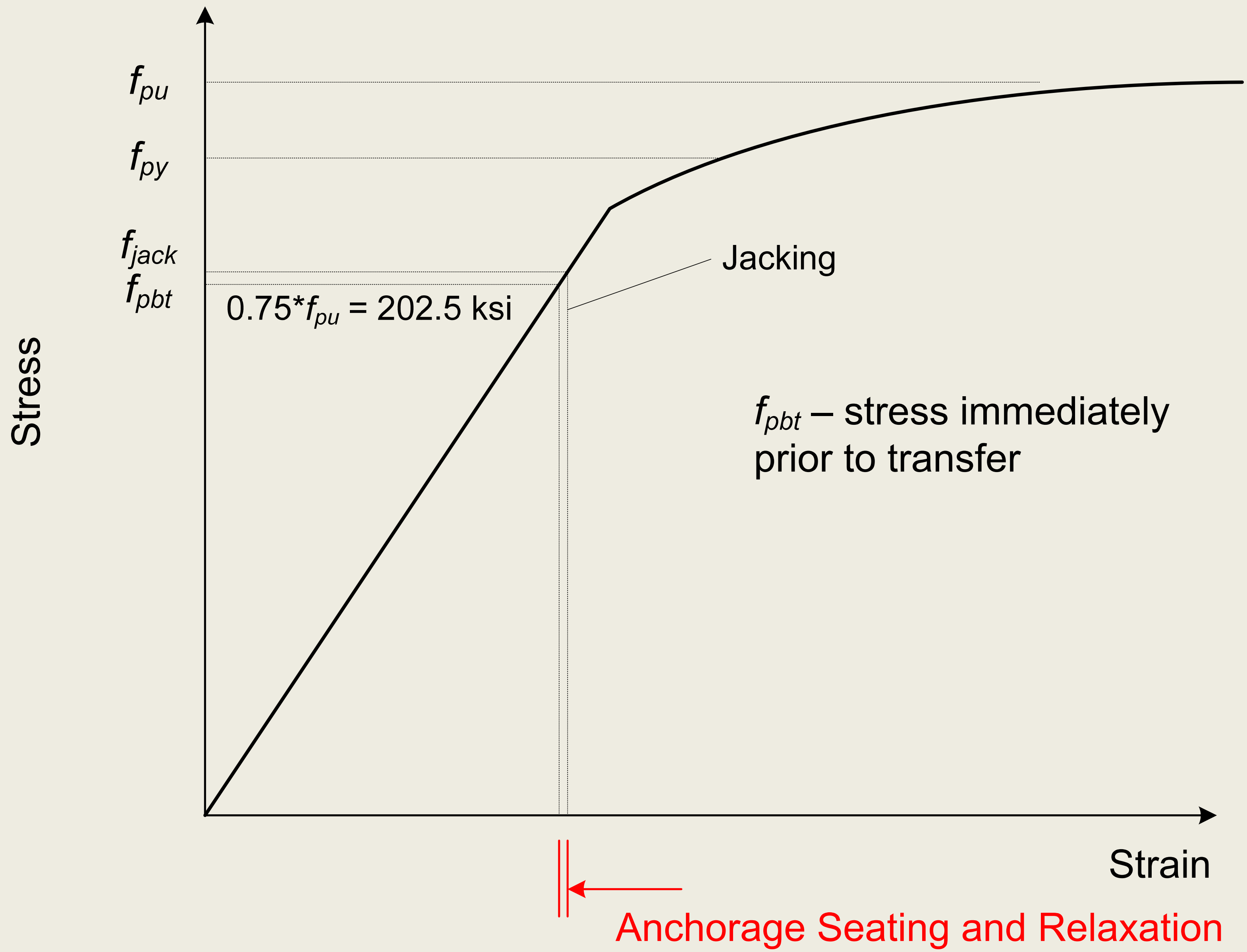


Figure 2.7 Typical effect of initial stress on relaxation of stabilized prestressing steel. *(Adapted from data by GKN, Somerset Wire and Strands, Cardiff, U.K.)*

Source: Naaman (2004)

Prestress Loss: Anchor Seating and Relaxation



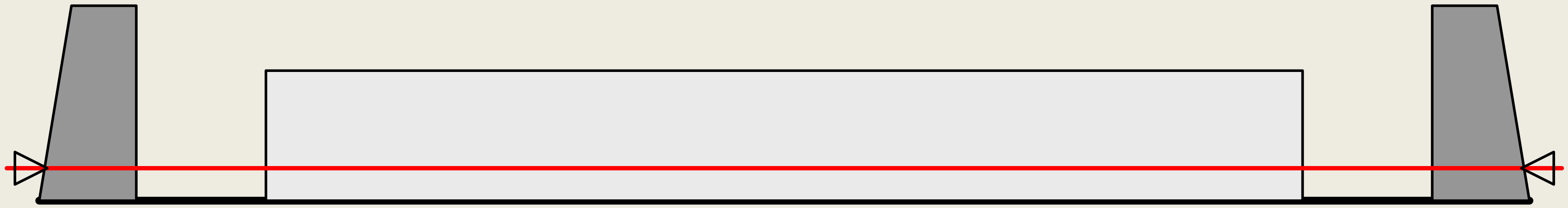
P/S Steel: Stress Limits

Table 5.9.3-1 Stress Limits for Prestressing Tendons.

Condition	Tendon Type		
	Stress-Relieved Strand and Plain High-Strength Bars	Low Relaxation Strand	Deformed High-Strength Bars
Pretensioning			
Immediately prior to transfer (f_{pbt})	$0.70\,f_{pu}$	$0.75\,f_{pu}$	—
At service limit state after all losses (f_{pe})	$0.80\,f_{py}$	$0.80\,f_{py}$	$0.80\,f_{py}$
Post-Tensioning			
Prior to seating—short-term f_{pbt} may be allowed	$0.90\,f_{py}$	$0.90\,f_{py}$	$0.90\,f_{py}$
At anchorages and couplers immediately after anchor set	$0.70\,f_{pu}$	$0.70\,f_{pu}$	$0.70\,f_{pu}$
Elsewhere along length of member away from anchorages and couplers immediately after anchor set	$0.70\,f_{pu}$	$0.74\,f_{pu}$	$0.70\,f_{pu}$
At service limit state after losses (f_{pe})	$0.80\,f_{py}$	$0.80\,f_{py}$	$0.80\,f_{py}$

Source: AASHTO (2009)

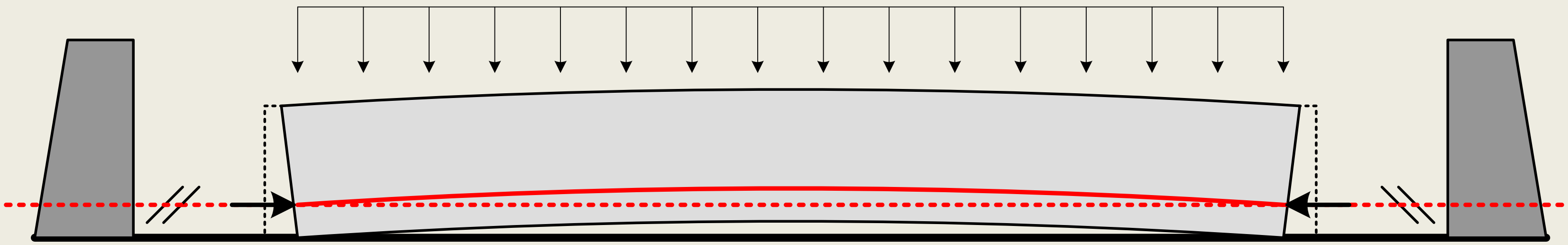
Construction Timeline: Cast Concrete



- Steel: Tension Concrete: Zero Stress

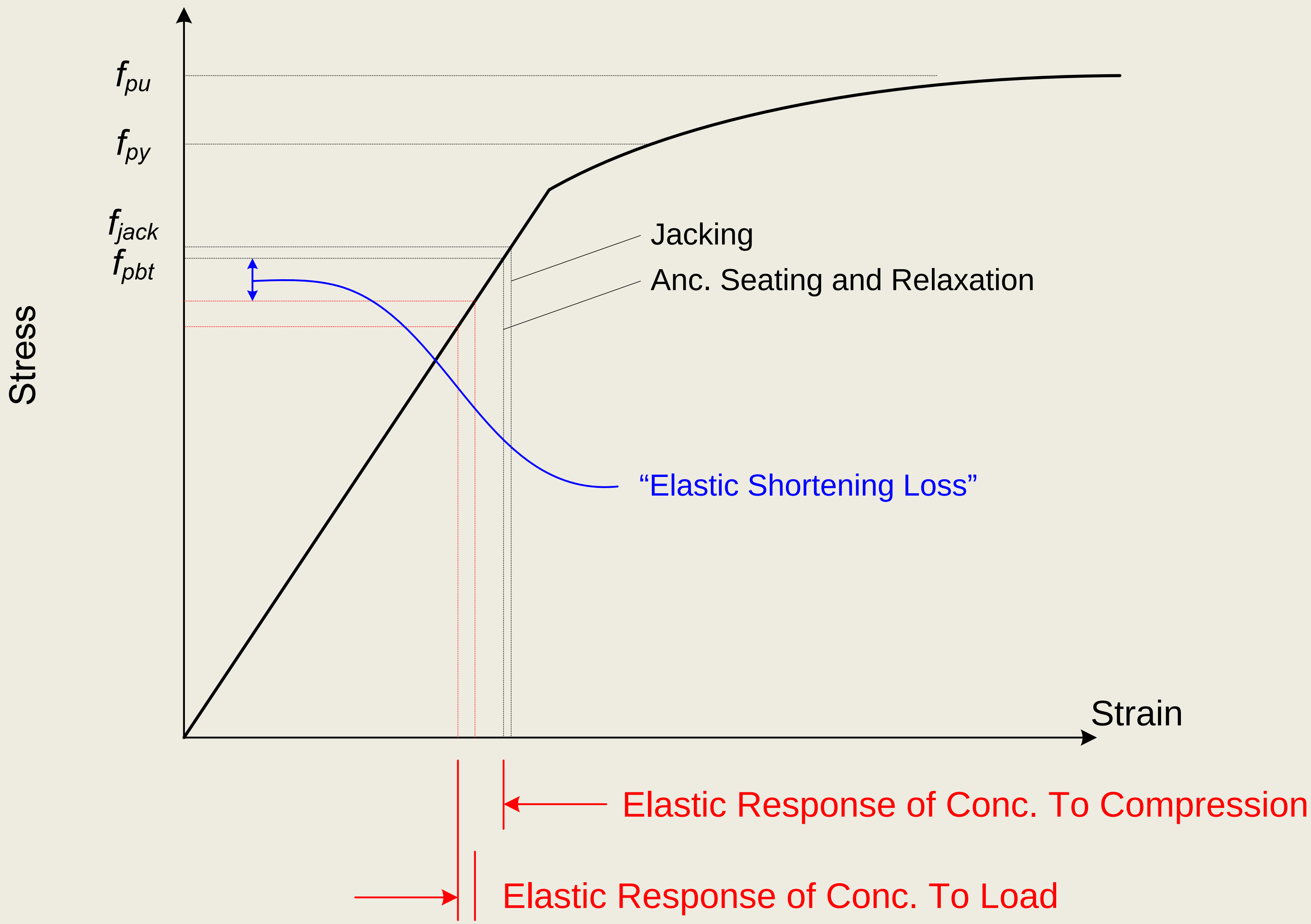
- Steel–Concrete Bond = Strain Compatibility

Construction Timeline: Transfer



- Steel shortens (towards zero-stress point)
- Strain compatibility (bonded to concrete)
- Concrete shortens
  - Shorter than zero-stress length = compression
- Eccentric prestressing produces camber
- If beam cambers, it must carry its selfweight

Prestress Loss: Elastic Shortening



Prestress Loss: Elastic Shortening

- AASHTO 5.9.5.2.3a-1 (requires iteration)

$$\boxed{\Delta f_{pES} = \frac{E_p}{E_{ct}} f_{cgp}} = E_p\left(\frac{f_{cgp}}{E_{ct}}\right) = E_p \varepsilon_{concrete} = E_p \varepsilon_{steel}$$

- AASHTO C5.9.5.2.3a-1 (no iteration)

$$\Delta f_{pES} = \frac{A_{ps} f_{pbt}\left(I_g + e_m^2 A_g\right) - e_m M_g A_g}{A_{ps}\left(I_g + e_m^2 A_g\right) + \frac{A_g I_g E_{ci}}{E_p}}$$

Concrete: Stress Limits (Transfer)

5.9.4 Stress Limits for Concrete

5.9.4.1 For Temporary Stresses Before Losses—Fully Prestressed Components

5.9.4.1.1 Compression Stresses

The compressive stress limit for pretensioned and post-tensioned concrete components, including segmentally constructed bridges, shall be $0.60 f'_{ci}$ (ksi).

5.9.4.1.2 Tension Stresses

The limits in Table 1 shall apply for tensile stresses.

Source: AASHTO (2009)

Concrete: Stress Limits (Transfer)

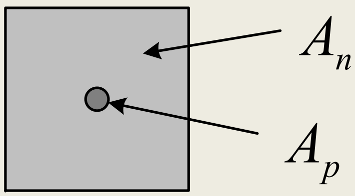
Table 5.9.4.1.2-1 Temporary Tensile Stress Limits in Prestressed Concrete Before Losses, Fully Prestressed Components.

Bridge Type	Location	Stress Limit
Other Than Segmentally Constructed Bridges	• In precompressed tensile zone without bonded reinforcement	N/A
	• In areas other than the precompressed tensile zone and without bonded reinforcement	$0.0948\sqrt{f'_{ci}} \leq 0.2$ (ksi)
	• In areas with bonded reinforcement (reinforcing bars or prestressing steel) sufficient to resist the tensile force in the concrete computed assuming an uncracked section, where reinforcement is proportioned using a stress of $0.5 f_y$, not to exceed 30 ksi.	$0.24\sqrt{f'_{ci}}$ (ksi)
	• For handling stresses in prestressed piles	$0.158\sqrt{f'_{ci}}$ (ksi)
Segmentally Constructed Bridges	Longitudinal Stresses Through Joints in the Precompressed Tensile Zone • Joints with minimum bonded auxiliary reinforcement	

Source: AASHTO (2009)

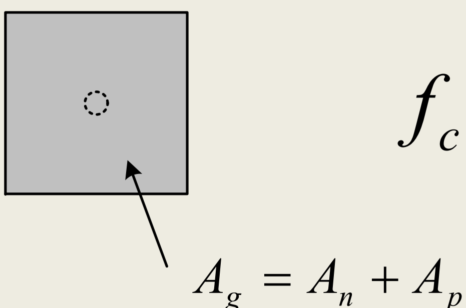
Calculating Concrete Stresses: Transfer

- Net Section Properties
  - Calculate elastic shortening losses explicitly



$$f_c = A_{ps}\left(f_{pbt} - \Delta f_{pES}\right)\left[-\frac{1}{A_n} \pm \frac{e_n y_n}{I_n}\right] \pm \frac{My_n}{I_n}$$

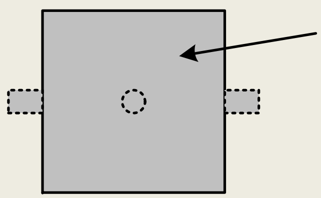
- Gross Section Properties
  - An approximation of net section properties
  - Not exact, but (usually) most convenient



$$f_c = A_{ps}\left(f_{pbt} - \Delta f_{pES}\right)\left[-\frac{1}{A_g} \pm \frac{e_g y_g}{I_g}\right] \pm \frac{My_g}{I_g}$$

Calculating Concrete Stresses: Transfer

- Transformed Section Properties
  - Exactly equivalent to use of net section properties
  - Elastic shortening is considered implicitly in the method



$$A_{TR} = A_n + \frac{E_p}{E_c} A_p$$

$$f_c = A_{ps} f_{pbt} \left[-\frac{1}{A_{TR}} \pm \frac{e_{TR} y_{TR}}{I_{TR}} \right] \pm \frac{M y_{TR}}{I_{TR}}$$

Calculating Concrete Stresses: Transfer

- Example: Bottom Fiber Stress using Gross Section Properties
  - change in bottom fiber stress due to transfer…

$$\Delta f_{cb1} = A_{ps}\left(f_{pbt} - \Delta f_{pES}\right)\left[-\frac{1}{A_g} - \frac{e_m y_b}{I_g}\right] + \frac{M y_b}{I_g}$$

Construction Timeline: Transfer → Final Time

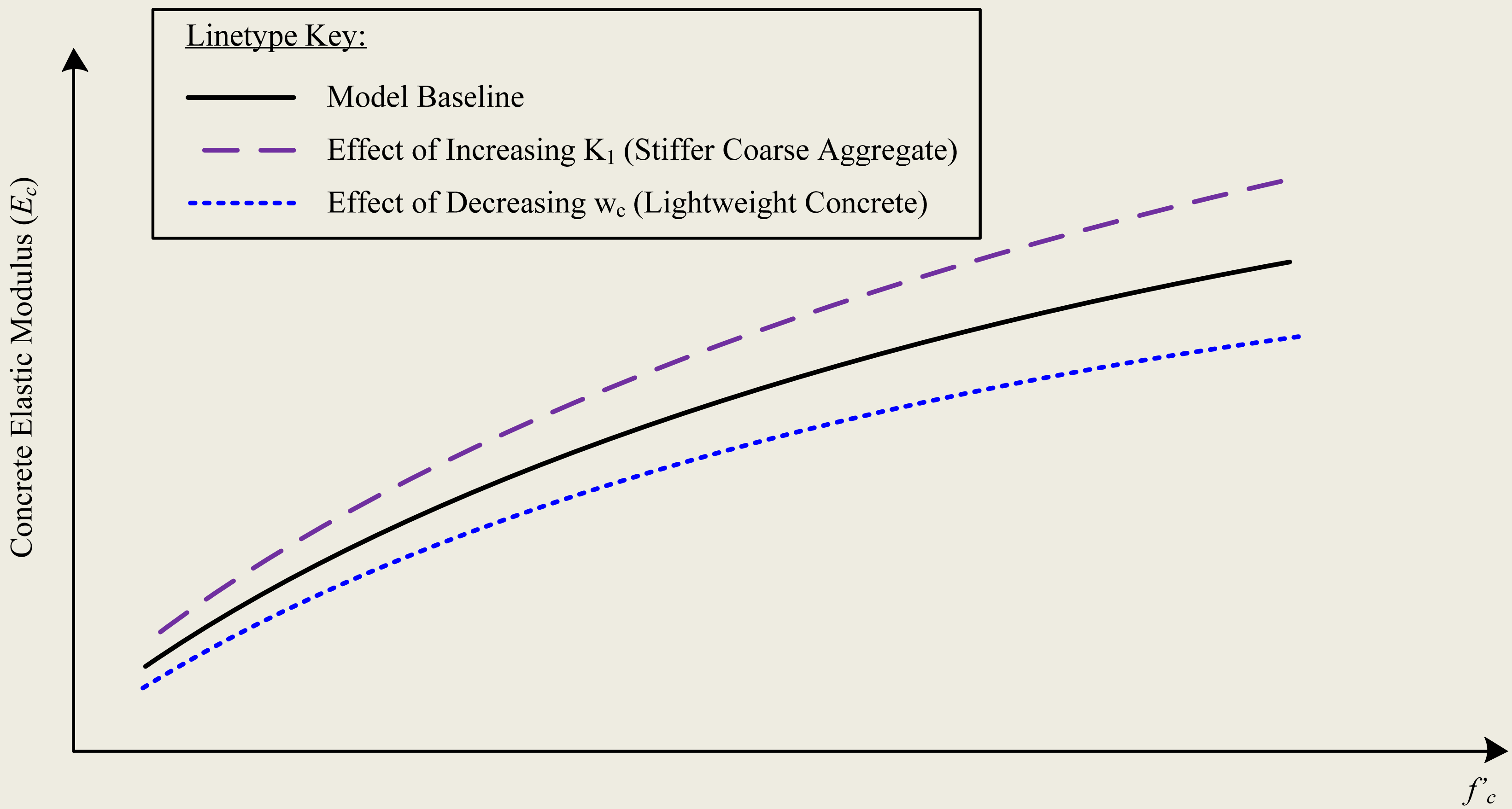
- Current AASHTO Method uses two stages:
  1. Transfer → Deck Placement
  2. Deck Placement → Final Time

- Consider:
  - Volumetric changes in concrete: shrinkage & creep
  - Application of loads
  - Implications of composite behavior

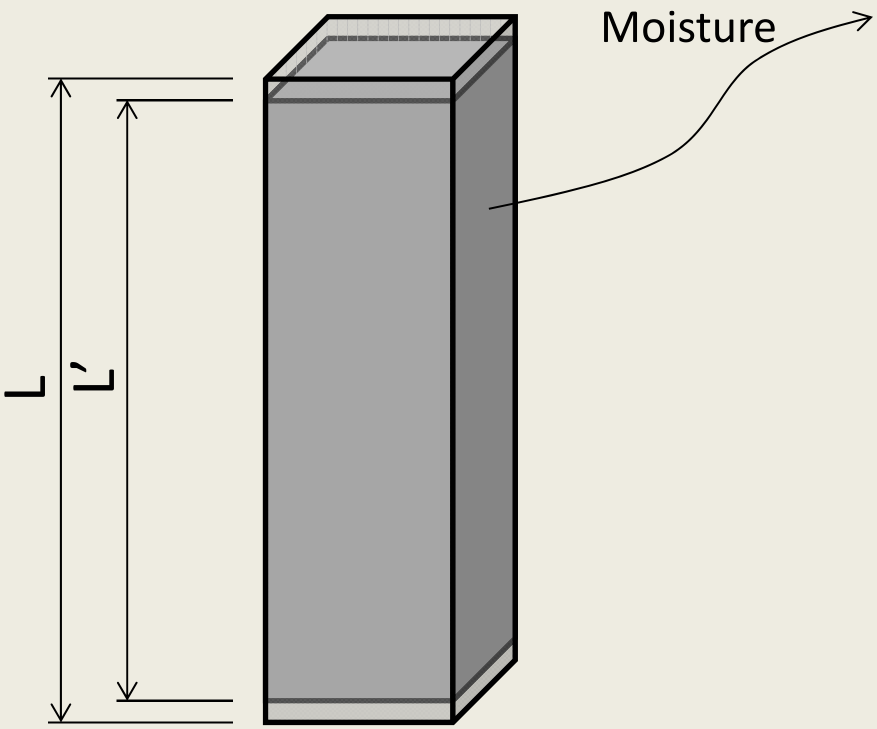
Concrete Properties: Elastic Modulus

- AASHTO 5.4.2.4 (K_1 added in 2005 – NCHRP Report 496)

$$E_c = 33{,}000 K_1 w_c^{1.5} \sqrt{f_c^{'}}$$



Concrete Properties: Shrinkage

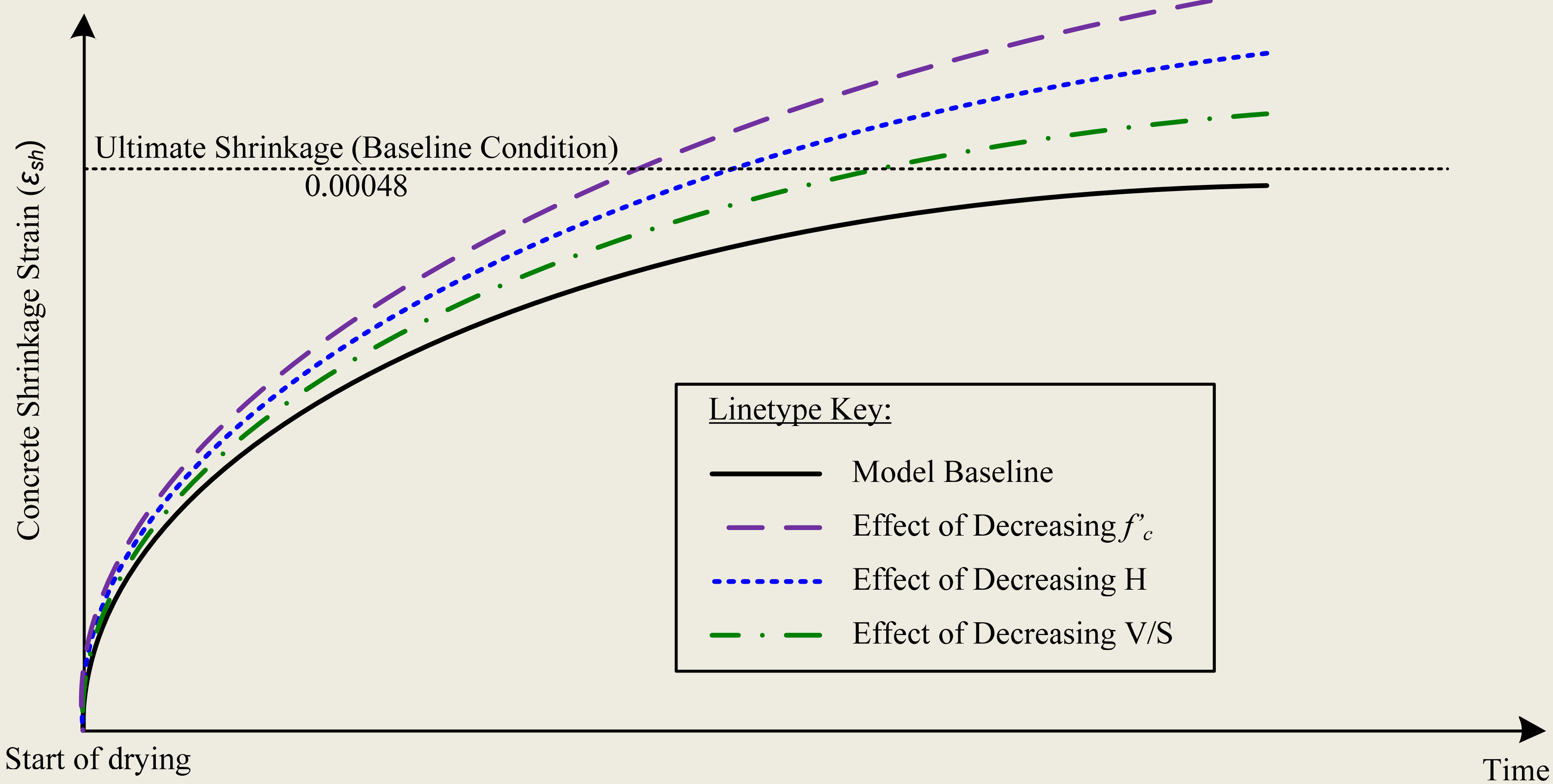


$$\varepsilon_{sh} = \frac{\Delta L}{L} = \frac{L - L'}{L}$$

Concrete Properties: Shrinkage

- AASHTO 5.4.2.3.3 (new in 2005 for high-strength concrete – NCHRP Report 496)

$$\varepsilon_{sh} = k_s k_{hs} k_f k_{td} 0.48x10^{-3}$$



NCHRP 496 Shrinkage Data

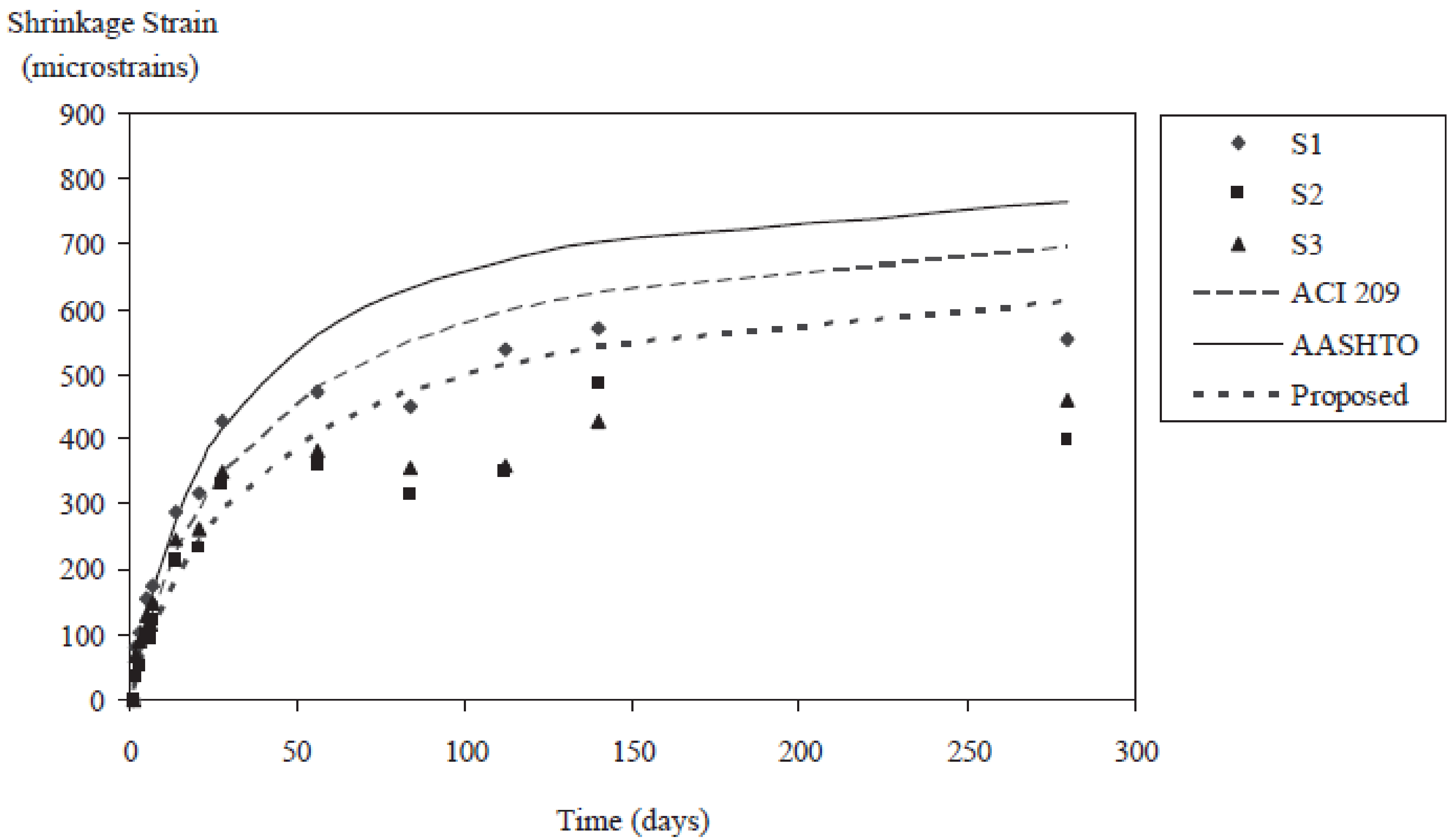
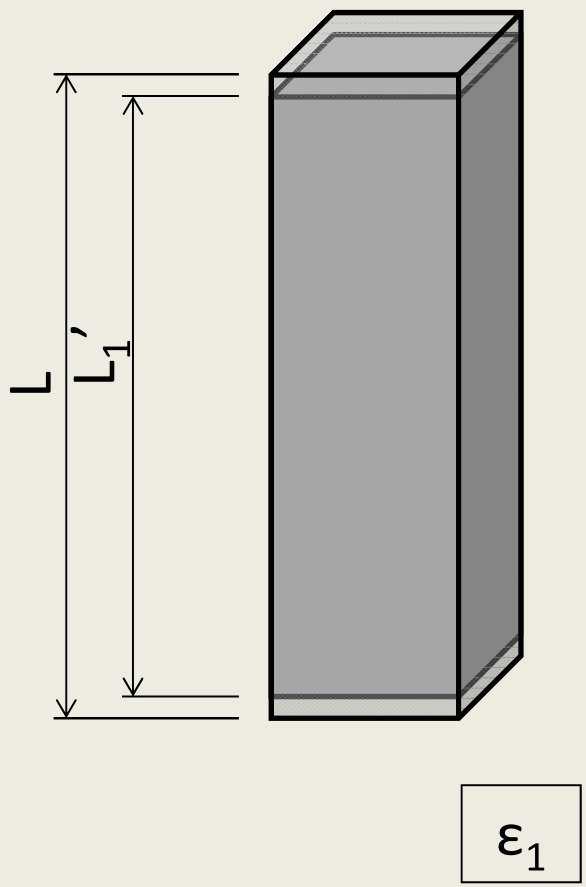


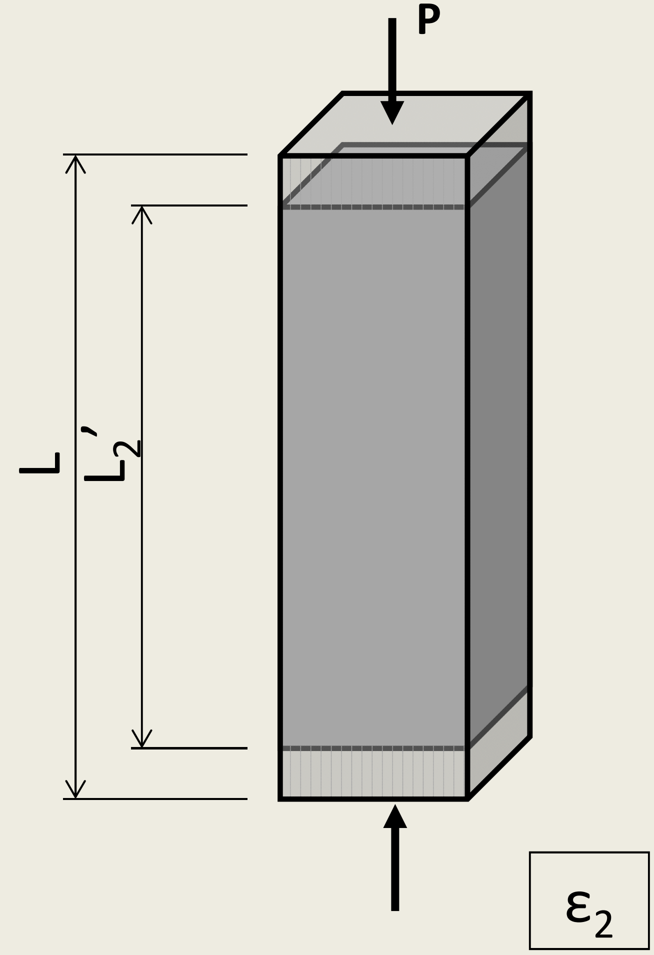
Figure 9. Shrinkage for Nebraska mix NE09G-S.

Concrete Properties: Creep

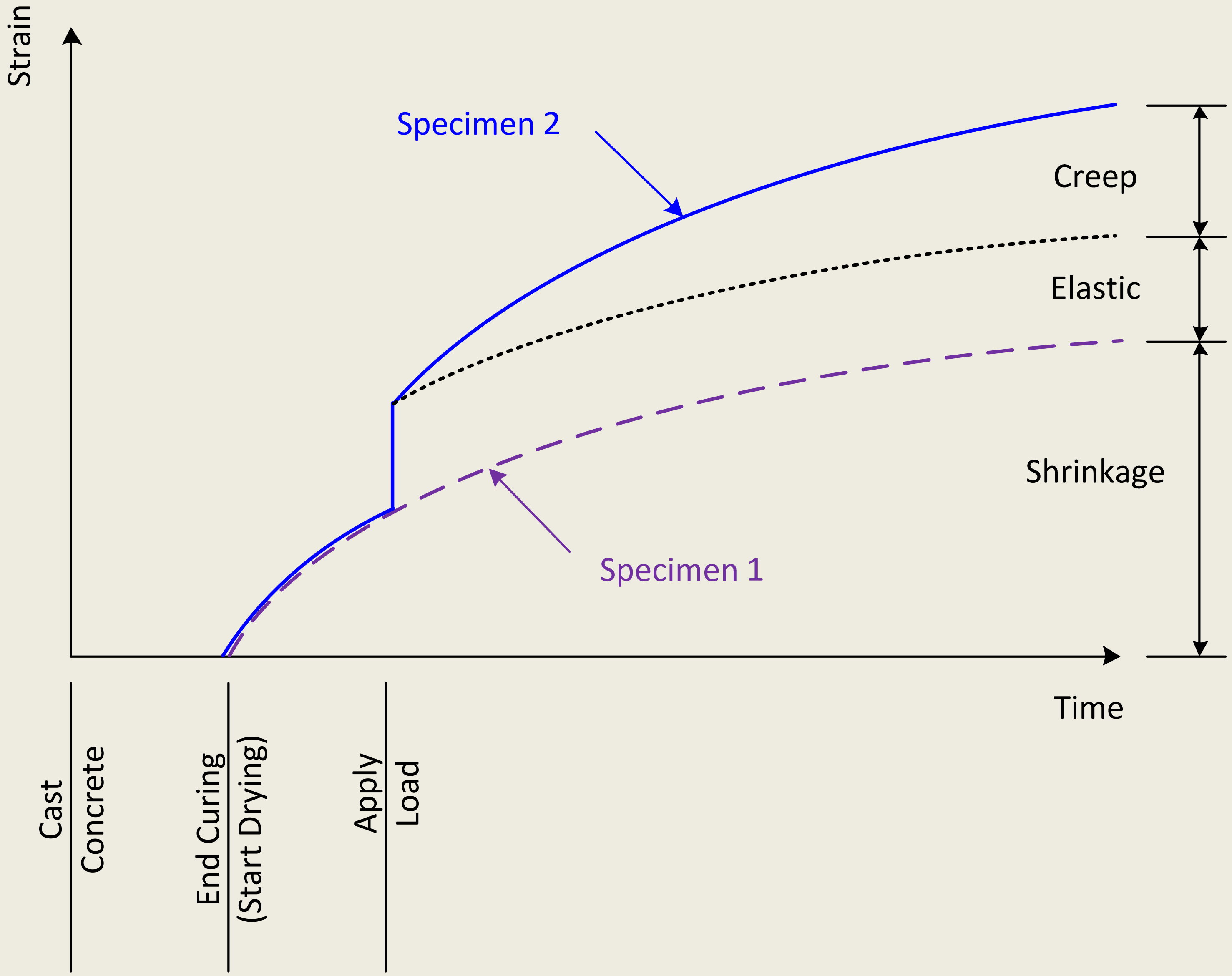
Shrinkage Specimen



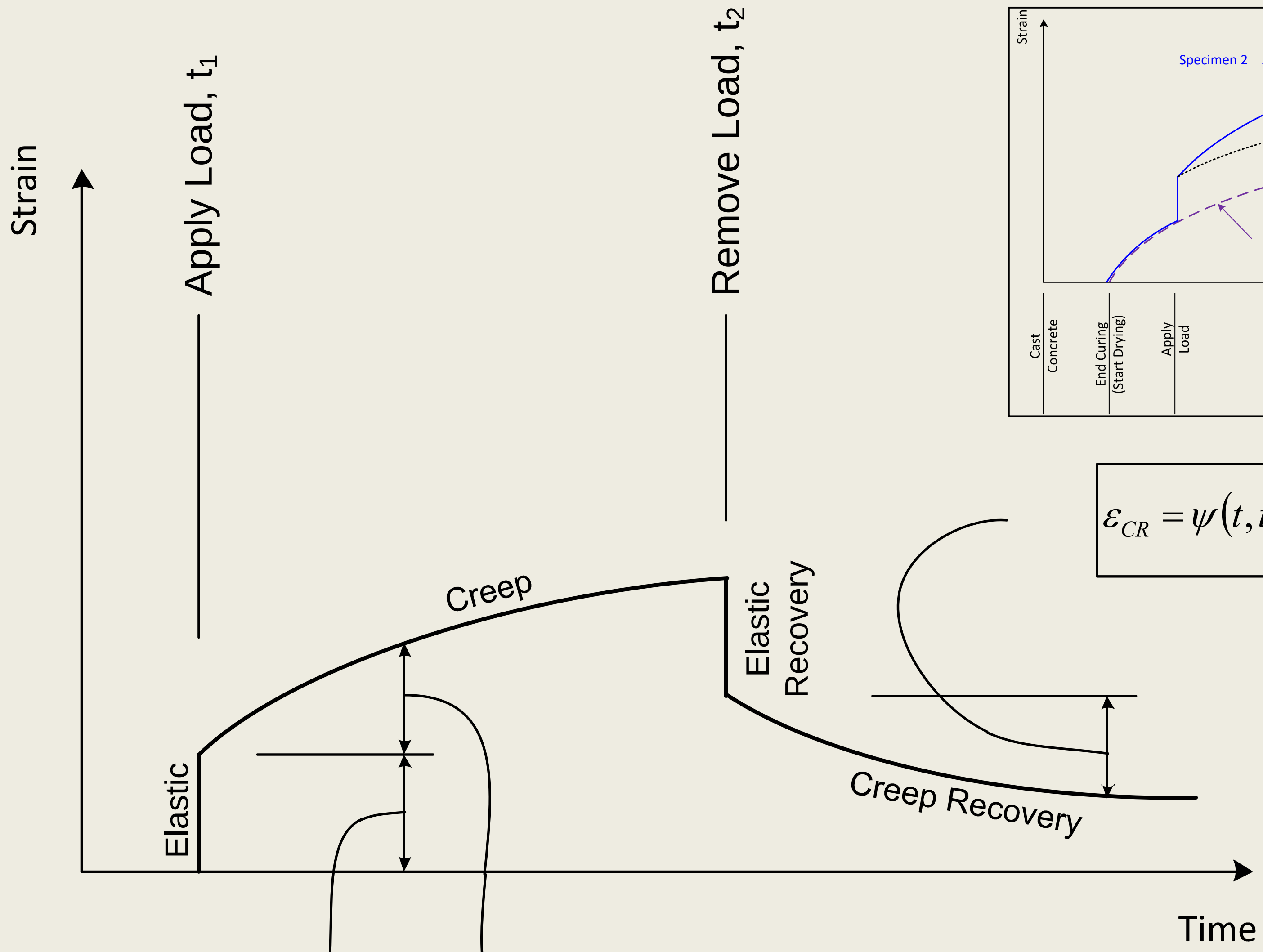
Creep Specimen

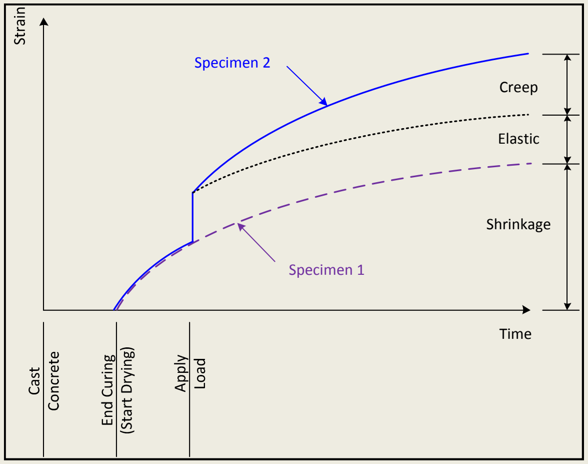


Concrete Properties: Creep



Concrete Properties: Creep





$$\varepsilon_{CR} = \psi(t, t_2)\frac{f_c}{E_c}$$

$$\varepsilon_{EL} = \frac{f_c}{E_c}$$

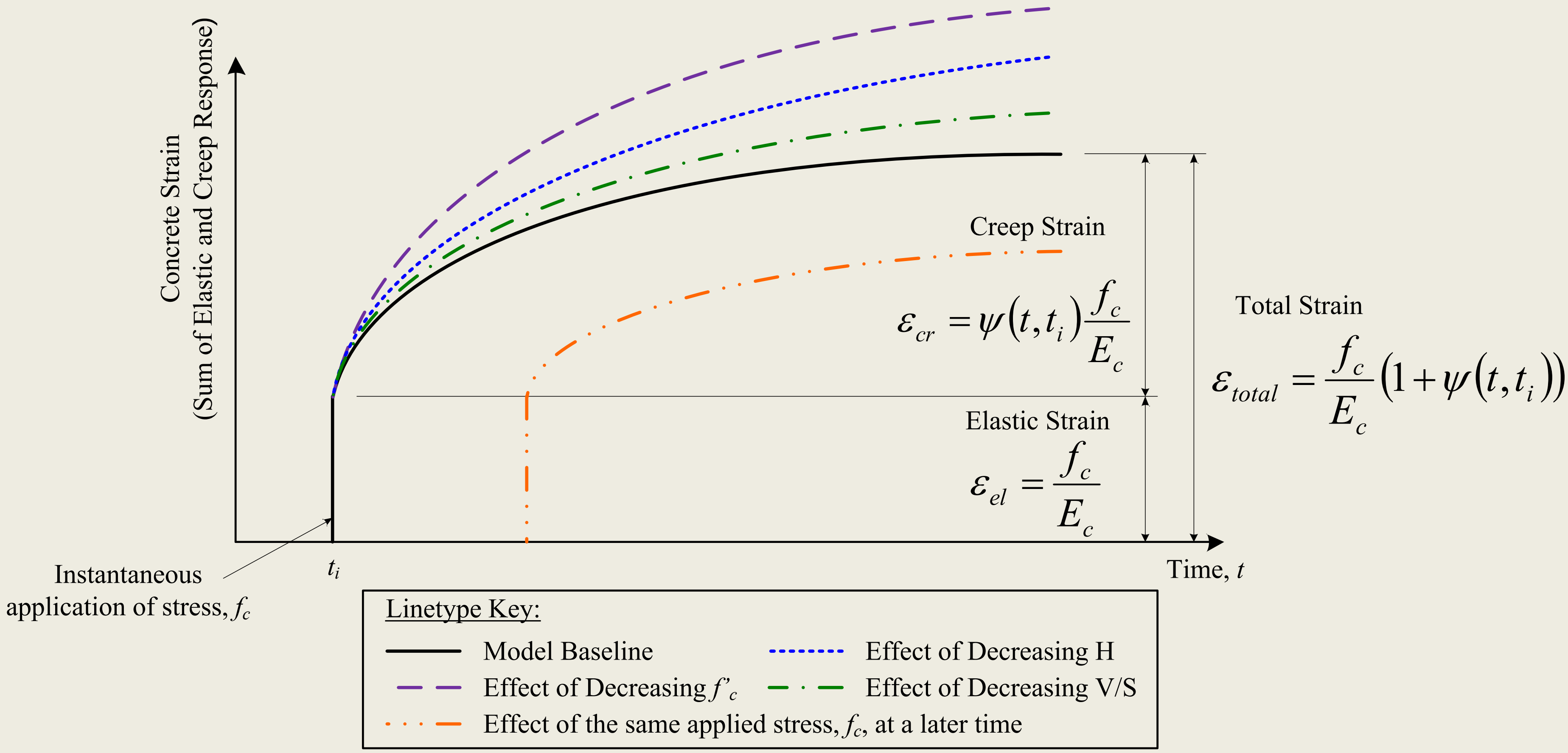
$$\varepsilon_{CR} = \psi(t, t_1)\frac{f_c}{E_c}$$

Creep Coefficient

Concrete Properties: Creep

- AASHTO 5.4.2.3.2

$$\psi(t,t_i) = 1.9 k_s k_{hc} k_f k_{td} t_i^{-0.118}$$



NCHRP 496 Creep Data

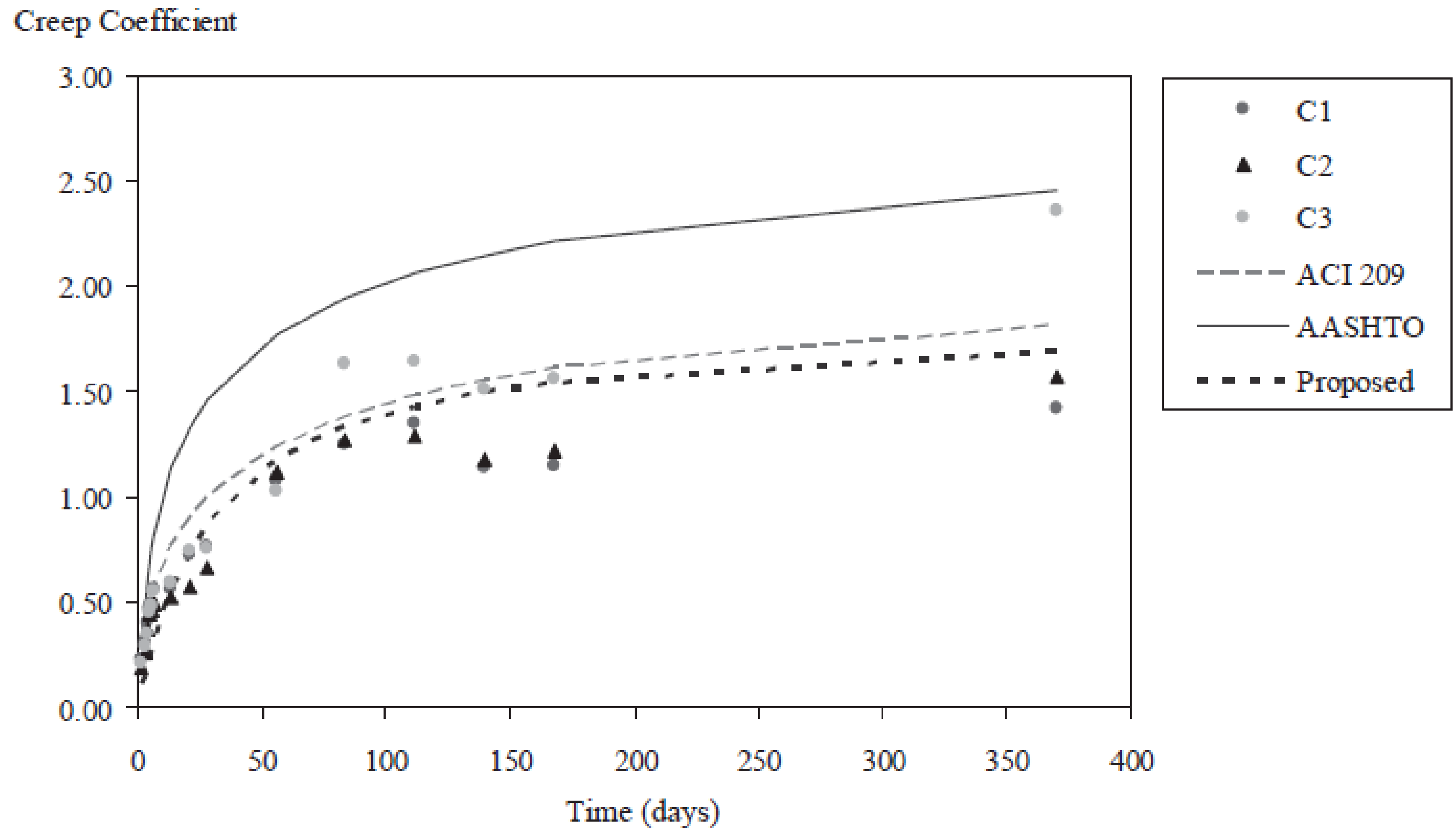
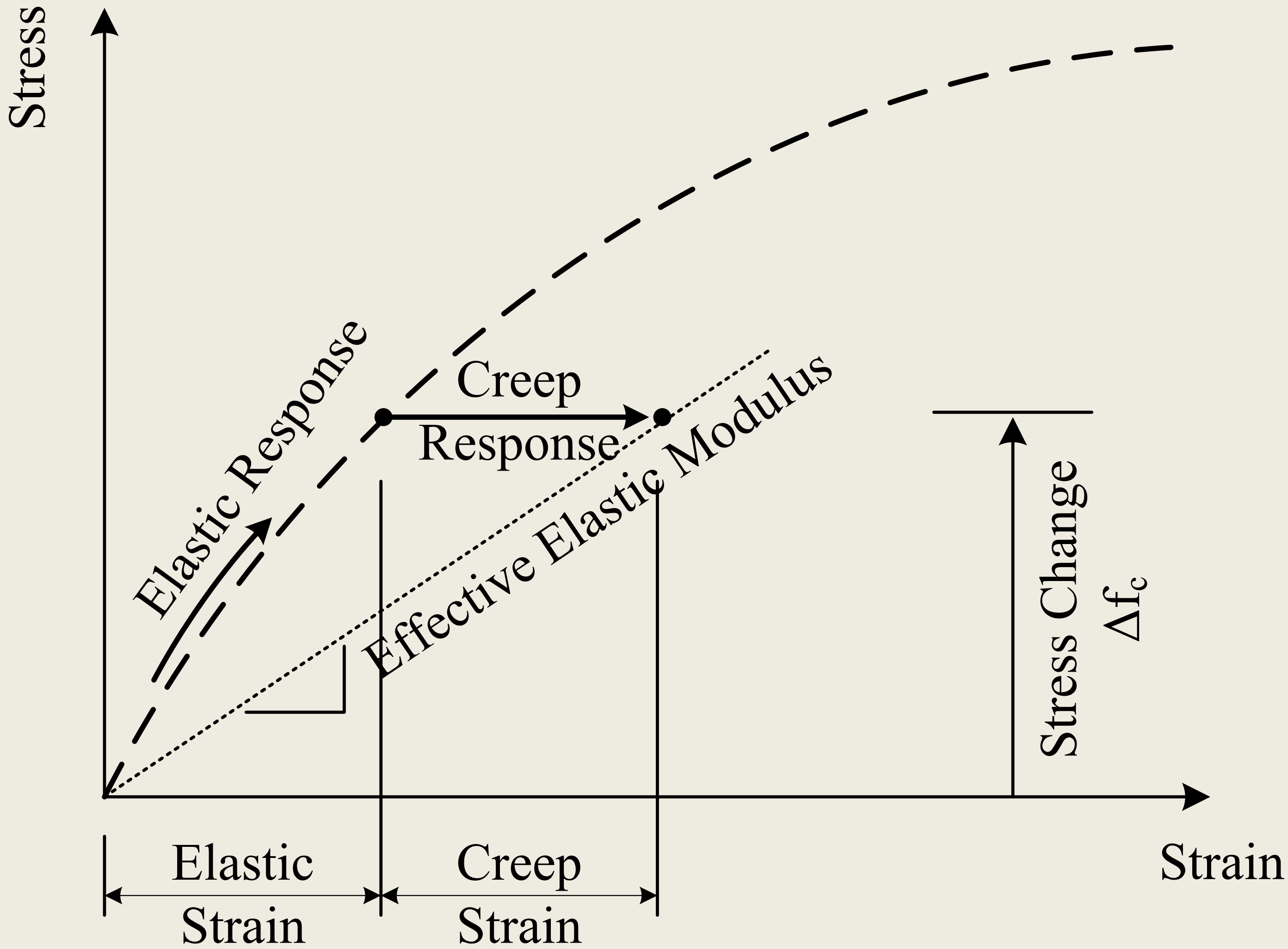


Figure 16. Creep for Washington mix WA10G-01 loaded at 1 day.

Concrete Properties: Creep



Prestress Loss: Girder Shrinkage (Before Deck)

- AASHTO 5.9.5.4.2a

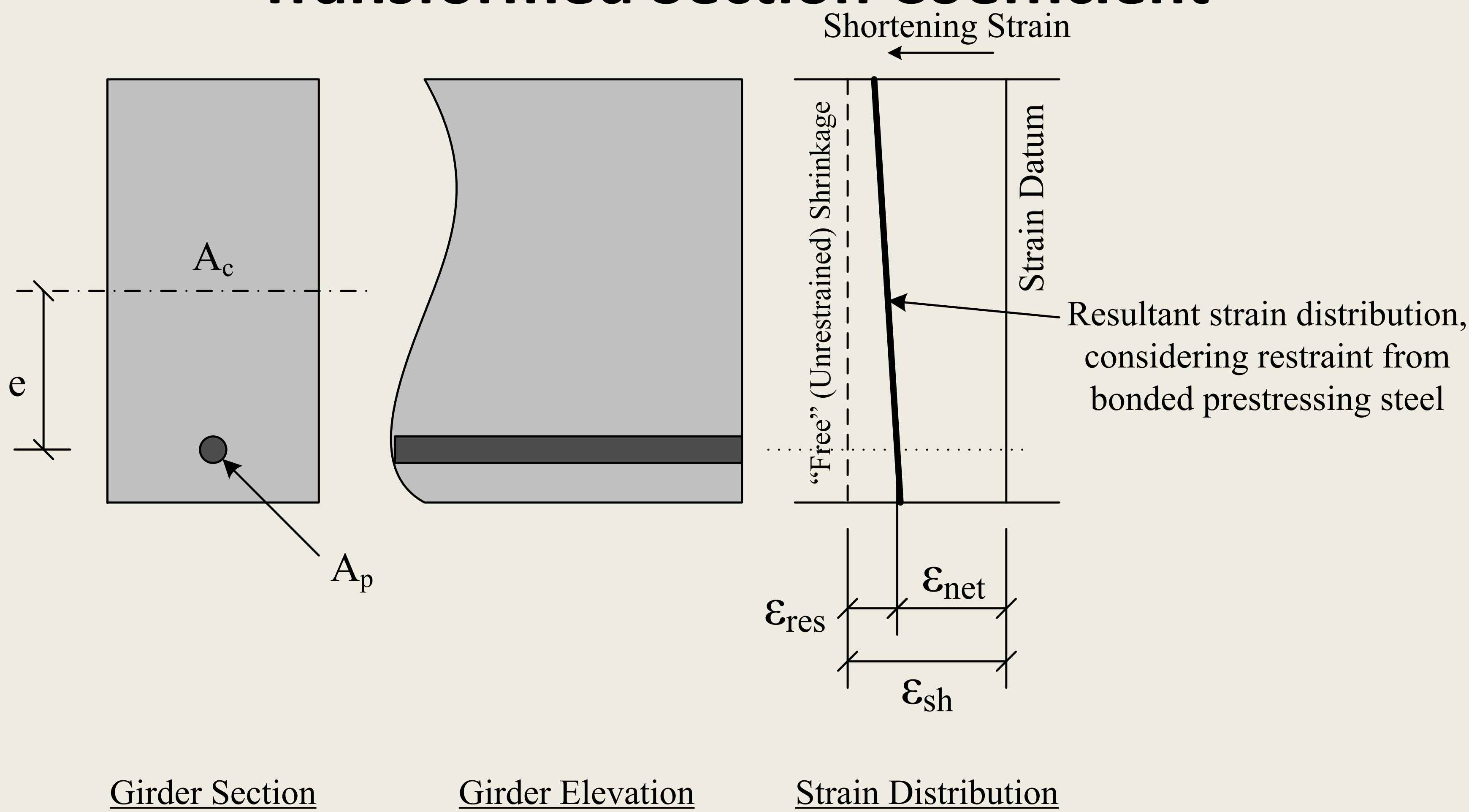
Concrete Shrinkage Strain

$$\boxed{\Delta f_{pSR} = \varepsilon_{bid} E_p K_{id}} = E_p \left(\underbrace{\varepsilon_{bid} K_{id}} \right)$$

"Net" strain for (concrete + steel)

ε_{bid}	***b***: "beam" (girder) ***i***: "initial" (end of curing) ***d***: "deck" (time after end of curing that deck is placed)

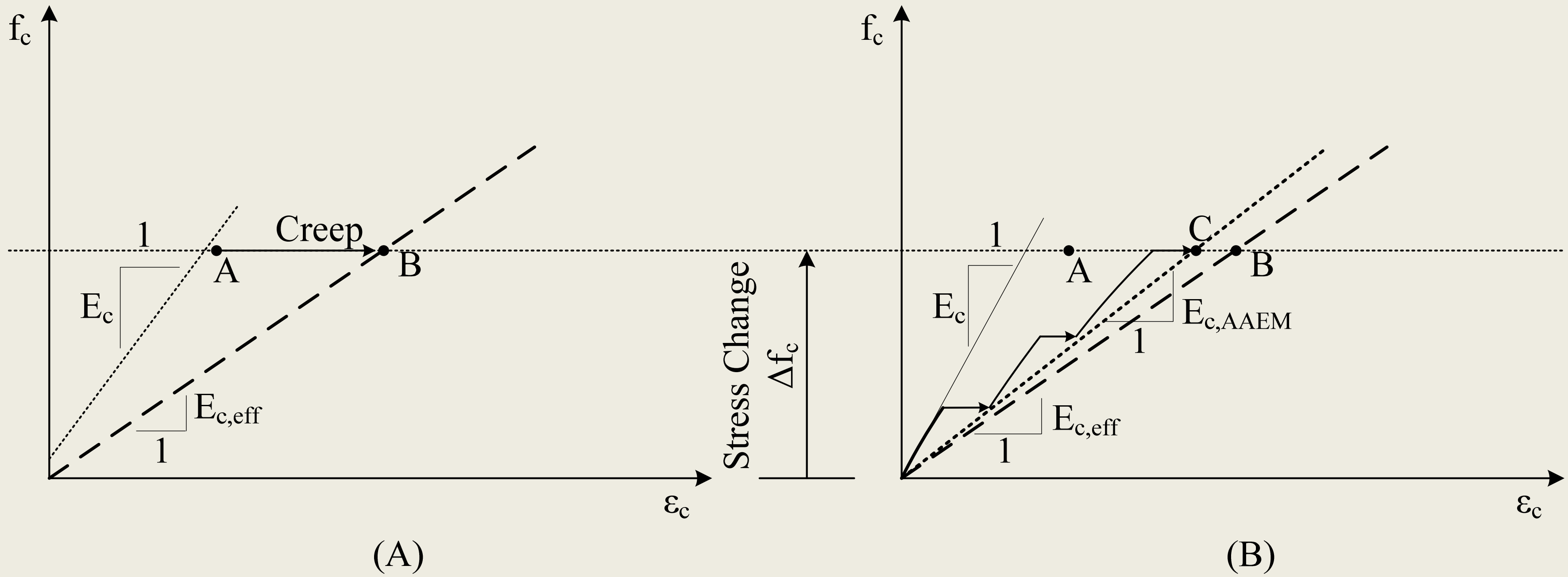
Transformed Section Coefficient



$$K_{id} = \frac{1}{1 + \frac{E_p}{E_{ci}} \frac{A_{ps}}{A_g} \left(1 + \frac{A_g e_{pg}^2}{I_g}\right) \left[1 + 0.7\psi_b\left(t_f, t_i\right)\right]} = \frac{\varepsilon_{net}}{\varepsilon_{sh}}$$

Age-Adjusted Effective Modulus

Age-Adjusted Effective Modulus



$$E_{c,eff} = \frac{E_c}{1+\psi(t,t_i)}$$

$$E_{c,AAEM} = \frac{E_c}{1+\chi\psi(t,t_i)}$$

$$\chi \approx 0.7$$

Prestress Loss: Girder Creep (Before Deck)

- AASHTO 5.9.5.4.2b

$$\boxed{\Delta f_{pCR} = \frac{E_p}{E_{ci}} f_{cgp} \psi_b\left(t_d, t_i\right) K_{id}} = E_p \left\{ \left[\underbrace{\left(\frac{f_{cgp}}{E_{ci}} \right)}_{\text{Elastic Strain}} \psi_b\left(t_d, t_i\right) \right] K_{id} \right\}$$

Elastic Strain: $\left(\frac{f_{cgp}}{E_{ci}} \right)$

Creep Strain: $\left[\left(\frac{f_{cgp}}{E_{ci}} \right) \psi_b\left(t_d, t_i\right) \right]$

"Net" creep strain for (concrete + steel): $\left[\left(\frac{f_{cgp}}{E_{ci}} \right) \psi_b\left(t_d, t_i\right) \right] K_{id}$

$$\psi_b\left(t_d, t_i\right)$$

b: "beam" (girder)
i: "initial" (transfer)
d: "deck" (time after transfer that deck is placed)
t_d: time of interest for creep strain
t_i: age of concrete when stress change occurred

Prestress Loss: Relaxation (Before Deck)

- AASHTO 5.9.5.4.2c

$$1.5ksi$$

$$\Delta f_{pR1} = 1.2ksi$$

…for low-relaxation strands

For more detailed calculation procedure:

Magura, D.D., Sozen, M.A., and Siess, C.P. 1964. A Study of Stress Relaxation in Prestressing Reinforcement. PCI Journal. V. 9, No. 2: pp. 13-57.

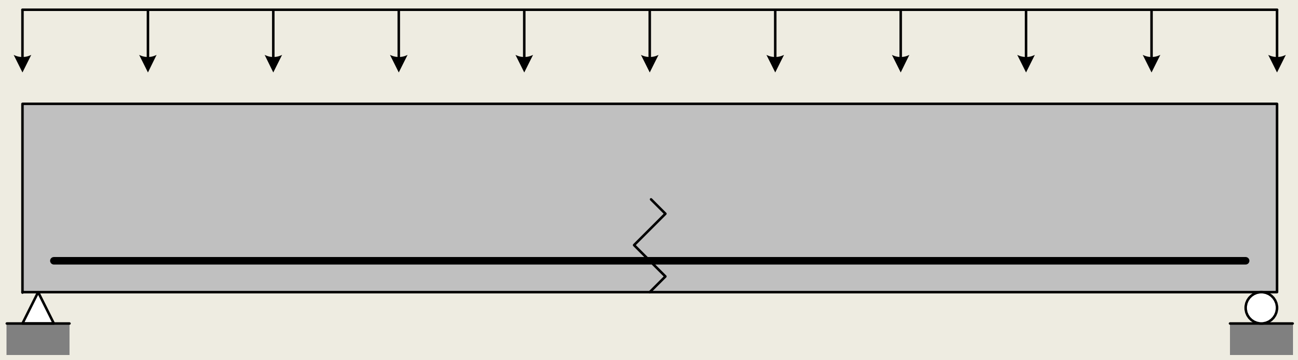
Concrete Stresses: Losses (Before Deck)

- Change in bottom fiber stress due to losses before deck placement…

$$\Delta f_{cb2} = A_{ps}\left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)\left(\frac{1}{A_g} + \frac{e_m y_b}{I_g}\right)$$

Application of Deck Weight

- Concrete Tension or Prestress "Gain" ??
  - Both!
- Reinforced Concrete analogy:



  - Tension in the steel does NOT "pre-compress" the surrounding concrete

Concrete Stress: Deck Weight

$$\Delta f_{cb3} = \frac{M_{deck} y_b}{I_g}$$

Concrete Stress: Superimposed Dead Load

$$\Delta f_{cb4} = \frac{M_{SIDL} y_{bc}}{I_c}$$

Prestress Loss: Girder Shrinkage (After Deck)

- AASHTO 5.9.5.4.3a

Concrete Shrinkage Strain

$$\boxed{\Delta f_{pSD} = \varepsilon_{bdf} E_p K_{df}} = E_p \left(\varepsilon_{bdf} K_{df} \right)$$

"Net" strain for (concrete + steel)

ε_{bdf}	***b***: "beam" (girder) ***d***: "deck" (age of concrete at deck placement) ***f***: "final" (final time)

Prestress Loss: Girder Creep (After Deck)

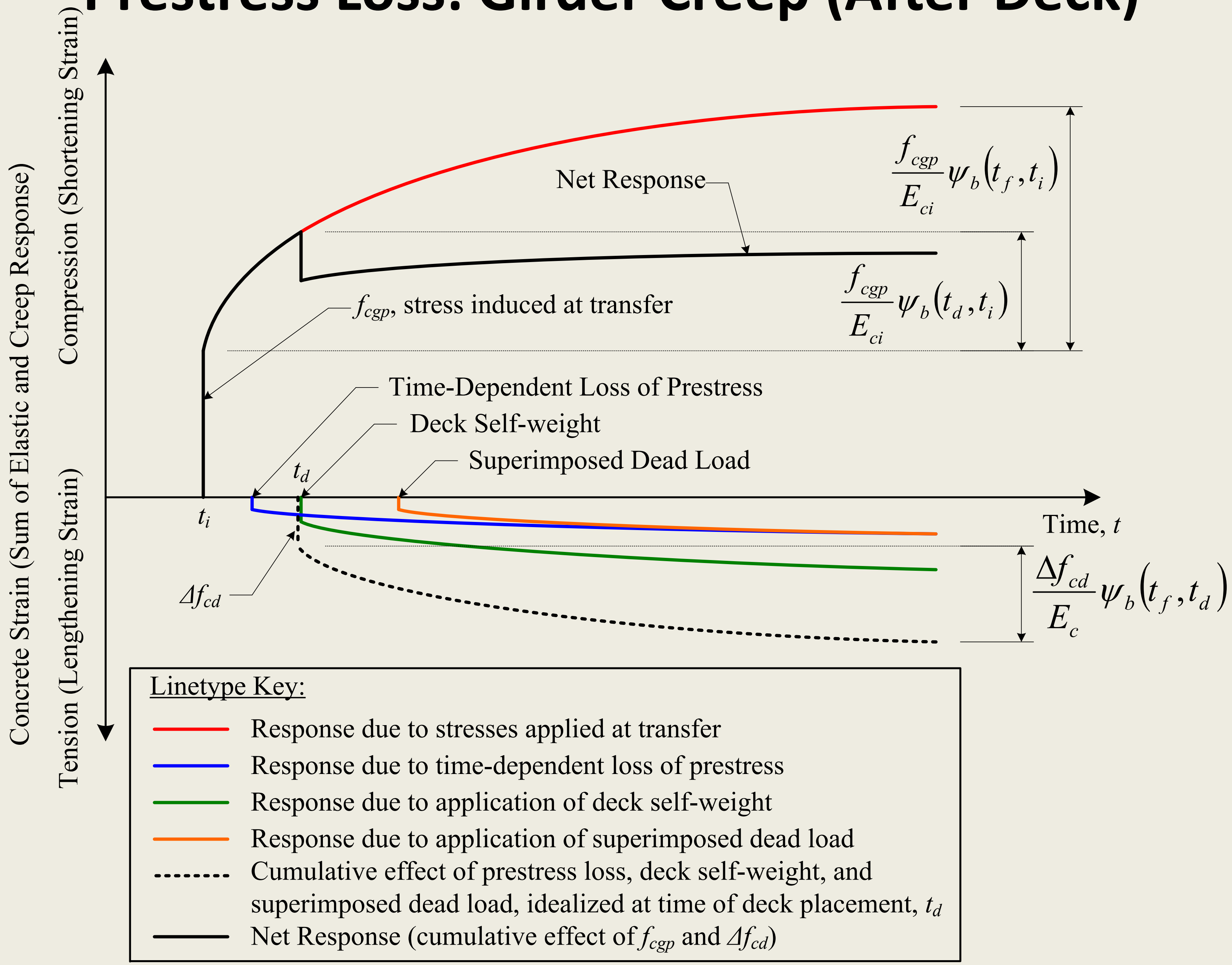
- AASHTO 5.9.5.4.3b

$$\Delta f_{pCD} = \frac{E_p}{E_{ci}} f_{cgp}\left[\psi_b\left(t_f, t_i\right) - \psi_b\left(t_d, t_i\right)\right]K_{df} + \frac{E_p}{E_c}\Delta f_{cd}\psi_b\left(t_f, t_d\right)K_{df}$$

$$\Delta f_{pCD} = E_p\left\{\left[\left(\frac{f_{cgp}}{E_{ci}}\right)\left(\psi_b\left(t_f, t_i\right) - \psi_b\left(t_d, t_i\right)\right)\right]K_{df}\right\} + E_p\left\{\left[\left(\frac{\Delta f_{cd}}{E_c}\right)\psi_b\left(t_f, t_d\right)\right]K_{df}\right\}$$

Δf_{cd}	Change in concrete stress at the centroid of the prestressing strands due to time-dependent loss of prestress between transfer and deck placement, combined with deck weight and superimposed loads

Prestress Loss: Girder Creep (After Deck)



Prestress Loss: Relaxation (After Deck)

- AASHTO 5.9.5.4.3c

$$1.5ksi$$

$$\Delta f_{pR2} = 1.2ksi$$

…for low-relaxation strands

Concrete Stress: Losses (After Deck)

- Change in bottom fiber stress due to losses after deck placement…

$$\Delta f_{cb5} = A_{ps}\left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2}\right)\left(\frac{1}{A_c} + \frac{e_{pc} y_{bc}}{I_c}\right)$$

Shrinkage of Deck Concrete

- AASHTO 5.9.5.4.3d
  - "The prestress gain due to shrinkage of deck composite section, Δf_{pSS}, shall be determined as":

$$\Delta f_{pSS} = \frac{E_p}{E_c} \underline{\Delta f_{cdf}} K_{df} \left[1 + 0.7\psi_b \left(t_f, t_d \right) \right]$$

$$\Delta f_{cdf} = \frac{\varepsilon_{ddf} A_d E_{cd}}{\underbrace{\left[1 + 0.7\psi_d \left(t_f, t_d \right) \right]}_{\text{“}P_{deck}\text{”}}} \left(\frac{1}{A_c} - \frac{e_{pc} e_d}{I_c} \right)$$

Shrinkage of Deck Concrete

force, stress, strain

$$P_{deck} = \varepsilon_{ddf}\left(\frac{E_{cd}}{\left[1+0.7\psi_d\left(t_f,t_d\right)\right]}\right)A_d$$

Age-adjusted eff. modulus

More appropriately: $\left(\varepsilon_{ddf} - \varepsilon_{bdf}\right)$

ε_{ddf}
- ***d***: "deck" (deck concrete properties)
- ***d***: "deck" (age of concrete at deck placement)
- ***f***: "final" (final time)

$\psi_d\left(t_f,t_d\right)$
- ***d***: "deck" (deck concrete properties)
- ***d***: "deck" (age of concrete at deck placement)
- ***f***: "final" (final time)
- t_f: time of interest for creep strain
- t_d: age of concrete when stress change occurred

Concrete Stress: Shrinkage of Deck Concrete

$$\Delta f_{cb6} = P_{deck}\left(-\frac{1}{A_c} + \frac{y_{bc}e_d}{I_c}\right)$$

Concrete Stress: Live Load

$$\Delta f_{cb7} = \frac{M_{LL} y_{bc}}{I_c}$$

Concrete Stress: Total

$$f_{cb} = \sum_{i=1}^{7} f_{cbi}$$

Concrete: Stress Limits (Service)

Table 5.9.4.2.1-1 Compressive Stress Limits in Prestressed Concrete at Service Limit State After Losses, Fully Prestressed Components.

Location	Stress Limit
• In other than segmentally constructed bridges due to the sum of effective prestress and permanent loads	$0.45\,f'_c$ (ksi)
• In segmentally constructed bridges due to the sum of effective prestress and permanent loads	$0.45\,f'_c$ (ksi)
• Due to the sum of effective prestress, permanent loads, and transient loads **as well as** during shipping and handling	$0.60\,\phi_w f'_c$ (ksi)

Source: AASHTO (2009)

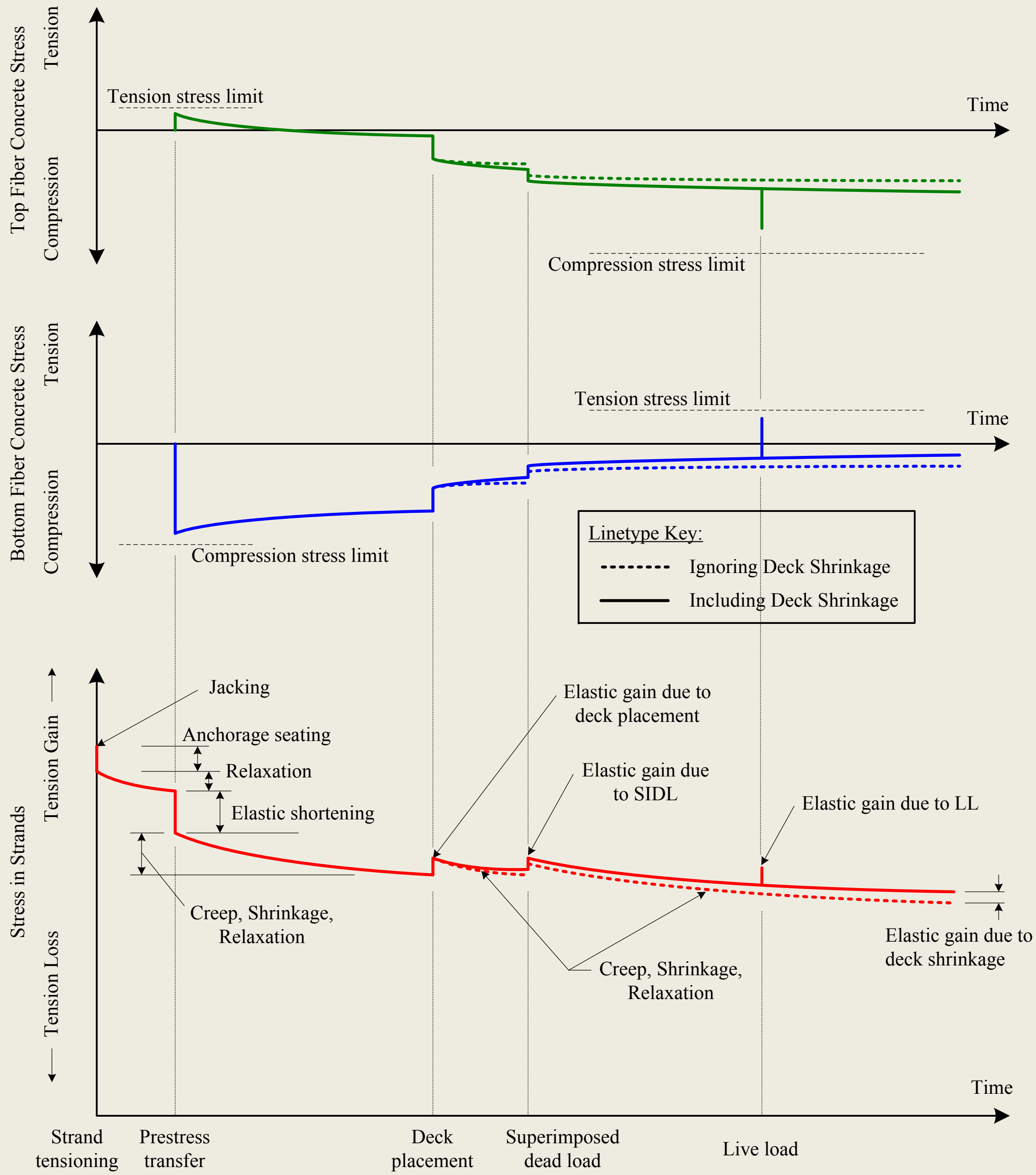
Concrete: Stress Limits (Service)

Table 5.9.4.2.2-1 Tensile Stress Limits in Prestressed Concrete at Service Limit State After Losses, Fully Prestressed Components.

Bridge Type	Location	Stress Limit
Other Than Segmentally Constructed Bridges	Tension in the Precompressed Tensile Zone Bridges, Assuming Uncracked Sections	
	• For components with bonded prestressing tendons or reinforcement that are subjected to not worse than moderate corrosion conditions	$0.19\sqrt{f'_c}$ (ksi)
	• For components with bonded prestressing tendons or reinforcement that are subjected to severe corrosive conditions	$0.0948\sqrt{f'_c}$ (ksi)
	• For components with unbonded prestressing tendons	No tension
Segmentally Constructed Bridges	Longitudinal Stresses Through Joints in the Precompressed Tensile Zone	

Source: AASHTO (2009)

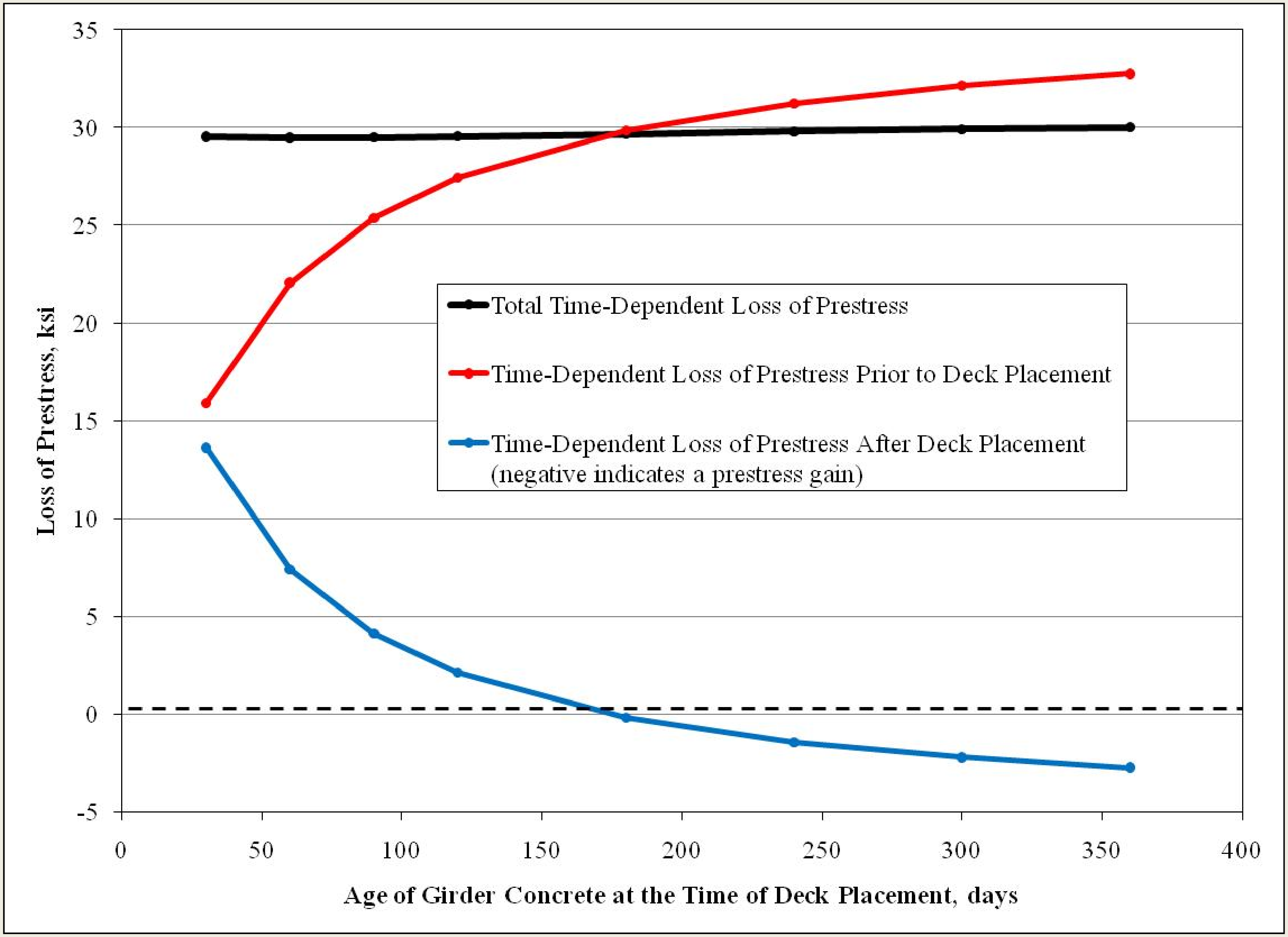
Construction Timeline: Summary



Uncertainty in Loss Calculations

- Concrete Compressive Strength
- Material Property models:
  - Elastic modulus, shrinkage, creep
- Initial jacking force
- Environmental conditions:
  - Relative humidity
- Geometric tolerance (“as-built”)
- Magnitude of Loads
- Construction Sequence (time of deck placement)

Time of Deck Placement



Post-Tensioned Construction

- Friction
- Anchorage Seating
- Elastic Shortening

Conclusion

- Calculation of prestress loss relies on basic mechanics, and assumptions about material behavior
- Concrete stress is really the bottom line; not prestress loss
- Losses cannot be known precisely (too many uncertainties)

Acknowledgements and References

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