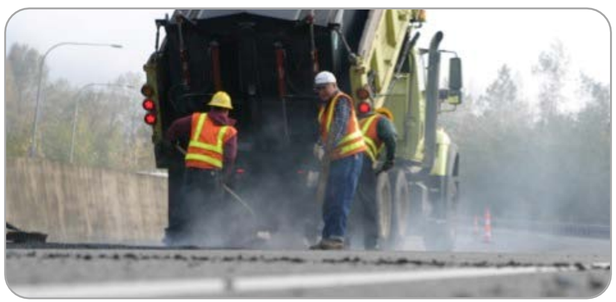
# Computer-Aided Design, Analysis and Load Rating of Precast-Prestressed Spliced Girder Bridges





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Washington State
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# Outline

- LRFD Requirements for Spliced Girder Bridges
- Overview of Spliced Girder Analysis
- Computer Aided Design, Analysis, and Load Rating

- Basic requirements of conventional precast-prestressed girder bridges
  - Service stress limitations, ultimate strength requirements, etc.
- LRFD 5.14.1.3 – Spliced Precast Girders
  - Additional requirements for contract documents
  - Additional service stress limitations
  - Additional analysis requirements

# LRFD Requirement for Time-Step Analysis

LRFD 5.9.5.4.1

For segmental construction and **post-tensioned spliced precast girders, other than during preliminary design, prestress losses shall be determined by the time-step method**... **including consideration of the time-dependent construction stages** and schedule shown in the contract documents.

**For components with combined pretensioning and post-tensioning**, and where post-tensioning is applied in more that one stage, **the effects of subsequent prestressing on the creep loss of previous prestressing shall be considered.**

## Introduction to Time-Step Analysis

- Models design life through discrete time intervals
- Uses fundamental principles of engineering mechanics
- Accounts for time-dependent material properties and responses ($f_c'$, $\psi$, $\varepsilon_{shrinkage}$, $relaxation$)

- Step-wise pseudo-linear solution to a nonlinear problem

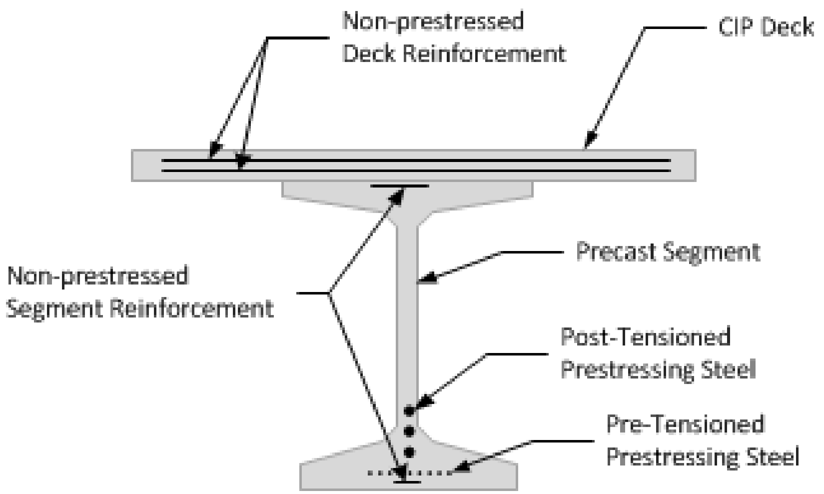
- Structural response at the end of any interval is the summation of the responses of all the preceding intervals

## Challenge of Time-Step Analysis

- Sheer quantity of computations that must be performed
  - Deformations are computed at many locations
  - Deformations are computed in every piece of the spliced girder
  - Deformations are computed for the design life of the structure
  - Transformed section properties change with time and location
    - Non-prismatic segments (haunches, varying tendon locations)
    - $E_c$ and thus the modular ratios vary with time
  - Loading conditions change with time
    - Staged application of superimposed loads
    - Multi-staged post-tensioning
  - Statical structural system changes with time
    - Composite closure joints
    - Composite deck
    - Temporary support removal

# Composition of Spliced Girders

- Precast concrete segments
- CIP concrete closure joints and deck
- Prestressing Strands and Tendons
- Non-prestressed reinforcement



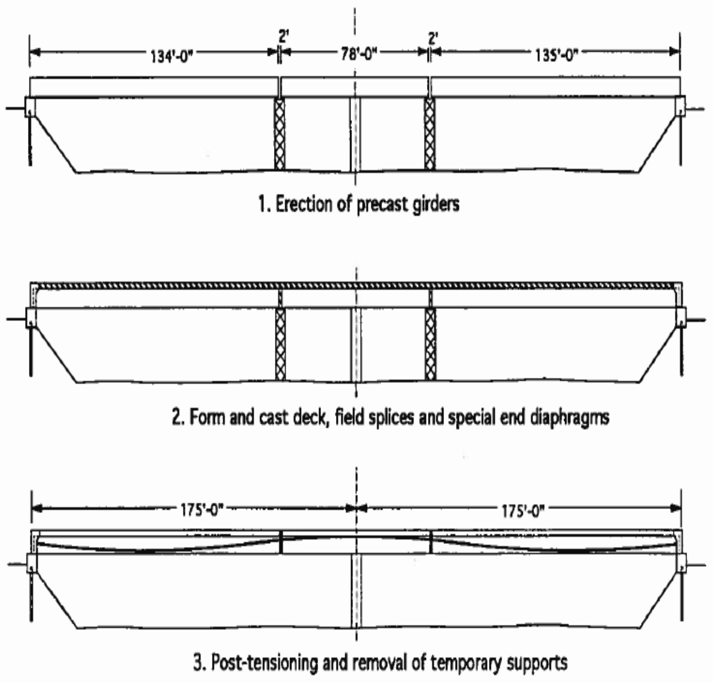
## Time Variation of Material Properties

- Three distinct materials
- Concrete
  - Strength ($f_c'$) and stiffness ($E_c$) vary with time
  - Creep rate varies with time and time of loading
  - Shrinkage rate varies with time
- Prestressing steel
  - Relaxation rate varies with time and loading
- Non-prestressed Reinforcement
  - Constant with time. Obeys Hooke’s Law

# Timeline Modeling

- Modeled as a sequence of discrete intervals
  - Begins when segments are constructed
  - Ends at conclusion of design life
- Interval duration is based on changes in loading and the statical structural system
- Intervals are sub-divided to capture time-dependent material responses immediately following a change in forces

# Typical Timeline




| Construction Event | Day of Occurrence |
|---|---|
| Construct Segments | 0 |
| Erect Segments | 28 |
| Cast Closure Joints and Deck | 35 |
| Install tendons | 42 |
| Install traffic barrier | 60 |
| Open to traffic | 70 |

# Incremental Deformations

- Time-step analysis is simply computing incremental deformations during each interval
- Axial strain and curvature
  - Computed for every part of the girder
  - Caused by
    - externally applied loads
    - change in statical structural system
    - creep and shrinkage of concrete
    - relaxation of prestressing strands and tendons

# Computing Incremental Deformations

$$\Delta\varepsilon_c(i_e,i_b)=\frac{\Delta P_c(i_m)}{A_cE_c(i_m)}[1+\psi(i_e,i_m)]+\left\{\sum_{j=1}^{i-1}\frac{\Delta P_c(j_m)}{A_cE_c(j_m)}[\psi(i_e,j_m)-\psi(i_b,j_m)]+\Delta\varepsilon_{sh}(i_e,i_b)\right\}$$

$$\Delta\varphi_c(i_e,i_b)=\frac{\Delta M_c(j_m)}{I_cE_c(j_m)}[1+\psi(i_e,i_m)]+\left\{\sum_{j=1}^{i-1}\frac{\Delta M_c(j_m)}{I_cE_c(j_m)}[\psi(i_e,j_m)-\psi(i_e,j_m)]\right\}$$

$$\Delta\varepsilon_{ps}(i_e,i_b)=\frac{\Delta P_{ps}(i_m)}{A_{ps}E_{ps}}+\left\{-\frac{\Delta f_r(i_e,i_b)}{E_{ps}}\right\}$$

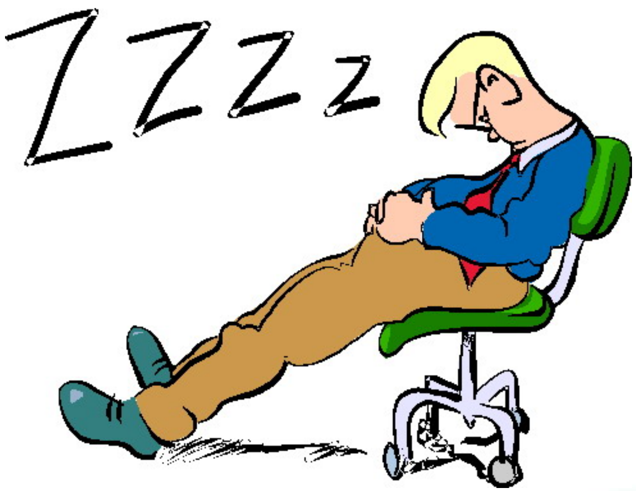
$$\Delta\varepsilon_{ns}(i_e,i_b)=\frac{\Delta P_{ns}(i_m)}{A_{ns}E_{ns}}$$

$$\Delta P_k=\left[\frac{\Delta P}{A_{tr}E_{tr}}+\frac{\Delta M(Y_{tr}-Y_k)}{I_{tr}E_{tr}}\right]A_kE_k,\ \Delta M_k=\Delta M\frac{I_kE_k}{I_{tr}E_{tr}}$$

$$\bar{P}_k=-E_kA_k\varepsilon_k,\ \bar{M}_k=-E_kI_k\varphi_k$$

$$\bar{P}=\sum_{k=1}^{n}\bar{P}_k,\ \bar{M}=\sum_{k=1}^{n}\left(\bar{M}_k+\bar{P}_k(Y_{tr}-Y_k)\right)$$

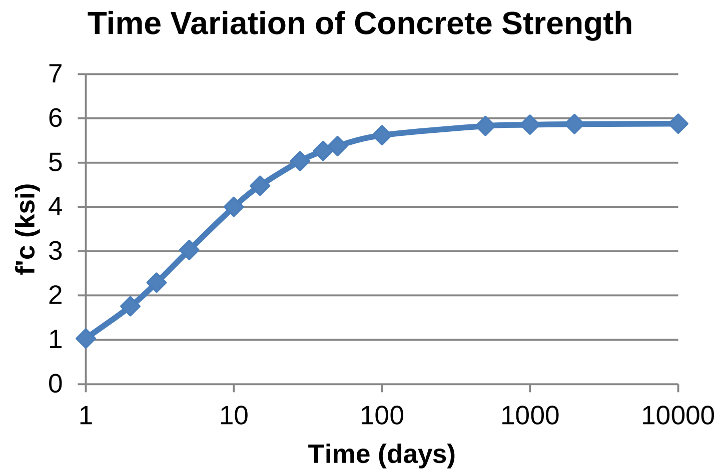
$$\bar{\varepsilon}=\frac{\bar{P}}{E_{tr}A_{tr}},\ \bar{\varphi}=\frac{\bar{M}}{E_{tr}I_{tr}}$$

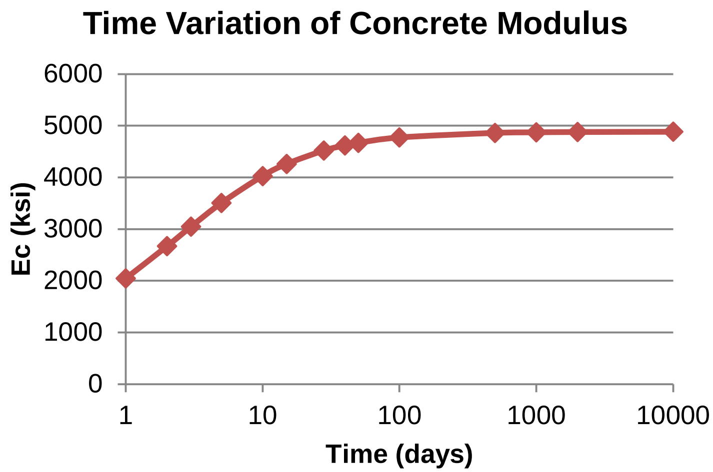


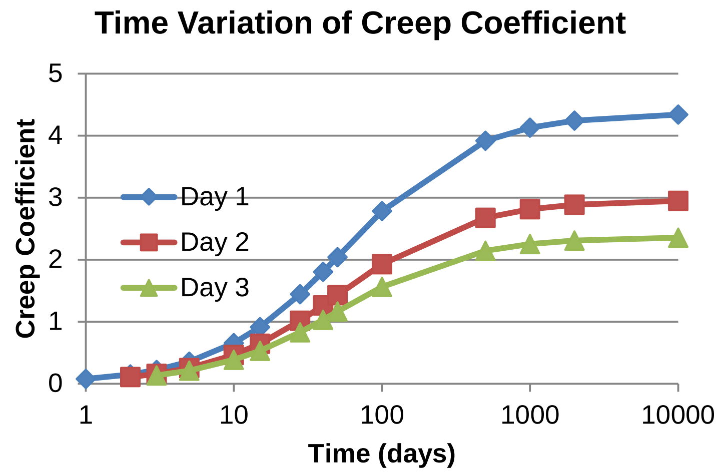
## Time-Step Analysis By Example

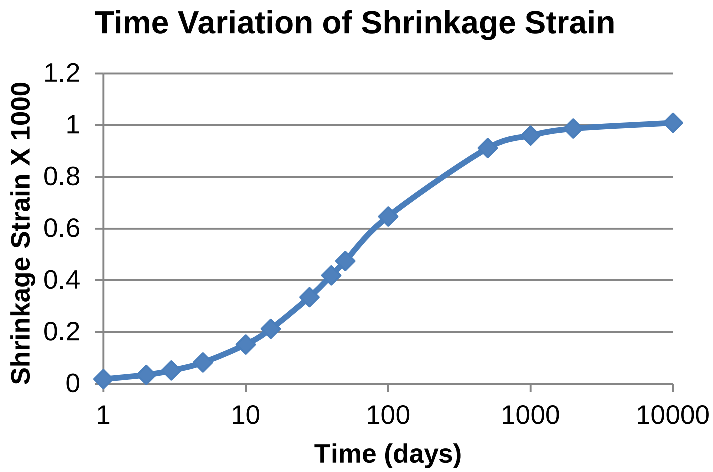
- Simple span reinforced concrete beam
- Self-weight loading

# Time Variation of Material Properties



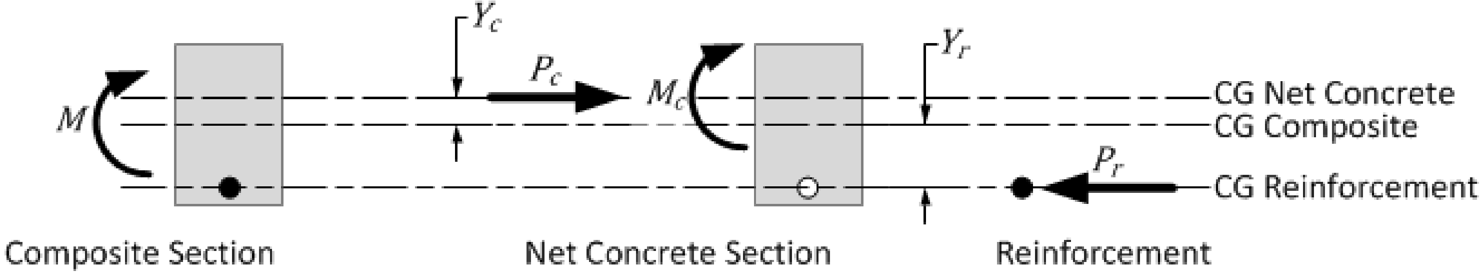



## Time Step 1 – Analyze Loading Condition

- Moment due to self-weight (external force)
- Use transformed section analysis
  - Neglect bending stiffness of reinforcement



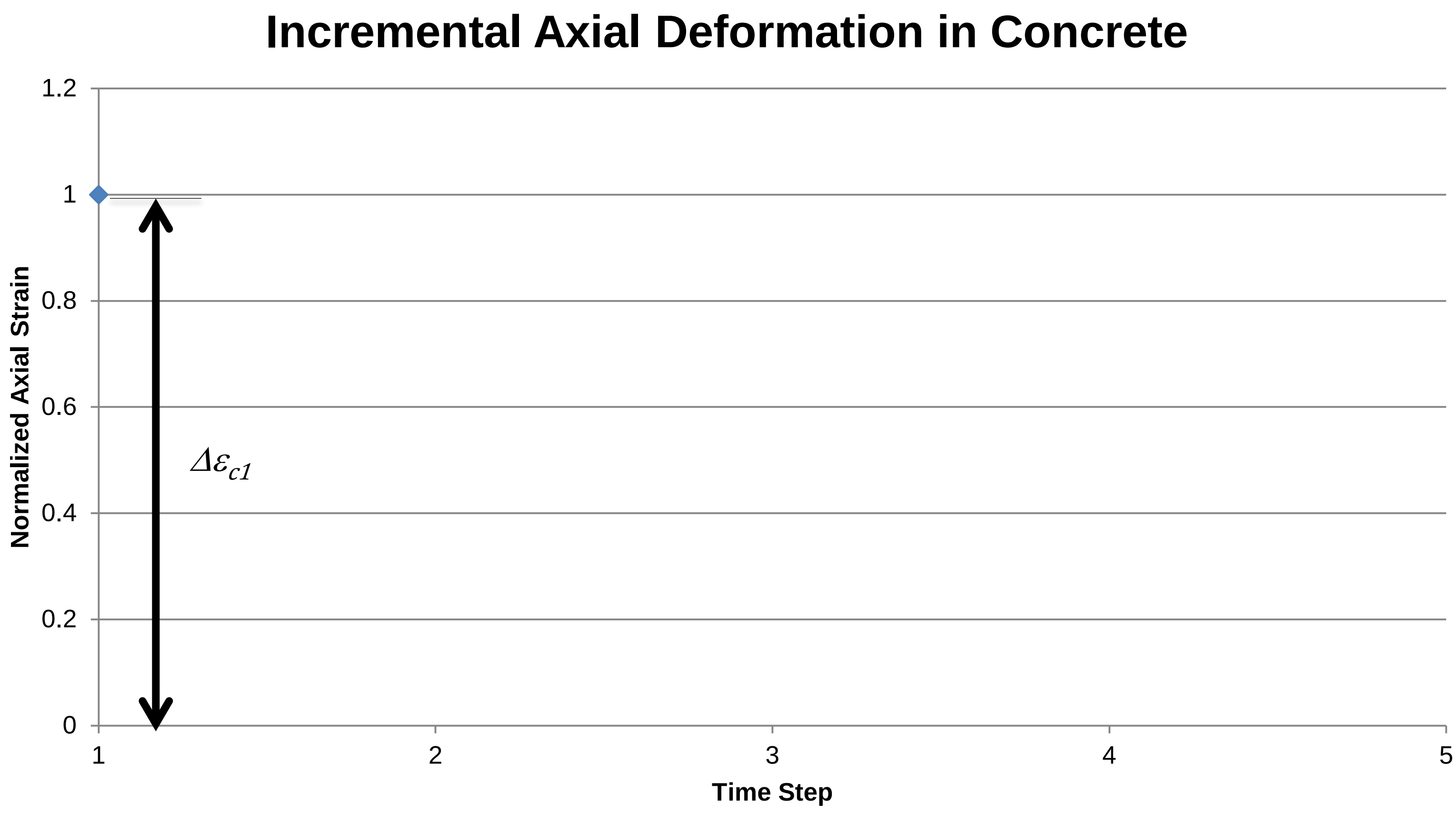

$$\sum External\ Forces = \sum Internal\ Forces$$

$$\sum P = 0 = P_c - P_r \qquad \sum M = M = M_c + P_c Y_c - P_r Y_r$$

## Time Step 1 – Incremental Deformations

- Incremental forces on the various parts of the cross section are determined by a transformed section analysis
  - $\Delta P_{c1} = P_c, \Delta M_{c1} = M_c, \Delta P_{r1} = P_r$
- Incremental Deformations
  - Computed using modulus at time of loading and net section properties
  - $\Delta \varepsilon_{c1} = \frac{\Delta P_{c1}}{E_{c1} A_{cn}}, \Delta \varphi_{c1} = \frac{\Delta M_{c1}}{E_{c1} I_{cn}}$
  - $\Delta \varepsilon_{r1} = \frac{\Delta P_{r1}}{E_s A_s}$

# Time Step 1 – End of Interval

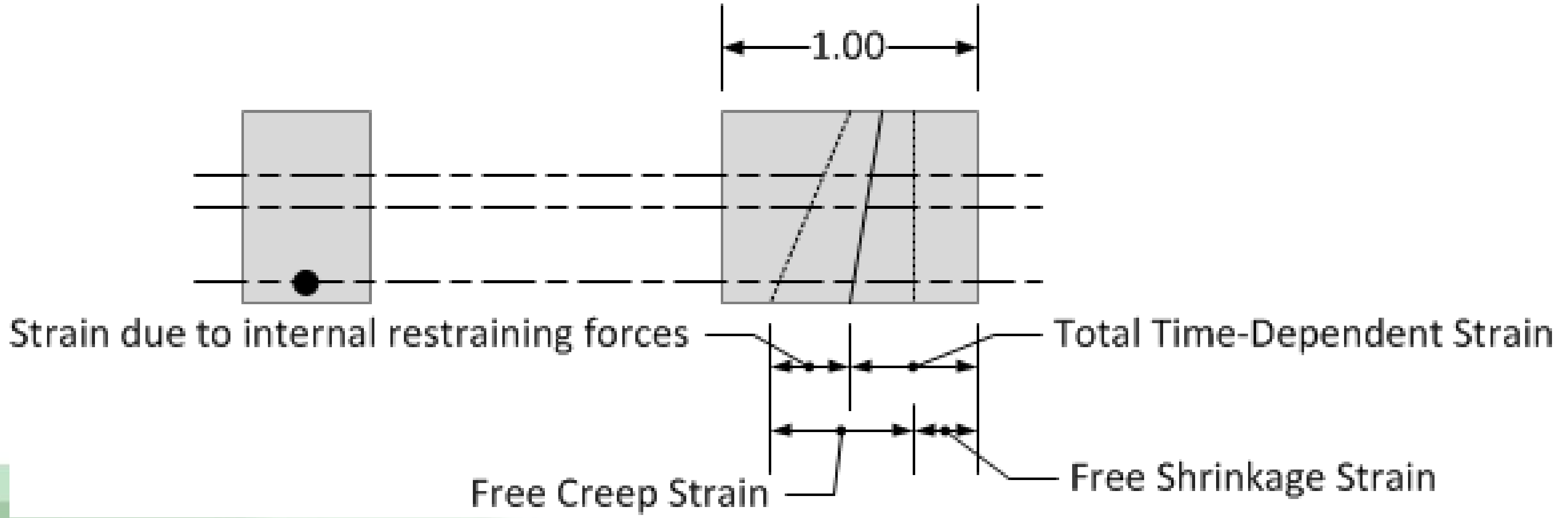


# Time Step 2 – Time-Dependent Effects

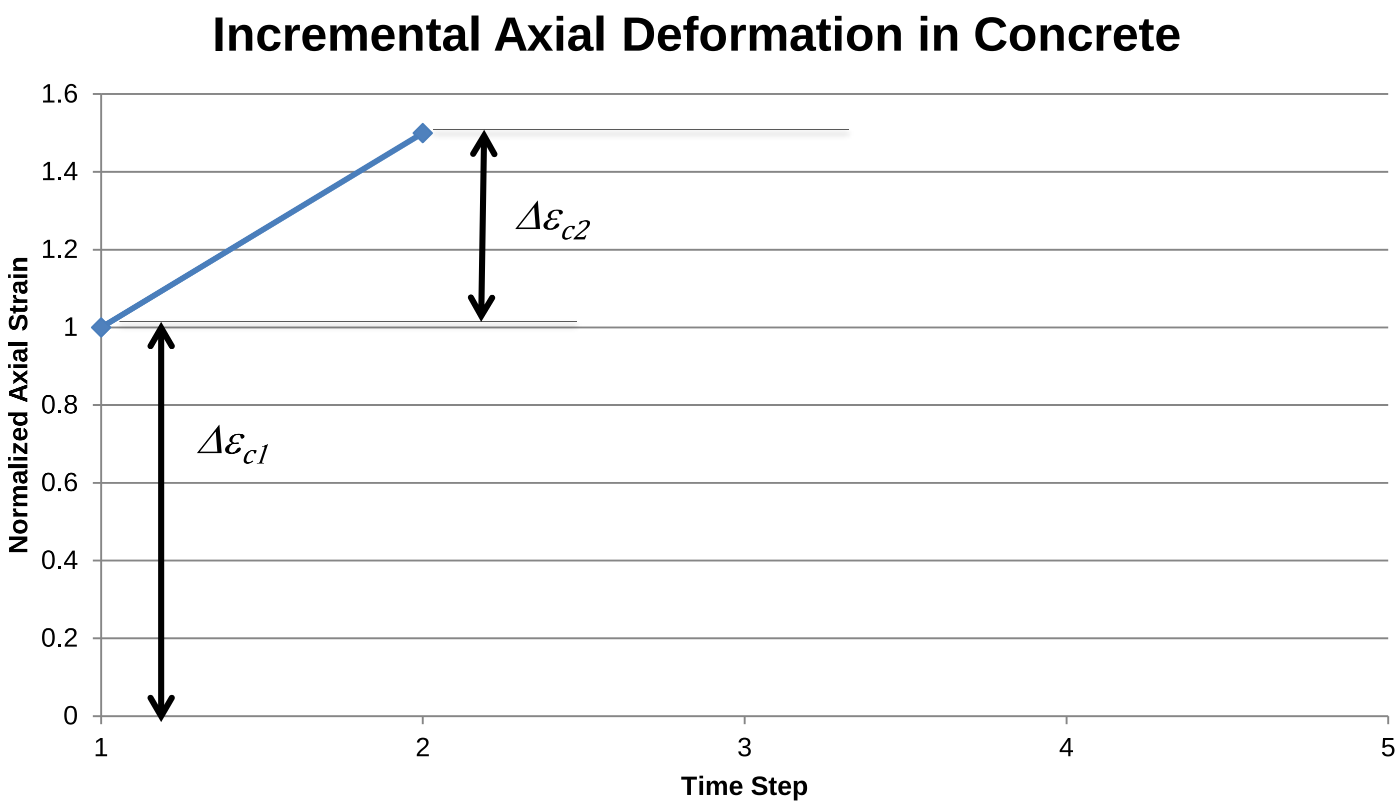
- Only Time Passes
- Time-dependent response of materials
  - Unrestrained Creep of Concrete
    - $\Delta\varepsilon_{cr} = \frac{\Delta P_{c1}}{E_1 A_c}\psi(t_2, t_1)$
    - $\Delta\varphi_{cr} = \frac{\Delta M_{c1}}{E_1 I_c}\psi(t_2, t_1)$
  - Unrestrained Shrinkage
    - $\Delta\varepsilon_{sh}(t_2, t_1)$

## Time Step 2 – Initial Strain Analysis

- Reinforcing causing internal restraint
- Compute restrained deformations and internal restraining forces, $\Delta\varepsilon_{c2}, \Delta\varphi_{c2}, \Delta\varepsilon_{r2}, \Delta P_{c2}, \Delta M_{c2}, \Delta P_{r2}$



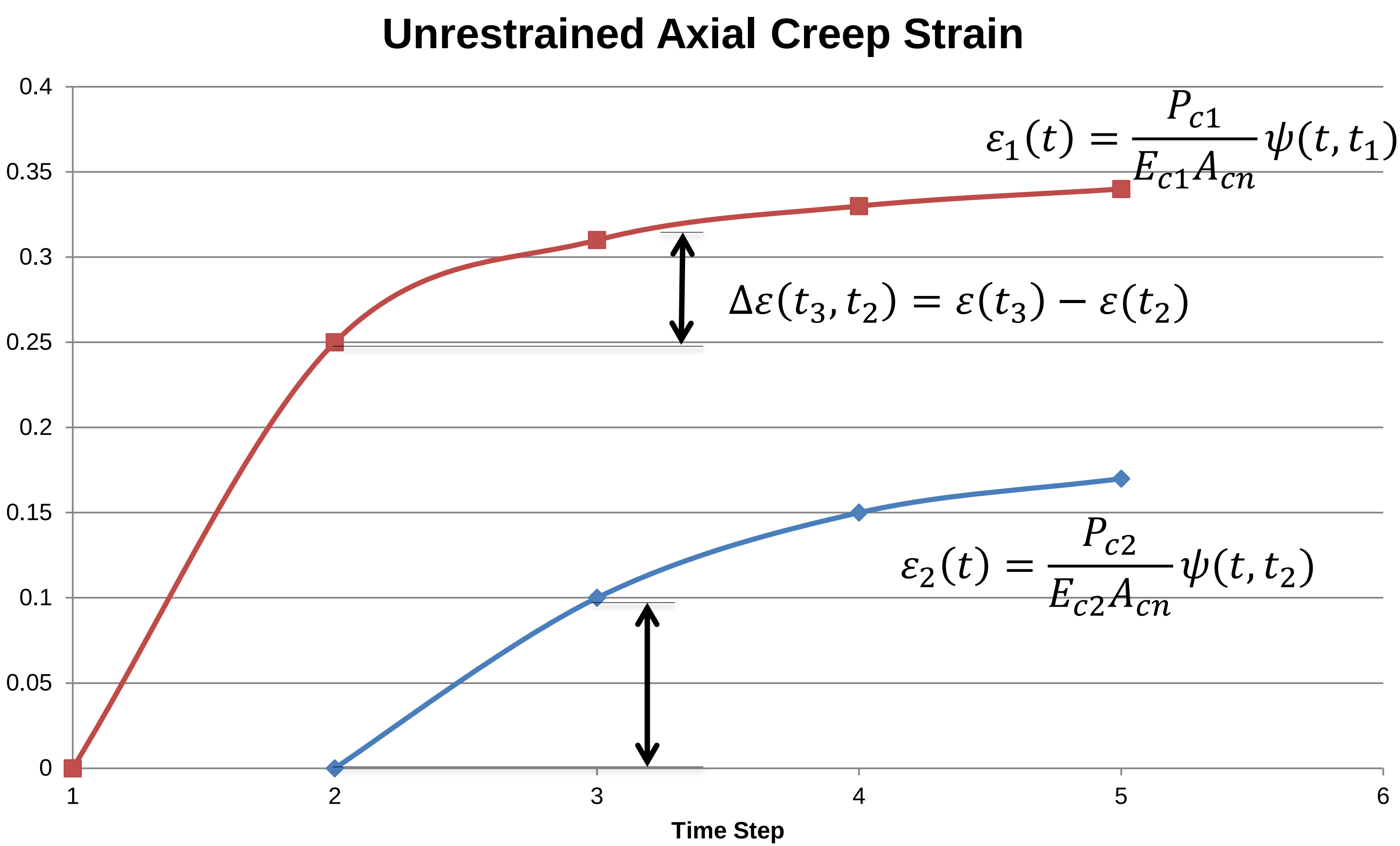
# Time Step 2 – End of Interval



## Time Step 3 – Time-Dependent Effects

- Only Time Passes
- Time-dependent response of materials
  - Unrestrained Creep of Concrete
    - $\Delta\varepsilon_{cr} = \frac{\Delta P_{c1}}{E_1 A_c}[\psi(t_3, t_1) - \psi(t_2, t_1)] + \frac{\Delta P_{c2}}{E_2 A_c}\psi(t_3, t_2)$
    - $\Delta\varphi_{cr} = \frac{\Delta M_{c1}}{E_1 I_c}[\psi(t_3, t_1) - \psi(t_2, t_1)] + \frac{\Delta M_{c2}}{E_2 I_c}\psi(t_3, t_2)$
  - Unrestrained Shrinkage
    - $\Delta\varepsilon_{sh}(t_3, t_2)$

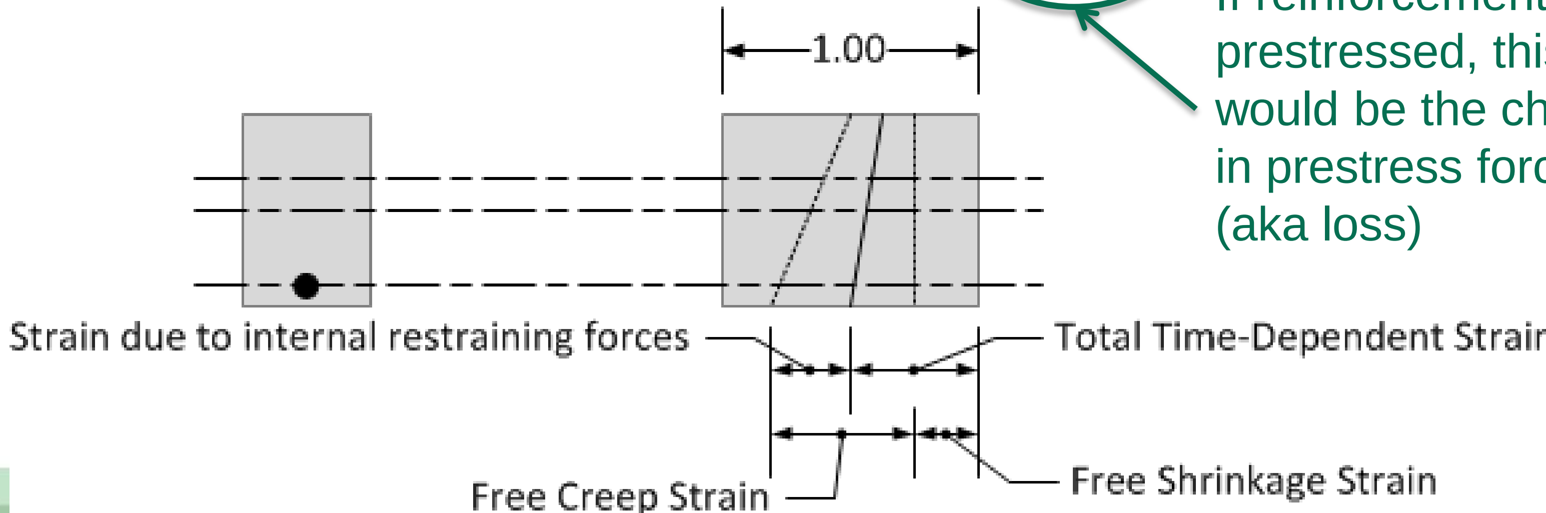
# Time Step 3 – Incremental Unrestrained Deformations



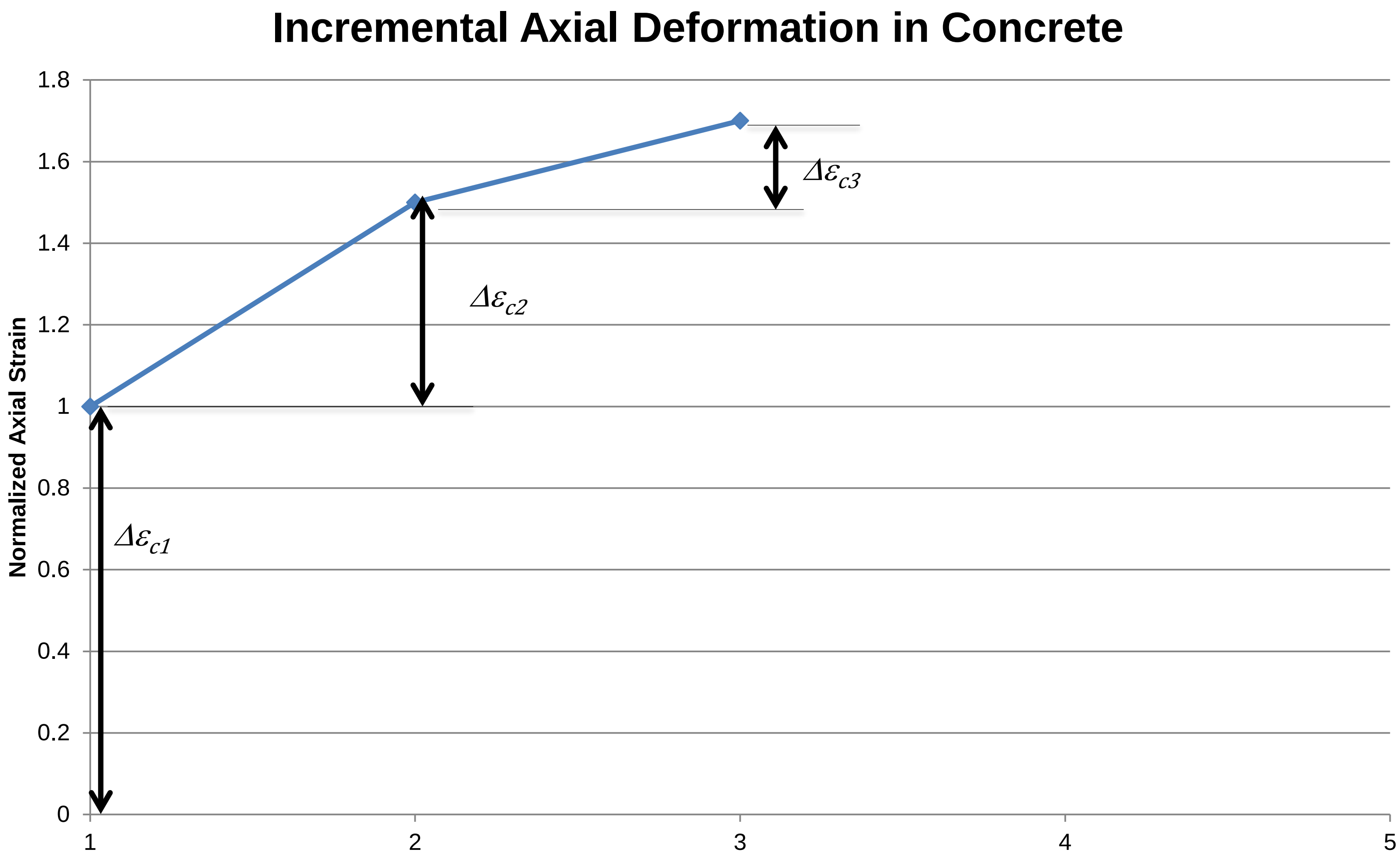
## Time Step 3 – Initial Strain Analysis

- Reinforcing causing internal restraint
- Compute restrained deformations and internal restraining forces, $\Delta\varepsilon_{c3}, \Delta\varphi_{c3}, \Delta\varepsilon_{r3}, \Delta P_{c3}, \Delta M_{c3}, \Delta P_{r3}$

If reinforcement were prestressed, this would be the change in prestress force (aka loss)



# Time Step 3 – End of Interval



# Time Step *i* – Repeat, Repeat, Repeat

- This procedure is repeated for every cross section and every time interval
- Analysis is more involved for spliced girders
  - Continuity externally restrains free deformations
  - Several concrete types cast at different times
  - Changes in statical structural system
  - Pretensioning and multi-stage post-tensioning
  - Intrinsic and reduced relaxation of prestressed steel
- Computers are great at performing repetitive computations and keeping track of numbers!

## Computer Aided Design of Spliced Girders

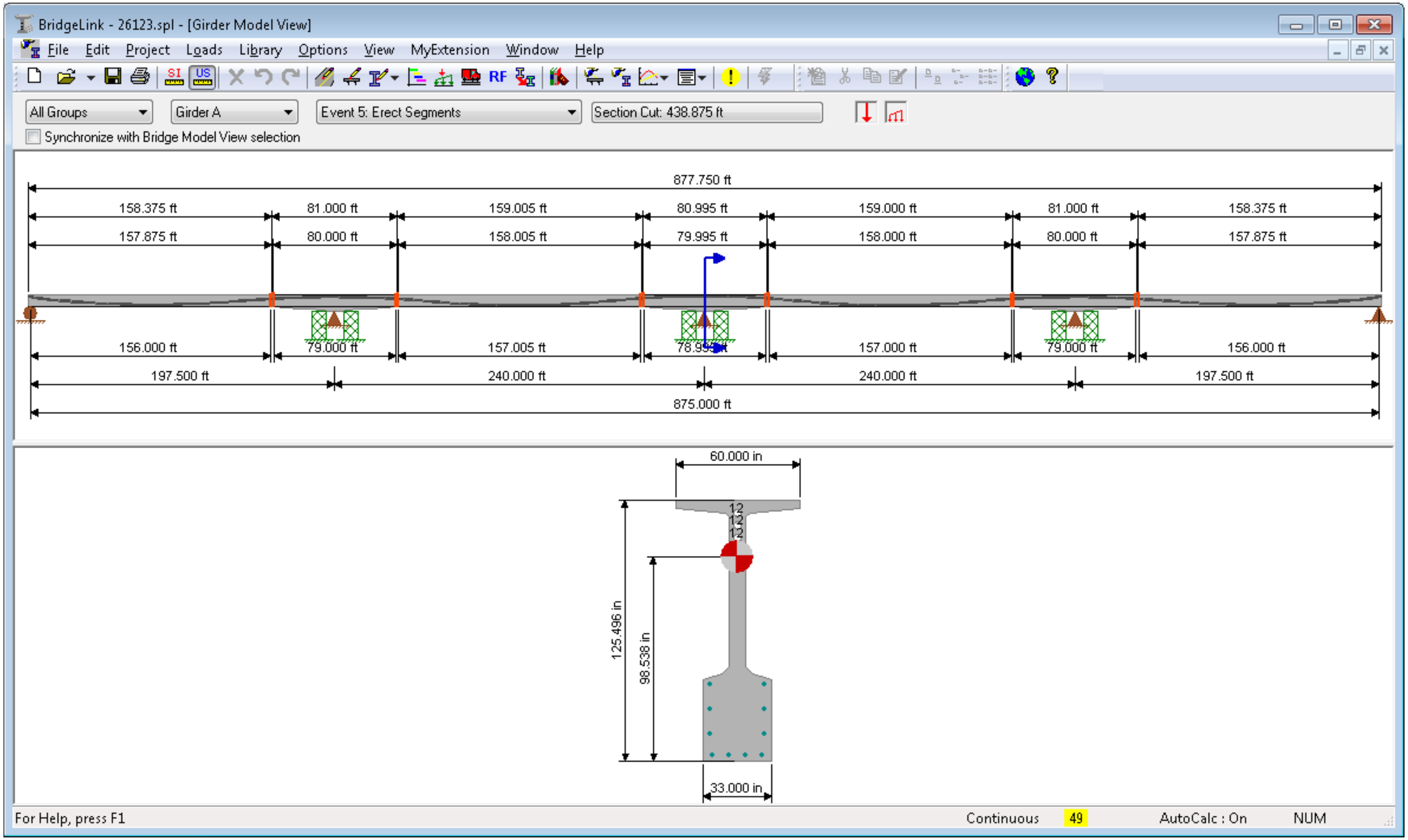

- NCHRP Report 517 – Extending Spans
  - Suggests DOT produced software was a significant contributing factor for wide-spread use of PT Box Girder technology
  - Implies same will be true for adoption of spliced girder technology
  - Notes the lack of a preferred industry standard
  - Recommends owner agencies and industry pursue development of high quality software tools for spliced girder bridges

# PGSplice™

- Part of the new WSDOT BridgeLink™ suite of software
- Design, analyze, and load rate continuous precast-prestressed spliced girder bridges
- Modeling
  - Cantilever pier segments
  - Drop-in field segments
  - Temporary erection towers
  - Strong back hangers
  - Multi-stage post-tensioning
- Analysis
  - Non-linear time step analysis
  - AASHTO, ACI 209 and CEB-FIP Model Code
- User interface, modeling, graphing and reporting features are very similar to PGSuper™

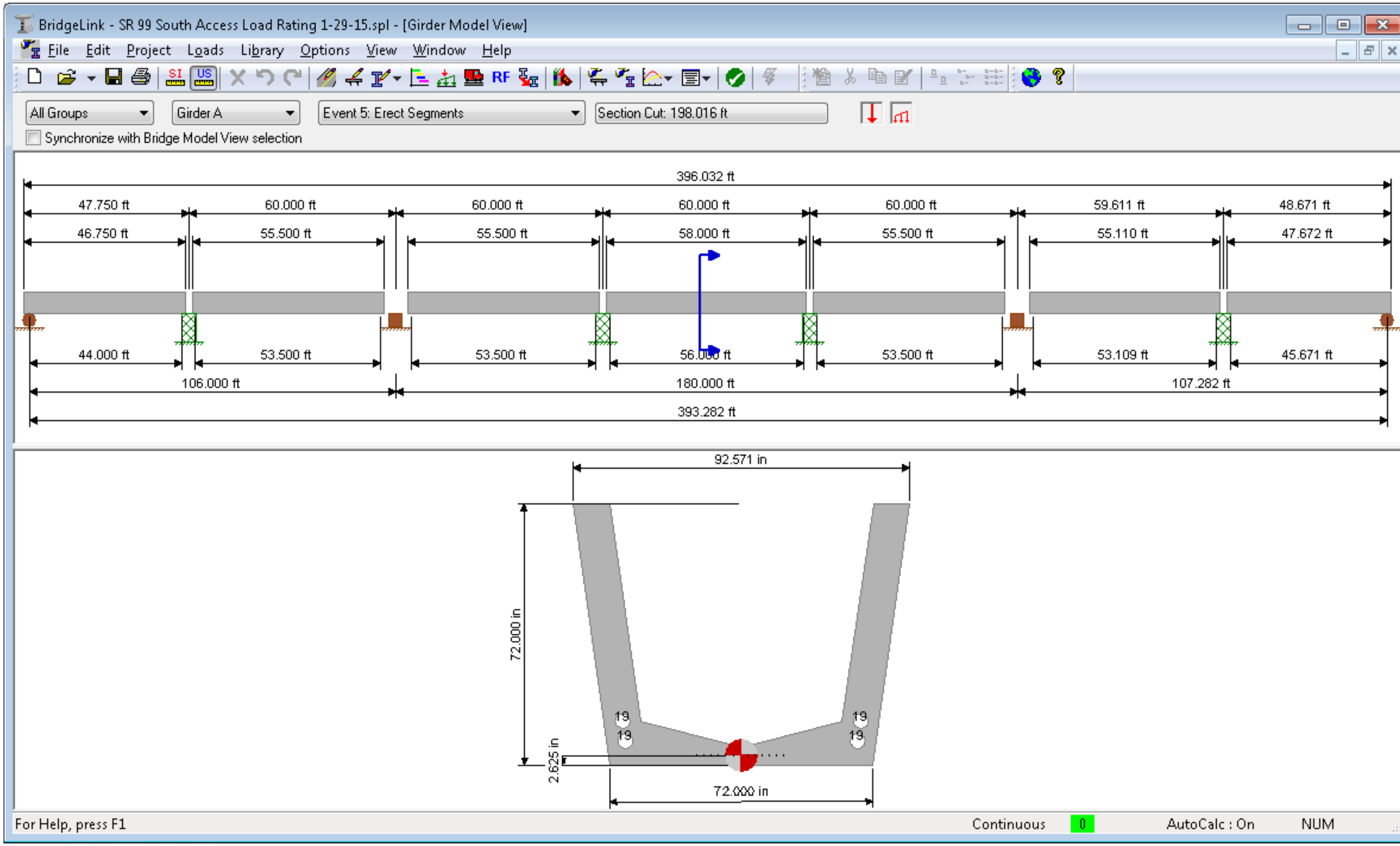
# Bridge Configurations

4 Span Variable Depth Girder with Cantilever Piers Segments and Drop In Field Segments



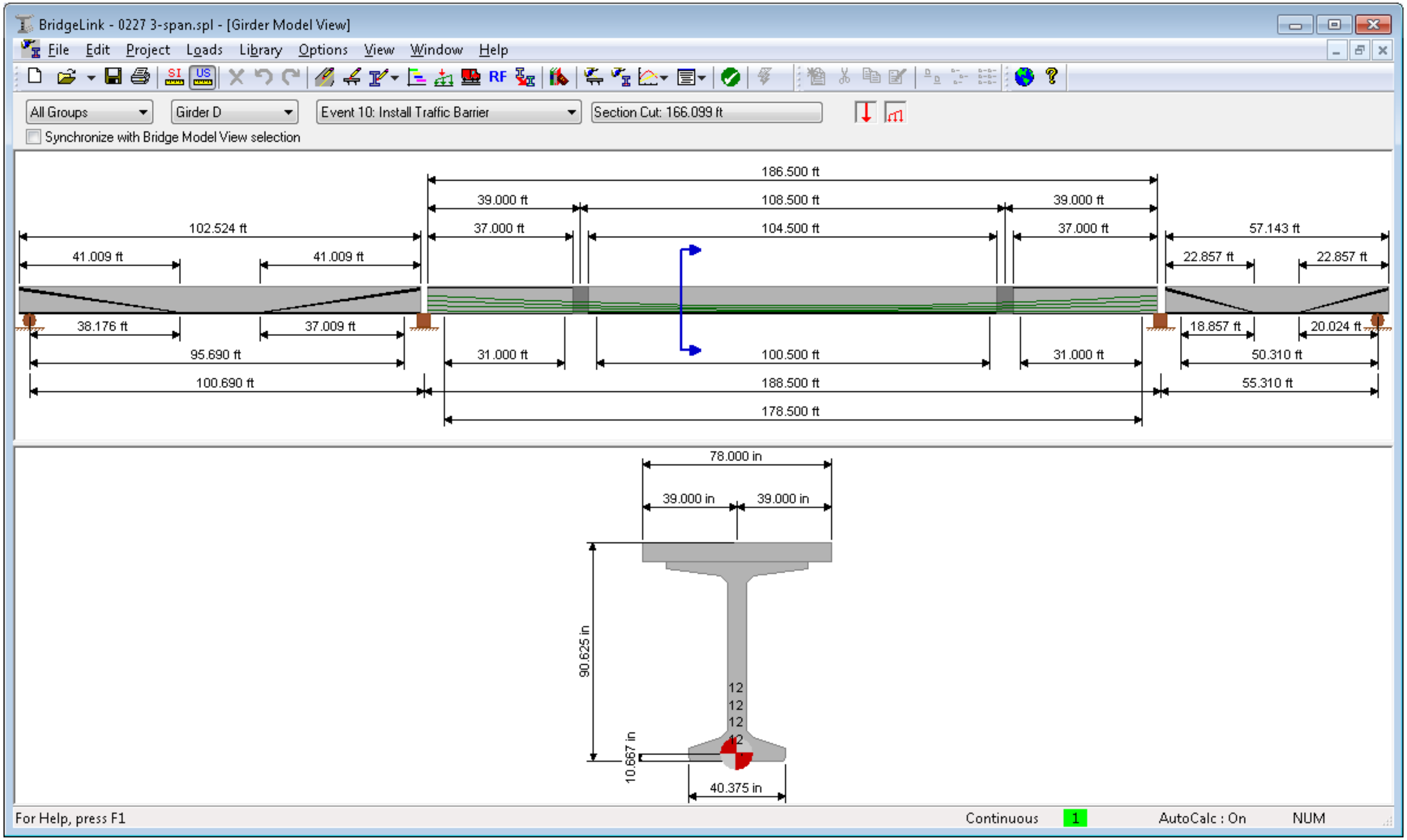
# Bridge Configurations

3 Span U-Beam with Segments Supported at Permanent Piers and Temporary Erection Towers



# Bridge Configurations

End Spans are pretensioned girders - center span three segment spliced girder

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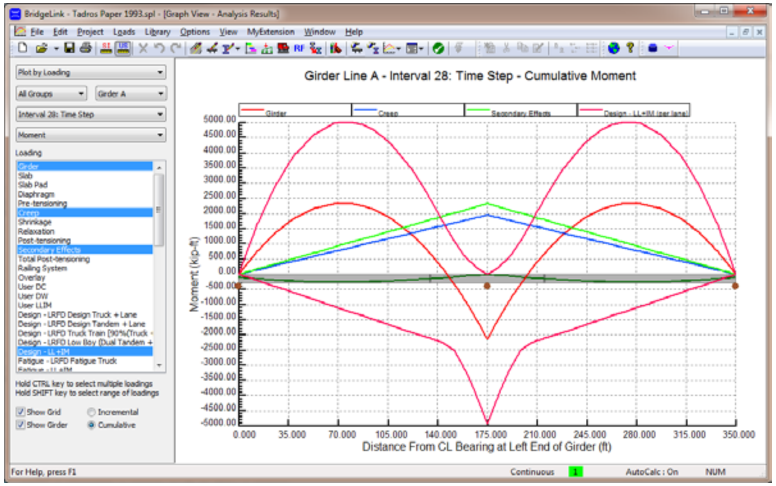
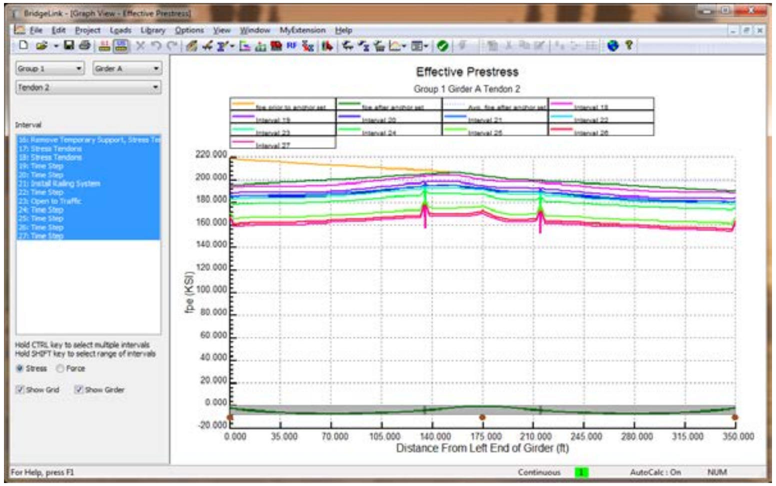
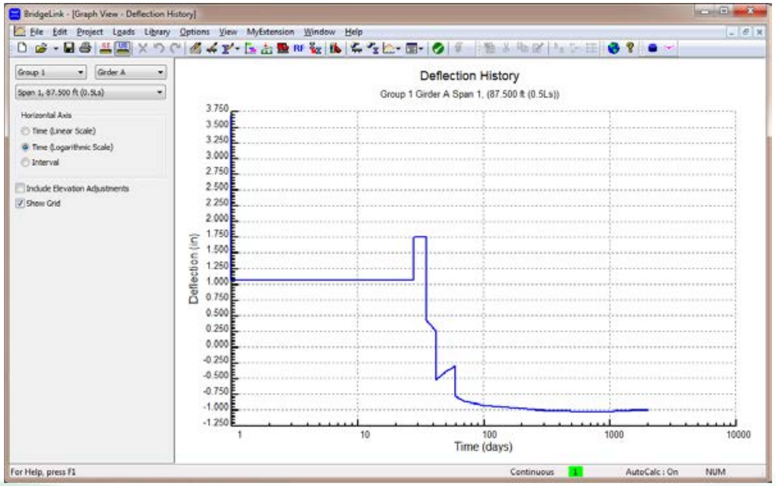
# Graphical Results

- Visualize Complex Results with Simple Graphical Representations





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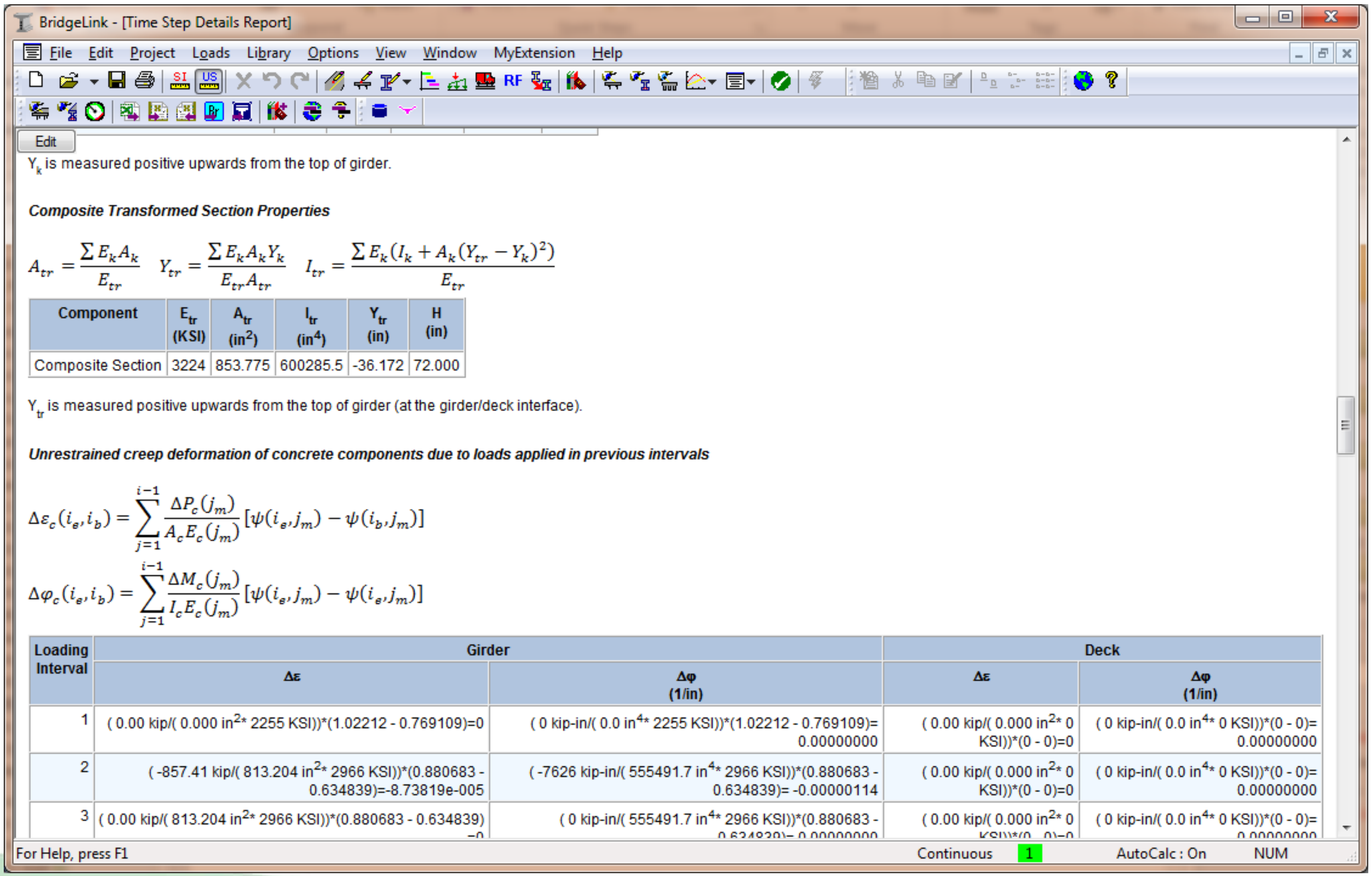
# Detailed Reporting

- Transparent – eliminate frustration with “black boxes”





$Y_k$ is measured positive upwards from the top of girder.

***Composite Transformed Section Properties***

$$A_{tr} = \frac{\sum E_k A_k}{E_{tr}} \quad Y_{tr} = \frac{\sum E_k A_k Y_k}{E_{tr} A_{tr}} \quad I_{tr} = \frac{\sum E_k (I_k + A_k (Y_{tr} - Y_k)^2)}{E_{tr}}$$

| Component | $E_{tr}$ (KSI) | $A_{tr}$ ($in^2$) | $I_{tr}$ ($in^4$) | $Y_{tr}$ (in) | H (in) |
|---|---|---|---|---|---|
| Composite Section | 3224 | 853.775 | 600285.5 | -36.172 | 72.000 |

$Y_{tr}$ is measured positive upwards from the top of girder (at the girder/deck interface).

***Unrestrained creep deformation of concrete components due to loads applied in previous intervals***

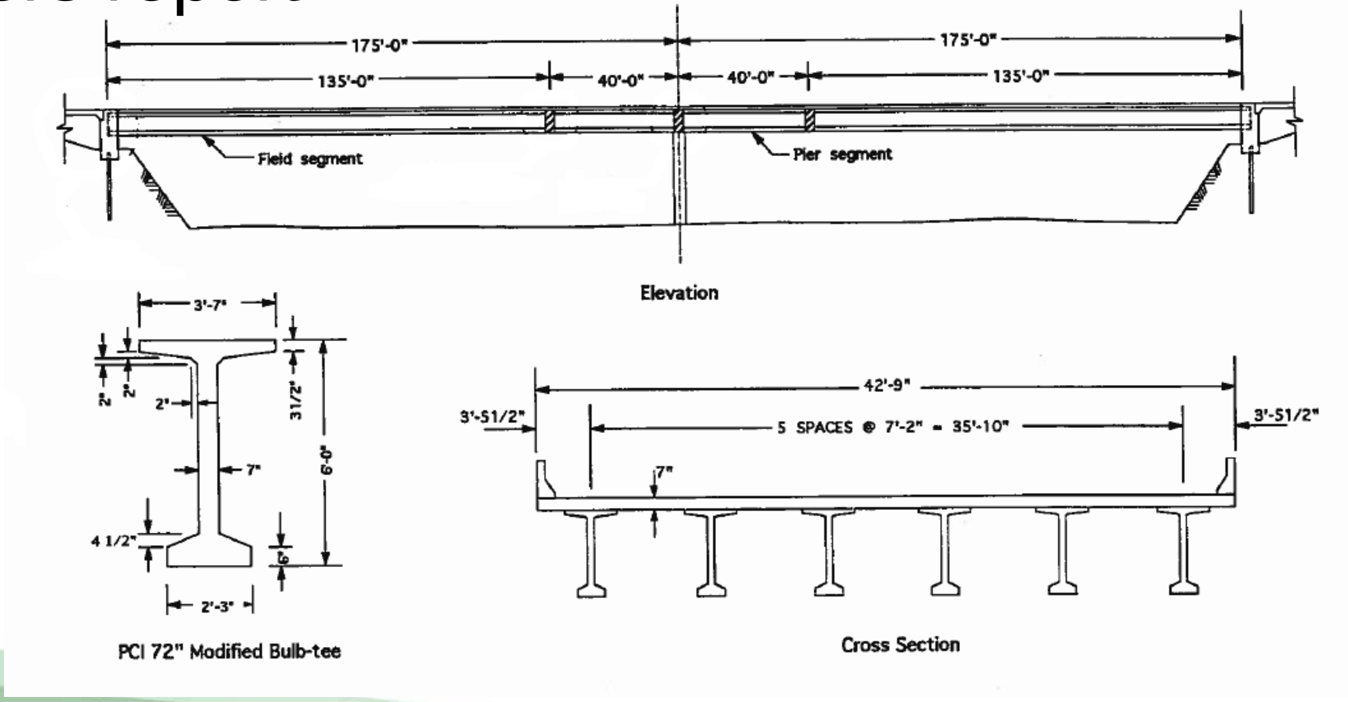
$$\Delta\varepsilon_c(i_e, i_b) = \sum_{j=1}^{i-1} \frac{\Delta P_c(j_m)}{A_c E_c(j_m)} [\psi(i_e, j_m) - \psi(i_b, j_m)]$$

$$\Delta\varphi_c(i_e, i_b) = \sum_{j=1}^{i-1} \frac{\Delta M_c(j_m)}{I_c E_c(j_m)} [\psi(i_e, j_m) - \psi(i_e, j_m)]$$

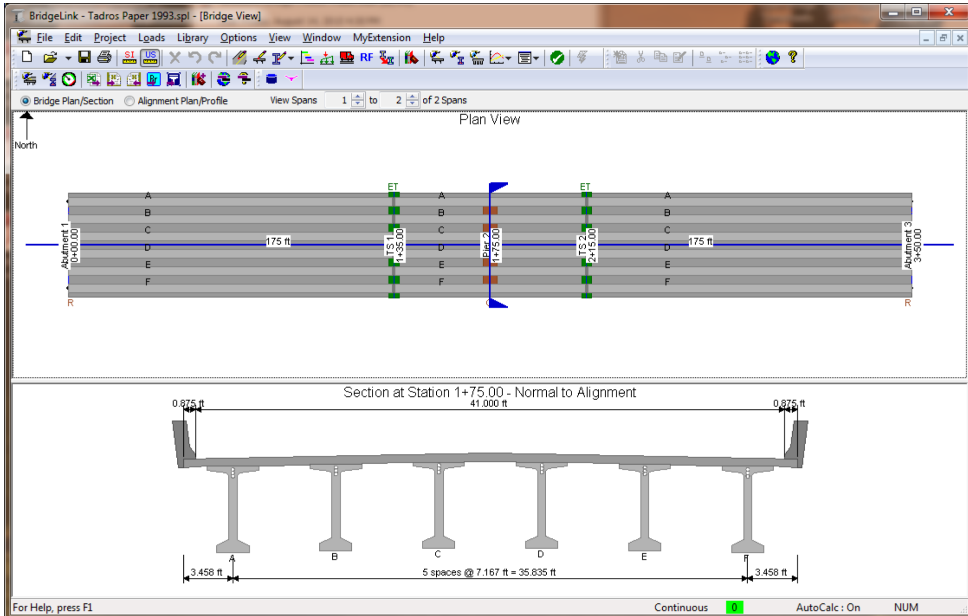
| Loading Interval | Girder | | Deck | |
|---|---|---|---|---|
| | Δε | Δφ (1/in) | Δε | Δφ (1/in) |
| 1 | ( 0.00 kip/( 0.000 $in^2$* 2255 KSI))*(1.02212 - 0.769109)=0 | ( 0 kip-in/( 0.0 $in^4$* 2255 KSI))*(1.02212 - 0.769109)= 0.00000000 | ( 0.00 kip/( 0.000 $in^2$* 0 KSI))*(0 - 0)=0 | ( 0 kip-in/( 0.0 $in^4$* 0 KSI))*(0 - 0)= 0.00000000 |
| 2 | ( -857.41 kip/( 813.204 $in^2$* 2966 KSI))*(0.880683 - 0.634839)=-8.73819e-005 | ( -7626 kip-in/( 555491.7 $in^4$* 2966 KSI))*(0.880683 - 0.634839)= -0.00000114 | ( 0.00 kip/( 0.000 $in^2$* 0 KSI))*(0 - 0)=0 | ( 0 kip-in/( 0.0 $in^4$* 0 KSI))*(0 - 0)= 0.00000000 |
| 3 | ( 0.00 kip/( 813.204 $in^2$* 2966 KSI))*(0.880683 - 0.634839) | ( 0 kip-in/( 555491.7 $in^4$* 2966 KSI))*(0.880683 - | ( 0.00 kip/( 0.000 $in^2$* 0 | ( 0 kip-in/( 0.0 $in^4$* 0 KSI))*(0 - 0)= |

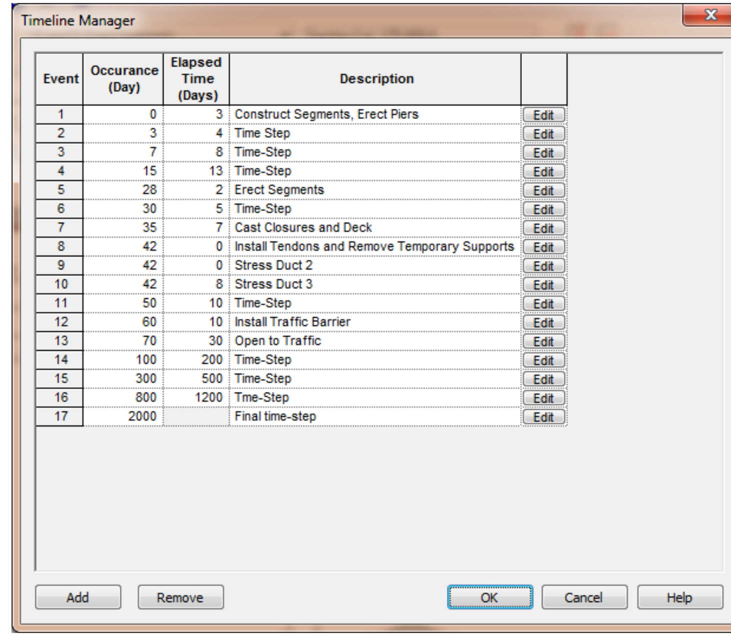
## Case Study

- Two Span Continuous Spliced Girder Bridge
- Presented in PCI State-of-the-Art of Spliced-Girders report



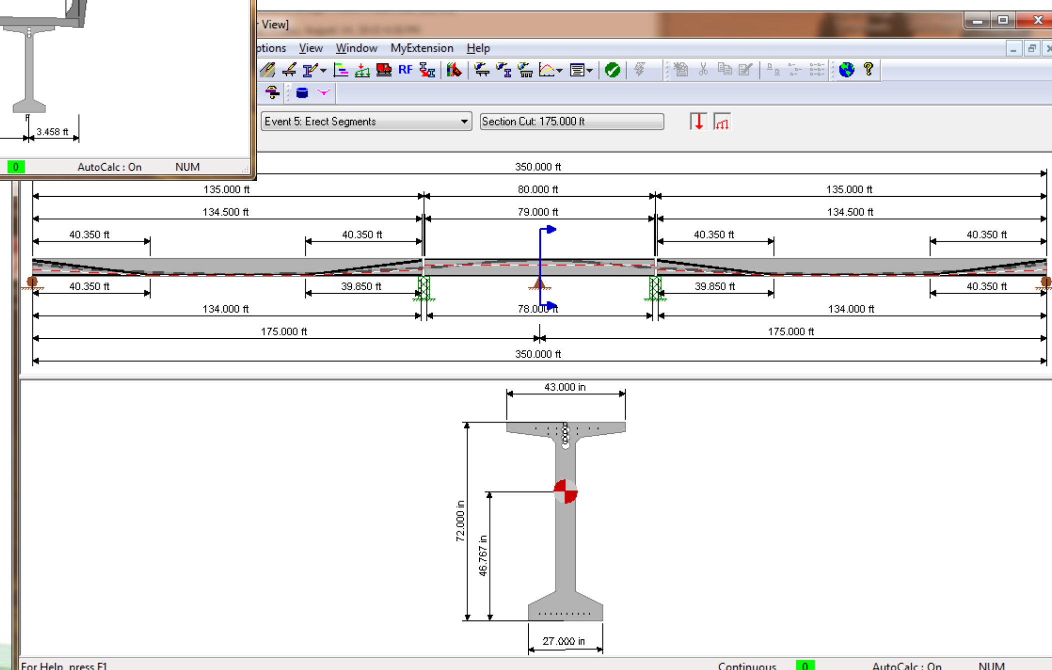
# PGSplice™ Models





Timeline Manager

| Event | Occurance (Day) | Elapsed Time (Days) | Description | |
|---|---|---|---|---|
| 1 | 0 | 3 | Construct Segments, Erect Piers | Edit |
| 2 | 3 | 4 | Time Step | Edit |
| 3 | 7 | 8 | Time-Step | Edit |
| 4 | 15 | 13 | Time-Step | Edit |
| 5 | 28 | 2 | Erect Segments | Edit |
| 6 | 30 | 5 | Time-Step | Edit |
| 7 | 35 | 7 | Cast Closures and Deck | Edit |
| 8 | 42 | 0 | Install Tendons and Remove Temporary Supports | Edit |
| 9 | 42 | 0 | Stress Duct 2 | Edit |
| 10 | 42 | 8 | Stress Duct 3 | Edit |
| 11 | 50 | 10 | Time-Step | Edit |
| 12 | 60 | 10 | Install Traffic Barrier | Edit |
| 13 | 70 | 30 | Open to Traffic | Edit |
| 14 | 100 | 200 | Time-Step | Edit |
| 15 | 300 | 500 | Time-Step | Edit |
| 16 | 800 | 1200 | Tme-Step | Edit |
| 17 | 2000 | | Final time-step | Edit |

Add Remove OK Cancel Help

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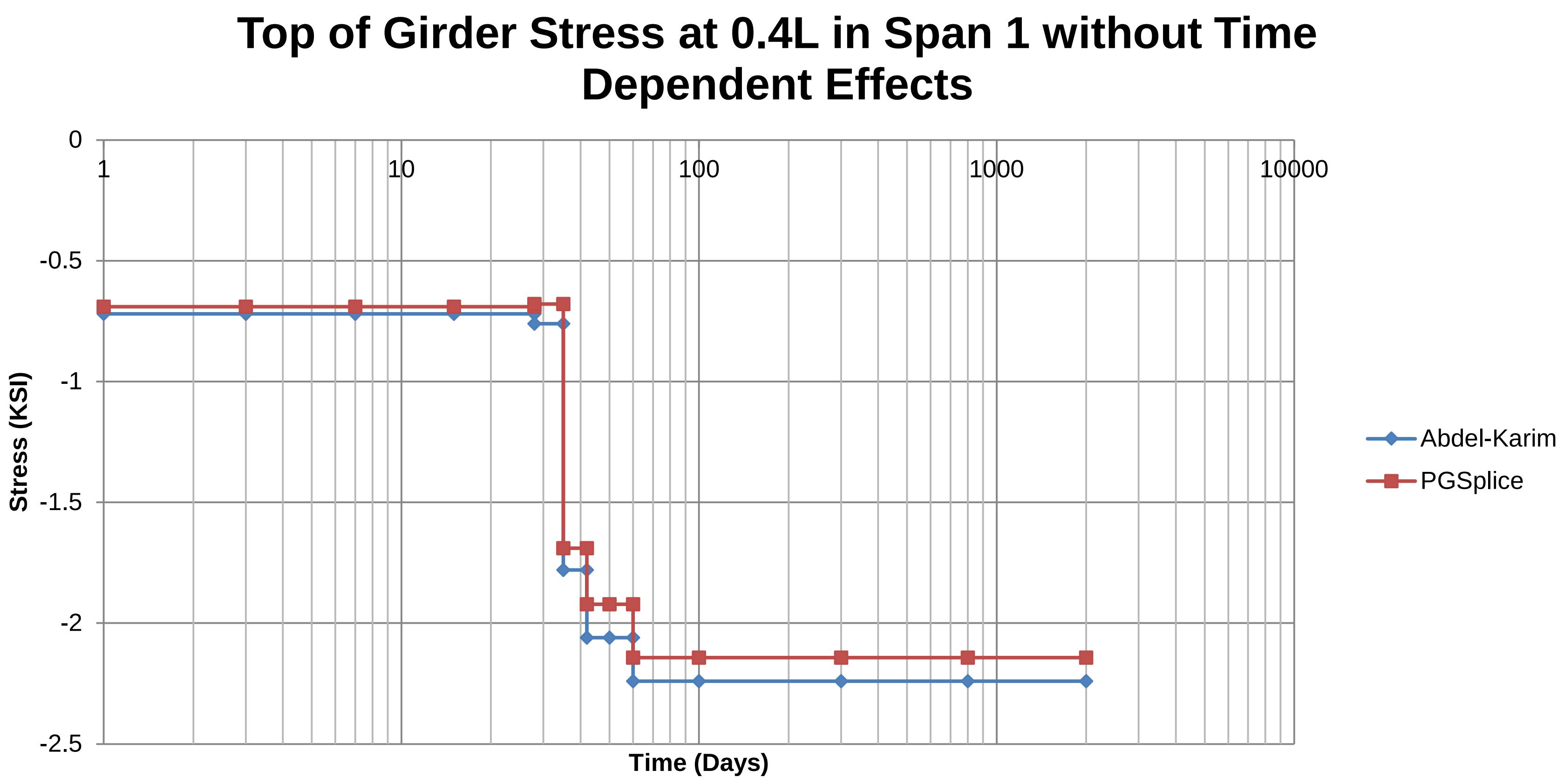
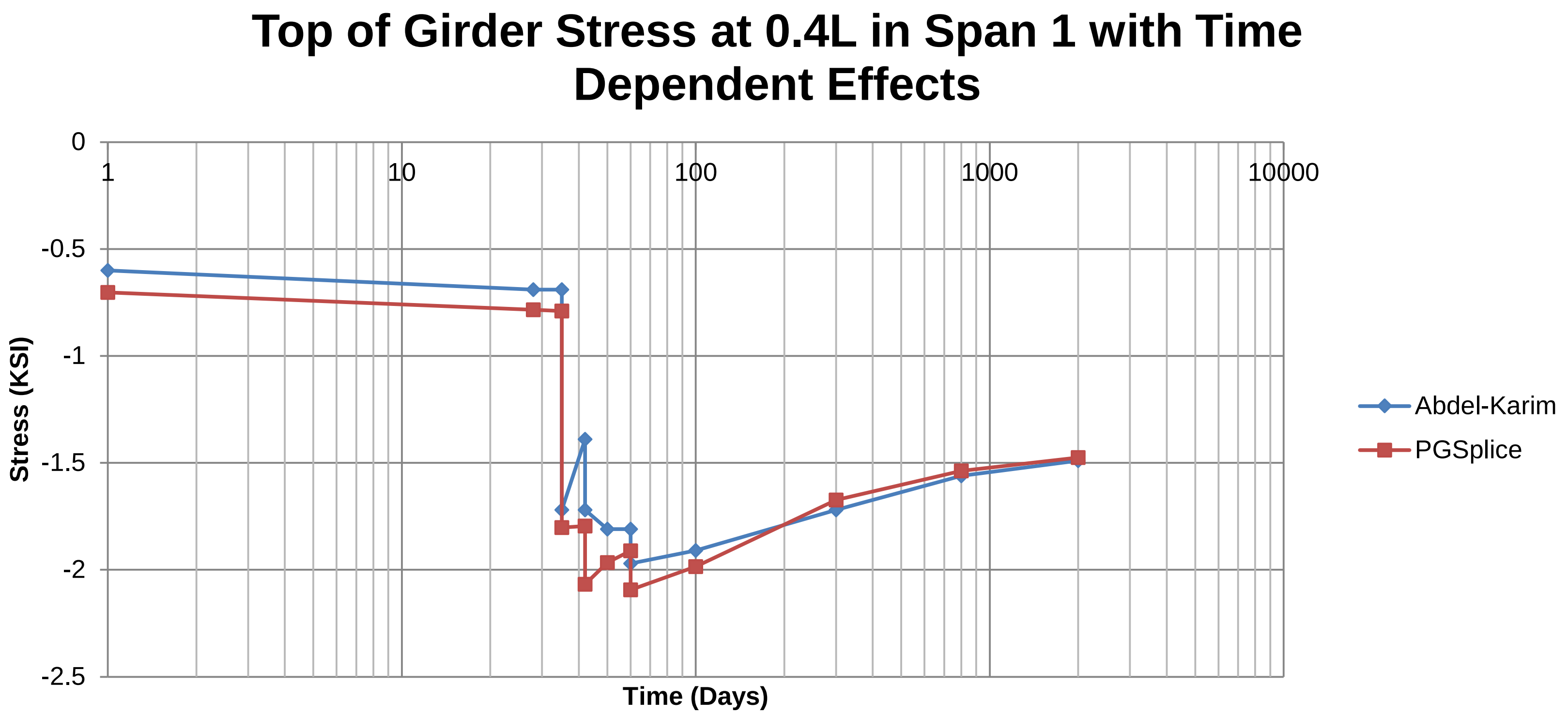
# Baseline Comparison



# Comparison including Time-Dependent Effects



## Software Availability

- Free download from WSDOT
  - http://www.wsdot.wa.gov/eesc/bridge/software
- Open Source
- BridgeLink™ v1.0
  - PGSuper™ v3.0 (Beta)
  - PGSplice™ v3.0 (Beta)
  - BEToolbox™ v3.0

http://www.wsdot.wa.gov/eesc/bridge/software