

**Paper Title: PRESTRESSED CONCRETE GIRDER BRIDGES – FROM 2D TO 3D
MODELING**

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PRESTRESSED CONCRETE GIRDER BRIDGES – FROM 2D TO 3D MODELING

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ABSTRACT

Two Windows-based computer programs, WIN-PBEAM and VBDS, are described in this paper. WIN-PBEAM is a two-dimensional (2D) prestressed/post-tensioned precast concrete girder analysis and design program. WIN-PBEAM performs a complete analysis of simple-span and multi-span prestressed/post-tensioned highway bridges in accordance with the 1996 AASHTO Specifications and 1998 AASHTO LRFD Specifications and their updated Interims to 2000. The WIN-PBEAM system contains features generalized to a level that allows universal usage. The program was developed using a WINDOWS GUI and the latest numerical analysis techniques to accommodate general usage of strand patterns, arbitrary loadings, and user-defined girder members. The program computes and prints the results in tabular form for any defined points along the span with section properties for composite and non-composite; dead load and live load reactions; shears, moments, and displacements; stresses for various construction stages; prestressing losses and forces; ultimate moments provided and required; and cracking moments. A 5-span prestressed/post-tensioned girder bridge was adopted as the example of this program.

On the other hand, VBDS, Visual Bridge Design System, a three-dimensional (3D) general-purpose bridge finite element analysis (FEA) program, is usually used for major or more sophisticated bridge structures. The embedded time dependent analysis of the concrete, following the AASHTO LRFD Specifications, is a perfect tool to analyze segmentally erected prestressed concrete bridges and other spatial frame structures. As the WIN-PBEAM program, VBDS can accommodate general usage of tendons, arbitrary loadings and girder members. Graphic output of an example segmental bridge is given for demonstration.

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PRINCIPLE AND MODELING OF PRESTRESSING

Based on Reference (1), any method, which satisfies the requirements of equilibrium and compatibility and utilizes stress-strain relationships for the proposed material, can be used in the analysis. As it is commonly known, the prestressing force used in the stress computation does not remain constant with time. The collective loss of prestress is the summation of all individual losses, which may be examined individually or considered for a lump sum loss.

Four most critical conditions in the structural modeling of tendons:

- 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. The retraction of the tendon results in an additional stress loss over a short length of the tendon at the stressing end. The combined loss is commonly referred to as the friction and seating loss.
- Elastic shortening: The elastic shortening of the concrete due to the increase in compressive stress causes a loss of prestressing force in tendons.
- Long-term losses: Several factors cause long-term losses: (1) Relaxation of the prestressing steel, (2) Shrinkage in concrete, and (3) Creep in concrete. In grouted (bonded) posttensioning systems, creep strain in the concrete adjacent to the tendon causes a decrease in tendon stress. For unbonded tendons, the decrease in stress along the tendons due to creep of the concrete is generally a function of the overall (average) precompression of the concrete member.
- Change in stress due to bending of the member under applied loading: For a rigorous evaluation of the affected member, change in stress must be taken into account, particularly when large deflections are anticipated.

In general, prestressing/post-tensioning tendon modeling and its analysis can be categorized to two major groups:

1. Tendon modeled as applied loading

Within this group there are three subgroups depending on the modeling technique:

- *Simple load balancing* – The force of the tendon on the concrete is considered to balance (offset) a portion of the load on the member, hence the “load balancing” terminology. The shortcoming 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 at any location along a member is defined as the prestressing force P times its eccentricity e . The eccentricity of the force is the distance between the resultant of the tendon force and the centroid of the member. The primary moment can be used as an applied loading in lieu of the balanced loading for structural analysis. Bridge designers more commonly use this modeling technique than building designers. In practice, the primary moment diagram is discretized into a number of steps. Each discrete moment is equal to the change in the value of moment between two adjacent steps in the primary moment diagram.
- *Equivalent load through discretization of the tendon force*– the force distribution is represented by a series of straight segments. Hence, the force distribution would be represented by a series of sloping lines with steps at the discretization points. 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 1). WIN-PBEAM adopts this method for the consideration of varied sections and prestressing forces.

2. Tendon modeled as load resisting elements

The tendon is not considered as removed from the concrete member. Rather, the tendon is modeled as a distinct element linked to the concrete member (Figure 2). The change in prestressing force due to relaxation is automatically accounted for in the equilibrium equations set up for the analysis of the segment. VBDS (Visual Bridge Design System) adopts this technique for the consideration of prestressing.

WIN-PBEAM PROGRAM SCOPE

WIN-PBEAM (Post-tensioned, Prestressed Precast Beam Bridge System) analyzes and performs the analysis, design, code check and rating according to the most current AASHTO specifications (1). A flowchart of the program is shown in Figure 3. Structural analysis of the beam is performed by the program stiffness matrix solver. The program assumes the beam is a line element with translational and rotational degrees-of-freedom. The sizes of the elements and locations of the joints are totally dependent on the user input. Besides defining members and joints, part of the modeling process includes setting of the boundary conditions. Since the program assumes simply supported beam at the first stage and then makes it continuous at later stages, the boundary conditions have to be preset for Dead Load Stage, Superimposed Dead Load Stage, and Live Load Stage.

AASHTO specifies that live load distribution factors and impact factors be input by the users. With live load distribution factors, AASHTO permits computation of the truck applied to a single beam instead of the whole bridge system. With internally generated influence lines, AASHTO or any arbitrary trucks can be calculated individually.

Features - Full ranges of features that allow for the most general usage have been incorporated into the WIN-PBEAM program and are summarized in Table 1. Specific features apply to specifications, loadings, and structural configurations are summarized as follows:

Specifications: Prestressed girder bridges are modeled, analyzed, and code-checked in accordance with the 1996 AASHTO Specifications and 1998 AASHTO LRFD Specifications and the updated Interims to 2000.

Structural Configuration: A number of features is available in WIN-PBEAM that allows analysis of various structural bridge configurations. Since WIN-PBEAM is matrix-based and modular, it is upgradeable easily for incorporation of other features.

Loads: WIN-PBEAM incorporates both joint and member loads. A summary of the loads is given in Table 2. Incorporated within the WIN-PBEAM system is the widest and most general range of live load capabilities with the utilization of influence lines. The methodology incorporated with the live load portion of WIN-PBEAM was developed to be the as general as possible. The determination of all maxima is accomplished by utilization of influence lines. The influence lines were developed by placing unit loads at any user-defined point along the girder.

Output and Output Levels: All output appear in tabular format. All the output tables contain self-explanatory headings. PBEAM is constructed so that various levels of output are available to the user. The two levels of output are Level I for the basic engineering output level and Level II for the detailed engineering output level.

Window pull-down menu: For use on single workstation or network using the Microsoft Windows environment (3). This version utilizes a Windows-based pull-down menu structure to access WIN-PBEAM's input, execution, graphic, print and help utilities (Figure 4).

Methodology - Detailed within this section is a brief description of the methodology, which pertains to the structural analysis, used within WIN-PBEAM.

Analysis Method: Incorporated within WIN-PBEAM is an analysis capability in which the direct stiffness method is utilized. This method has many advantages including a more generalized definition of the structure over previously popular methods (e.g., moment distribution, slope deflection, etc.).

Mesh Generation: Automatically generated within WIN-PBEAM is a mesh, which defines all nodal points and section properties for each construction stage. Refer to Example Problems for typical mesh patterns. The mesh changes for various loading and construction conditions and is achieved without user intervention.

Element Library: Incorporated in the WIN-PBEAM program is a series of elements, which allow the user to model most bridge structures.

Dead load: The dead load portion of the program consists of two main categories. The first relates to the AASHTO requirements for both composite and non-composite construction. The second, a feature that is to be added in the future, pertains to the effects of construction staging for composite construction. These are summarized in Table 2. The program automatically places all prestressed girder, slab, and superimposed dead loads on the bridge and combines them with the modular ratios as specified by AASHTO (see Table 2). Other concentrated or partial uniform load can be placed on the bridge at any point in the analysis cycle.

Live loads: The program generates maximum/minimum live load moment and shear along the girder at any point specified by the user. The live load module in the program is very general so that any type of AASHTO loading can be specified by the user. Taking advantage of the influence lines, an infinite number of user defined arbitrary trucks can be analyzed. All AASHTO live loading, interstate and various user defined arbitrary trucks could be analyzed in one execution. The list of allowable live loads is given in Table 2.

Prestressing tendons: Any type of tendon layout can be defined by the user, i.e., straight, depressed, and parabolic for post-tension. Prestressing tendon and post-tensioning geometry can be defined span by span.

Continuity: Continuity between precast-prestressed simple span girders is accomplished using the following methods:

- 1) Design of non-prestressed reinforcement for negative moment at the interior supports based on ultimate strength method;
- 2) Design of posttension cables for negative moment region.

Multi-stage prestressing and post-tensioning: Simple and continuous span girders are designed using the following three stage pretensionings:

- 1) Conventional prestressing during fabrication in the plant will carry only the precast girder weight;
- 2) Second stage is posttensioning in the field and will carry only the wet slab load;
- 3) Third stage is also posttensioning in the field and will carry the live loading.

VBDS PROGRAM SCOPE

Finite Element bridge analysis program, VBDS (Visual Bridge Design System), is an integrated CAD system for analysis and design of all types of bridges. It is a new generation of CAD system for bridge analysis and design under the Windows 95/98/NT/2000 environment. It performs a three-dimensional (3-D) spatial bridge structural analysis for multiple construction phases. The program also allows linear/non-linear static, dynamic and stability analysis. Its 3D finite element analysis specially designed for bridges can be used for simulating multi-phase construction processes of a bridge. The special features, which are unique for the bridge structure and are usually not available in the generic finite element analysis package, include:

- By means of graphical interaction via a popular commercial CAD system, the finite element analysis (FEA) model can be created to simulate different phases of bridge construction with assignments of boundary conditions for different construction phases.
- The bridge girders are modeled by space frame element. The prestressing tendons are modeled by space bar elements to simulate their prestressing and stiffness enhancement to the structure.
- Curved geometry is allowed due to the program's 3-D features.
- Each construction phase may consider unlimited different load cases to simulate various construction conditions. And each load case can consist of an unlimited number of loads that are specially designed for simulating bridge construction.
- Creep and shrinkage analyses using the AASHTO LRFD provisions are built in.
- Standard AASHTO truck and lane loadings (HS or HL-93) specified in the AASHTO Standard or LRFD Specifications can be used for the live loading.
- Construction process analyses can be visualized.
- Analysis includes structural behavior of (1) each girder segment weight, (2) each time the tendon prestressed, (3) secondary moment and displacement caused by concrete creep and shrinkage at each construction stage and during service, and (4) extreme force and stress caused by AASHTO live loads.
- Dynamic modal analysis and elastic stability analysis were used to check the validity of the wind load analysis.

ILLUSTRATED EXAMPLES

Example 1 - A design case for a concrete alternate with a continuous prestressed then post-tensioned precast I-beam bridge is analyzed by the WIN-PBEAM program. The total length of the bridge is 198.86 m (652'-5") with five (5) continuous spans of 39.5 m (129'-7.1") each (see Figure 5.a). The clear roadway width is 13.41 m (44') and out-to-out distance is 17.98 m (59') with 3-3.66 m (12') lanes. Five 1880 mm (74") deep precast bulb-T girders are used in the design with 3.81 m (12'-6") girder spacing (see Figure 5.b). A 200 mm (8") deck slab is used in the composite construction with another 13 mm (1/2") wearing surface.

Precast girder is formed by the semi-light weight concrete with initial concrete strength (f_{ci}') of 31 MPa (4,500 psi) and final concrete strength (f_c') of 48.3 MPa (7,000 psi). Concrete strength of the cast-in-place concrete is 34.5 MPa (5,000 psi). All the prestressing tendons are 1862 MPa (270 ksi) stress-relieved 7-wire strands with modulus of elasticity of 1.9×10^5 MPa (28 x 106 psi). The prestressing steel strand's diameter is 13 mm (1/2") and the post-tensioning steel strand's diameter is 15 mm (0.6"). Results show that the program checks stress limits of the concrete (Figure 6) and the steel under the serviceability limit states as well as ultimate moments and shears under the strength limit states.

Example 2 - A three-span single cell haunched prestressed box girder bridge (4) is taken as an illustrated example in this study. Figure 7 shows its elevation profile and Figure 8 shows its cross section geometry. The haunched girder is cantilevered from the piers using cast-in-place segments, and is later made continuous with short, conventionally erected, cast-in-place segments near the abutments and with the adjoining cantilevered girder at midspan. Each cantilever segment is post tensioned to the previous segments with several cantilever tendons. After the closures at the abutments and at midspan the entire bridge is prestressed with several additional continuity tendons extending the full length of the bridge.

The modulus of elasticity of the prestressing tendon is 1.9×10^5 MPa. The modulus of elasticity of the concrete girder is 2.86×10^4 MPa. The geometry properties for the girder cross-section, pier cross-section and tendons are listed in Table 3.

The unit weight of the concrete of this bridge is 24.8 kN/m³. Totally, 37.2kN/m will be imposed along the deck after closure. For comparison purposes, the live loading is 4 lanes of AASHTO HS-20 without any multi-lane deduction. If the design is based on the AASHTO LRFD Specifications (1), HL-93 can be employed. The modified ACI 209 creep and shrinkage model (5) is adopted in the AASHTO LRFD Specifications (1). SFRAME (4) developed in the University of California at Berkeley in the 80's, as a comparison with VBDS, however, adopts the original ACI 209 as its creep and shrinkage model. Although the creep models are different between two numerical models, when some parameters are taken as standards, the two creep models are very similar in nature. One great shortcoming of applying LRFD creep model is the maximum volume-surface area ratio used in the evaluation is limited to 6, while some of the structures may require ratio over 6".

The construction sequence is modeled in 41 stages to simulate the erection and tendon prestressing of each section. It takes one week for each launching and prestressing. At day 100, the 18.3 meter long girder at side span starts to be cast and the side spans and the center span close at day 168 and 182, respectively. All prestressing tendons are jacked at a unique stress of 1393 MPa and the losses are taken as 15% of the jack stress. Unlike SFRAME, all losses are simply treated to be a constant along its path in this analysis by VBDS.

The time dependent analysis for the 27 years following construction is performed by a smart step adjustment. The basic step is one week. It will be increased by one week whenever the differences of two adjacent analysis is less than a designated threshold, or will be decreased by one week if it is above the threshold. Usually it varies among one to 12 weeks.

Table 4 shows the results and its comparison between VBDS and SFRAME. The differences between two numeric solutions are checked. Stresses of cases for maximum dual cantilever, read to serve and 27 years later Based on the Figures 9 to 12 are some screens captured from VBDS which show only the stress distribution on top flange of the box girder at maximum dual cantilever stage, after secondary dead load imposed, 27 years later and the stress envelop of HS20, respectively. The jagged stress plots shown on Figures 9 to 11 are caused by the axial forces induced by the cantilever or local tendons. Jagged locations are where tendons terminate. The live load stresses are showing the smoothness across the whole girder. The live load analysis indicates that live load stress

along the girder may be wrong if it is calculated by using simple girder principles based on its moment and axial force envelope. Unlike the dead load, which is already distributed over a statically determined structure before closure, the live load will cause significant axial force over the girder (-6300kN/4000kN at center of main span) because the bridge is fixed with two piers and the centroid of the girder shapes a flat arch. Therefore, the main span behaves like an arch bridge. In this case, it may not be accurate enough by taking the extreme moment and its correspondent axial force, or the extreme axial force and its correspondent moment to calculate the stress over the girder in the main span. In VBDS, however, the extreme stress is calculated by loading over the stress influence surfaces or influence lines, not that of the simple axial force or bending moment.

CONCLUSION

Two programs, WIN-PBEAM for 2-D analysis and VBDS for 3-D analysis is introduced in this study. The advantage of using WIN-PBEAM is its simplicity and easy handling of the more commonly used slab or girder bridges with short to medium span lengths. Most input items, such as impact factors and distribution factors used in the simplification of a bridge system to a line girder, can be incorporated into the program, unless for special condition or user's override.

VBDS, with its power feature, can be used for any type of structural system (such as segmental bridges and cable stayed bridges) under all kinds of loading conditions and loading stages. Understanding the CAD system and Finite Element Method (FEM) is required in order to correctly perform the three-dimensional analysis. The advantage is that all the processes can be visualized and results tabulated to be systematically reviewed and inspected. In this paper, two different programs for prestressed concrete girder bridges display two different modeling techniques for different application occasions. AASHTO LRFD Specifications are used where they are applicable for both the analysis and the design processes.

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TABLE 1 –	WIN-PBEAM SUMMARY OF GENERAL FEATURES
TABLE 2 –	WIN-PBEAM LOADING CAPABILITY
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TABLE 1 – WIN-PBEAM SUMMARY OF GENERAL FEATURES

ITEM	REF/STATUS
Full Analysis Capability	
Full Code Check Capability with all AASHTO Provision	
Preliminary Design of Prestressing Tendons	
Prestressing Tendons, Straight or Harped	
Post-tensioning Tendons, Straight, Harped or Parabolic	
Most Design Parameters May Be Overriden by User	
Impact factors for moments, shears, displacements, and reactions can be defined by the user	
Distribution factors can be defined by the user	
Generalized AASHTO and Truck Live Loading	
AASHOT LRFD Live Loading	
Generalized Truck Configurations Specified by User	
Generalized Girder Configurations	
Generalized Tendon Configurations	
Generalized Dead Load Configurations	
Prestressed Beam Composite or Non-Composite	
Analysis Based upon the Stiffness Method	
Prismatic Sections	
Non-Prismatic Sections with Various Parabolic Haunches	In working
AASHTO Standard Prestress Losses	
AASHTO LRFD Prestress Losses	
Hinges for Construction Stages	
AASHTO Section (Built-in)	
Optimization	In working
Completely Modular and Easily Modifiable System	
Indexed Tabular Output	
Graphics	In working
Full AASHTO LRFD Specifications	

TABLE 2 – WIN-PBEAM LOADING CAPABILITY

LOADING TYPE	MODULAR RATIO
Prestressed Girder Loading	Infinity
Web Slab Loading	Infinity
Additional Uniform and Concentrated Loads	Infinity
Initial Prestress Loading	Infinity
Superimposed Dead Loads	3N
Additional Uniform and Concentrated Loading	Infinity, 3N or N
Stationary Live Loading	N
AASHTO HL-93 Loading	N
AASHTO Lane	N
AASHTO HS – Truck	N
AASHTO H – Truck	N
Interstate or Military	N
Arbitrary Trucks (User Defined) up to 20 axles	N
Ultimate Prestress Loads	N

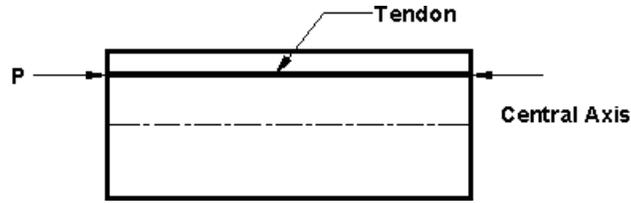
Note: N = Modulus ratio of E_{slab} to E_{beam}

TABLE 3 - EXAMPLE 2 SEGMENTAL BRIDGE SECTION PROPERTIES

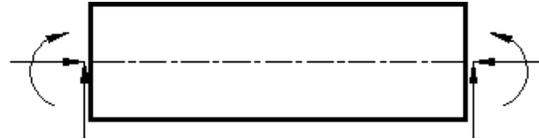
Component	Moment Inertia (m ⁴) / Area(m ²)	Component	Moment Inertia (m ⁴) / Area(m ²)
S 22-23	173.9/20.7	S 21,24	155.1/20.2
S 20,25	131.9/19.5	S 19,26	111.6/18.8
S 18,27	94.0/18.0	S 17,28	78.8/17.3
S 16,29	65.7/16.5	S 15,30	54.6/15.9
S 14,31	45.1/15.1	S 13,32	37.1/14.4
S 12,33	30.4/13.7	S 11,34	24.7/13.0
S 10,35	20.0/12.4	S 9,36	16.1/11.7
S 8,37	13.5/11.3	S 7,38	12.2/11.2
S 6,39	11.5/11.1	S 1	15.3/13.3
S 2	12.1/11.5	S 3,4	11.2/11.1
S 5, 40	11.2/11.1	T 1-16,25-28	0/0.008292
T 17-18	0/0.0166	T 19-24,29-53	0/0.004146
Pier(rigid zone)	180.0/20.9	Pier	10.7/21.6
Note: S for girder segment, T for tendon.			

TABLE 4 - EXAMPLE 2 SEGMENTAL BRIDGE STRESSES (KN/M²) AND COMPARISONS AT THE CENTER OF MAIN SPAN AND OVER THE PIER

Stage and Category	Position	VBDS	SFRAME
Maximum dual cantilever	TC	N/A	N/A
	BC	N/A	N/A
	TP	-2640	N/A
	BP	-11865	N/A
Ready to serve	TC	-4757	-4886
	BC	-8614	-10405
	TP	-3562	-3817
	BP	-12785	-13407
	MC	-14100	-17280*
	MP	-218900	-230500*
	DC	1.1(in)	1.9(in)*
27 years later	TC	-5430	-6025 [-5662**]
	BC	-6158	-3810 [-8774**]
	TP	-3070	-2658
	BP	-12700	-13619
	MC	-3000	1152*
	MP	-229300	-276500*
	DC	4.9(in)	5(in)*
4 lanes of HS-20	TC	-2215	-2334
	BC	2932	3248
	TP	2151	1554
	BP	-2742	-1603
Notes: TC – top flange at center of main span, BC – bottom at center of main span, TP – top over pier, BP – bottom over pier, MC moment at center span, MP moment at pier DC – displacements at center of main span * measured from graphs ** recalculated based on the provided moments and section properties			



(a) Tendon as External Force of an Element

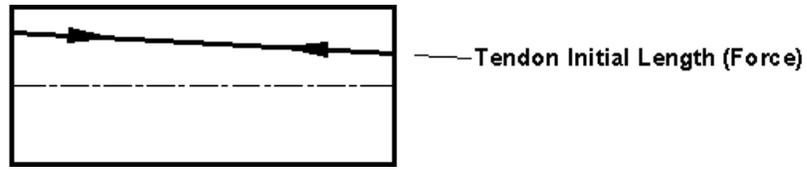


(b) Equivalent Tendon Force of an Element

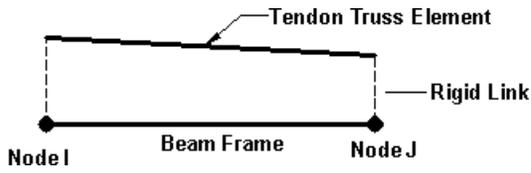


(c) Equivalent Tendon Forces along the Central Axis of the Beam

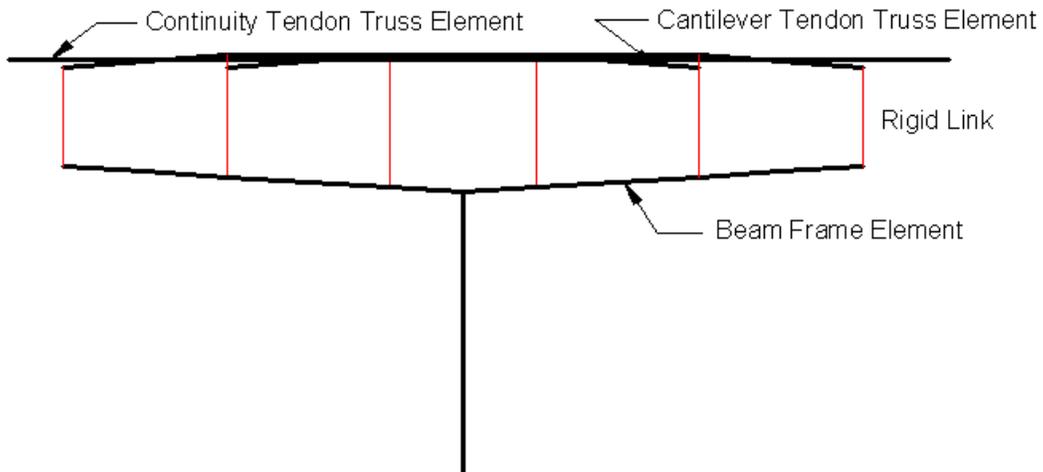
FIGURE 1 - EQUIVALENT LOAD THROUGH DISCRETIZATION OF THE TENDON FORCE



(a) Tendon as Element



(b) Tendon Element Geometry



(c) Finite Element Modeling of the Segmentally Erected Bridge with Post-Tensioning Tendons

FIGURE 2 - TENDON MODELED AS AN ELEMENT LINKED TO THE CONCRETE MEMBER

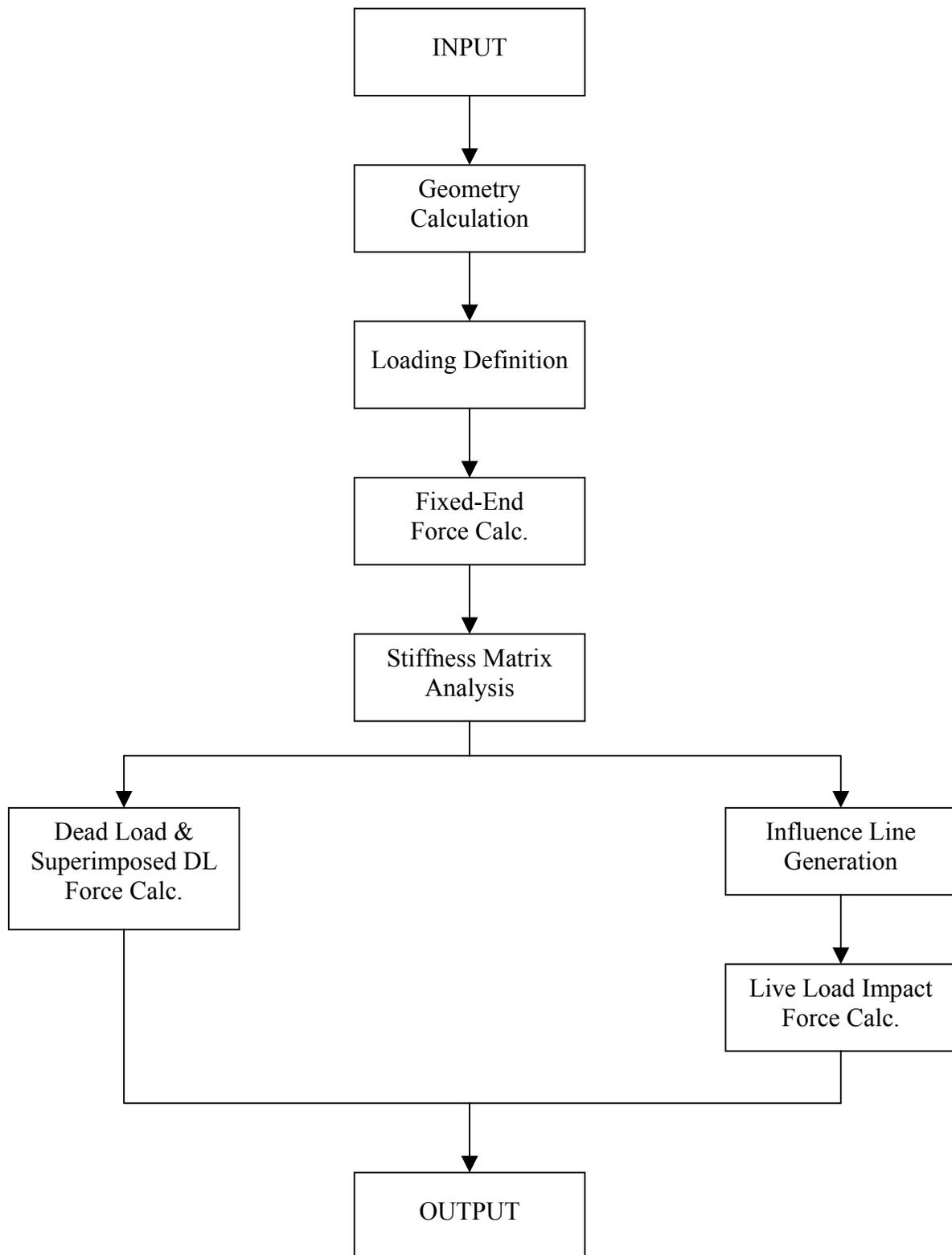


FIGURE 3 - FLOWCHART OF WIN-PBEAM

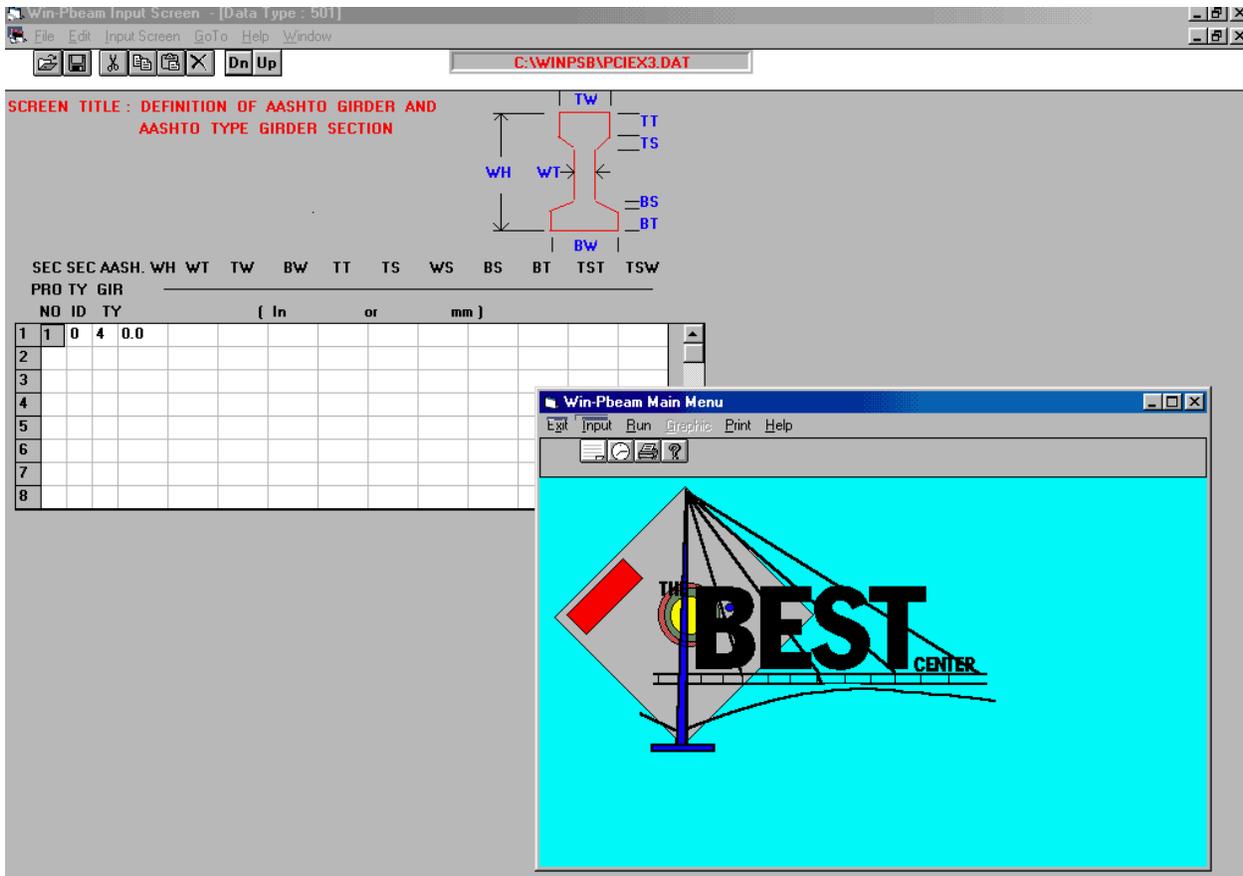
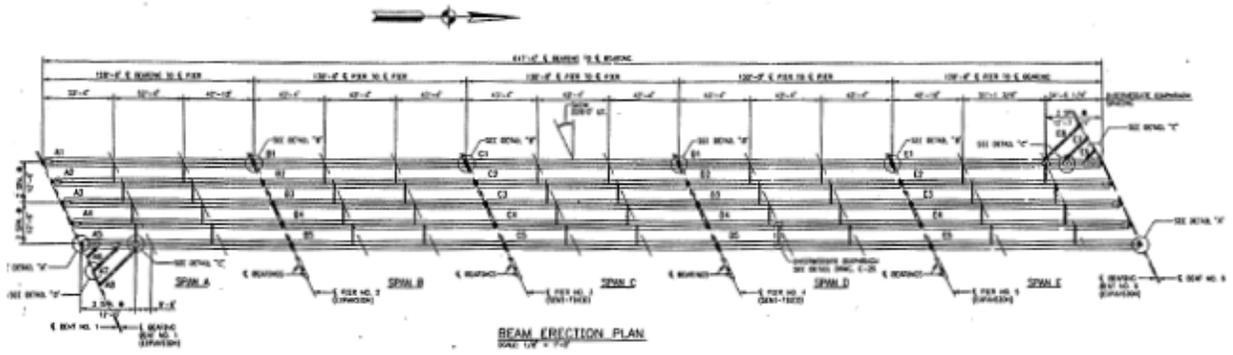
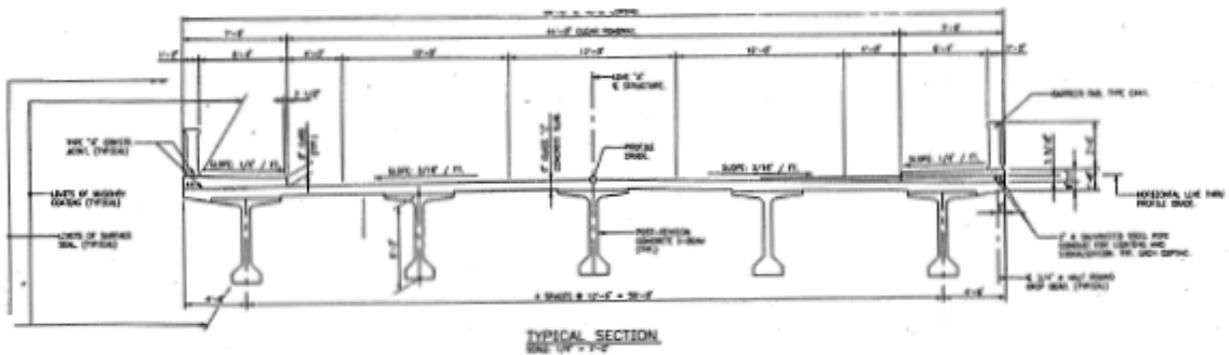


FIGURE 4 - WIN-PBAM PULL-DOWN MAIN MENU



(a) Framing Plan



(b) Cross Section

FIGURE 5 - FIVE-SPAN PRECAST, PRESTRESSED CONCRETE BRIDGE MADE CONTINUOUS WITH POST-TENSIONING TENDONS (EXAMPLE 1)

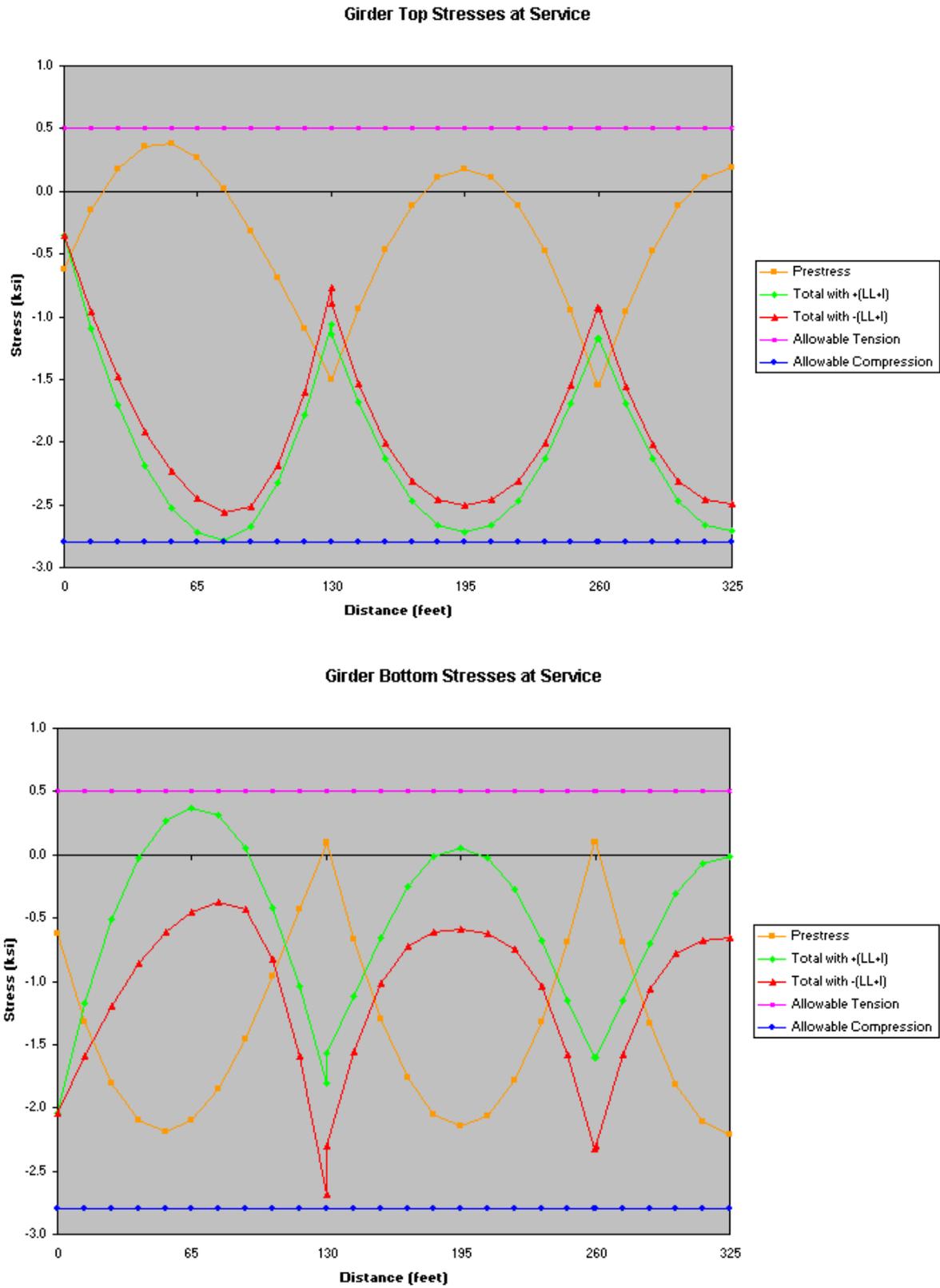


FIGURE 6 - TOP AND BOTTOM STRESS GRAPHIC RESULTS IN EXAMPLE 1

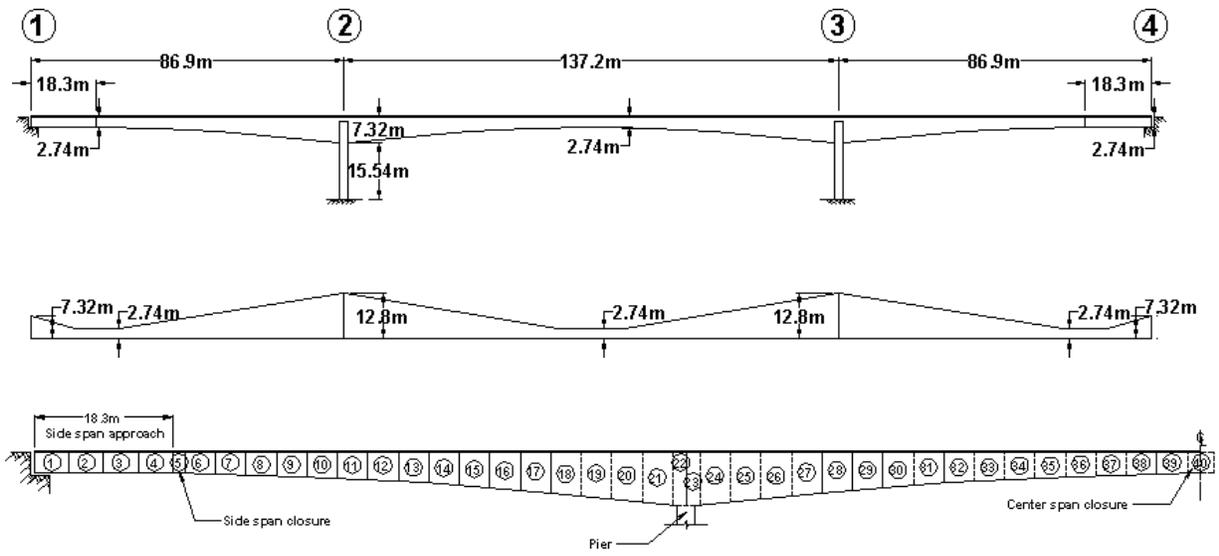


FIGURE 7 - BRIDGE ELEVATION PROFILE, BOTTOM SLAB THICKNESS VARIATION AND SEGMENT DIVISION

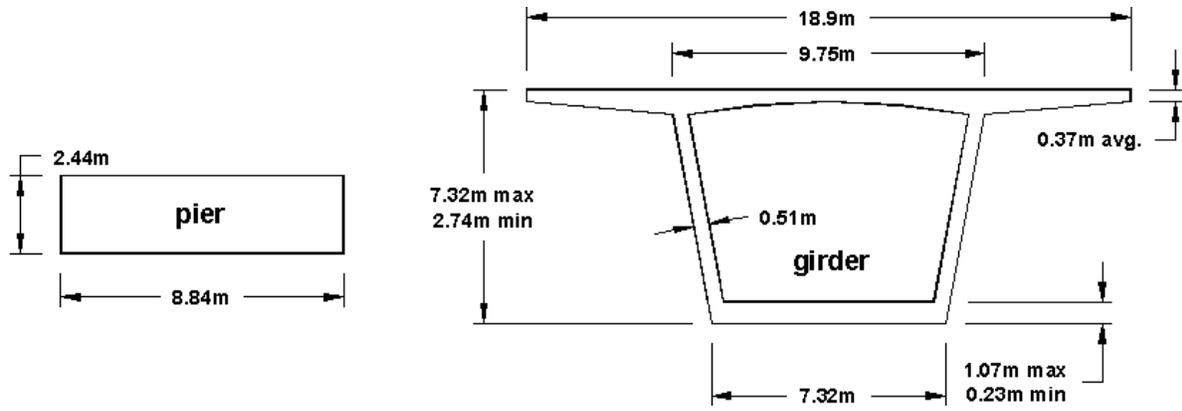


FIGURE 8 - CROSS SECTION OF THE PIER AND MAIN GIRDER

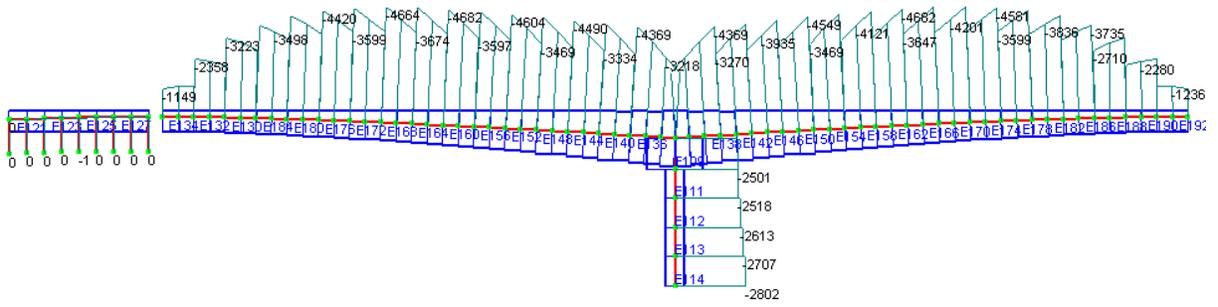


FIGURE 9 - STRESS (KN/m²) DISTRIBUTIONS ON THE TOP FLANGE OF THE BOX GIRDER AT MAXIMUM DUAL CANTILEVER STAGE

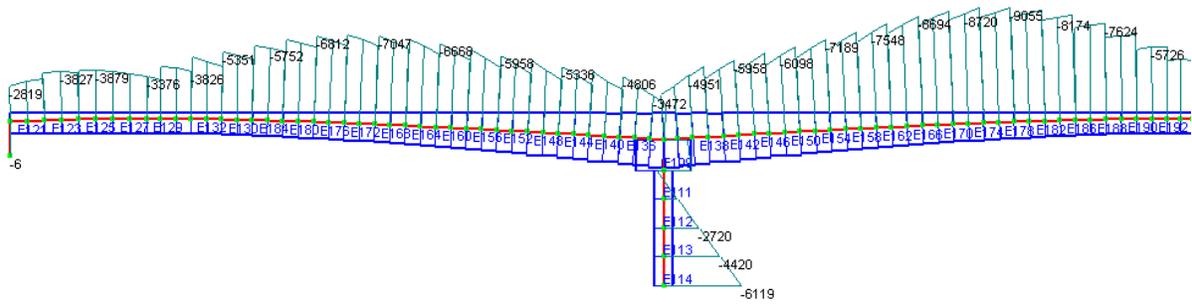


FIGURE 10 - STRESS (KN/m^2) DISTRIBUTIONS ON THE TOP FLANGE OF THE BOX GIRDER WHEN THE BRIDGE IS READY TO SERVE

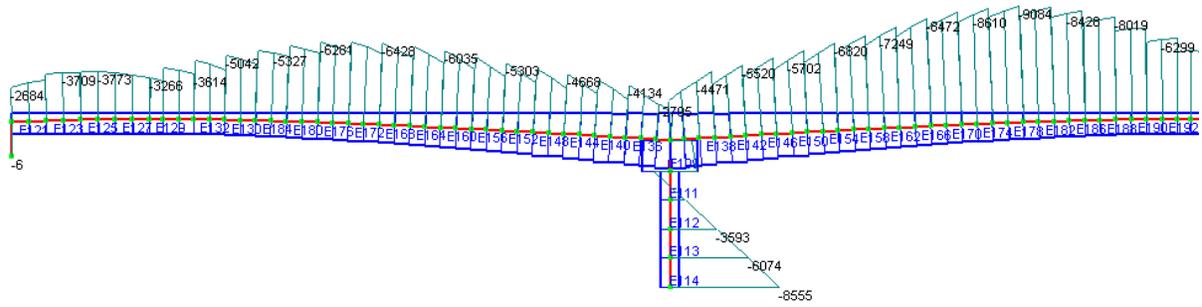


FIGURE 11 - STRESS (KN/m²) DISTRIBUTIONS ON THE TOP FLANGE OF THE BOX GIRDER AFTER 27 YEARS

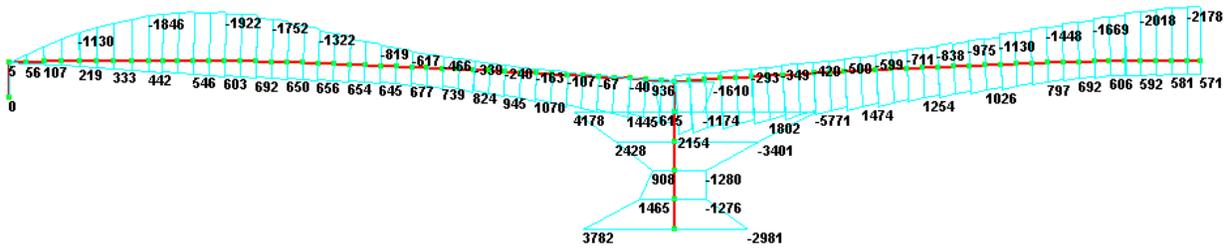


FIGURE 12 - STRESS (KN/m²) DISTRIBUTIONS ON THE TOP FLANGE OF THE BOX GIRDER DUE TO 4 LANES OF AASHTO LIVE LOADS