ENCE717 – Bridge Engineering
Reinforced and Prestressed Concrete Bridges

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(http: www.best.umd.edu)

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Concrete Bridges

1. Reinforced Concrete (RC) Bridges (4.0)
2. Prestressed Concrete (PC) Bridges (5.0)
   i. Precast Pre-tensioned Concrete Bridges
   ii. Precast/Cast-in-place post-tensioned Concrete Bridge
   iii. PC Bridge Modeling
   iv. PC Bridge Load Rating
3. Curved Concrete Bridges (6.0)

Portland Cement Types in Bridges

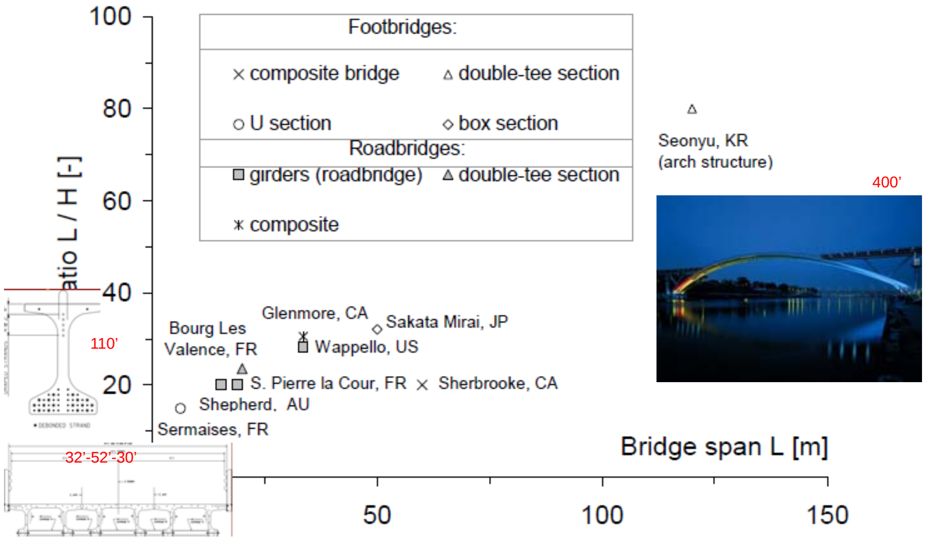
The AASHTO Specification M85 lists ten types of portland cement :

1. Type I Normal
2. Type IA Normal, air-entraining
3. Type II Moderate sulfate resistance
4. Type IIA Moderate sulfate resistance, air-entraining
5. Type II(MH) Moderate heat of hydration, moderate sulfate resistance
6. Type II(MH)A Moderate heat of hydration, moderate sulfate resistance, air-entraining
7. Type III High early strength
8. Type IIIA High early strength, air-entraining
9. Type IV Low heat of hydration
10. Type V High sulfate resistance

High-Performance Concrete in Bridges

- **High-Strength Concrete –** in excess of 8.0 ksi specified at 56 days to achieve longer span lengths, wider beam spacing, or the use of shallower sections.
- **Low-Permeability Concrete -** beneficial in reducing the rate of penetration of chlorides into the concrete; most high-strength concretes have a low permeability but not all low permeability concretes have high strength.
- **Self-Consolidating Concrete (SCC) -** a highly flowable, nonsegragating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation; using a high-rangewater-reducing admixture, and, in some cases, including a viscosity-modifying admixture; more expensive due to more stringent quality control
- **Ultra-High-Performance Concrete (UHPC) -** compressive strength greater than 21.7 ksi; a cementitious composite material that contains cement, fine sand, silica fume, ground quartz, superplasticizer, steel or plastic fibers, and water

UHPC applications to footbridges and roadbridges



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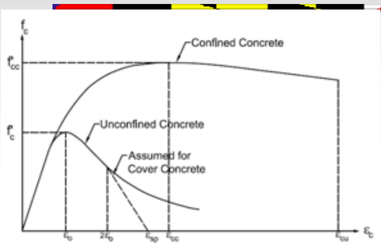
UHPC Application

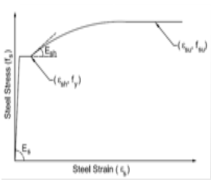
curing at ambient temperatures, or steam curing up to 115ºF (46ºC), until the compressive strength of match-cured cylinders attained 14,500 psi (100 MPa).

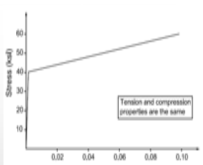
thermal treatment of approximately 190ºF (88ºC) along with relative humidity of at least 95% for at least 48 hours [5400 psi (37 MPa) at 28 hours, 14,900 psi (103 MPa) at 50 hours, and 32,400 psi (223 MPa) after the second stage curing./

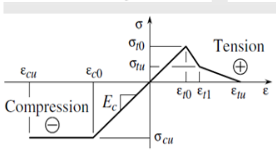
The first UHPC bridge constructed in the United States. The bridge includes three UHPC prestressed I-girders spanning a creek in rural Iowa.

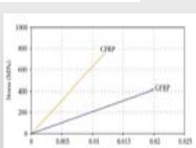
Concrete and Steel Material Properties











- Stress-strain relation for monotonic loading of confined and unconfined concrete based on Mander, et al. model
- True and Idealized steel stress-strain relationships
- Stress-strain response of SFRC

$$\sigma(\varepsilon) = \begin{cases} \sigma_{cu} & for\ (\varepsilon_{cu} \le \varepsilon \le \varepsilon_{c0}) \\ E\varepsilon & for\ (\varepsilon_{co} \le \varepsilon \le \varepsilon_{t0}) \\ \sigma_{to} + \psi(\varepsilon - \varepsilon_{t0}) & for\ (\varepsilon_{to} \le \varepsilon \le \varepsilon_{t1}) \\ \sigma_{tu} + \lambda(\varepsilon - \varepsilon_{t1}) & for\ (\varepsilon_{t1} \le \varepsilon \le \varepsilon_{tu}) \end{cases}$$

- FRP uniaxial stress-strain curve for carbon and glass FRP composites in the fiber direction

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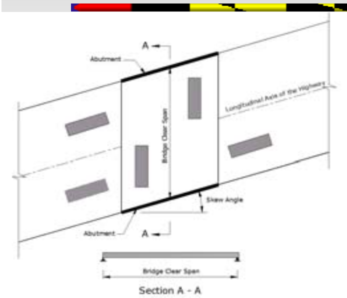
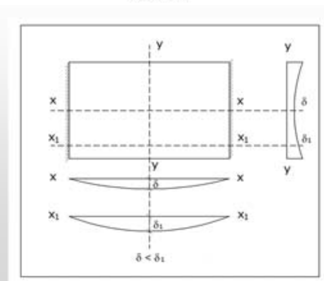
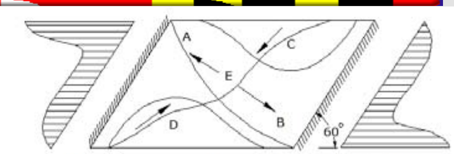
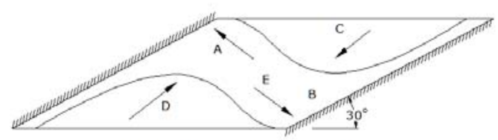
Behavior of Non-skewed/Skewed Concrete Beam-Slab Bridges



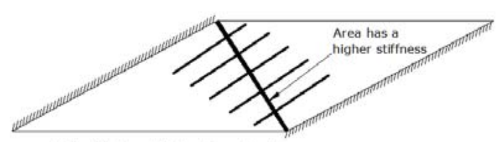




a) Load transferred from Zone C and D to E and then to the supports



b) Greater the skew, narrower the load transfer strip



c) Simplified model of load transferring

Principle and Modeling of Concrete Beam-Slab Bridges

- Linear elastic modeling – production purposes
  - It can be simplified as a beam or a grid
  - The equivalent stiffness can be calculated from equation 2.6 for rectangular void block or equation 2.7 for circular block.
  - The most common types of finite element used are flat shell elements
  - A beam-and-slab or cellular bridge deck may require a three-dimensional (3D) finite element analysis.
- Nonlinear modeling – research/study purposes
  - as an equivalent uniaxial material which is distributing throughout the finite element. It is often referred as "smeared" steel (smeared model);
  - as discrete bars connected to the nodes in the finite element model (discrete model);
  - as a uniaxial element which is embedded in a larger finite element (embedded model).
- FRC/FRP modeling – research/study purposes
  - The FE model uses a smeared cracking approach for the concrete and three-dimensional layered elements to model FRP composites

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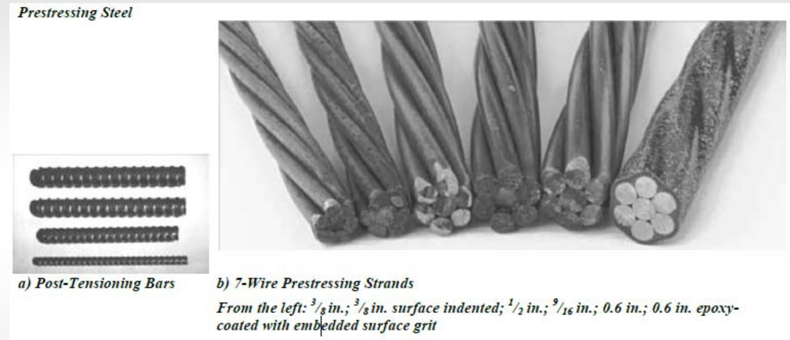
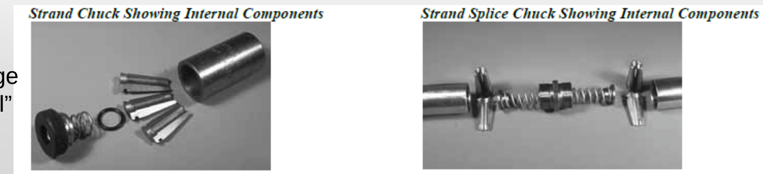
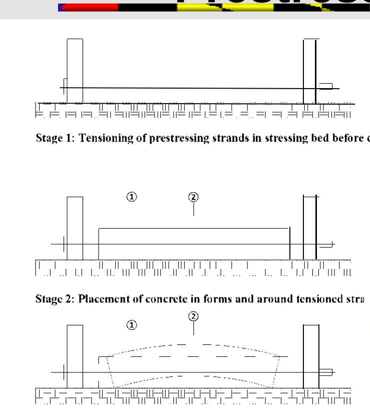
Prestressing steel, Strand Anchors and Couplers



Ref: "PCI Bridge Design Manual"



Pretensioning Method – Prestress loading stages



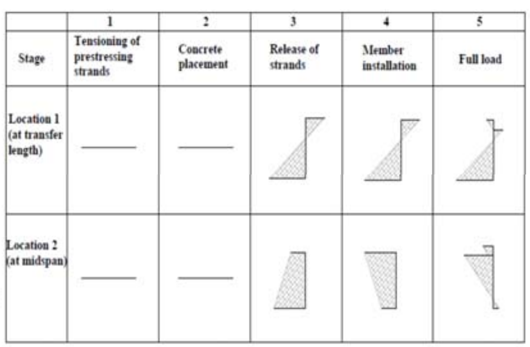
Stage 1: Tensioning of prestressing strands in stressing bed before casting concrete.

Stage 2: Placement of concrete in forms and around tensioned stra

Stage 3:Release of strands causing shortening of member.

Stage 4:Member placed on piers and/or abutments and deck slab, i

Stage 5:Full service load after all prestress losses.



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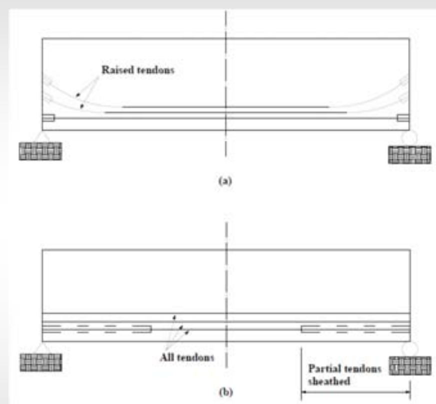
Tensile Stress Release of Precast Prestressed Concrete Girders



Prestressing strand profiles (a) harped strands (b) debonded strands (the dashed lines indicate debonding material around prestressing strand)

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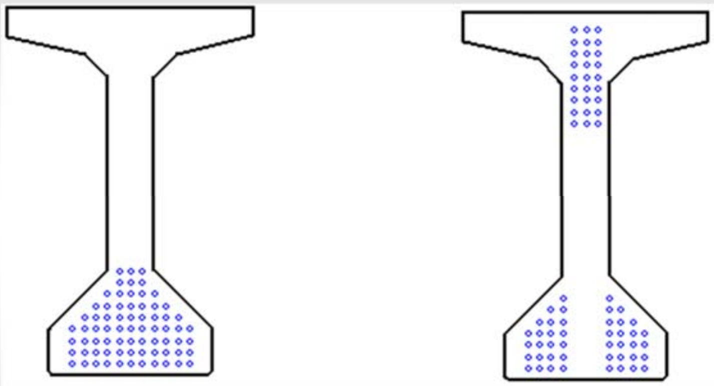
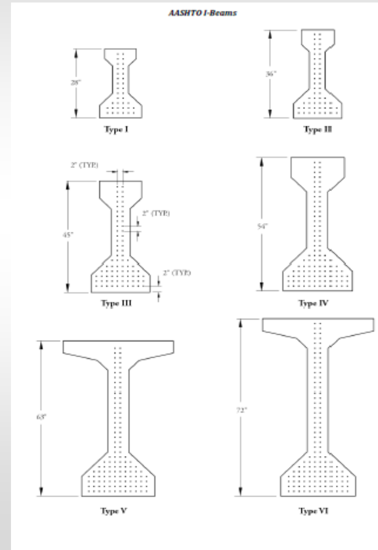
Precast Prestressed Concrete Girders

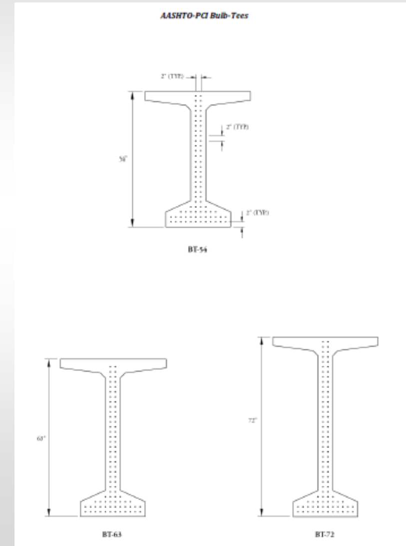


(a) Mid section (b) End section

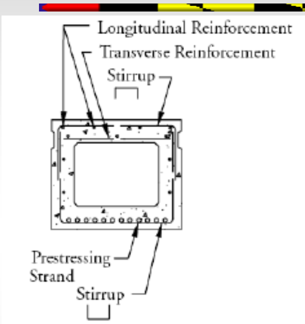
Figure 5.35 - Section of the AASHTO beams with strands

Precast Prestressed Concrete Girders

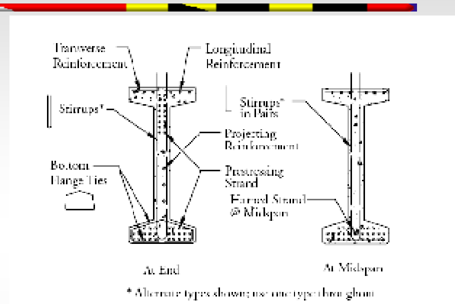




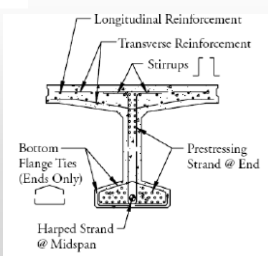
Nonprestressed Reinforcement Configurations for Precast Prestressed Concrete Girders



Box Beam



I- & Bulb-Tee Beam



Deck Bulb-Tee

Ref: "PCI Bridge Design Manual"

Precast Prestressed Concrete Girders

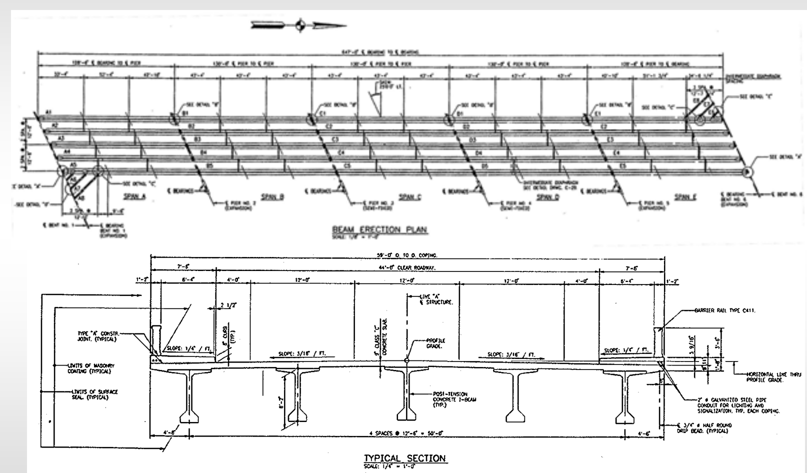
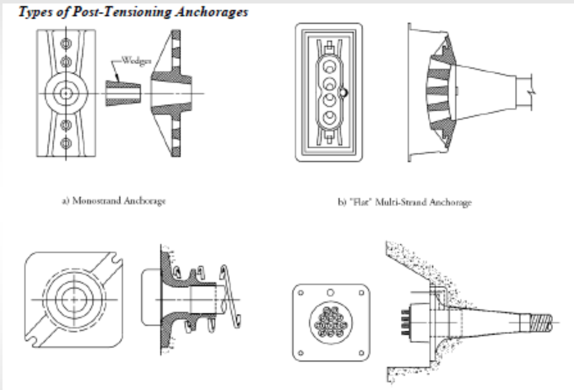
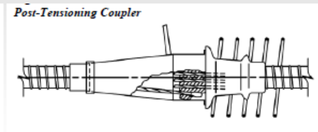


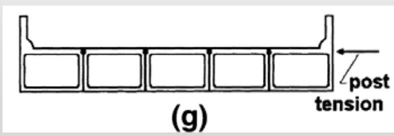
Figure 5.35 - Section of the AASHTO beams with strands

Post-tensioning Strand Anchors & Couplers

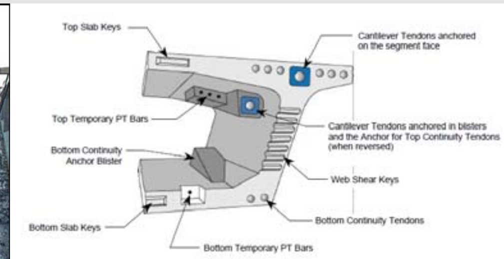




Ref: “PCI Bridge Design Manual”

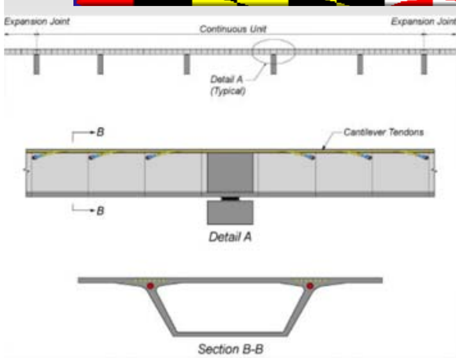


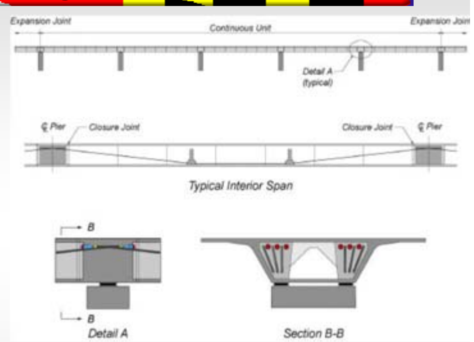
Post-tensioning Method



- Figure 5.4 illustrates a post-tensioned beam before concrete pouring and post-tensioning to show its rebar cages and conduits.
- Figure 5.5 shows a perspective of a typical precast balanced cantilever segment with the various types of tendons

Post-tensioning Method – Typical Layout





- Figure 5.6 – Cantilever Post-Tensioning Tendons Anchored on the Segment Faces
- Figure 5.7 – Interior Span Post-Tensioning for Span-By-Span Construction

Principle and Modeling of Prestressing

The four most critical conditions in the structural modeling of tendons are:

- Immediate loss of stress in tendon - Friction between the strand and its sheathing or duct causes two effects: (1) curvature friction, and (2) wobble friction.
- Elastic shortening of the concrete
- Long-term losses - (1) relaxation of the prestressing steel, (2) shrinkage in concrete, and (3) creep in concrete.
- Change in stress due to bending of the member under applied loading

Pretensioning/Post-tensioning tendon modeling

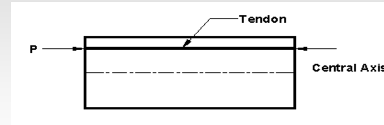
- Tendon modeled as applied loading
- Tendon modeled as load resisting elements

Principle and Modeling of Prestressing - Tendon modeled as applied loading

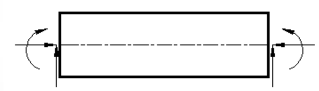
Tendon modeled as applied loading:

- Simple load balancing - The shortcoming to this method is that the immediate and long-term stress losses in prestressing must be approximated and accounted for separately.
- Tendon modeling through primary moments - The primary moment M_p due to the prestressing force P may be used as an applied loading in lieu of the balanced loading for structural analysis.
- Equivalent load through discretization of the tendon force - The force distribution can be further simplified by considering the force in each tendon segment to be equal to the force at the midpoint of the segments (Figure 5.8).

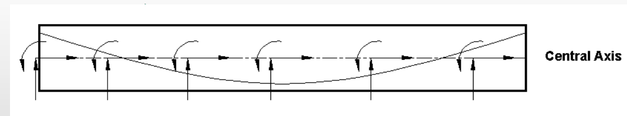
Principle and Modeling of Prestressing – Tendon modeled as applied loading



(a) Tendon as External Force of an Element



(b) Equivalent Tendon Force of an Element



(c) Equivalent Tendon Forces along the Central Axis of the Beam

Figure 5.8 - Equivalent Load through Discretization of the Tendon Force

Principle and Modeling of Prestressing – Tendon modeled as applied loading

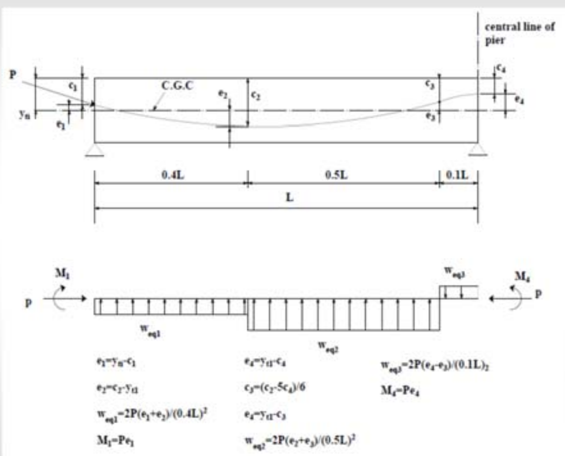
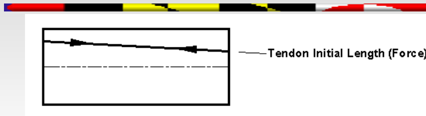
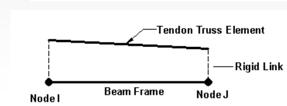


Figure 5.9 - Post-tensioning Equivalent Loads for Two-span Continuous Bridge to calculate "secondary moments."

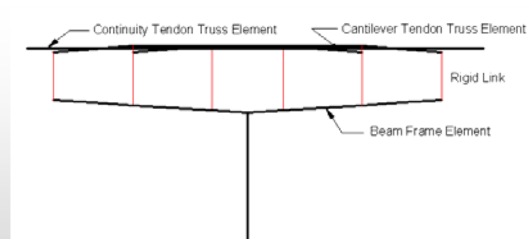
Principle and Modeling of Prestressing – Tendon modeled as load resisting elements



(a) Tendon as Element



(b) Tendon Element Geometry



•Finite Element Modeling of the Segmentally Erected Bridge with Post-Tensioning Tendons

Figure 5.10 - Tendon Modeled as an Element Linked to the Concrete Member

Principle and Modeling of Prestressing – Tendon modeled as load resisting elements

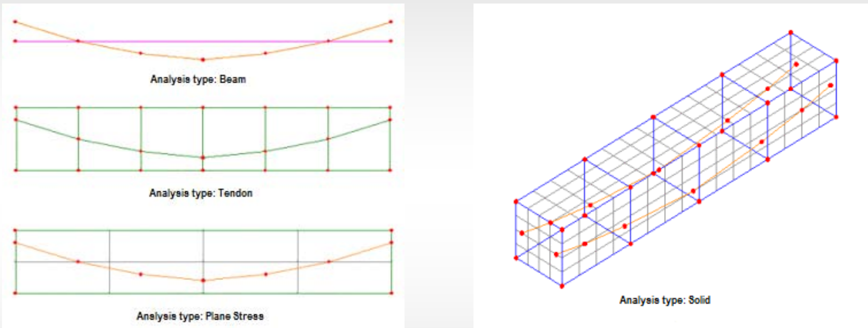


Figure 5.11 – 2D and 3D Post-tensioning Analysis Types

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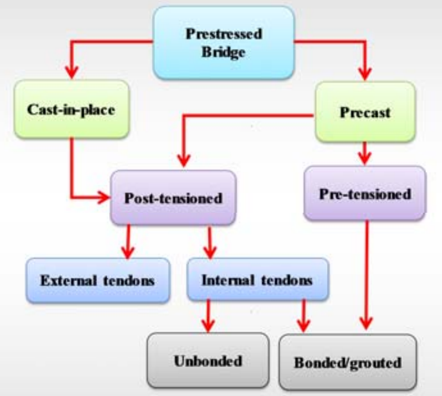
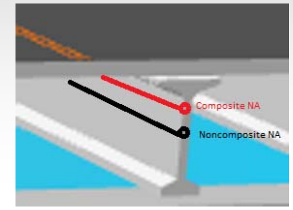
Types of Prestressing Analysis





For a 2D beam model, moments and shears are direct results from analysis and there is no need to integrate stresses in order to get beam moments for strength limit state capacity check. No matter which code is adopted for design, stress limits for concrete and steel are always given.

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Post-tensioned Concrete Bridge

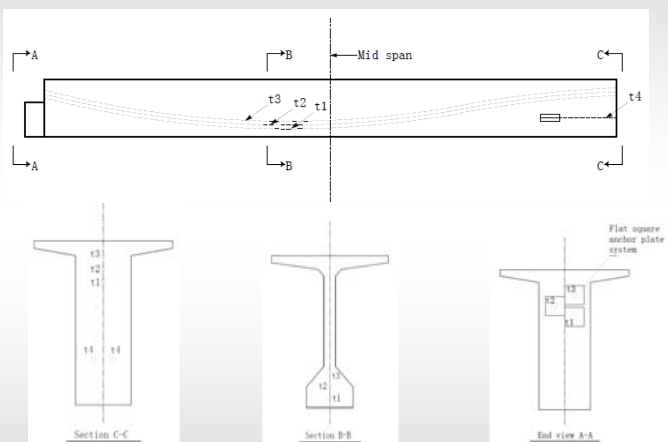

Figure 5.15 – Post-tensioning (a) layout and their (b) cross sections at the end span of a continuous precast prestressed/post-tensioned concrete bridge

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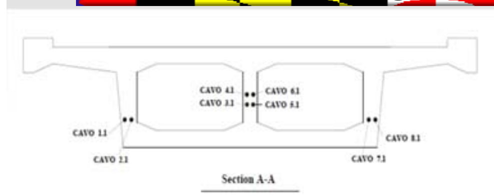
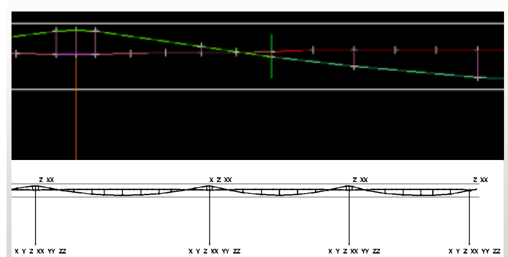
Post-tensioned Concrete Bridge Example – Verzasca 2 Bridge Models in Switzerland





- To model the post tensioning tendons, truss elements are created.
- Only one truss element represents all eight of the individual tendons that are distributed over the cross section.
- The geometry of the tendon is approximately at the middle of the actual positions.
- It is important that they end at the same vertical location as the beam elements, so that they can be connected with vertical rigid elements.
- Beam and tendon elements are connected with rigid elements and model is provided with proper boundary conditions

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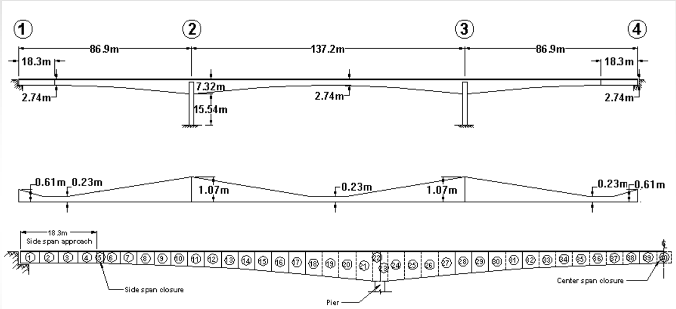
Segmental Post-tensioned Concrete Bridge



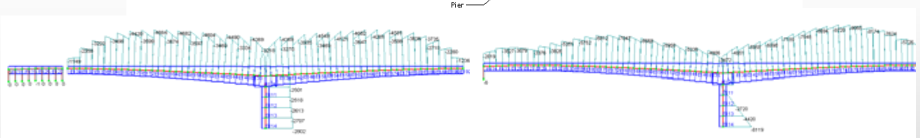


Figure 5.38 - Bridge Elevation Profile, Bottom Slab Thickness Variation and Segment Division

Figures 5.40 & 5.41 – Top flange stresses before and after closure

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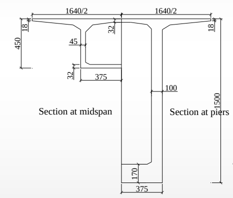
Post-tensioned Concrete Bridge Example – Sutong Bridge approach spans in China



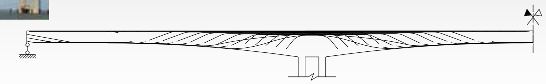


Figure 5.44 - Conventional layout of longitudinal tendons

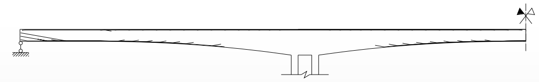


Figure 5.45 - Straight layout of longitudinal tendons (end of 1980s)

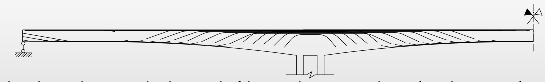


Figure 5.46 - Current layout of longitudinal tendons with the webs' bent-down tendons (early 2000s)

- The continuous rigid frame of Sutong Bridge approach spans is a segmental, cast-in-place concrete cantilever bridge completed in 2007
- The span distribution is 140m+268m+140m (460'+880'+460'), among the longest spans in the world

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Post-tensioned Concrete Bridge Example – Sutong Bridge approach spans in China

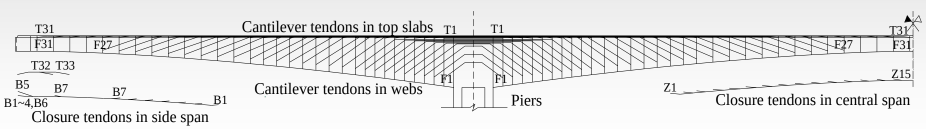

Figure 5.49 - Segments and layout of

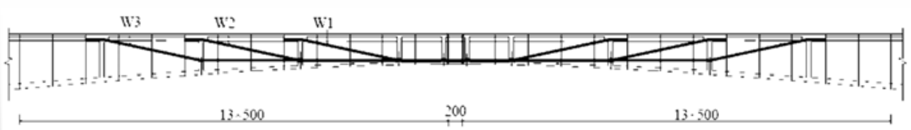

Figure 5.50 - Layout of the preparatory external tendons

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Post-tensioned Concrete Bridge Example – Sutong Bridge approach spans in China

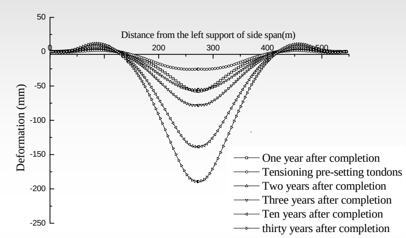

Figure 5.52 - Increment of deflections of the bridge after completion with the pre-setting internal tendons

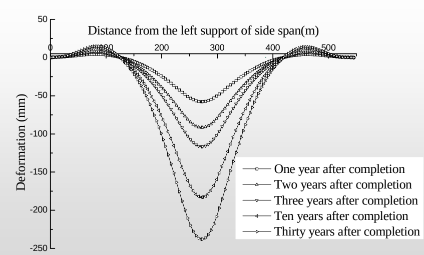

Figure 5.53 - Increment of deformations of the bridge after completion without the pre-setting internal tendons

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PC Bridge LRFR Rating Equation

$$RF = \frac{C - (\gamma_{DC})(DC) - (\gamma_{DW})(DW) \pm (\gamma_P)(P)}{\gamma_{LL}\,(LL + IM)}$$

where:

- RF = rating factor
- C for strength $= \phi_c\, \phi_s\, \phi\, R_n$
- C for service $= f_r$
- ϕ_c = condition factor
- ϕ_s = system factor
- ϕ = LRFD resistance factor
- R_n = nominal member resistance (as inspected)
- DC = dead load effect due to structural components and attachments
- DW = dead load effect due to wearing surface and utilities
- P = permanent loads other than dead loads
- LL = live load effect
- IM = dynamic load allowance
- γ_{DC} = LRFD load factor for DC
- γ_{DW} = LRFD load factor for DW
- γ_P = LRFD load factor for permanent loads other than dead loads = 1.0
- γ_{LL} = evaluation live load factor

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PC Bridge LRFR Rating Equation

- LFR moment $RF = \frac{\phi M_n - \gamma_D \Sigma M_D}{\gamma_L M_L (1 + I)}$

Inventory rating

1) $M_u = 1.3[DL + 1.67(LL + I)]$
2) $M_u = 1.3[DL + 1.25(LL + I) + LL_{SW}]$

Operating rating

1) $M_u = 1.3[DL + (LL + I)]$
2) $M_u = 1.3[DL + 0.75(LL + I) + LL_{SW}]$

- LRFR moment $RF = \frac{C - (\gamma_{DC})(DC) - (\gamma_{DW})(DW)}{\gamma_{LL}(LL + IM)}$

Inventory rating

1) $M_u = 1.25\,DL + 1.5\,DW + 1.75(LL + I)$
2) $M_u = 1.25\,DL + 1.5\,DW + 1.3(LL + I) + LL_{SW}$

Operating rating

1) $M_u = 1.25\,DL + 1.5\,DW + 1.35(LL + I)$
2) $M_u = 1.25\,DL + 1.5\,DW + (LL + I) + LL_{SW}$

- LRFR shear $V_n = V_c + V_s + V_p$

Where, Vc, Vs, and Vp are the shear resistance components due to the concrete, shear reinforcement, and the inclined prestressing strand, respectively.

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PC Bridge LRFR Rating Equation

Limit States and Load Factors for Load Rating [AASHTO, 2008]

Bridge Type	Limit State	Dead Load γ_{DC}	Dead Load γ_{DW}	Design Load: Inventory γ_{LL}	Design Load: Operating γ_{LL}	Legal Load γ_{LL}	Permit Load γ_{LL}
Prestressed Concrete	Strength I	1.25	1.50	1.75	1.35	Table 18.3.2.1.2-1 and 18.3.2.1.2-2	—
	Strength II	1.25	1.50	—	—	—	Table 18.3.2.1.3-1
	Service III	1.00	1.00	0.80	—	1.00	—
	Service I	1.00	1.00	—	—	—	1.00

Service III Load Rating

$$RF_{IN} = \frac{(f_{allow} - (f_{pe} + f_{DL}))}{0.8\, f_{LL+I}}$$

Service I Load Rating

Case I: The stress at the top of girder under 0.5 (permanent + transient loads)

$$RF = \frac{f_{allow} - 0.5(f_{Nt} + f_{Ct} + f_{prt})}{f_{CLL}}$$

Case II: The stress at the top of girder under permanent + transient loads

$$RF = \frac{f_{allow} - (f_{Nt} + f_{Ct} + f_{prt})}{f_{CLL}}$$

Case III: The stress at the top of slab under 0.5 (permanent + transient loads)

$$RF = \frac{f_{allow} - 0.5\, f_{Ct}}{f_{CLL}}$$

Case IV: The stress at the top of slab under permanent +transient loads

$$RF = \frac{f_{allow} - f_{Ct}}{f_{CLL}}$$

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PC Bridge LFR and LRFR Comparison

Standard Specifications Rating Factors

	Inventory Rating (Notional load)	Operating Rating
LFD Strength (HS20)	1.25	2.09 (HS41.4)
LFD Service (HS20)	1.21	
LFD Proof Test (HS20)	2.50	4.32 for interior use (HS33)

LRFD Specifications Rating Factors

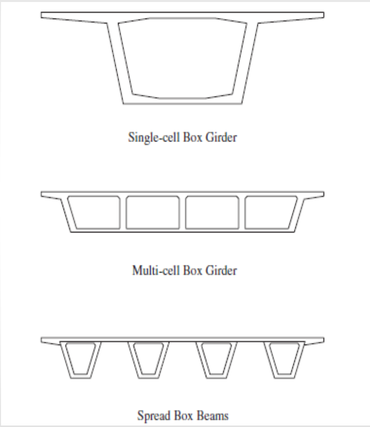
	Inventory Rating	Operating Rating
LRFD Strength I (HL-93)	1.18	1.53
LRFD Service III (HL-93)	1.15	
LRFD Service I (HL-93)		2.06
LRFD Strength II (HL-93) Routine Blanket Permit in mixed traffic		1.00
LRFD Service I(HL-93) Routine Blanket Permit in mixed traffic		1.58
LRFD Strength II(FL-120) Escorted single trip without others lanes loaded		2.29
LRFD Strength II(FL-120) Escorted single trip with other lanes loaded		1.17 (HS39.1)

Comparing LFD Operating RF = (2.07)HS20 = capacity of HS41.4 tons.

Remember the FL-120 is the HS20 truck with an RF =1.67, therefore with LRFD Strength II operating with other lanes loaded (1.17)(HS20)(1.67) = capacity of HS39.1 tons. One may anticipate that LRFD would have a slightly lower permit capacity (HS 39.1) because it has a 75 year service life calibration for strength limits states and the *Standard Specifications* (HS 41.4) was published to target a 50-year service life.

Ref: “PCI Bridge Design Manual”

Curved Concrete Bridges



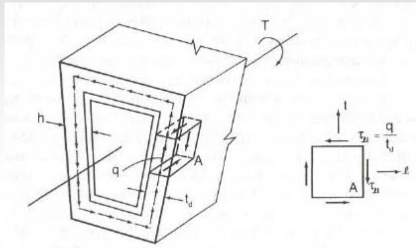


Figure 6.2 – Hollow box subjected to torsion

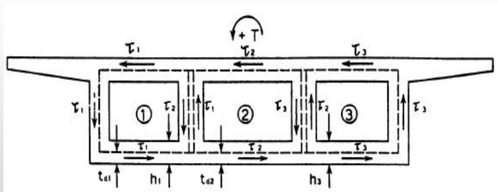
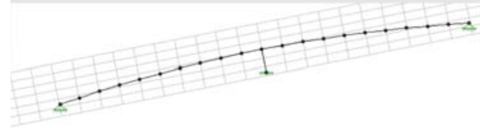


Figure 6.3 - Shear stresses in multi-cell section

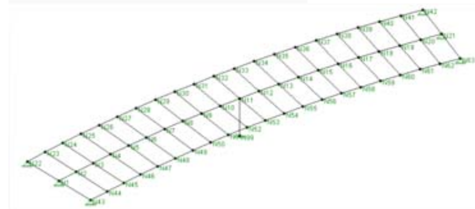
Principle and Modeling of Curved Concrete Bridges



(a) Typical spine beam model

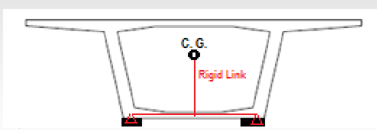
Linn Cove Viaduct, NC

3D FEM model of example 3

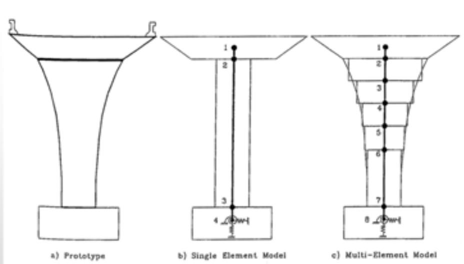


(b) Typical grillage model

Principle and Modeling of Curved Concrete Bridges



(a) Bearing supported connection



(b) Monolithic connection

Figure 6.6 – Super- and sub-structure connection

Principle and Modeling of Curved Concrete Bridges

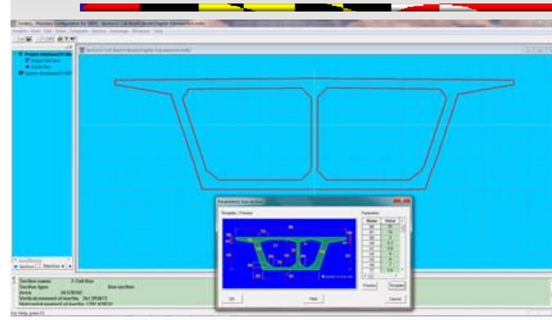


Figure 6.7 – Box sectional property calculation

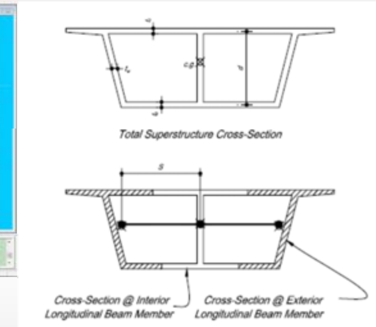


Figure 6.8 – Grillage modeling of a longitudinal box cross section