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

Richard Brice, P.E., Washington State DOT, Olympia, Washington

ABSTRACT

Without automated computations, the design, analysis and load rating of precast-prestressed spliced girder bridges is a complex and time consuming endeavor. This paper will discuss general concepts of computer-aided analysis for spliced girder bridges and will present a case study of a new computer-aided design tool from the Washington State Department of Transportation. Spliced girder designs must account for the effects of construction stages, changes to the statical structural system, pre-tensioning, post-tensioning, secondary actions, non-homogeneous non-prismatic composite cross sections, and time dependent material responses including creep and shrinkage of concrete, and relaxation of prestressing steel. An extensive set of calculations must be carried out for a rigorous analysis. Additionally, engineers must ensure designs meet or exceed the numerous requirements of the AASHTO LRFD Bridge Design Specifications. Load ratings must conform to the requirements of the AASHTO Manual for Bridge Evaluation for design, legal, and permit loading conditions. Computer-aided design is the most feasible solution for precast-prestressed spliced girder bridges.

Keywords: Spliced Girders, LRFD, LRFR, Design, Load Rating, Computer Software

INTRODUCTION

Spliced girders have been used to extend the span range of prestressed concrete bridges. Spans in excess of 300 feet have been achieved. Despite the advantages and proven track record of spliced girder bridges, their use is still limited. One reason limiting their use is unfamiliarity with the design requirements and procedures. The design requirements for spliced girder bridges are more extensive than those for conventional prestressed concrete design and the analysis procedures differ greatly. The most relevant differences are considerations for staged construction, multiple tendon stressing activities, and combined effects of pre-tensioning and post-tensioning. For cases other than preliminary design, the AASHTO LRFD Bridge Design Specifications[1] (AASHTO LRFD) requires that prestress losses are determined by the time-step method and the combined effects of pretensioning and multi-stage post-tensioning on creep losses are considered. The available technical literature presents either highly theoretical or generalized project-specific information. Detailed examples which demonstrate the time-step analysis method and application of the relevant design provisions of AASHTO LRFD and the relevant load rating provisions of the AASHTO Manual for Bridge Evaluation[2] (AASHTO MBE) are not generally available.

The design of spliced girder bridges involves greater complexity than is required for conventional precast girder designs. Advanced software with special features is needed to automate the analysis and design process of these special structures[3]. The Washington State Department of Transportation has recently developed a new software tool that automates and simplifies the design, analysis, and load rating of precast-prestressed spliced girder bridges. This software serves as both a production engineering tool and a teaching tool. The capabilities of the software are robust enough to accommodate a wide variety of spliced girder configurations. The output generated by the software is sufficiently detailed to allow for in depth verification of the analyses performed and serves as instructional information for engineers with limited experience using the advanced analysis methods required for spliced girder bridges.

TIME-STEP ANALYSIS

The time-step analysis method models the design life of a structure through discrete intervals of time. The deformations, stresses, and internal forces that develop in response to external loads and time-dependent material effects are computed for each time interval. The time-dependent material effects include changes in concrete strength and elastic modulus as a function of time, creep and shrinkage of concrete, and relaxation of prestressing strands. The response of the structure at the end of any time interval is taken to be the summation of the responses of the preceding intervals.

Conceptually, time-step analysis is a straightforward method based on fundamental principles of engineering mechanics. The method of time-step analysis discussed below was originally presented by Tadros, et.al.[4] in 1977. A summary will be presented that focuses on the key elements of the analysis method. The challenge of time-step analysis is the enormous quantity of calculations that must be performed. Several factors contribute to the computational burden of this method. Concrete strength, and thus the modulus of elasticity, increases as a function of time resulting in different transformed section properties in each time interval. Spliced girders are often non-prismatic with deeper sections at intermediate piers than in the main spans. Tendon profiles typically have varying eccentricities which further compounds the computation of section properties. Creep strain rates change as a function of time and incremental loading. Shrinkage strain and strand relaxation rates also vary with time. The sheer quantity of calculations that must be performed for a rigorous time-step analysis make computer aided design the only feasible option.

TIME VARIATION OF MATERIAL PROPERTIES

Precast concrete spliced girders are a composition of precast concrete segments, cast-in-place closure joints, a cast-in-place concrete deck, strands, tendons, and reinforcing bars. The parts of a spliced girder can be classified into three distinct materials; concrete, prestressing steel, and nonprestressed reinforcing bars. Concrete has a time-dependent stress strain relationship because of creep and shrinkage. Prestressing steel has a time-dependent stress strain relationship due to relaxation. Nonprestressed reinforcement is assumed to be a linear elastic material obeying Hooke's law.

Any suitable time variation relationship for elastic modulus, creep, shrinkage and relaxation can be used in the time-step analysis. AASHTO LRFD provides general relationships for elastic modulus, creep and shrinkage that can be used in lieu of project-specific material data. However, AASHTO LRFD does not provide time variation relationships for the strength of concrete or intrinsic relaxation of prestressing steel. AASHTO LRFD permits the use of the time variation relationships from American Concrete Institute Committee 209[5] (ACI 209) and the CEB-FIP Model Code[6] (CEB-FIP).

TIMELINE MODELING

A mathematical model of time is central to the time-step analysis method. A sequence of discrete time intervals is used to model the design timeline. The duration of each interval is determined by the time at which changes in loading and the statical structural system are assumed to occur. Suddenly applied loads (e.g. prestress force, self-weight, and superimposed loads) and sudden changes to the statical structural system (e.g. removal of temporary supports) are assumed to cause an instantaneous response in the structure at a specific time. Because the time-dependent material responses are most appreciable immediately following a sudden change in internal resisting forces the timeline is further divided into small time intervals following the load application. The length of intervals can be increased progressively as time goes on. Time dependent changes are continuous during an interval. The total change in loading during an interval is assumed to occur at the middle of the interval and that the duration of intervals when sudden changes occur is zero. The design timeline generally begins when the first pretension strand is stressed and concludes at the end of the design life of the structure.

INCREMENTAL DEFORMATIONS

The time-step method analyzes deformations, stresses, and forces in each part of a spliced girder as a summation of the incremental responses in the preceding intervals. The incremental deformations, axial strain ($\Delta\varepsilon$) and curvature ($\Delta\varphi$), of each part of the spliced girder during the i^{th} interval are presented below. The variables *i* and *j* represent the i^{th} and j^{th} interval. The subscripts *b*, *m*, and *e*, represent the beginning, middle, and end of the interval, respectively. ΔP and ΔM are changes in axial force and moment on the composite spliced girder section or on the individual part when accompanied by a subscript. *A* and *I* are the net cross sectional area and moment of inertia about the centroid of the part. *E* is the elastic modulus of the part. The subscripts indicate the cross section part type (*c* = concrete, *ps* = prestressed reinforcement, *ns* = nonprestressed reinforcement, and *k* = the k^{th} part). ψ is the ratio of creep deformation at the end of an interval to the instantaneous deformation caused by the sustained loading introduced in the middle of a previously occurring interval.

Concrete Parts

The incremental deformations in concrete parts of a spliced girder can be obtained from Equations (1) and (2).

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

$$\Delta\varphi_c(i_e,i_b)=\frac{\Delta M_c(j_m)}{I_cE_c(j_m)}[1+\psi(i_e,i_m)] + \left\{\sum_{j=1}^{i-1}\frac{\Delta M_c(j_m)}{I_cE_c(j_m)}[\psi(i_e,j_m)-\psi(i_e,j_m)]\right\} \tag{2}$$

The first term in Equations (1) and (2) represent the elastic and creep deformations due to incremental loads that occur during the interval. The terms inside the braces are “initial deformations” which are deformations that are independent of the stress introduced during the interval. For concrete parts the source of initial deformation is creep and shrinkage.

The first term in the braces represents the increment of creep deformation for all loads introduced prior to the current interval. The operand of the summation is the deformation that occurs during interval *i* due to a load introduced at the middle of interval *j*.

A deeper examination of the operand of the summation in Equation (1) reveals $\frac{\Delta P_c(j_m)}{A_cE_c(j_m)}$ is the axial strain caused by a load increment on the concrete part occurring at the middle of interval *j* where $\Delta P_c(j_m)$ is the incremental axial force on the concrete part, A_c is the net area of the concrete part and $E_c(j_m)$ is the modulus of elasticity of the concrete part at the middle of interval j. $\frac{\Delta P_c(j_m)}{A_c E_c(j_m)}\psi(i_e,j_m)$ is the creep strain at the end of interval *i* due to loading applied at the middle of interval j. $\frac{\Delta P_c(j_m)}{A_c E_c(j_m)}\psi(i_b,j_m)$ is the creep strain at the beginning of interval *i* due to loading applied at the middle of interval *j*. Hence, $\frac{\Delta P_c(j_m)}{A_c E_c(j_m)}[\psi(i_e,j_m) - \psi(i_b,j_m)]$ is the change in creep strain occurring during interval *i* due to a load increment occurring at the middle of interval *j*.

Similarly, the summation in Equation (2) is the incremental curvature occurring during interval *i* due to load increments that occurred at the middle of the previous intervals.

The last term in the braces of Equation (1) is the incremental shrinkage strain occurring during the interval.

Prestressing Steel Parts

Assuming the flexural rigidity of prestress steel parts is negligible compared to the overall composite cross section; the incremental deformation is limited to axial strain and can be obtained from Equation (3).

$$\Delta\varepsilon_{ps}(i_e,i_b) = \frac{\Delta P_{ps}(i_m)}{A_{ps}E_{ps}} + \left\{-\frac{\Delta f_r(i_e,i_b)}{E_{ps}}\right\} \qquad (3)$$

The first term in Equation (3) is the elastic deformation of the prestressing steel due to incremental loads that occur during interval *i*. The term inside the braces is the time-dependent deformation due to relaxation where Δf_r is the reduced relaxation occurring during interval *i*. This is also an "initial deformation".

The intrinsic relaxation of prestressing steel is determined from tests in which the steel tendon is stretched between two fixed points. The length of the test specimen remains constant. However, as part of a composite concrete member, the reduction in steel stress due to shortening of the tendon results in a reduced relaxation compared to the intrinsic value.

Various empirical equations expressing the intrinsic relaxation as a function of time and initial stress are available[7]. The shortening of the tendon in a composite concrete member is a function of the change in stress due to the various sources of incremental load and the relaxation that occurs during an interval, neither of which is known. An iterative procedure is needed to determine the reduced relaxation during an interval.

A suitable approximation of the reduced relaxation can be obtained by substituting the effective stress in the tendon at the beginning of the i^{th} interval into the intrinsic relaxation equation. This approximation avoids a substantial increase in computation time. The error is relatively small, especially for short intervals. Relaxation is the least significant of the time dependent effects so a high degree of accuracy is not warranted.

Nonprestressing Steel Parts

The incremental deformation of nonprestressing steel parts is also limited to axial strain when assuming the flexural rigidity of the part is negligible.

$$\Delta\varepsilon_{ns}(i_e, i_b) = \frac{\Delta P_{ns}(i_m)}{A_{ns}E_{ns}} \tag{4}$$

The deformation in non-prestressed steel is given by Equation (4) and is simply the deformation due to loads that occur during this interval.

INCREMENTAL FORCES

Equations (1) through (4) require the incremental loading on the various parts of the spliced girder due to the overall change in loading on the composite section. Using transformed section analysis, the change in force in the k^{th} part of the cross section due to the loading increment, ΔP and ΔM, is obtained from Equations (5) and (6).

$$\Delta P_k = \left[\frac{\Delta P}{A_{tr}E_{tr}} + \frac{\Delta M(Y_{tr} - Y_k)}{I_{tr}E_{tr}}\right] A_k E_k \tag{5}$$

$$\Delta M_k = \Delta M \frac{I_k E_k}{I_{tr}E_{tr}} \tag{6}$$

A_{tr}, I_{tr}, and Y_{tr} are the cross sectional area, moment of inertia about the centroidal axis, and the location of the centroid, respectively, of the transformed composite section based on the modulus of elasticity, E_{tr}, at the middle of the interval when the loading is applied. A_k, I_k, and Y_k are the cross sectional area, moment of inertia about the centriodal axis, and the location of the centroid, respectively, of the k^{th} part based on its net section. E_k is the modulus of elasticity of the part's material.

ANALYSIS OF INITIAL DEFORMATIONS

Analysis for the effects of initial deformations can be performed in the same manner as solving for the effects of temperature change. Secondary actions (moments, shears, axial forces, and reactions) result whenever deformations that would normally occur are prevented. The internal stress that develops as a result of initial deformations is analogous to the internal stress due to the secondary effects of post-tensioning.

It is convenient to consider two circumstances under which these stresses occur; 1) conditions such that there would be no stresses except for the constraint of external forces and 2) stresses that are produced in the absence of external constraint solely because of the incompatibility of the deformations of the different parts of the element[8]. Stresses in the first circumstance may be found by determining the deformations that would occur if the system were unconstrained and then imposing those deformations on the constrained system. The deformations that would occur in the unconstrained system are found by analyzing the second circumstance.

The deformations of the unconstrained system are determined by applying an artificial restraining force to the k^{th} part to prevent its deformations ε_k and φ_k, which are the axial strain and curvature that would occur if the part was free to deform. Internal stresses will develop. At any section of the k^{th} part, the stress resultants are

$$\bar{P}_k = -E_k A_k \varepsilon_k \quad (7)$$

$$\bar{M}_k = -E_k I_k \varphi_k \quad (8)$$

For the whole composite section consisting of *n* parts the initial deformation stress resultants are

$$\bar{P} = \sum_{k=1}^{n} \bar{P}_k \quad (9)$$

$$\bar{M} = \sum_{k=1}^{n} \left(\bar{M}_k + \bar{P}_k (Y_{tr} - Y_k) \right) \quad (10)$$

The deformations at each section of the unrestrained system are

$$\bar{\varepsilon} = \frac{\bar{P}}{E_{tr} A_{tr}} \quad (11)$$

$$\bar{\varphi} = \frac{\bar{M}}{E_{tr} I_{tr}} \quad (12)$$

The continuous deformation of the unrestrained system is approximated with section deformations at regularly spaced intervals assuming a linear variation between sections. The bridge frame is analyzed for these deformations. The results of the analysis give the incremental displacement of the restrained structure as well as the incremental internal stress resultants for the interval under consideration.

The incremental internal stress resultants are proportioned to the various parts of the spliced girder with Equations (5) and (6). These stress resultants are incremental loads that cause creep in the concrete parts that is in addition to the creep caused by suddenly applied loads and changes to the statical structural system. The incremental forces on the concrete parts due to initial deformations are accounted for in the first term of Equations (1) and (2) during the interval when the forces first develop and in the summation in subsequent intervals.

EXAMPLE

Consider a spliced girder that is subjected to an external loading that produces forces P and M on the composite section during interval 1. Determine the incremental axial strain in a concrete part occurring during interval 3. Intervals 2 and 3 are time steps in which the statical structural system remains unchanged and no additional external loading is applied to the structure.

The net section properties and the elastic modulus of each concrete part, as well as the transformed section properties of the composite section, are computed for intervals 1 through 3.

Using Equation (5), the axial force in the concrete part at the middle of interval 1 is

$$\Delta P_c(1_m) = \left[\frac{P}{A_{tr}(1_m)E_{tr}(1_m)} + \frac{M[Y_{tr}(1_m) - Y_c]}{I_{tr}(1_m)E_{tr}(1_m)}\right] A_c E_c(1_m)$$

Regardless of whether the spliced girder is externally constrained (e.g. the bridge is an indeterminate structure) or is free to deform (e.g. the bridge is a simple span structure) internal forces develop due to initial deformations occurring during intervals 2 and 3. The incremental forces introduced to the concrete part during intervals 2 and 3 are $\Delta P_c(2_m)$ and $\Delta P_c(3_m)$, respectively.

Using Equation (1), the incremental axial strain in the concrete part during interval 3 is

$$\begin{aligned}\Delta\varepsilon_c(3_e, 3_b) = &\frac{\Delta P_c(3_m)}{A_c E_c(3_m)}[1 + \psi(3_e, 3_m)] + \frac{\Delta P_c(1_m)}{A_c E_c(1_m)}[\psi(3_e, 1_m) - \psi(3_b, 1_m)] \\ &+ \frac{\Delta P_c(2_m)}{A_c E_c(2_m)}[\psi(3_e, 2_m) - \psi(3_b, 2_m)] + \Delta\varepsilon_{sh}(3_e, 3_b)\end{aligned}$$

To complete the time-step analysis for interval 3, similar computations are performed to determine the curvature of the concrete part as well as the deformations of all the other parts of the composite section. These computations must also be performed at regularly spaced intervals along the girder to ensure reasonable accuracy of the analysis. Sections that are to be evaluated for deflections, stress limitations, and ultimate strength requirements should also analyzed.

For a complete time-step analysis, these computations must be performed for all parts of the composite section, at all sections under consideration, for all of the intervals in the design timeline. As described above, time-step analysis is a straight forward method based on fundamental principles of engineering mechanics. The challenge is the enormous quantity of calculations that must be performed for a complete analysis.

SPLICED GIRDER DESIGN SOFTWARE

Bridge owners and designers do not usually venture into new designs without having the proper design resources. Given the enormous computational burden of the required time-step analysis procedure, software that is capable of analyzing complex spliced girder structures is an essential resource. The availability and successful application of such software has a positive impact on designers and may encourage the use of spliced girders to extend span ranges on future design projects. NCHRP Report 517 suggests that DOT produced software was a contributing factor to the widespread use of cast-in-place, post-tensioned box girder bridges in California and implies that spliced girder software would make a similar contribution to the adoption of spliced girder technology.

There has been progress in the development of software for the design of spliced girder bridges. Several programs are now available with varying degrees of sophistication, specialization, and cost. However, there is currently no industry-preferred software product. NCHRP Report 517 recommends the software industry, owner agencies, and the precast industry continue to pursue the development of easy-to-use and reliable software for the design of bridges utilizing specialized methods of extending span ranges.

THE PGSPLICE SOFTWARE APPLICATION

The Washington State Department of Transportation (WSDOT) has recently developed a precast-prestressed spliced girder software program named PGSplice. This software is part of a new suite of bridge engineering software tools named BridgeLink. PGSplice can be used for the design, analysis, and load rating of spliced girder bridges.

PGSplice uses the familiar *bridge-centric* user interface pioneered in WSDOT's renowned precast-prestressed girder design software, PGSuper. The *bridge-centric* user interface presents information with traditional plan, section, and elevation views and supports direct manipulation of the graphical representations of spans, piers, and girders. This keeps the designer focused on the bridge and the engineering problem at hand resulting in a more satisfying and successful interaction with the software compared to interactions with the commonly used *data-centric* user interface of other software tools. Given the widespread use of and familiarity with PGSuper, engineers will quickly become proficient with PGSplice.

PGSplice is capable of modeling spliced girder bridges with variable depth cantilever pier segments, drop-in field segments supported by strong-back hangers, temporary erection towers, and multi-stage post-tensioning. Analysis, design reviews, and load ratings are performed in accordance with current AASHTO Specifications. Time-dependent material models from AASHTO LRFD, ACI 209, and CEB-FIP can be used in the time-step analysis. Detailed analysis for lifting and transporting precast segments can be performed.

The output generated by PGSplice is sufficiently detailed to allow for in depth verification of the analysis results. The software offers a multitude of graphical and tabular representations of analysis results. Intermediate computations, including details of the time-step analysis, are reported. A primary goal is for PGSplice to be as transparent as possible to eliminate the common frustration engineers have with "black box" programs.

PGSplice can be customized with owner-agency specific girder sections, requirements, and project criteria. Cloud-based software configurations make these customizations available to agency and consulting engineers virtually anywhere in the world. Like the PGSuper software, the capabilities of PGSplice can be customized and extended by third-party software developers to provide new and useful capabilities beyond those provided by the basic application.

The BridgeLink suite of bridge engineering tools, including PGSplice and PGSuper, are open source programs. The software is available for download from the WSDOT web site at http://www.wsdot.wa.gov/eesc/bridge/software.

CASE STUDY

A two span continuous spliced girder bridge example will be used to illustrate computer aided design with the PGSplice software. The essential bridge data is summarized below. Figure 1 shows the bridge layout and cross section. The assumed construction sequence is shown in Figure 2. The pretensioning strands and tendon profile are shown in Figure 3 and Figure 4.

This particular example was originally published by Abdel-Karim, et.al.[9] and is also available from the Precast/Prestressed Concrete Institute[10] (PCI).

The material properties are:

- Precast Segments
  - Unit Weight: 150 lbs/ft^3
  - 28 day concrete strength: $(f_c')_{28} = 7.0\ ksi$
- Cast-in-Place Closure Joints and Deck
  - Unit Weight: 150 lbs/ft^3
  - 28 day concrete strength: $(f_c')_{28} = 4.0\ ksi$
- Prestressing Steel
  - Grade 270 low-relaxation
  - $E_{ps} = 28{,}500\ ksi$
- Non-prestressed Steel
  - Grade 60 steel
  - $E_{ns} = 29{,}000\ ksi$

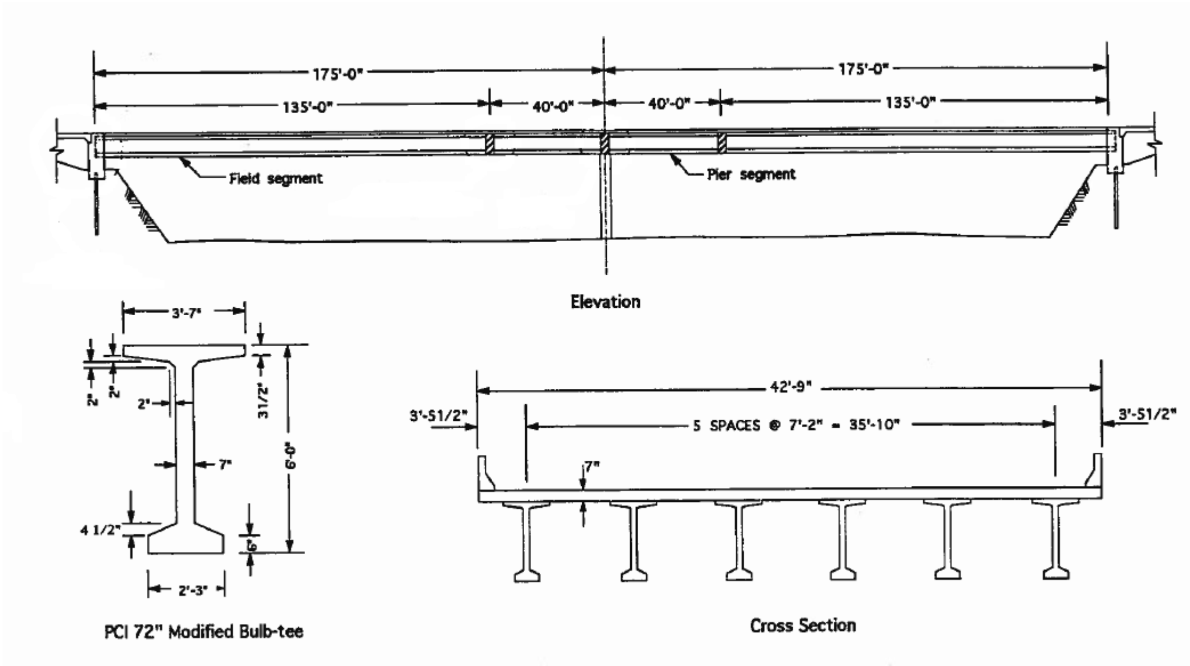


Figure 1 General Layout of Case Study Bridge

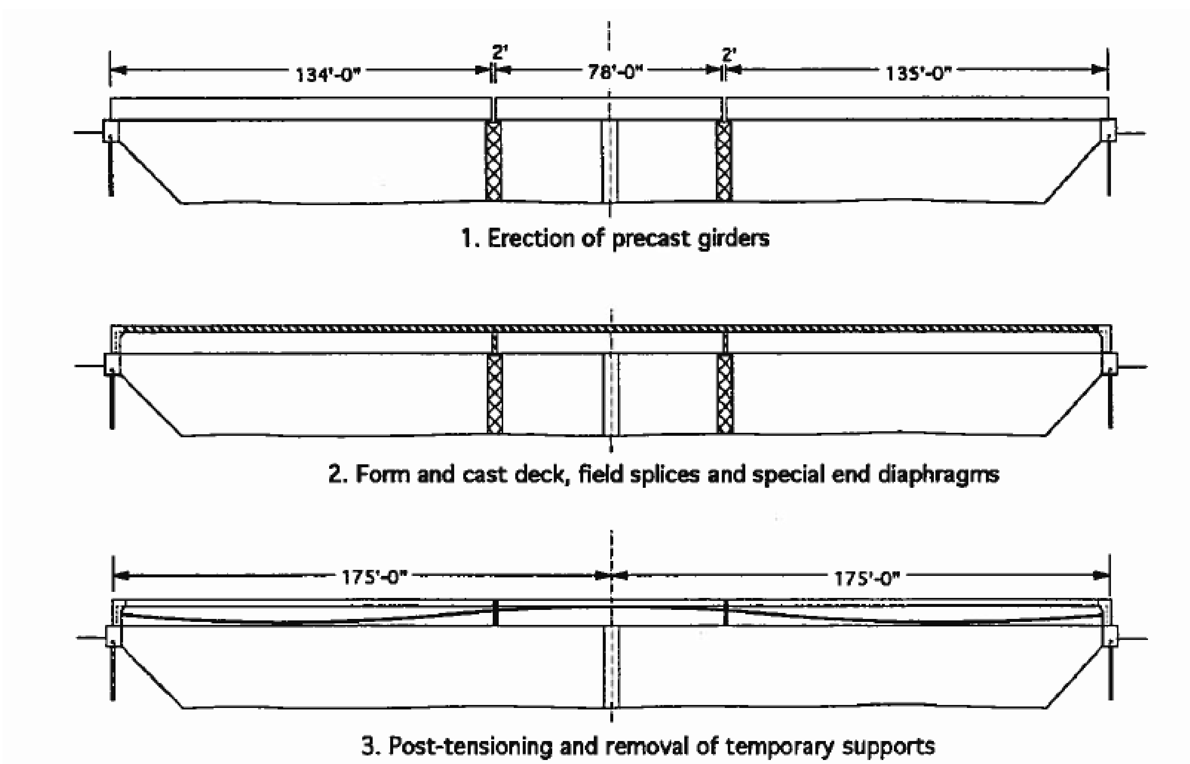


Figure 2 Construction Sequence

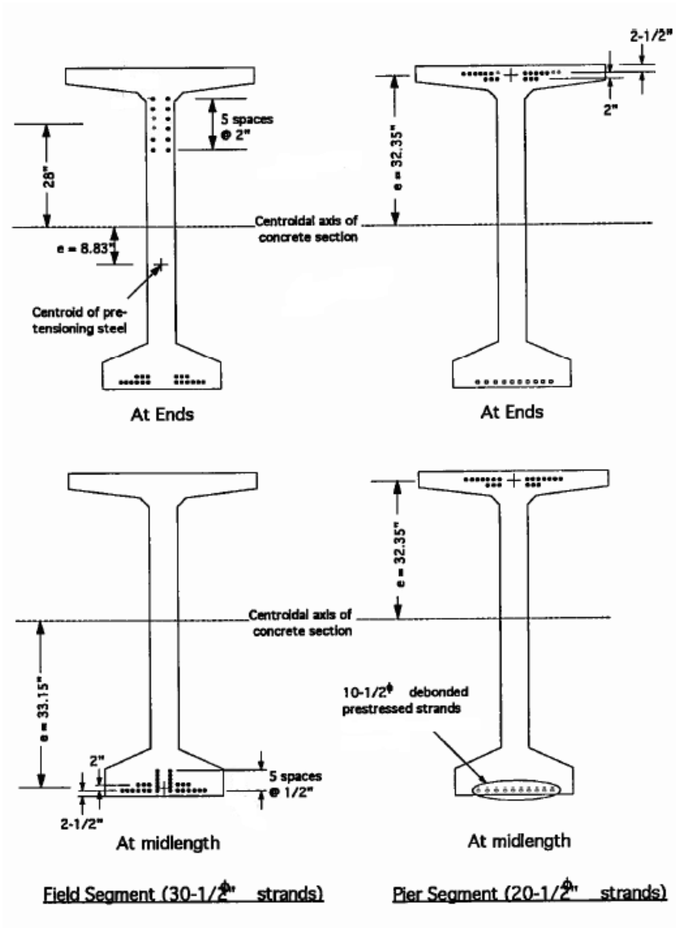


Figure 3 Pretensioned Strands

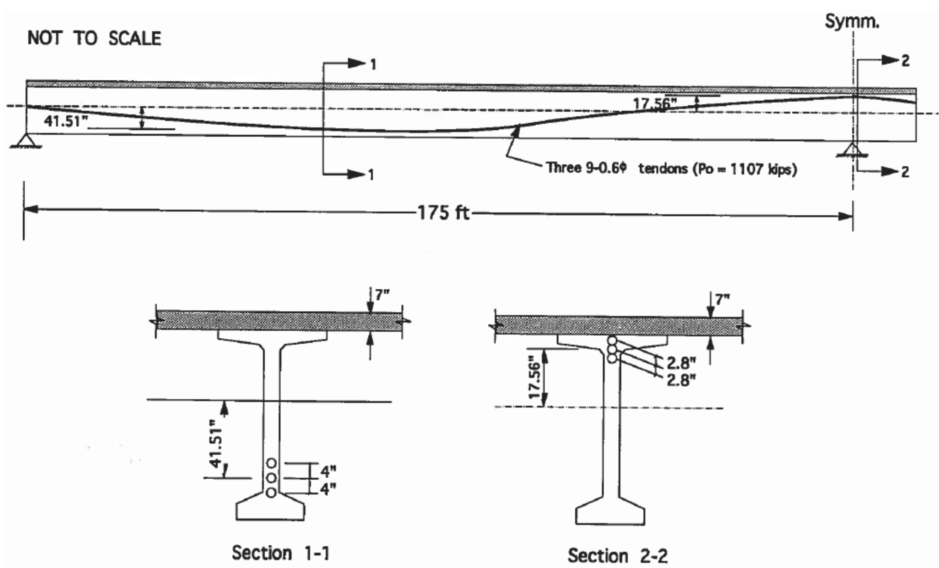


Figure 4 Tendon Profile

Bridge Modeling

When using PGSplice to model spliced girder bridges, input begins with a project template. The template contains basic information about a bridge project including default span arrangements, material properties, girder configurations, and project criteria. Users can customize PGSplice by creating and publishing their own templates that reflect owner-agency standard requirements.

Once the PGSplice project is created, the bridge layout is refined with specific project information. Start by defining the roadway alignment, profile, and superelevation transitions. Then define the pier locations, temporary support locations, and the overall cross section of the bridge.

The model for the example bridge is shown in Figure 5.

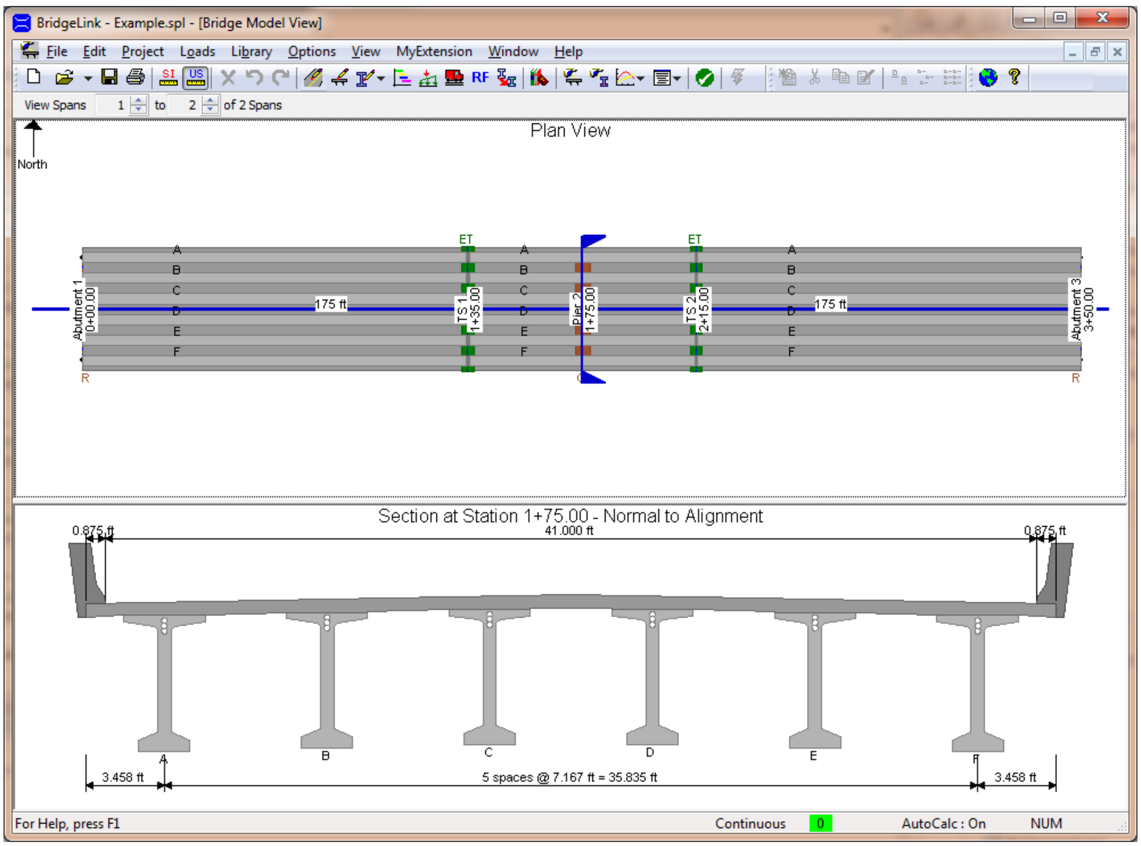


Figure 5 Model of Example Bridge

Girder Details

Once the overall geometry and framing plan of the bridge has been defined, the details of the precast-segments, cast-in-place closure joints, and post-tensioning are input. Figure 6 shows the definition of a girder including access to the segment details, closure joint details, and the post-tensioning details. Figure 7 shows the prestressing details for one of the end segments. Figure 8 shows an elevation and section of the girder.

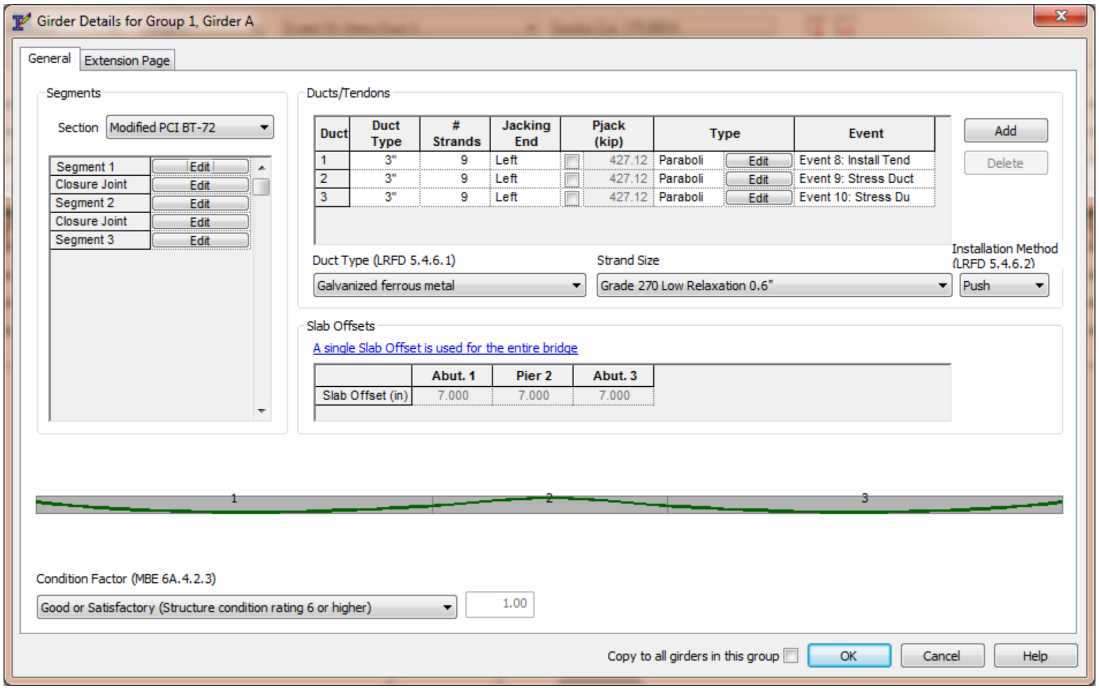


Figure 6 Girder Definition

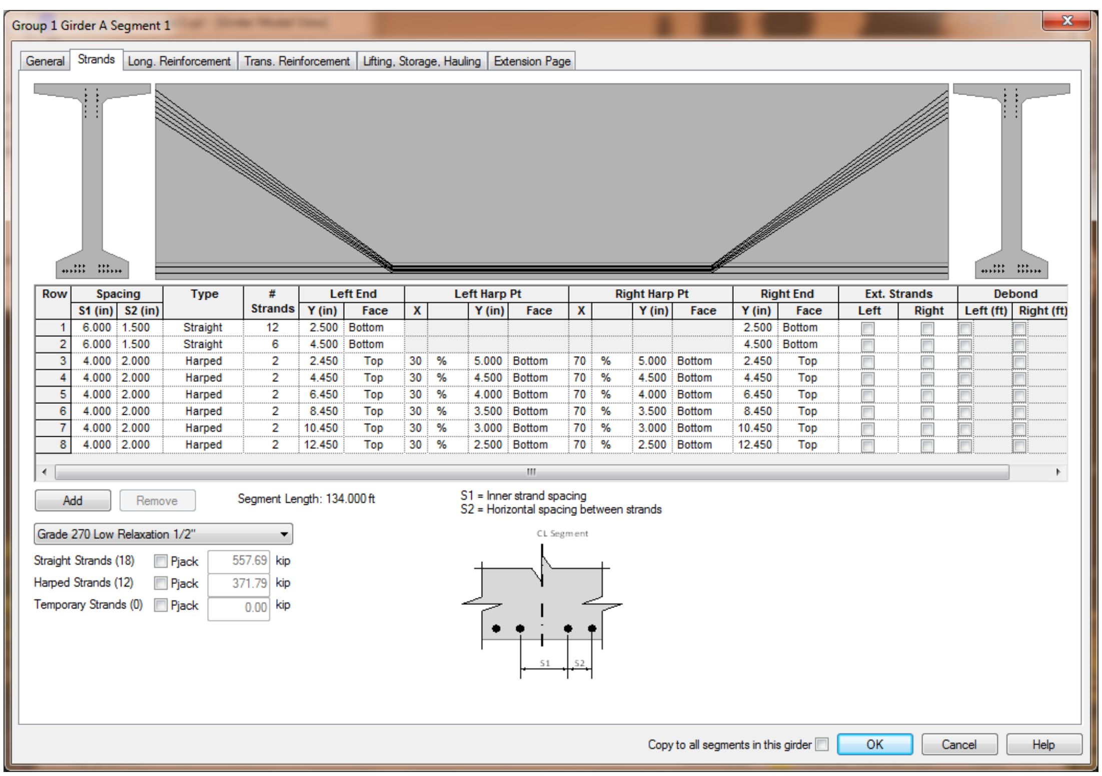


Figure 7 Prestressing Details

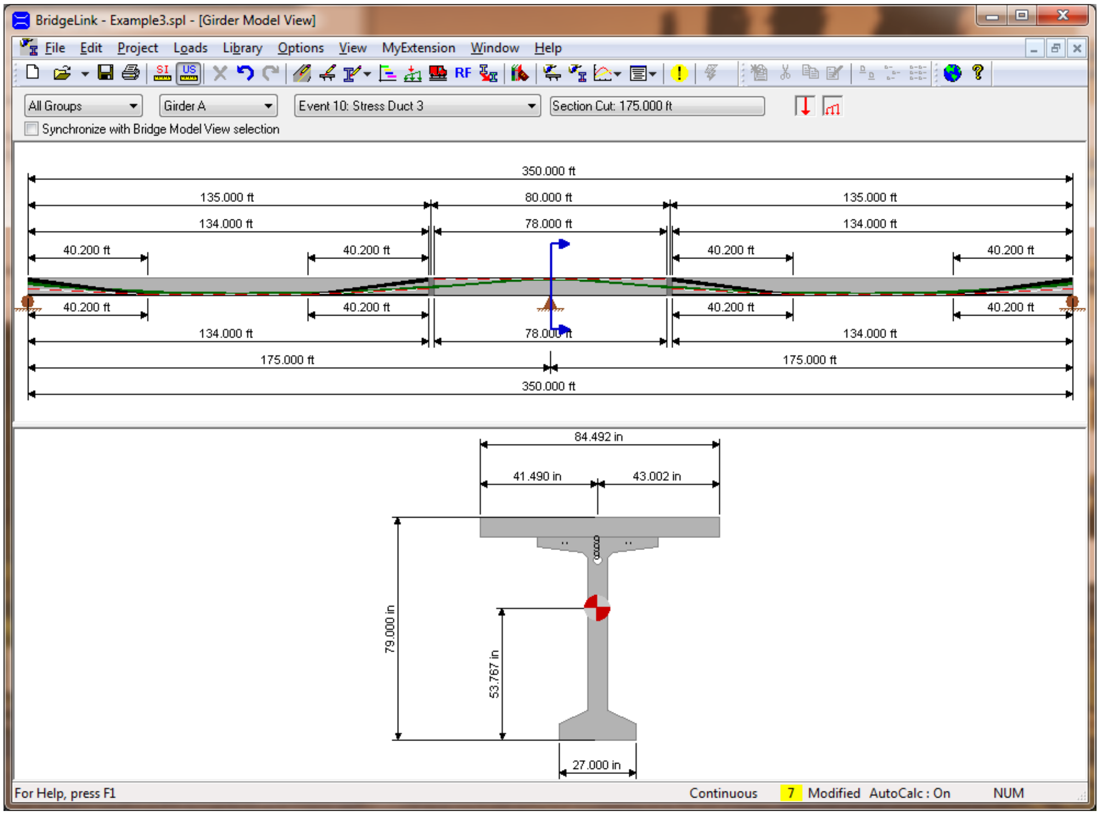


Figure 8 Section and Elevation of Spliced Girder

Timeline Modeling

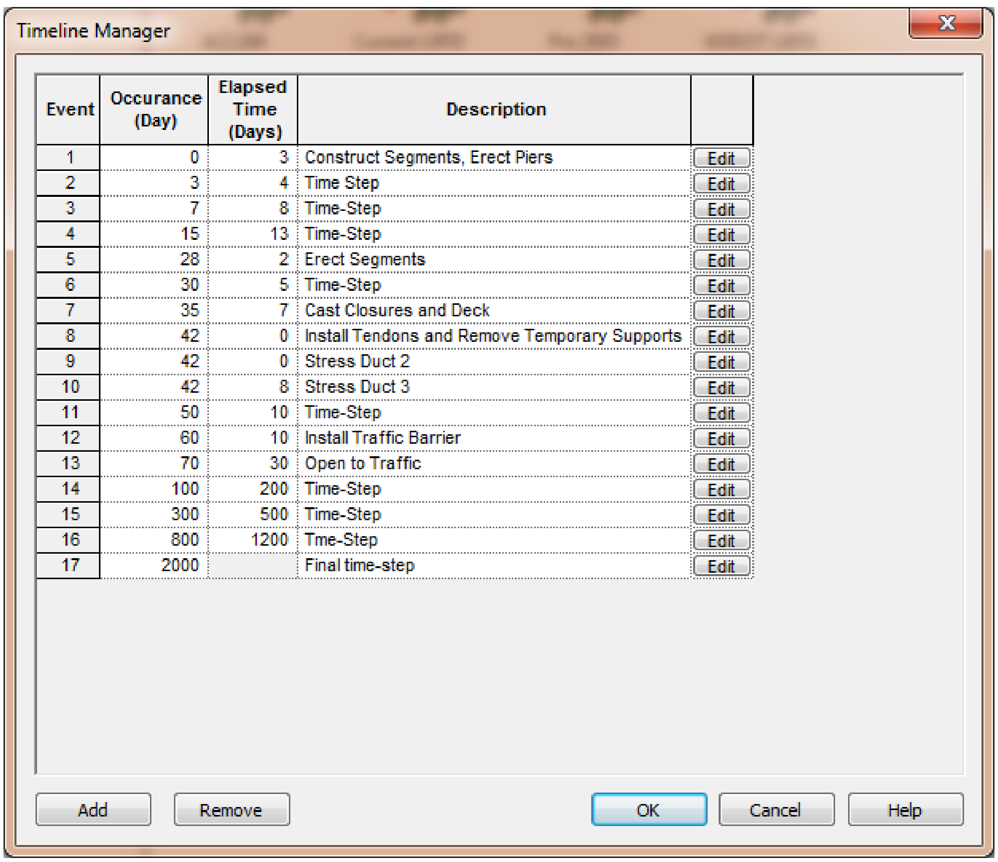
The last significant input is the timeline model. PGSplice simplifies the timeline definition by modeling a sequence of common construction activities. General events that represent significant occurrences during the timeline are created at specific times. Common construction activities, such as Construct Segments, Cast Deck, and Install Tendons are assigned to the timeline events. Certain construction activities, such as Construct Segments, require multiple analysis intervals in the time-step analysis. The analysis intervals relating to Construct Segments are stressing of the strands to capture relaxation prior to release, casting and curing the segment concrete, releasing of prestress force into concrete segments, and elapsed time during storage of the segments at the precasting facility to capture deformations related to creep, shrinkage, and relaxation. PGSplice creates the time-step intervals from the timeline events and construction activities. In the case of the Construct Segments activity, the engineer defines the occurrence of this single activity and PGSplice automatically generates the related time-step analysis intervals.

The construction sequence for the example bridge is given in Table 1.

Table 1 Construction Sequence

Construction Event	*Day of Occurrence*
Construct Segments and Erect Piers and Temporary Supports	0
Erect Segments	28
Cast Closure Joints and Deck	35
Install tendons and remove temporary supports	42
Install traffic barrier	60
Open to traffic	70

Additional time-steps are modeled at day 3, 7, and 15 to capture the time-dependent effects during the early age of the segment concrete. A time-step is added at day 50 to capture the time-dependent effects following the application of the post-tensioning loading. Time-steps are also modeled at day 100, 300, 800, and 2000 to complete modeling of the design life of the structure. The construction timeline is modeled in the PGSplice Timeline Manager as shown in Figure 9.



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

Figure 9 Construction Sequence modeled in the PGSplice Timeline Manager

Analysis Results

The graphical representations of analysis results provided by PGSplice are highlighted here. Figure 10 shows a traditional moment diagram for the girder self-weight loading at several key intervals. The moment, shear, displacement, stress, and reaction diagrams show cumulative and incremental analysis results for all of the loads during a specific interval or for a single load as it changes through time.

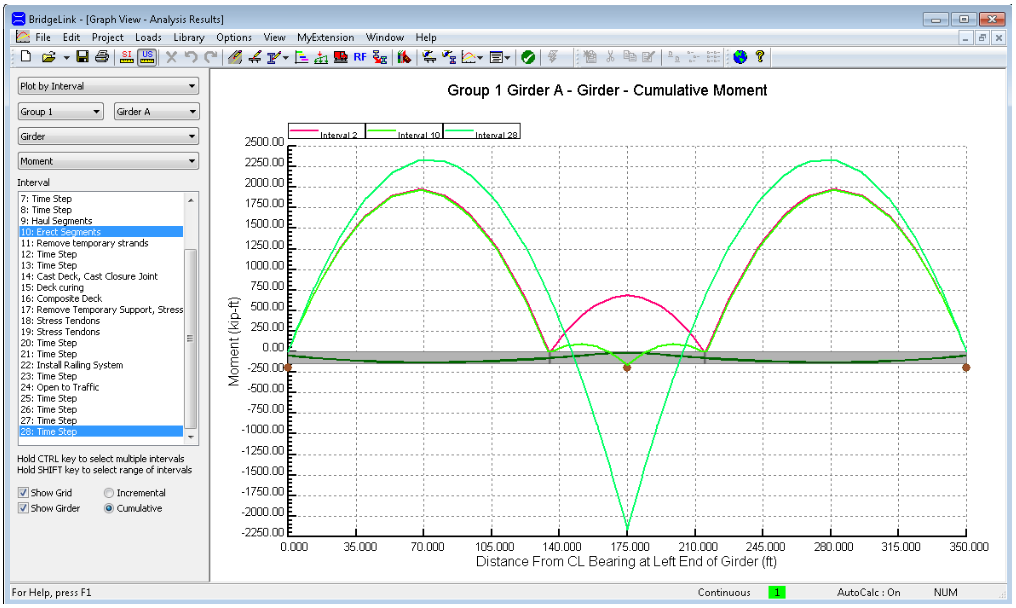


Figure 10 Girder Self-Weight Moments

Figure 11 shows the effective stress in a tendon as it changes through time.

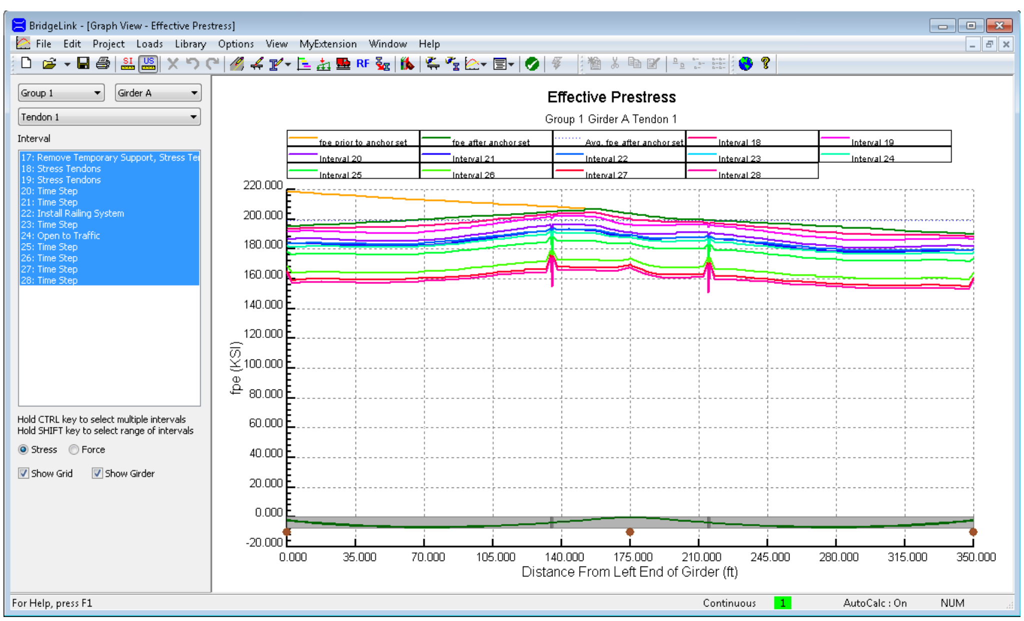


Figure 11 Effective Prestress in Tendon 1

Figure 12 shows a comparison of the top of girder stress computed by PGSplice with published results for the example bridge. The top of girder stress is computed at the 0.4L point of Span 1. The stress is computed for elastic effects only (time-dependent effects are neglected) to provide a baseline comparison between the bridge modeling done by PGSplice and the published example. The basic trend and magnitude of the stress have good agreement. The differences in the stress history can be attributed to minor differences in modeling between PGSplice and the published example.

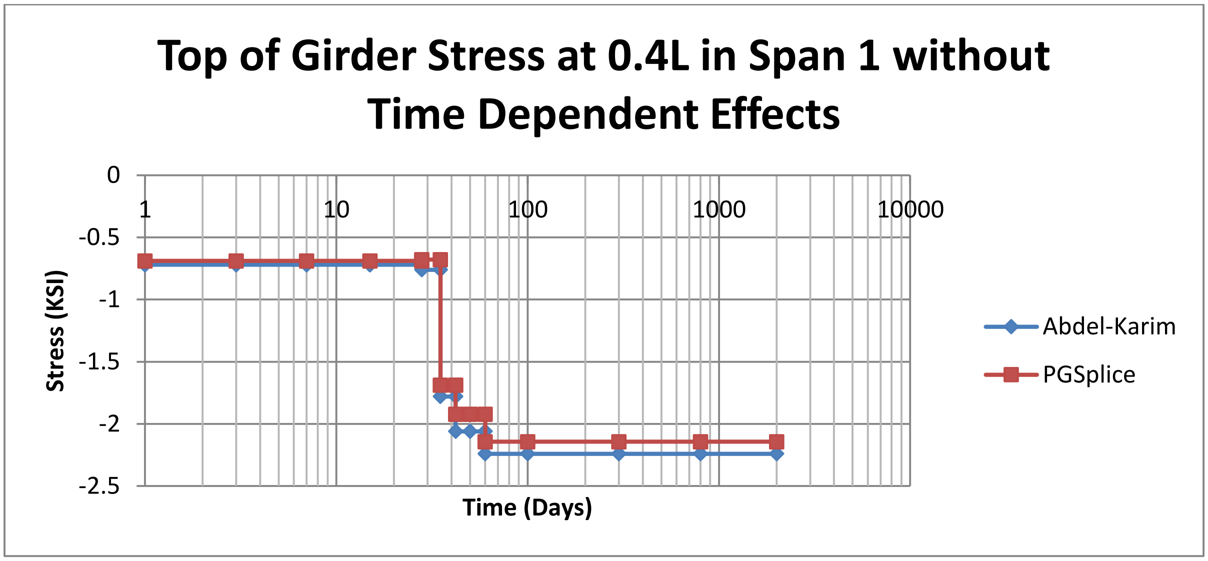


Figure 12 Baseline Stress History Comparison

Figure 13 compares the stress history at the same point, including time-dependent effects. The stress history computed by PGSplice is based on the CEB-FIP Model Code. Again the results are in good agreement with published values and the differences in the stress history can be attributed to modeling differences.

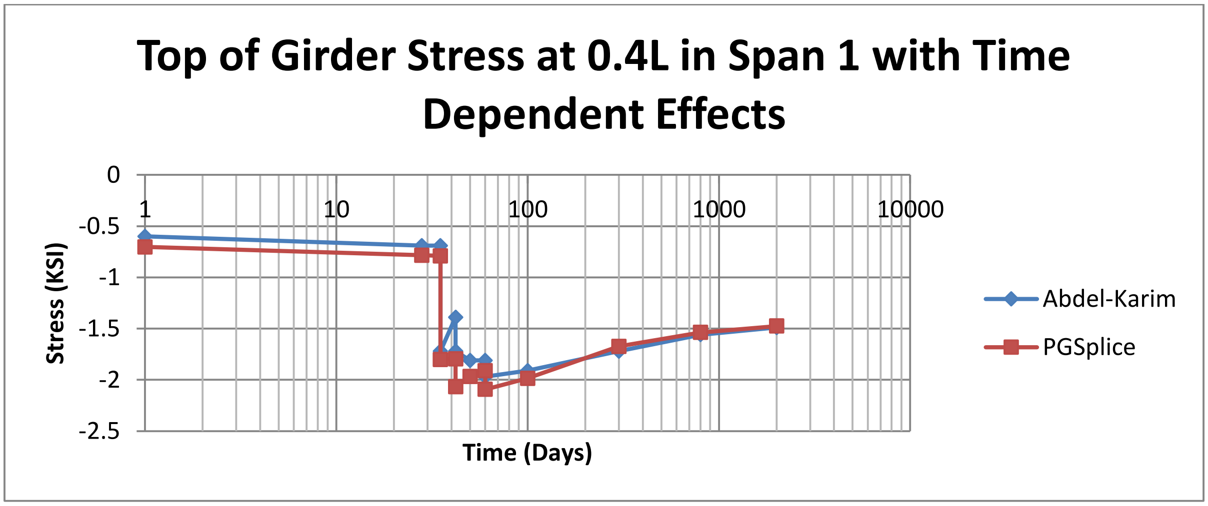


Figure 13 Stress History Comparison with Time-Dependent Effects

CONCLUSION

Computer-aided analysis is essential for the successful design of precast-prestressed spliced girder bridges. Rigorous time-step analysis methods are required for final design of these complex bridge types. Software tools are well suited to perform the enormous quantity of computations involved in a time-step analysis.

Ensuring a spliced girder structure meets or exceeds the numerous requirements of the AASHTO LRFD and AASHTO MBE is also a complex and involved process. Significantly more design evaluations must be made compared to conventional precast girder structures. Computer software tools make the design and load rating of spliced girder bridges efficient, feasible, and reliable.

The BridgeLink-PGSplice software developed by the Washington State Department of Transportation represents a significant step forward, satisfying the growing need for easy to use and accurate design tools that are necessary to advance the use of precast concrete for long span structures.

REFERENCES

1. American Association of State Highway and Transportation Officials (AASHTO). 2015. AASHTO LRFD Bridge Design Specification. 7th Edition with 2015 Interim Revisions, Washington, DC: AASHTO.
2. American Association of State Highway and Transportation Officials (AASHTO). 2013. The Manual for Bridge Evaluation. 2^{nd} Edition with 2013 Interim Revisions, Washington, DC: AASHTO.
3. Castrodale, R., White, C., 2004, Extending Span Ranges of Precast Prestressed Concrete Girders. National Cooperative Highway Research Program Report 517, Transportation Research Board, Washington, DC.
4. Time-Dependent Analysis of Composite Frames. Tadros, Maher K., Ghali, Amin and Dilger, Walter H. ST4, s.l. : ASCE, April 1977, ASCE Journal of Structural Engineering, Vol. 103, pp. 871-884.
5. ACI Committee 209, "Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures", American Concrete Institute, Detroit, 1982.
6. CEB-FIP, *Model Code for Concrete Structures*, 1990
7. A Study of Stress Relaxation in Prestressing Reinforcement. Magura, Donald D.,Sozen, Mete A., Seiss, Chester P., April 1964, PCI Journal, pp. 13-57
8. Roark, Raymond J., and Warren C. Young. *Roark's Formulas for Stress and Strain*. 6^{th} ed. New York: McGraw-Hill, 1989
9. Computer Analysis of Spliced Girder Bridges. Abdel-Karim, Ahmad M. and Tadros, Maher K. 1, January-February 1993, ACI Structural Journal, Vol. 90, pp. 21-31.
10. Precast/Prestressed Concrete Institute. State-of-the-Art Of Precast/Prestressed Concrete Spliced-Girder Bridges. 1st, second printing. Chicago : PCI, 1995.