USER'S MANUAL FOR

LFD ARCH ANALYSIS AND DESIGN
(ARCH)

pennsylvania
DEPARTMENT OF TRANSPORTATION

Version 1.1.0.0

USER'S MANUAL FOR
COMPUTER PROGRAM ARCH
LFD ARCH ANALYSIS AND DESIGN
VERSION 1.1.0.0

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Pennsylvania Department of Transportation
Bureau of Business Solutions and Services
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SUMMARY OF APRIL 1985 REVISIONS – VERSION 1.0

The following revisions are made to the Department's Arch Analysis and Design program. The revised program is referred to as Version 1.0.

1. The program was extensively revised to allow for Load Factor Design.

2. New input items were added to accommodate Load Factor Design.

3. The output was revised to accommodate Load Factor Design.

SUMMARY OF JULY 1996 REVISIONS – VERSION 1.1

The following revisions were made to the Department's Arch Analysis and Design program. The revised program is referred to as Version 1.1.

1. The section thickness for a particular analysis point is computed as the distance between the intrados and extrados along a line perpendicular to the tangent of the arch axis.

2. Errors in the reinforcement design portion of the program, which caused excessive steel design, were corrected.

3. The maximum number of segments in each half of the arch has been increased from 10 to 25.

4. The requirement that successive center horizontal ordinates be greater than the previous center horizontal ordinates has been removed. In addition, several input checks for center ordinate input were added.

5. New input items for temperature rise and temperature fall were added to the Specification Data input line to allow users to enter appropriate values for their locale. Previously, these values were hard coded in the program.

6. The straight-line approximation for axial strength and moment strength between pure bending and the balanced strain condition has been replaced by a more accurate static solution.

7. The program input and output have been updated. A new output table for "COMPUTED RADII AND CENTERS" replaces the "COMPUTED RADII" table. In addition, a new output table was added to report the unfactored loads applied at each segment centroid.

8. The Service Load Design option was removed.

9. The program now computes the actual points of tangency for the arch axis, intrados and extrados based on the input intrados (SINT) and extrados (SEXT) tangent slopes instead of using the input YN distance. The YN distance input is no longer required and was, therefore, removed.

10. The previous version of the program assumed that the points of tangency for the intrados and extrados lie on the same plane perpendicular to the axis point of tangency. Since this is not always the case, the program was revised to account for the possibility that the points of tangency are not on the same cross section when computing the intrados and extrados coordinates perpendicular to the analysis points.

11. The Structure Identification input fields were updated to use the segment / offset format.

12. Shrinkage, temperature change and rib shortening calculations have been revised to use a computed modulus of elasticity for concrete based on the input concrete strength. Previously, the program used a constant value. This change requires that the concrete strength (FPC) always be entered.

13. The User's Manual has been revised for the above changes and updated to current Department documentation standards.

Note: Due to input changes in ARCH Version 1.1, input files prepared for ARCH Version 1.0 will not run with Version1.1. Refer to Chapter 5 for new input forms.

1 GENERAL DESCRIPTION

1.1 PROGRAM IDENTIFICATION

Program Title: LFD Arch Analysis and Design

Program Name: ARCH

Version: 1.1.0.0

Subsystem: Substructure

Authors: Engineering Software Section
Bureau of Business Solutions and Services
Pennsylvania Department of Transportation

ABSTRACT:

The Arch Analysis and Design program analyzes or designs an arch culvert in accordance with the 1996 AASHTO Standard Specifications for Highway Bridges using the Load Factor Design method. The program analyzes or designs fixed or tied arches that have an axis of symmetry and are loaded symmetrically. The arch can be defined either by the intrados and extrados centers or by the coordinates, segment lengths and thicknesses of segments for the axis of the arch barrel. Computed values include geometric properties; factored moments, shears, thrusts and axial forces; and areas of reinforcement at sections along the arch barrel.

1.2 ABBREVIATIONS

This section provides definitions of abbreviations that are commonly used throughout this User's Manual.

AASHTO - American Association of State Highway and Transportation Officials.

AASHTO Specifications - AASHTO Standard Specifications for Highway Bridges, Sixteenth Edition, 1996. This publication can be ordered from:

American Association of State Highway and Transportation Officials
444 North Capitol Street, N.W., Suite 249
Washington, D.C. 20001

ARCH - LFD Arch Analysis and Design Program.

DM-4 - Pennsylvania Department of Transportation Design Manual Part 4, August 1993 Edition. This publication can be ordered from:

Pennsylvania Department of Transportation
Publication Sales
P.O. Box 2028
Harrisburg, PA 17105

PennDOT - Pennsylvania Department of Transportation.

2 PROGRAM DESCRIPTION

2.1 GENERAL

The Arch Analysis and Design program analyzes fixed or tied arches with symmetric geometry and symmetric loading. The program then designs the required reinforcement at each design sections in accordance with AASHTO and DM-4 using the Load Factor Design method.

2.2 PROGRAM FUNCTIONS

The program performs the following functions:

1. Computes the arch geometry including axis coordinates, section thickness and section properties.

2. Computes moments, shears, and thrusts at specified cross sections of the arch ring and tie.

3. Computes influence line ordinates due to a unit loading. The influence lines may then be used to determine the effect of unsymmetrical loads.

4. Designs the specified cross-sections for AASHTO Group X Loading with temperature changes. Intrados and extrados steel areas are computed for the governing load conditions. Bar size and spacing must be selected by the designer.

This program is applicable only for arches with an axis of symmetry. Therefore, only half of the arch is described in the input. There are two ways of describing its geometry, either by entering the intrados and extrados centers or by entering the section properties. A maximum of three curvature centers can be defined for interior and exterior surfaces.

The input consists of geometry and strength data, locations of centers of curvatures, and section properties.

The output consists of the following values:

1. Arch geometry.
2. Computed radii.
3. Elastic center properties.
4. Loads.
5. Moments.
6. Shears.
7. Thrusts.
8. Thicknesses.
9. Areas of reinforcement required at specified sections of the arch.
10. As an option, a tabulation of influence line ordinates for each section.

2.3 ASSUMPTIONS AND LIMITATIONS

Certain assumptions, constants and design criteria used in the program are listed here for reference. For details on specifications, refer to AASHTO and DM-4.

1. The program is applicable to fixed or tied arches that have an axis of symmetry and are loaded symmetrically.

2. One-foot length of the structure is considered for both analysis and design.

3. The weight of concrete (w_c) is assumed equal to 150 lbs/ft^3.

4. The modulus of elasticity of concrete (E_c) is computed by the following formula:

   $$E_c = w_c^{1.5}\, 33 \sqrt{f'_c}$$

5. The modulus of elasticity of steel (E_s) assumed to be equal to 29,000 ksi.

6. The maximum usable strain at the extreme concrete compression fiber is equal to 0.003.

7. The distance from the compression face of the member to the centroid of the compression steel (d′) is assumed to be 2.4 inches.

8. The effects of rib shortening, shrinkage and temperature change for a tied arch are negligible and thus are not included in the load combination.

9. The sign conventions used by the program are as follows:

Loads:	Positive when acting as shown in Figure 3.4.1.
Reactions:	V, H and M positive when acting as shown in Figure 3.4.1.
Force Effects:	Thrust and shear forces positive when acting as shown in Figure 3.4.1.

10. In the arch ribs and barrels, the amount of longitudinal reinforcement is equally divided between the intrados and extrados in accordance with AASHTO 8.14.3.4.

11. Effects of the full value and the reduced value of horizontal earth pressure are considered in accordance with AASHTO 3.20.2.

12. The elastic center method of analysis used by ARCH does not consider axial deformation. Therefore, any attempt to match ARCH's analysis results using any multi-purpose structural analysis software must account for this assumption.10. Effect of loads.

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3 METHOD OF SOLUTION

3.1 GENERAL

Analysis of the arch is based on the elastic center method. Refer to any standard text on structural analysis theory for a detailed description of the elastic center method. The design of a section is based on the Load Factor method.

The following definitions apply to terminology in this manual. Refer to the illustrations throughout this documentation for further clarification.

Tie - The slab portion of a tied arch.

Ring - The hoop portion of an arch, not including the tie slab when present.

Barrel - The combined tie and ring of a tied arch.

Centerline - The axis of symmetry. A vertical line through the center of the arch crown.

Axis - The circumferential reference line around the entire ring or barrel. All arch cross sections are referenced to the axis.

For analysis and design of a reinforced concrete arch, the program performs the following calculations:

1. Calculate Arch Geometry.
2. Calculate Elastic Center Properties.
3. Generate Influence Lines at the Elastic Center.
4. Generate Influence Lines at Points of Interest.
5. Calculate Forces at Points of Interest.
6. Combine Forces for Load Factor method.
7. Design sections for Reinforcement.

The following sections explain the procedure used in the program.

3.2 NOTATIONS

The following notations are specific to this manual. They may not necessarily agree with notations used in the AASHTO Specifications.

a_b = Depth of equivalent rectangular stress block for balanced strain conditions - in.

a_j = Elastic area of segment.

A_g = Area of gross cross section - in^2.

A_s = Area of tension reinforcement - in^2.

A_{st} = Total area of reinforcement - in^2.

A'_s = Area of compression reinforcement - in^2.

b = Width of compression face of member - in.

C_c = Compressive force in concrete - kip.

C_s = Compressive force due to compression steel - kip.

d = Distance from extreme compression fiber to centroid of tension reinforcement - in.

d' = Distance from extreme compression fiber to centroid of compression reinforcement - in.

d" = Distance from centroid of gross section, neglecting the reinforcement, to centroid of tension reinforcement - in.

DS = Distance along the arch axis of arch section - ft.

e = eccentricity of the applied load - in.

e_b = eccentricity of a section at balanced strain conditions - in.

E_c = Modulus of elasticity of concrete - ksi.

E_s = Modulus of elasticity of steel - ksi.

f_c' = Compressive strength of concrete at 28 days - ksi.

f_s = Stress in tension reinforcement - ksi.

f_s' = Stress in compression reinforcement - ksi.

f_y = Specified yield strength of reinforcement - ksi.

H = Horizontal reaction at an analysis section due the applied load - kips.

H_0 = Fill height - ft.

H_{ho} = Horizontal reaction at the elastic center of the arch due to a horizontal unit load - kips.

H_{mo} = Moment at the elastic center of the arch due to a horizontal unit load - kip-ft.

H_{vo} = Vertical reaction at the elastic center of the arch due to a horizontal unit load - kips.

$H_{(R+S+T)j}$ = Horizontal force at the elastic center of the arch due to shrinkage, temperature change and rib shortening - kips.

I = Arch segment index.

I_x = Moment of inertia about the x-axis of the elastic section - ft^4.

I_y = Moment of inertia about the y-axis of the elastic section - ft^4.

j = Analysis point index.

L_h = Horizontal projection of the arch ring (axis-to-axis span) - ft.

M = Factored applied moment - kip-in.

M_b = Nominal moment strength of a section at balanced strain conditions - kip-in.

M_n = Nominal moment strength of a section - kip-in.

$M_{(R+S+T)j}$ = Moment at the elastic center of the arch due to shrinkage, temperature change and rib shortening - kip-in.

M_u = Ultimate moment strength of a section - kip-in.

P = Factored applied axial load - kips.

P_o = Nominal axial load strength of a section with no bending - kips.

P_c = Axial force at crown - kips.

P_b = Nominal axial load strength of a section at balanced strain conditions - kips.

P_{dj} = Dead load reaction on the bottom of a tie slab segment - kips.

P_{hj} = Lateral earth pressure on an arch segment - kips.

P_n = Nominal axial load strength of a section - kips.

P_o = Nominal axial load strength of a section with no bending - kips.

P_u = Ultimate axial load strength of a section - kips.

P_{vj} = Total vertical dead load on an arch segment - kips.

P_{vcj} = Weight of concrete on an arch segment - kips.

P_{vfj} = Weight of fill on an arch segment - kips.

R = Number of segments in half of the arch ring.

t = Section thickness - in.

t_c = Thickness of arch ring at crown - ft.

t_j = Section thickness - ft.

T = Number of segments in half of the tie slab.

T = Tensile force in tension reinforcement - kips.

T = Temperature change - ^oF.

V = Vertical reaction at an analysis section due the applied load - kips.

V_{ho} = Horizontal reaction at the elastic center of the arch due to a vertical unit load - kips.

V_{mo} = Moment at the elastic center of the arch due to a vertical unit load - kip-ft.

V_{vo} = Vertical reaction at the elastic center of the arch due to a vertical unit load - kips.

$V_{(R+S+T)j}$ = Vertical force at the elastic center of the arch due to shrinkage, temperature change and rib shortening - kips.

w_c = Unit weight of concrete - lbs/ft^3.

x = Distance from compression face of the section to neutral axis - in.

x_j = X-distance of analysis point along the arch axis relative to elastic center - ft.

X_j = X-coordinate of analysis point along the arch axis - ft.

$\overline{X}$ = X-coordinate of elastic center - ft.

y_j = Y-distance of analysis point along the arch axis relative to elastic center - ft.

Y_j = Y-coordinate of analysis point along the arch axis - ft.

$\overline{Y}$ = Y-coordinate of elastic center - ft.

β_1 = Ratio of depth of equivalent compression zone to depth from fiber of maximum compressive strain to the neutral axis - AASHTO 8.16.2.7.

β_D = Load combination coefficient for dead load - AASHTO 3.22.1.

β_{EH} = Load combination coefficient for horizontal earth pressure - AASHTO 3.22.1.

β_{EV} = Load combination coefficient for vertical earth pressure - AASHTO 3.22.1.

β_L = Load combination coefficient for live load - AASHTO 3.22.1.

β_R = Load combination coefficient for rib shortening, shrinkage and temperature - AASHTO 3.22.1.

γ = Load factor - AASHTO 3.22.

ε = Thermal coefficient for concrete

ε_c = Strain in concrete - in/in.

ε_s = Strain in tension steel - in/in.

ε'_s = Strain in compression steel - in/in.

ε_y = Strain when steel just reaches yield stress - in/in.

λ = Shrinkage coefficient

φ = Strength reduction factor, AASHTO 8.16.1.2.

3.3 GEOMETRY

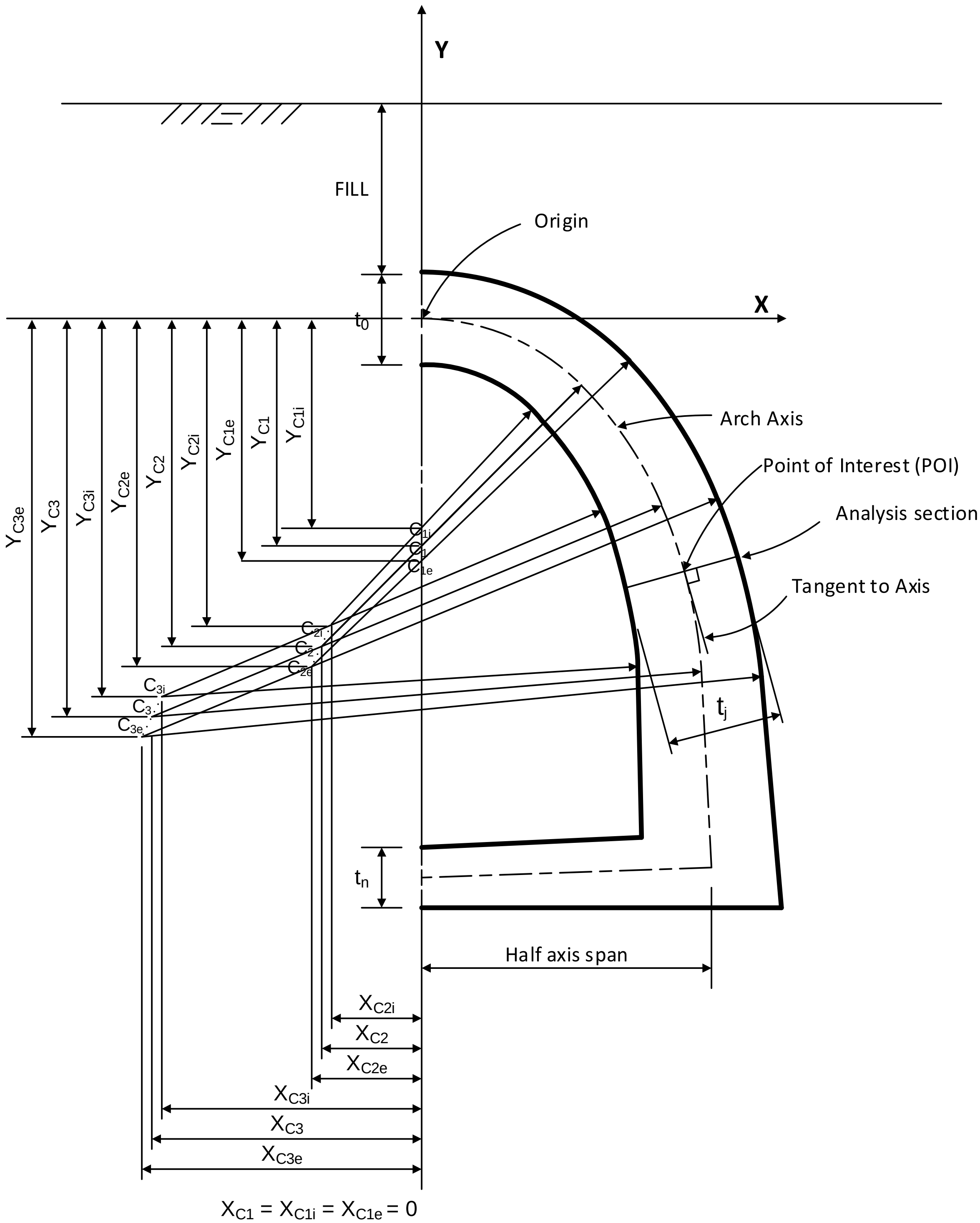
Because the program is applicable only to arches with an axis of symmetry, only half of the arch is defined in the input. There are two ways to define its geometry:

1. Enter the coordinates of the intrados and extrados centers. The program divides the arch ring (and tie if applicable) into the number of segments specified in the GEOMETRY AND STRENGTH Line (R + T). The boundaries of these segments are cross sections of the ring and tie. The sections are equally spaced and their thicknesses are defined by the difference between the extrados and intrados radii.

2. Enter the coordinates of the intersections of the cross sections and the axis of the ring and tie. Distances between sections and thicknesses of the sections are also input in this case. A maximum of eleven sections may be described (R + T + 1).

If the coordinates of the intrados and extrados centers are given, the program calculates the centers of the axis curve by calculating the coordinates of the midpoint of the intrados and extrados centers and the computes the radii of the axis curves. Next, the length of the axis in half of the arch ring and the length of half of the tie slab are computed. These lengths are then divided into a number of segments as specified by the user. Using the segment length and the radius of the axis curve, the program computes the coordinates of the point at the end of each segment along the axis. These are defined as points of interest (POIs). At each POI, the slope of the tangent is computed. Refer to Figure 3.2.1 on page **Error! Bookmark not defined.**.

Through each POI, a line perpendicular to the tangent to the axis curve is drawn. The slope of this line defines the orientation of the section through the POI. The coordinates of the intersection of this line and the intrados and extrados curves are then computed. For this, it is assumed that the cross section line intersects the intrados and extrados curves which correspond to the axis curve on which the POI lies. The section thickness is then calculated as the distance between the intrados and extrados coordinates. Refer to Figure 3.2.1 on page **Error! Bookmark not defined.**.



t_o = Thickness at arch crown
t_j = Thickness at an analysis section
t_n = Thickness at tie slab midpoint

Figure 3.2.1 – Arch Geometry

3.4 ELASTIC SECTION PROPERTIES

After computing the geometry of the arch, the program then computes the properties of elastic section. These properties include the location of the elastic center and the moments of inertia of the elastic section. These are required for calculation of influence lines.

The elastic center location is computed by:

$$\overline{X} = 0$$

$$\overline{Y} = \frac{\sum_{j=1}^{2n} a_j \left(\frac{Y_{j-1} + Y_j}{2} \right)}{A}$$

Where: $$a_j = \frac{DS_j}{EI} = \frac{DS_j}{E \frac{1}{12} b \left(\frac{t_{j-1} + t_j}{2} \right)^3}$$

Assuming E and b are constant, $$a_j = 12 \frac{DS_j}{\left(\frac{t_{j-1} + t_j}{2} \right)^3}$$

$$A = \sum_{j=1}^{2n} a_j$$

Moments of Inertia of the elastic section are computed by:

$$I_x = \sum_{j=1}^{2n} a_j \left(\frac{x_{j-1} + x_j}{2} \right)$$

$$I_y = \sum_{j=1}^{2n} a_j \left(\frac{y_{j-1} + y_j}{2} \right)$$

Where $x_j = X_j - \overline{X}$ and $y_j = Y_j - \overline{Y}$.

3.5 ANALYSIS

The program first computes the influence ordinates using both vertical and horizontal unit loads for the reactions (V_{vo}, V_{ho}, V_{mo}, H_{vo}, H_{ho} and H_{mo}) at the elastic center. See Figure 3.4.1 on page 3-9.

Using the influence line ordinates at the elastic center, the program then computes the influence ordinates for the reactions (V, H and M) at each cross-section specified in the input.

Next, the program computes the total vertical and horizontal dead loads at the center of each cross-section due to earth fill and any uniform live load (ULD). The influence ordinates for the reactions (V, H and M) are then used to calculate the actual reactions and moments at each cross-section due to the following load group. Thrust and shear forces are determined by summing the components of the reaction forces normal and parallel, respectively, to the section.

1. Vertical Load.

2. Horizontal Load.

3. Vertical + ½ Horizontal Load.
   AASHTO Groups X with or without temperature changes.

4. Vertical + Horizontal Load.
   AASHTO Groups X with or without temperature changes.

The program uses the full values for the weight of fill, the weight of concrete and the equivalent fluid pressure. In addition, the effects of temperature, shrinkage and rib shortening are considered. This is the final step of the program for an analysis problem.

For design applications only, the program calculates the areas of extrados and intrados steel for the critical loading condition of bending moment and axial force determined from the effects of AASHTO Group X Loading with or without temperature changes by the Load Factor Design Method. Critical shears and shear strengths at the cross sections are also computed.

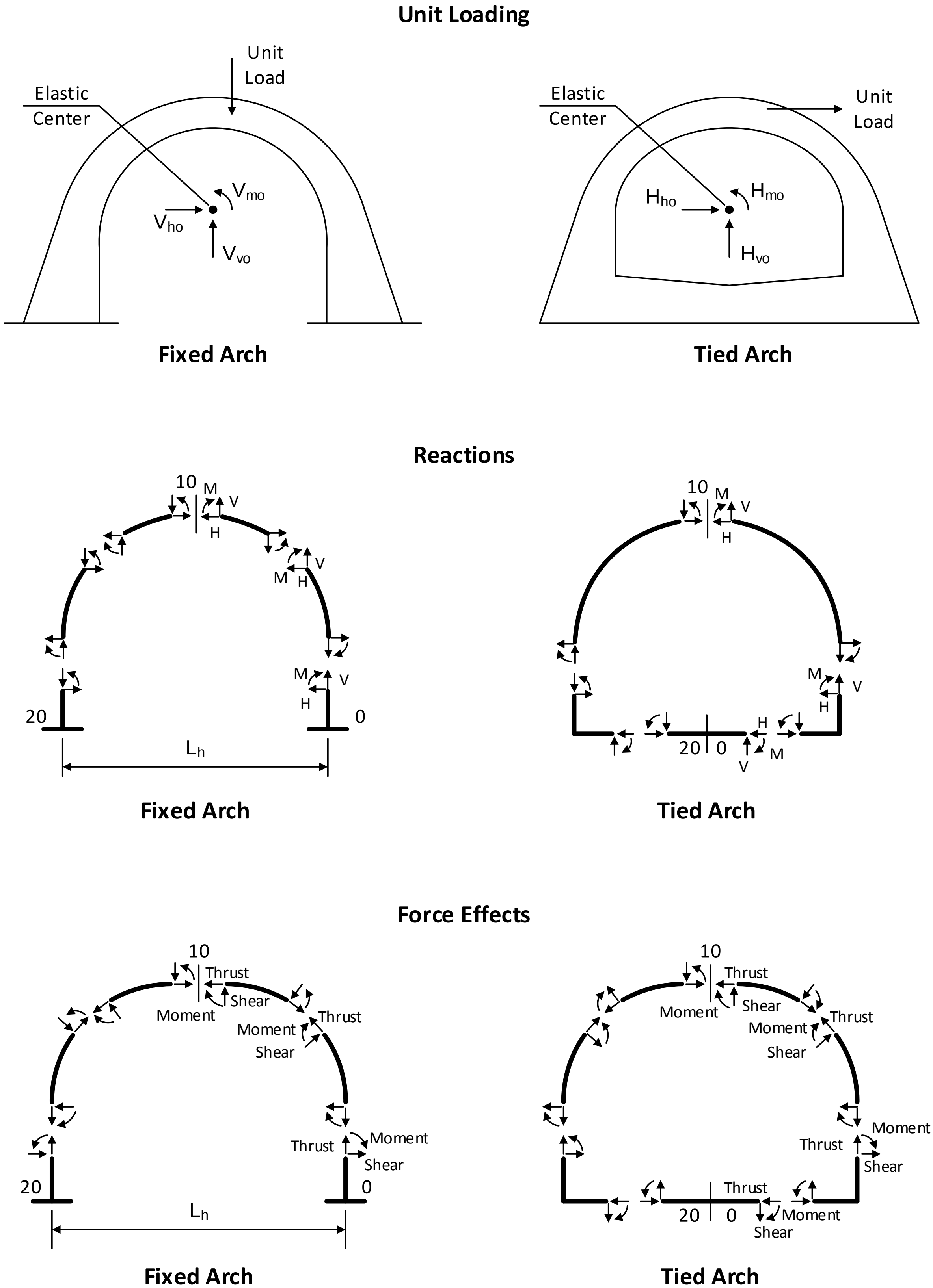


Figure 3.4.1 - Unit Loading, Reactions and Force Effects

3.6 LOADINGS

The arch is designed for the dead load, live load, lateral earth pressure, shrinkage, temperature change and rib shortening in accordance with the AASHTO Specifications using appropriate load factors for the load factor design. Loads are applied as joint loads on the ring portion of the arch and as member loads on the tie slab. The following loads and loading combinations are considered.

3.6.1 Dead Loads

The dead loads acting on the arch are due to the weight of concrete and the weight of fill material both of which are calculated by the program using the following equations.

P_{vj} = Vertical load on the jth segment (ring segments only).

$= P_{vcj} + P_{vf\,j}$

Where

P_{vcj} = Weight of concrete.

$$= DS_j\, w_c \frac{t_{j-1} + t_j}{2}$$

P_{vfj} = Weight of fill on the jth segment.

$$= w_e \left(x_{j-1} - x_j \right) \left(H_0 + \frac{t_c}{2} + Y_j \right)$$

P_{dj} = Dead load reaction on bottom of the jth tie slab segment.

$$= \frac{\sum P_{v_j}}{n}$$

Where n is the total number of tie slab segments and the jth segment is bounded by (j-1) and (j) sections.

NOTE: It is assumed that the tie slab is poured prior to the ring. Since the internal action is not realized until the concrete is set, the weight of tie slab concrete is not included when computing the dead load reaction acting on a tie slab segment.

3.6.2 Live Loads

The program considers uniform live load over the entire span, which is entered by the user. Currently, the program does not have the capability of moving a live load over the span. However, as an option, the program can generate influence lines for moment, shear and thrust which can be utilized to calculate the effect of a moving live load.

3.6.3 Earth Pressure

The arch is analyzed for a lateral earth pressure, which varies at a rate q kips per square foot per foot of fill height. The lateral earth pressure load is calculated by:

P_{hj} = Lateral earth pressure on the jth segment.

$$= q\left(y_{j-1} - y_j\right)\left(H_0 - \overline{Y} - y_j\right)$$

3.6.4 Rib Shortening, Shrinkage and Temperature Change

The reactions at the elastic center due to rib shortening, shrinkage and temperature change for a fixed arch are calculated by the following.

$$V_{(R+S+T)0} = 0$$

$$H_{(R+S+T)0} = \frac{L_h}{I_y}\left[\frac{P_c}{t_c} - \lambda E_c + \varepsilon T E_c\right]$$

$$M_{(R+S+T)0} = 0$$

Where: λ = Shrinkage coefficient = 0.0002

ε = Thermal coefficient = 0.000006 / °F

T = Temperature change (input or default Rise (+) and Fall (-)) – °F.

L_h = Horizontal projection of the axis of the ring (see Figure 3.4.1 on page 3-9).

P_c = Axial force at crown - kips.

t_c = Thickness of arch ring at crown - ft.

E_c = Modulus of Elasticity of concrete - ksf.

The forces at point, *j*, are calculated by:

$$V_{(R+S+T)} = V_{(R+S+T)_0}$$

$$H_{(R+S+T)} = H_{(R+S+T)_0}$$

$$M_{(R+S+T)} = H_{(R+S+T)_0}\ y_j + V_{(R+S+T)_0}\ x_j$$

3.6.5 Loading Combinations

AASHTO Group Loading X is considered for combinations of above-mentioned loads. This is given by the following equation:

$$\text{Group X} = \gamma\ [\ \beta_D\ D + \beta_L\ (L+I) + \beta_R\ E + \beta_R\ (R+S+T)\ ]$$

The Gamma and Beta factors in the above equations are either the input values entered by the user or the default values set by the program. The effects of these loads are combined using appropriate load factors and different conditions of lateral earth pressure (the full value of earth pressure and the half value of earth pressure) as specified by AASHTO. The governing factored loads (moments, shears and thrusts) acting on the section are stored.

3.7 SECTION DESIGN

For design problems (i.e., if REBAR GRADE is specified), the following procedures are used to calculate area of reinforcement (A_s), axial strength (P_u) and moment strength (M_u). The area of reinforcement is limited by a minimum of 1% of the gross section area and by a maximum of 8% of the gross section area in accordance with AASHTO 8.18.1.

First, the area of reinforcement required for a section is assumed to be 1% of the gross area of the concrete divided equally between the intrados and extrados. Then, the balanced strain condition (see Figure 3.6.1 on page **Error! Bookmark not defined.**) is computed by the equations given in AASHTO 8.16.4.2.3, assuming steel in the compression face is equal to steel in the tension face of the section.

$$P_b = 0.85\ f'_c\ b\ a_b + A'_s\ f'_s - A_s\ f_y$$

$$M_b = 0.85\ f'_c\ b\ a_b \left(d - d'' - \frac{a_b}{2} \right) + A'_s\ f'_s\ (\ d - d' - d''\ ) + A_s\ f_y\ d''$$

$$e_b = \frac{M_b}{P_b}$$

Where: $$a_b = \left[\frac{87{,}000}{87{,}000 + f_y} \right] \beta_1 d$$

$$f_s' = 87{,}000 \left[1 - \left(\frac{d'}{d} \right) \left(\frac{87{,}000 + f_y}{87{,}000} \right) \right] \leq f_y$$

The program then checks the strength of the cross section against the balanced strain condition by computing the eccentricity of the section using the equation:

$$e = \frac{M}{P}$$ Where M and P are applied factored moment and axial force.

When the eccentricity (e) of the applied load on the section is less than the balanced eccentricity (e_b), the strength of the cross section is controlled by compression and the section is design as a short column (refer the AASTHO Article 8.16.4.2.3). When the eccentricity (e) is greater than the balanced eccentricity (e_b), the strength of the cross section is controlled by tension (refer the AASTHO Article 8.16.4.2.4). If the section is subject to axial tension, as in a tied arch, the strength analysis for the section will be similar to a tension controlled section. The following three sections give the method of solution for each of these conditions.

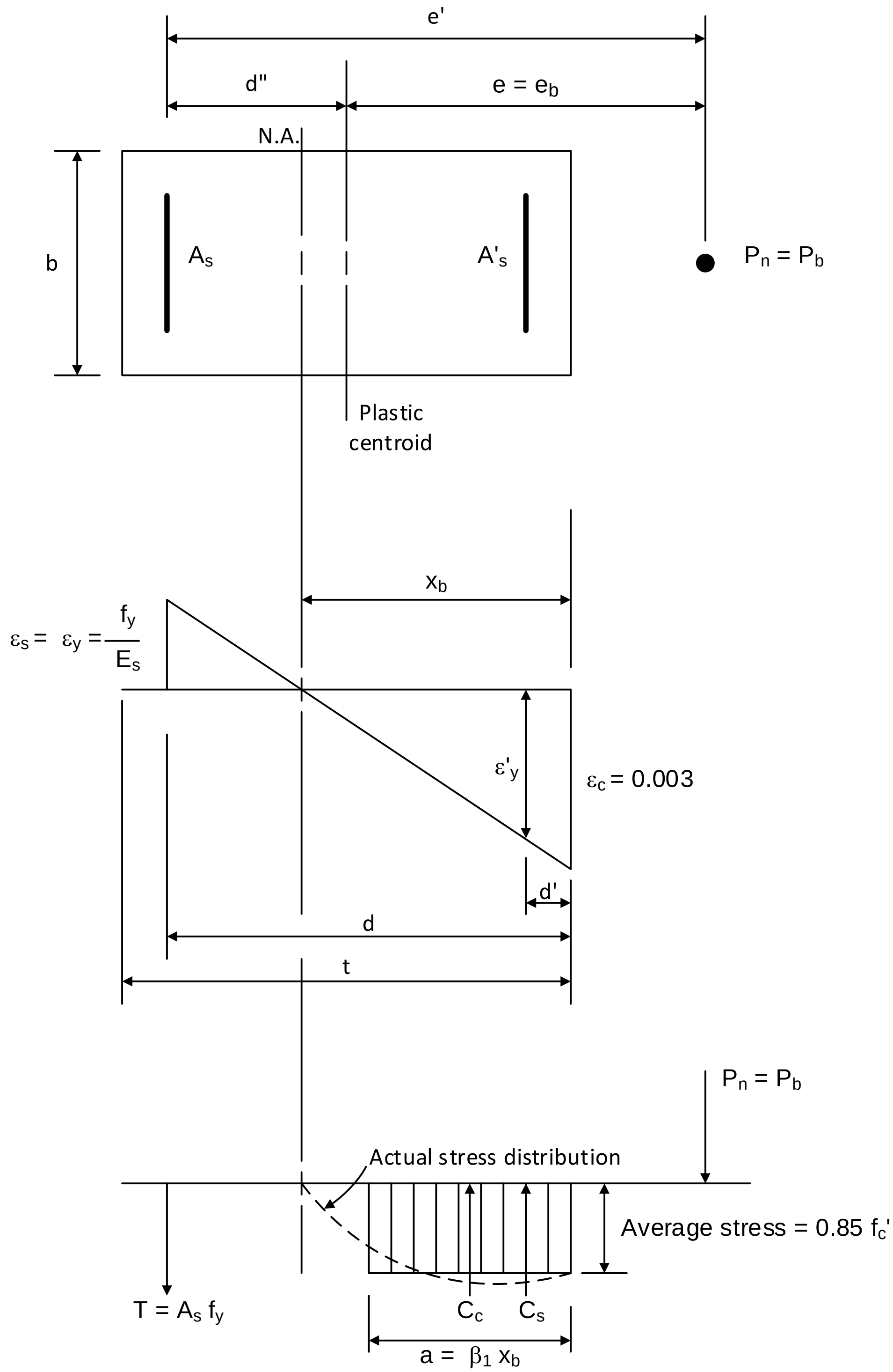


Figure 3.6.1 - Balanced Strain Condition

3.7.1 Compression Controls

When eccentricity e is less than the balanced eccentricity, e_b, (or the factored axial load exceeds the balanced load), the member acts more as a column than a beam. The following calculations are made.

First, the maximum nominal strength (P_o) at zero eccentricity is calculated by the following equation, AASHTO 8.16.4.2.1.

$$P_o = 0.85\, f'_c \left(A_g - A_{st}\right) + A_{st}\, f_y$$

The nominal strength (P_n) is obtained considering the actual strain variation and using the principles of statics. Referring to Figure 3.6.2 on page **Error! Bookmark not defined.**, the location of the neutral axis (x) is assumed and static conditions are checked. This process continues until the static conditions are satisfied. The following forces are calculated assuming the compression steel yields.

$$C_s = A'_s \left(f_y - 0.85\, f'_c\right)$$

$$C_c = 0.85\, f'_c\, b\, \beta_1\, x$$

$$T = A_s\, f_s$$

Where: $f_s = \left(\dfrac{x - d'}{x}\right) \varepsilon_c\, E_c \le f_y$

Taking moments about P_n, the following equations must be satisfied.

If $(\beta_1 x) \ge t$, then: $T\left(e + \dfrac{t}{2} - d'\right) - C_c\, e - C_s\left(e - \dfrac{t}{2} + d'\right) = 0$

Otherwise: $T\left(e + \dfrac{t}{2} - d'\right) - C_c\left(e - \dfrac{t}{2} + \dfrac{\beta_1 x}{2}\right) - C_s\left(e - \dfrac{t}{2} + d'\right) = 0$

When the above static conditions are satisfied to locate the neutral axis, the nominal axial strength is obtained using the following equations.

$$P_n = C_c + C_s - T \le P_0$$

$$P_u = \phi P_n$$

$$M_u = P_u\, e$$

Where $\phi = 0.7$ according to AASHTO 8.16.1.2.2 and 8.16.4.2.4.

If the axial strength (P_u) is greater than the applied factored load (P), the program prints out the area of reinforcement and the axial and moment strength for each loading condition. If P_u is less than the applied factored load, the area of reinforcement is increased by 0.01 in^2 in each face and computations are repeated until the above criteria are satisfied.

The shear requirements are checked using the equations given in AASHTO 8.16.6.2.2 and 8.16.6.2.3.

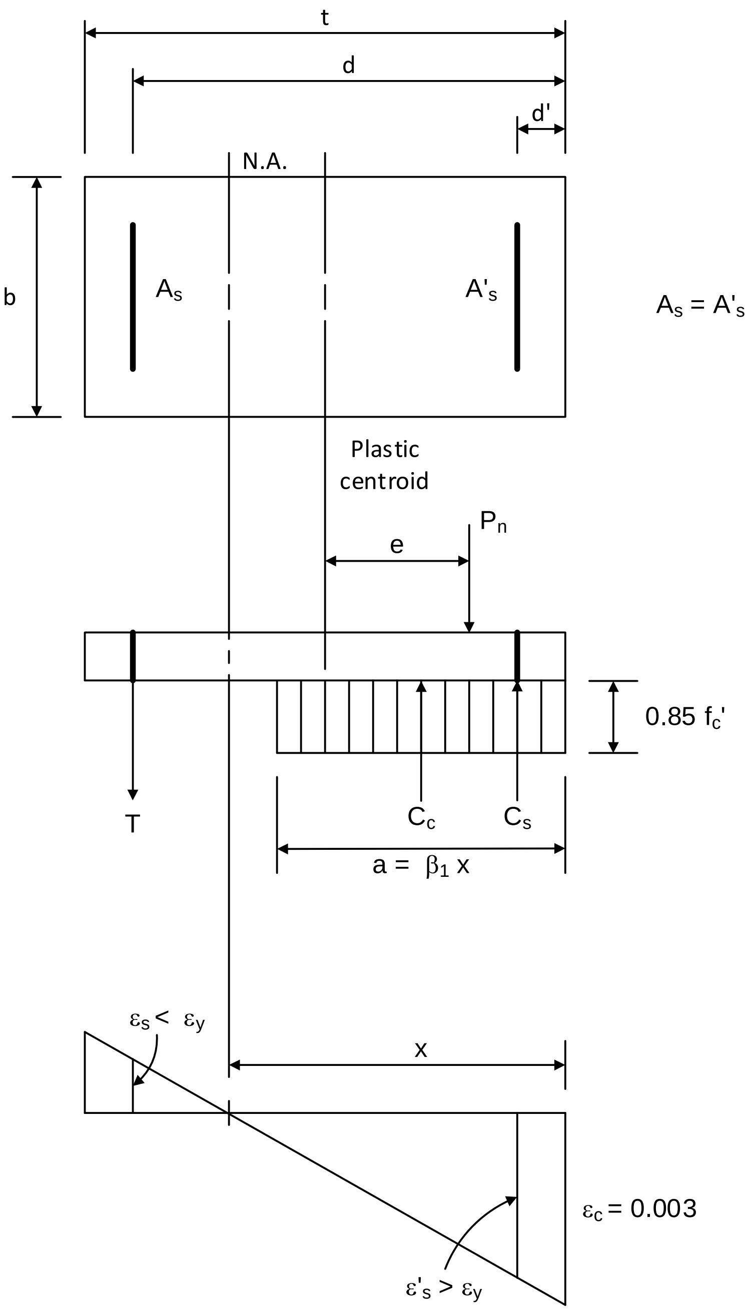


Figure 3.6.2 - Analysis in Compression Controlled Region

3.7.2 Tension Controls

When the eccentricity of the applied load is greater than the balanced eccentricity (or the factored axial load is less than the balanced load), the member behaves more as a beam than a column. The following calculations are made.

The nominal strength (P_n) is obtained considering the actual strain variation and using the principles of statics. Referring to Figure 3.6.3 on page 27, the location of the neutral axis (x) is assumed and static conditions are checked. This process continues until the static conditions are satisfied. The following forces are calculated assuming the tension steel yields.

If x is less d′, A'_s is in tension.

Therefore: $C_s = -A'_s f'_s$.

Otherwise: $C_s = A'_s \left(f'_s - 0.85 f'_c \right)$.

$$C_c = 0.85 f_c' b \beta_1 x$$

$$T = A_s f_y$$

Where: $f_s' = \left(\frac{x - d'}{x} \right) \varepsilon_c E_s \le f_y$

Taking moments about P_n, the following equations must be satisfied.

$$T\left(e + \frac{t}{2} - d' \right) - C_c\left(e - \frac{t}{2} + \frac{\beta_1 x}{2} \right) - C_s\left(e - \frac{t}{2} + d' \right) = 0$$

When the above static conditions are satisfied to locate the neutral axis, the nominal axial strength, the ultimate axial strength and the ultimate moment strength are obtained using the following equations.

$$P_n = C_c + C_s - T$$

$$P_u = \phi P_n$$

$$M_u = P_u e$$

Where: $\phi = 0.7$ for ϕP_n greater than the smaller of $0.10 f'_c A_g$ and ϕP_b,

and

ϕ increases linearly from 0.7 to 0.9 as ϕP_n decreases from the smaller of $0.10 f'_c A_g$ and ϕP_b to zero as per to AASHTO 8.16.1.2.2 and 8.16.4.2.4.

If the axial strength (P_u) is greater than the applied factored load (P), the program prints out the area of reinforcement and the axial and moment strength for each loading condition. If P_u is less than the applied factored load, the area of reinforcement is increased by 0.01 in^2 in each face and computations are repeated until the above criteria are satisfied.

The shear requirements are checked using the equations given in AASHTO 8.16.6.2.2 and 8.16.6.2.3.

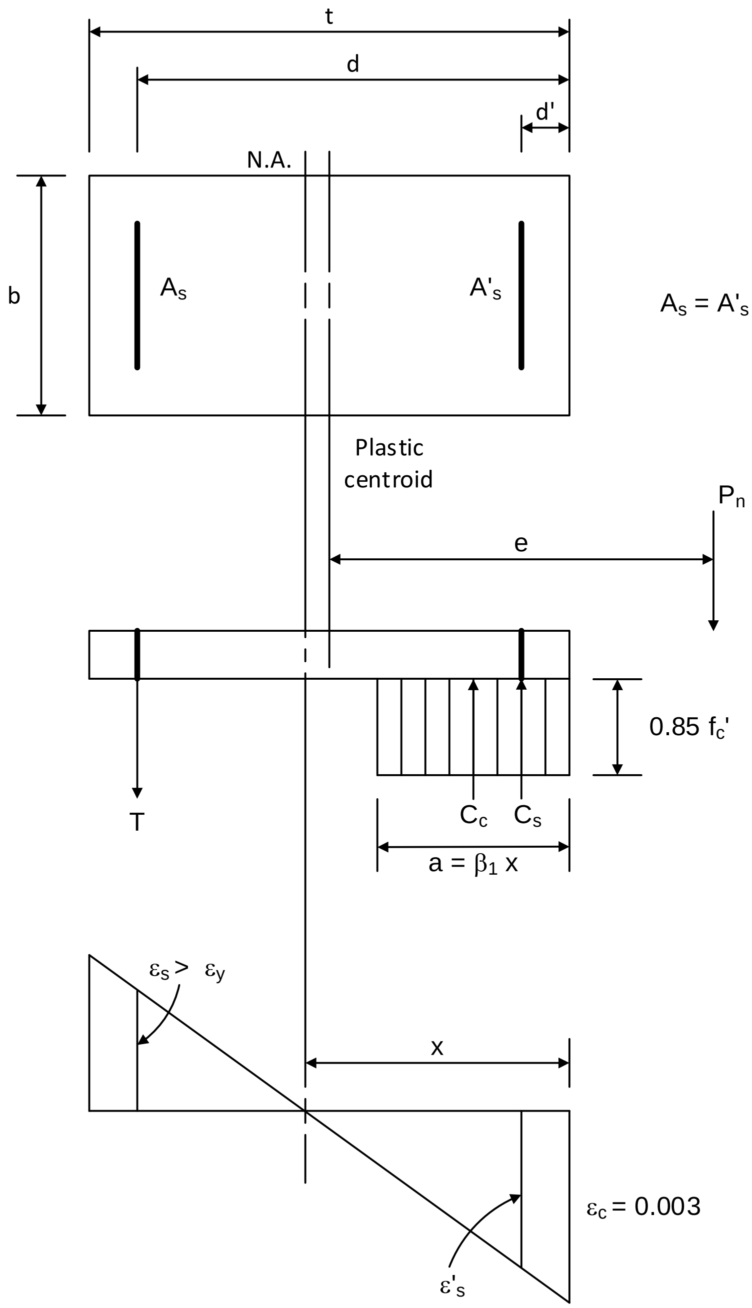


Figure 3.6.3 - Analysis in Tension Controlled Region

3.7.3 Axial Tension and Bending

In the tied section of the arch, the section is subject to axial tension in combination with bending moment. The analysis for nominal tension strength (P_n) is similar to the analysis for a section in axial compression and bending moment (Section 3.6.2 Tension Controls). The following calculations are made.

The nominal strength (P_n) is obtained considering the actual strain variation and using the principles of statics. Referring to Figure 3.6.4 on page 30, the location of the neutral axis (x) is assumed and static conditions are checked. This process continues until the static conditions are satisfied. The following forces are calculated assuming the compression steel yields.

If x is less d′, A'_s is in tension.

Therefore: $C_s = - A'_s\, f'_s$

Otherwise: $C_s = A'_s\,(f'_s - 0.85\, f'_c)$

$C_c = 0.85\, f'_c\, b\, \beta_1\, x$

$T = A_s\, f_y$

Where: $f'_s = \left(\dfrac{x - d'}{x}\right) \varepsilon_c\, E_s \le f_y$

Taking moments about P_n, the following equations must be satisfied.

$$T\left(e - \frac{t}{2} + d'\right) - C_c\left(e + \frac{t}{2} - \frac{\beta_1 x}{2}\right) - C_s\left(e + \frac{t}{2} - d'\right) = 0$$

When the above static conditions are satisfied to locate the neutral axis, the nominal axial strength, the ultimate axial strength and the ultimate moment strength are obtained using the following equations.

$P_n = C_c + C_s - T$

$P_u = \phi P_n$

$M_u = P_u\, e$

Where: $\phi = 0.7$ for ϕP_n greater than the smaller of $0.10\, f'_c\, A_g$ and ϕP_b

and

ϕ increases linearly from 0.7 to 0.9 as ϕP_n decreases from the smaller of $0.10\, f'_c\, A_g$ and ϕP_b to zero as per to AASHTO 8.16.1.2.2 and 8.16.4.2.4.

If the axial strength (P_u) is greater than the applied factored load (P), the program prints out the area of reinforcement and the axial and moment strength for each loading condition. If P_u is less than the applied factored load, the area of reinforcement is increased by 0.01 in^2 in each face and computations are repeated until the above criteria are satisfied.

The shear requirements are checked using the equations given in AASHTO 8.16.6.2.2 and 8.16.6.2.3.

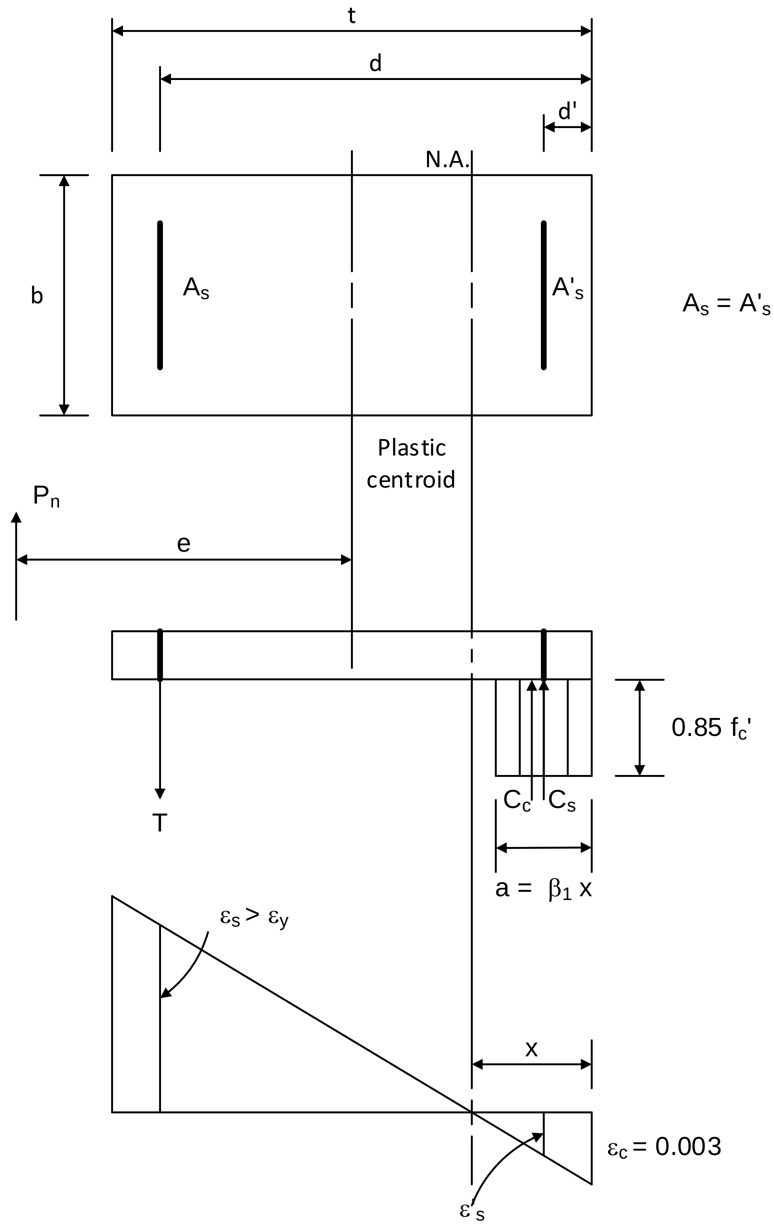


Figure 3.6.4 - Axial Tension

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4 GETTING STARTED

4.1 INSTALLATION

This program is delivered via download from the Department's website. Once payment has been received by PennDOT, you will receive a confirmation e-mail with instructions on how to download the software. The download file is a self-extracting installation file for the licensed PennDOT engineering software. The engineering program runs as a 32-bit application and is supported on Windows Vista, Windows 7 (32 and 64 bit versions), and Windows 8 (32 and 64 bit versions) operating systems.

Your license number, license key and registered company name, found in the e-mail received from the Department, are required to be entered when installing the program and must be entered exactly as shown in the e-mail. The license number, license key and registered company name will also be needed when requesting future versions of the program (i.e., enhancements, modifications, or error corrections), and requesting program support. A backup copy of the program download and e-mail instructions should be made and used for future installations. You may want to print the software license agreement, record the license number, license key and registered company name and keep it in a safe place.

To install the program, follow the installation instructions provided with the original e-mail from the Department.

The following files will be installed in the program destination folder, which defaults to "C:\Program Files\PennDOT\ARCH v<version_number>\" or "C:\Program Files (x86)\PennDOT\ARCH v<version number>\" for 64-bit operating systems:

1. ARCH.exe, ARCH_DLL.dll – Executable program and Dynamic Link Library.
2. ARCH Users Manual.pdf – Program User's Manual (PDF Format).
3. ARCHRevisionRequestForm.dotx – Revision Request form (MS WORD template).
4. GettingStarted.pdf – A document describing installation and running of the program.
5. LicenseAgreement.pdf – The program license agreement.
6. MSVCR71.dll – Runtime Dynamic Link Library.

The program example problem files (ex*.dat) will be installed in the program example folder, which defaults to "C:\PennDOT\ARCH v<*version_number*> Examples\". Users must have write access to this folder in order to run the input files from this folder.

The program example problem files (ex*.dat) will be installed in the program example folder, which defaults to "C:\PennDOT\ARCH v<*version_number*> Examples\". Users must have write access to this folder in order to run the input files from this folder.

4.2 PREPARING INPUT

The program requires an ASCII input file. The input file consists of a series of data lines. Each data line consists of a number of fixed length data fields. A decimal point must be included for any numerical data. Otherwise, the data will be read as an integer. Chapter 5 of the User's Manual includes descriptions of the input and input forms to facilitate data preparation. The input can be created using Engineering Assistant, described below, or any text editor.

4.3 ENGINEERING ASSISTANT

The Engineering Assistant (EngAsst) is a Windows application developed by the Pennsylvania Department of Transportation (PENNDOT) to provide a graphical user interface (GUI) for PENNDOT's engineering programs. The data for the input to the engineering program is presented in a user-friendly format, reflecting the implied structure of the data, showing each record type on a separate tab page in the display and showing each field on each record with a defining label.

With EngAsst the user can create a new input file, modify an existing input file, import input files, run the associated engineering program and view the output in a Windows environment. The help and documentation are provided, including text descriptions of each field, relevant images, and extended help text at both the record/tab level and the field level. The entire Engineering Program User's Manual is also accessible within EngAsst.

EngAsst is not included with this software. It requires a separate license that can be obtained through the Department's standard engineering software licensing procedures. Order forms can be obtained from the software support website at http://penndot.engrprograms.com.

4.4 RUNNING THE PROGRAM WITHOUT ENGINEERING ASSISTANT

ARCH is a FORTRAN console application program. It may be run from a command window, by double-clicking on the program icon from Windows Explorer, by selecting the shortcut from the Start menu under Programs\PennDOT, or by double-clicking the shortcut icon on the desktop. To run the program in a command window, the user must specify the directory in which the program has been installed or change to the directory.

The program will first prompt for an input file name, and the user should then enter the appropriate input file name. The input file must be created before running the program. The program will then prompt for whether the output should be reviewed on the screen. The user should enter "Y" if the output is to be reviewed on the screen after execution or "N" if the output is not to be reviewed on the screen. The program will then prompt for the name of the output file in which the output is to be stored, and the user should then enter the desired output file name. If a file with the specified output file name already exists, the program gives the option of overwriting the existing file or entering a new output file output file name. If no output file name is entered, a default output file will be used. The program will then execute.

To cancel the program during execution, press <Ctrl C> or <Ctrl Break>.

When the program completes execution, the user is prompted to "Press <ENTER> to exit program." This allows the user to view the last messages written to the screen when the program was started by double-clicking on the program icon from Windows Explorer.

The user can view the output file from within EngAsst or using a text editor.

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5 INPUT DESCRIPTION

5.1 GENERAL

Input forms (See Figure 5.0.1 on page 5-2 and Figure 5.0.2 on page 5-3) have been provided to facilitate data preparation for execution of this program. The input forms have data lines with appropriate headings. The first two data lines must be entered for all problems. The last data line entered must be either INTRADOS AND EXTRADOS CENTERS or SECTION PROPERTIES depending upon the option entered in GEOMETRY AND STRENGTH DATA, but not both. The following sections describe each data item. The decimal place for each data item is implied and shown on the forms and thus a decimal should not be entered. Refer to Chapter 4 for instruction on how to prepare an input file.

PENNSYLVANIA DEPARTMENT OF TRANSPORTATION
MAY 2002

Form 1 of 2

PROGRAM ARCH
ARCH ANALYSIS AND DESIGN

PROJECT IDENTIFICATION
*
*
*

SPECIFICATION DATA

PROGRAM IDENT	STRUCTURE IDENTIFICATION				DESCRIPTION	LOAD FACTOR						UNIT WT OF EARTH	EQUIV FLUID PRESS	TEMP.	
	COUNTY	STATE ROUTE	SEGMENT	OFFSET		GAMMA	BETA D	BETA L	BETA EV	BETA EH	BETA R			RISE	FALL
1	7	9	13	17	21	45	48	51	54	57	60	63	66	69	71
= S A R C H						.	.	.	.	.	.	.	.		

GEOMETRY AND STRENGTH DATA

CROWN TH	FILL	NO. OF SEGS		INFL CODE	GEOM CODE	YK	SINT	SEXT	ULD	REBAR GRADE	FPC	CORNER TIE TH
		RING	TIE									
1	5	10	12	13	14	15	20	25	30	34	36	40
.	.					.	.	.	.		.	.

INTRADOS AND EXTRADOS CENTERS

YC1i	YC1e	YC2i	XC2i	YC2e	XC2e	YC3i	XC3i	YC3e	XC3e	TIE TH	TIE SL
1	6	11	16	21	26	31	36	41	46	51	55
.	.	.	.	.	.	.	.	.	.	.	.

PREPARED BY …………………………………. DATE …../…../….. SHEET …..OF…..

Figure 5.0.1 - Input Form 1 of 2

PENNSYLVANIA DEPARTMENT OF TRANSPORTATION
MAY 2002

PROGRAM ARCH
ARCH ANALYSIS AND DESIGN

Form 2 of 2

SECTION PROPERTIES

POINT 0 / 4 / 8 / 12 / 16 / 20 / 24				POINT 1 / 5 / 9 / 13 / 17 / 21 / 25				POINT 2 / 6 / 10 / 14 / 18 / 22				POINT 3 / 7 / 11 / 15 / 19 / 23			
DS	X	Y	T	DS	X	Y	T	DS	X	Y	T	DS	X	Y	T
1	5	10	15	19	23	28	33	37	41	46	51	55	59	64	69
0.000															

PREPARED BY ………………………………….. DATE …../…../….. SHEET …..OF…..

Figure 5.0.2 - Input Form 2 of 2

5.2 PROJECT IDENTIFICATION

Any number of lines may be used to enter user comments for problem identification. The first column of each must contain an asterisk (*) to indicate that this is a user comment. These comments may be placed anywhere within the input data. The first three comment lines will be printed on the output for identification.

5.3 SPECIFICATION DATA

PROGRAM IDENT

Enter "=SARCH" to uniquely identify the data being submitted. The program initially checks the characters being input and will terminate the execution if the proper combination of characters is not present. The message "IDENT ERROR - EXECUTION TERMINATED" will appear.

STRUCTURE IDENTIFICATION

Enter a 14-digit Structure Identification number similar to that used in the Bridge Management System (BMS). This number is comprised of 4 data items for each bridge. The 4 data items are COUNTY, STATE ROUTE, SEGMENT and OFFSET.

DESCRIPTION

Enter a description of the bridge or problem being analyzed. Any alphanumeric characters up to a maximum of 24 can be entered.

LOAD FACTORS

Enter the following gamma and beta factors by which the loads must be multiplied in order to get factored loads acting on a section. If any of the factors is not specified, the program will assume a default value. Refer to AASHTO 3.22.1.

GAMMA (γ)

Gamma factor. The default value is 1.3.

BETA D (β_D)

Beta factor for dead loads. The default value is 1.0.

BETA L (β_L)

Beta factor for live load plus impact. The default value is 1.67.

BETA EV (β_{EV})

Beta factor for vertical earth pressure. The default value is 1.0.

BETA EH (β_{EH})

Beta factor for horizontal earth pressure. The default value is 1.0. The program will calculate ½ horizontal earth pressure internally.

BETA R (β_R)

Beta factor for rib shortening, shrinkage, and temperature. The default value is 1.0.

UNIT WT OF EARTH

The unit weight of earth in kip/ft^3. The default value for this item is 0.120 kip/ft^3.

EQUIV FLUID PRESS

The lateral earth pressure in kip/ft^3. The program checks for full earth pressure and half earth pressure conditions, and uses the critical condition for design. The default value for this item is 0.035 kip/ft^3.

TEMPERATURE

Enter the temperature range as a rise and fall in the assumed temperature at the time of construction. If left blank or set to zero, default values in accordance with DM-4 Section 3.16 will be used.

RISE

Temperature rise in °F. The default value is 32°F.

FALL

Temperature fall in °F. The default value is 58°F.

5.4 GEOMETRY AND STRENGTH DATA

Refer to Figure 5.4.1 on page 5-9 for further illustration of the following input arch geometry dimensions.

CROWN TH

The thickness (TC) of the arch ring at the crown - ft.

FILL

The height of fill above the arch - ft.

NO. OF SEGS

RING (R)

The number of segments in half of the arch ring. For fixed arches, R must not exceed 10.

TIE (T)

The number of segments in half of the tie slab. For tied arches, R plus T must not exceed 10.

INFL CODE

Influence line code. Enter "9" if the influence line ordinates for all sections are to be printed out. Enter "0" or leave blank if the influence line ordinates are not to be printed.

GEOM CODE

Geometry code. Enter "0" if the Intrados and Extrados Centers Line is entered. Enter "9" if the Section Properties Line is entered.

YK

Vertical distance from the center of crown to the center of tie for tied arches or to the point of fixity for fixed arches - ft.

SINT

The horizontal component to 1 ft. vertical of the slope of the interior surface of the tangent portion of the arch ring. Leave blank if no tangent portion exists.

SEXT

The horizontal component to 1 ft. vertical of the slope of the exterior surface of the tangent portion of the arch ring. Leave blank if no tangent portion exists.

ULD

Uniform live load, if any, over the entire span - k/ft.

The program does not separately consider dead load (due to fill) and uniform live load when computing moments, shears, and thrusts. Only the total effect of dead load plus uniform load will be listed.

If separate results are desired, two input forms should be completed, one with FILL = actual height and ULD = 0, and the second with FILL = 0 and ULD = desired load.

REBAR GRADE

Enter the grade of rebar as "40", "50", "60", or "65". This value is used as the yield stress of reinforcement in ksi. Leave blank if design of reinforcement is not desired.

FPC

Ultimate 28-day concrete compressive strength (f'_c) - ksi. A correct value must be entered even if design of reinforcement is not desired.

CORNER TIE TH

Enter only if GEOM CODE is "9". Enter the thickness of the tie slab at the intersection of the axis of the tie and the axis of the ring measured perpendicular to the base of tie - ft. Leave blank if design of reinforcement is not desired.

5.5 INTRADOS AND EXTRADOS CENTERS

If GEOM CODE was entered as "0" in the GEOMETRY AND STRENGTH DATA, enter this line. A maximum of three curves may define each surface, interior or exterior, of half of the arch ring. The curves are designated C1, C2 and C3, from top to bottom, and are described by giving the coordinates of their centers. Vertical ordinates of the centers are measured from the center of the crown. Horizontal ordinates are measured from the centerline of the arch. All ordinates are entered as positive numbers. Refer to Figure 5.4.1 on page 5-9 for further illustration of the following input arch geometry dimensions.

YC1I, YC2I, YC3I

Vertical ordinates of the centers of the interior curves (intrados) - ft.

YC1E, YC2E, YC3E

Vertical ordinates of the centers of the exterior curves (extrados) - ft.

XC2I, XC3I

Horizontal ordinates of the centers of the interior curves - ft. XC3I must be greater than zero.

XC2E, XC3E

Horizontal ordinates of the centers of the exterior curves - ft. XC3E must be greater than zero.

NOTE: No provision has been made for XC1I and XC1E. The center of curve C1 always falls on the centerline of the arch.

TIE TH

Thickness of the tie slab at the centerline of the arch - ft.

TIE SL

The vertical component to 1 ft. horizontal of the slope of the top surface of the tie slab.

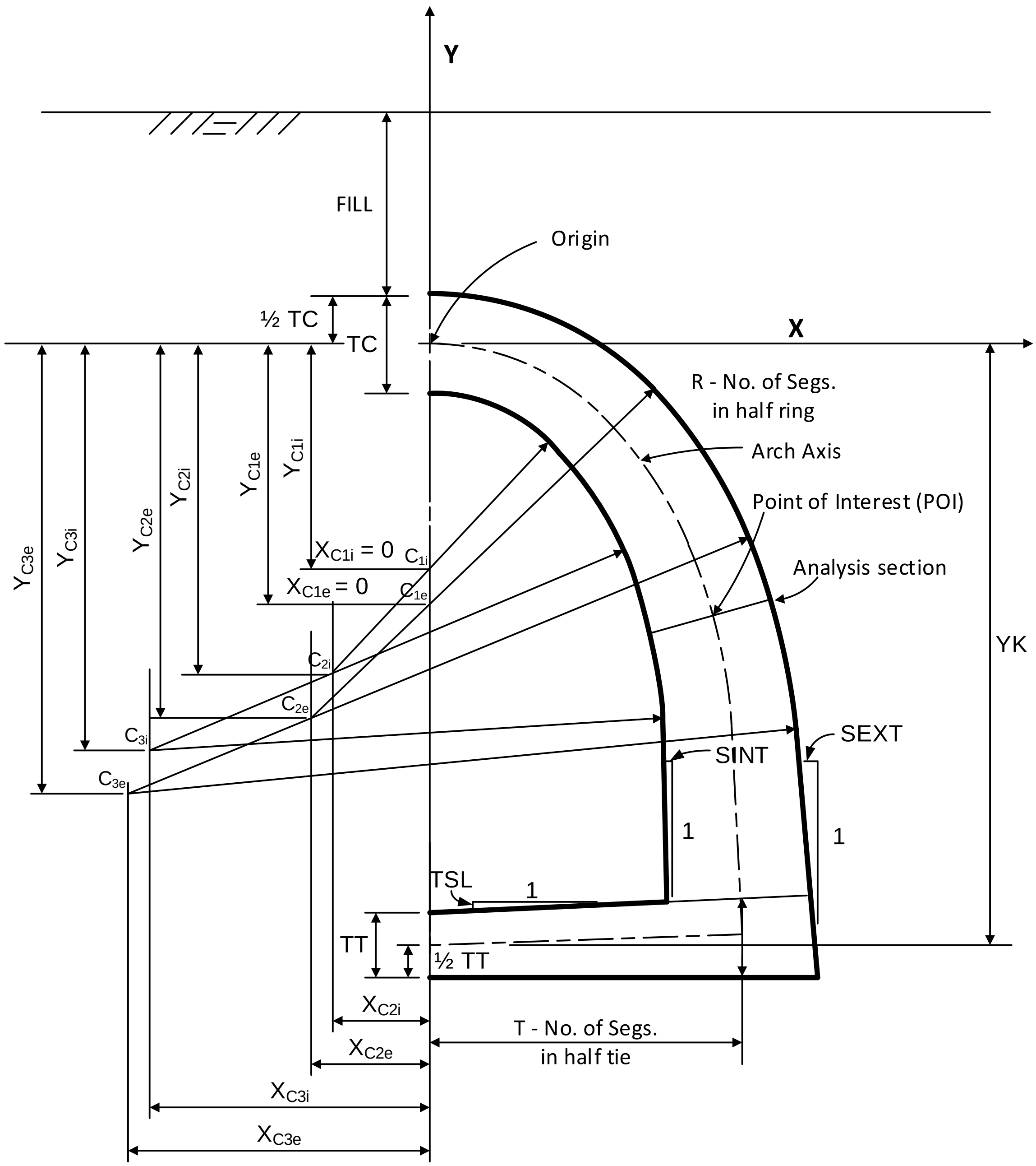

Figure 5.4.1 - Arch Centers

5.6 SECTION PROPERTIES

If GEOM CODE was entered as "9" in the GEOMETRY AND STRENGTH DATA, enter this line. A maximum of ten segments may define each half of the arch (NO. OF SEGS RING and NO. OF SEGS TIE on the GEOMETRY AND STRENGTH Line). The boundaries of these segments are cross sections of the ring and tie. Each cross section is referenced to the point of intersection of the cross section and the axis of the arch ring or tie. The intersection points are numbered 0, 1, 2, ... N. Point 0 is at the point of fixity for fixed arches (usually the top of the footing or footing equivalent) and at the center of the tie slab for tied arches. Point N is at the crown. The intersection of the axis of the tie and the axis of the ring must be one of the points. The cross section referenced to this point is perpendicular to the axis of the ring. Best results are obtained when the remaining cross sections are chosen such that the intersection points are equally spaced along the axis of the ring and tie.

DS

Distance from previous point-to-point being defined - ft. Distance for Point 0 is always 0.

X, Y

Coordinates of the point being defined measured with respect to the origin at the center of crown - ft. All coordinates are positive.

T

Thickness of arch ring or tie at the point in question - ft. The thickness is measured normal to the axis of the ring or tie.

6 OUTPUT DESCRIPTION

The program output consists of an echo of the input data followed by the program results printed in tabular format. A description of each output table is provided in the following sections. The final section of this chapter shows the actual format of the output tables.

6.1 INPUT DATA

The program first the output heading containing the program name, program number, license number, version number, last updated date, documentation date, the date and time of the run, and the input file name. Next, the first three comment lines are printed for identification. The input data is then printed in horizontal tabular format for each data type

6.2 ARCH GEOMETRY

The following data is printed for each point of intersection (PT.) of a cross section and the axis of the ring and tie:

1. Distance (DS) from the previous point, measured along the axis of the ring and tie - ft.
2. Coordinates (X, Y) of the point. Origin is at the crown of the arch.
3. Thickness (T) of the ring or tie at the point measured perpendicular to the arch axis - ft.
4. Sine and cosine of the angle formed by a horizontal line and the tangent to the axis at the point.

Distances, coordinates and thicknesses are echo prints of input when SECTION PROPERTIES are provided. They are computed when INTRADOS AND EXTRADOS CENTERS are provided. Coordinates are printed with the correct sign.

For fixed arches, point numbering begins at the point of fixity on the right and continues over the arch to the point of fixity on the left. For tied arches, numbering begins at the center of the tie slab and continues counterclockwise around the barrel and back to the center.

6.3 COMPUTED RADII AND CENTERS

The intrados radius, extrados radius, axis radius and axis centers are computed and printed for each curve when arch geometry is defined by Intrados and Extrados Centers. Radii are not computed when arch geometry is defined in the SECTION PROPERTIES Line.

6.4 ELASTIC CENTER PROPERTIES

YBAR is the position of the elastic center on the centerline of the arch, measured down from the axis of the ring at the crown. IX and IY are the moments of inertia of the arch through the elastic center as defined in the METHOD OF SOLUTION section.

6.5 LOADS

The unfactored vertical and horizontal loads applied at the centroid of the segment are printed for the arch ring segment. The vertical loads include the segment weight, the weight of the vertical column of fill above the segment, and the uniform live load. The horizontal load consists of the lateral earth pressure. For tied arches, the total reaction on the tie is reported as the total of the vertical loads applied to the arch ring. The total reaction is then divided by the number of tie segments to get the reaction loading on each tie segment. All loads are reported in kips.

Internal forces due to rib shortening, shrinkage and temperature change are reported for fixed arches. The unfactored internal horizontal forces at the crown are reported for the rib shortening effects for both the full lateral earth pressure and the half lateral earth pressure load cases, the shrinkage effects, and the temperature change (rise and fall) effects. All loads are reported in kips. These loads are then projected to each analysis point, and the reactions and moments are reported in the TOTAL FACTORED RIB SHORTENING, SHRINKAGE & TEMPERATURE CHANGE EFFECTS output table. Since the rib shortening effect is dependent on the axial force, the UNFACTORED INTERNAL HORIZONTAL FORCES AT CROWN output table is printed after the FACTORED HORIZONTAL LOAD EFFECTS table in the ANALYSIS portion of the output.

6.6 INFLUENCE LINE ORDINATES

For applications of unit vertical and horizontal loads at each cross section of half of the arch, ordinates are printed for the points around the entire barrel. The points are those defined in the geometry table mentioned above. The ordinates are the reactions V, H and M at each point.

A unit loading is applied just to the left of a cross section and then just to the right, causing an extra influence ordinate to be calculated. In other words, the tabulation of ordinates caused by unit loading at section 2 will show two sets of ordinates at point 2.

6.7 ANALYSIS RESULTS

The factored reaction, thrust, shear and moment effects at each segment cross-section are tabulated for the following loading combinations. For a design problem only, axial strengths and moment strengths are also printed. Moments are in kip-feet, reactions, thrusts and shears are in kips.

1. Vertical
2. Horizontal
3. Internal Effects - Rib Shortening, Shrinkage and Temperature Change
4. Group X
    - Vertical + ½ Horizontal
    - Vertical + Horizontal
5. Group X with Temperature Drop
    - Vertical + ½ Horizontal
    - Vertical + Horizontal
6. Group X with Temperature Rise
    - Vertical + ½ Horizontal
    - Vertical + Horizontal

NOTE: Results for Internal effects and Group X Loadings with temperature change are printed for fixed arches only. The sign convention for positive reactions (V, H and M) and for positive thrust and shear is defined in Figure 3.4.1. A moment causing tension at the intrados or top of the tie is positive. A thrust causing tension in the ring or compression in the tie is positive. A shear acting downward to the right of the section is positive.

6.8 DESIGN STEEL AREA AND SHEAR STRENGTHS (Design Only)

For each cross section of half of the arch, the following values are tabulated:

1. Thickness of the ring or tie, as supplied in the SECTION PROPERTIES Lines or as computed and as explained in the METHOD OF SOLUTION section.

2. Area of Extrados Steel.

3. Area of Intrados Steel.

4. Factored Shear.
5. Shear Strength.

For sections at which reinforcement is not required at either face, the minimum area of steel is printed. The minimum area of reinforcement is taken as one percent of the gross area of the section distributed equally between intrados and extrados steel as per AASHTO 8.14.3.4.

6.9 ERROR MESSAGES

The program prints an error message when an input error is detected. These messages are self-explanatory. The user should correct errors and resubmit the job for execution.

6.10 FORMATTED OUTPUT TABLES

The following pages contain the format (i.e., the title, output parameters, units, field widths and decimal locations) for each of the output tables described in this chapter. On each table, the character “a” represents a character value for that column, and the number of “a” characters shows the number of characters possible there. The character “i” represents an integer value for that column, and the character “x” represents a real value with the decimal location indicated. The characters “nn” represent the analysis point number at the connection point of the ring and the tie. For tied arches, output data is provided for the ring section and the tie section immediately adjacent to this point.

The output available for every run of the program may not include all of the output tables shown. Depending on such items as the arch type (fixed or tied), the influence line code, the geometry input method and reinforcement design, the program will print different combinations of these output tables.

```
                           ARCH ANALYSIS AND DESIGN

PROGRAM P4356020                                             ii/ii/iiii ii:ii
VERSION i.i.i.i          LAST UPDATED ii/ii/iiii        DOCUMENTATION ii/iiii

INPUT: aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
 aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa

STRUCTURE ID - aaaaaaaaaaaaaa - aaaaaaaaaaaaaaaaaaaaaaaa

                            * I * N * P * U * T *

                  * * * * *  SPECIFICATION DATA  * * * * *

                 LOAD FACTORS                       UNIT WT  EQ. FL.  TEMPERATURE
 GAMMA  BETAD   BETAL   BETAEV  BETAEH  BETAR   EARTH    PRES.  RISE    FALL
                                                (kcf)    (kcf) (deg F) (deg F)
  x.xx   x.xx    x.xx    x.xx    x.xx    x.xx   .xxx     .xxx   xx.x    xx.x


              * * * * *  GEOMETRY AND STRENGTH DATA  * * * * *

     CROWN          NO OF SEGS  INFL  GEOM
      TH      FILL   RING TIE   CODE  CODE    YK     SINT    SEXT
     (ft)     (ft)                           (ft)   (ft/ft) (ft/ft)
     x.xxx   xxx.xx   ii   i     i     i    xx.xxx  x.xxxx  x.xxxx

            REBAR          CORNER
     ULD    GRADE    FPC   TIE TH
    (k/ft)  (ksi)   (ksi)   (ft)
     x.xxx   ii     x.xxx   x.xxx
```

For CENTERS input only:

```
               * * * * *   INTRADOS EXTRADOS CENTERS  * * * * *

    YC1I     YC1E     YC2I     XC2I     YC2E     XC2E     YC3I     XC3I
    (ft)     (ft)     (ft)     (ft)     (ft)     (ft)     (ft)     (ft)
   xx.xxx   xx.xxx   xx.xxx   xx.xxx   xx.xxx   xx.xxx   xx.xxx   xx.xxx

    YC3E     XC3E     TIE TH      TIE SL
    (ft)     (ft)      (ft)      (ft/ft)
   xx.xxx   xx.xxx     xx.xx      x.xxxx
```

For SECTION PROPERTIES input only:

```
                  * * * * *  SECTION PROPERTIES  * * * * *

        PT.          DS          X          Y          T
                    (ft)        (ft)       (ft)       (ft)

        ii         xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx

        nn  TIE    xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx

        nn  RING   xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx

        ii         xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx

        ii  CROWN  xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx


                         O * U * T * P * U * T
```

For CENTERS input only:

```
             * * * * *  COMPUTED RADII AND CENTERS  * * * * *

          INTRADOS     EXTRADOS      AXIS        AXIS        AXIS
   CURVE   RADIUS       RADIUS      RADIUS     CENTER X    CENTER Y
            (ft)         (ft)        (ft)        (ft)        (ft)

     i     xxx.xxx      xxx.xxx     xxx.xxx     xxx.xxx     xxx.xxx
```

For CENTERS input only:

```
                   * * * * *  ARCH GEOMETRY  * * * * *

  PT.          DS          X          Y          T          SIN          COS
              (ft)        (ft)       (ft)       (ft)

  ii         xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx

  nn  TIE    xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx

  nn  RING   xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx   x.xxxxxx    x.xxxxxx

  ii         xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx   x.xxxxxx    x.xxxxxx

  ii  CROWN  xx.xxxx    xxxx.xxxx  xxxx.xxxx  xxxx.xxxx   x.xxxxxx    x.xxxxxx
```

For SECTION PROPERTIES input only:

```
  NOTE:  RADII AND COORDINATES OF CENTERS ARE NOT COMPUTED WHEN GEOMETRY
         IS DESCRIBED BY SECTION PROPERTIES.
```

```
              * * * * *  ELASTIC CENTER PROPERTIES  * * * * *

                       YBAR          IX        IY
                       (ft)        (ft^4)    (ft^4)

                    xxx.xxxx    xxxxxx.xx  xxxxxx.xx



                        * * * * *  LOADS  * * * * *


         U N F A C T O R E D   L O A D S   O N   A R C H   R I N G

                   VERTICAL LOAD @ SEGMENT CENTROID       HORIZONTAL
        RING   ----------------------------------------     EARTH
        SEG.   SEG. WT.   FILL WT.   LIVE LOAD    TOTAL    PRESSURE
                (kips)     (kips)     (kips)     (kips)     (kips)

        ii     xxx.xxx    xxx.xxx    xxx.xxx    xxx.xxx    xxx.xxx
```

For tied arches only (when INFL CODE “9” entered):

```
                                                ________
               TOTAL REACTION LOADING ON TIE =  xxx.xxx kips


        REACTION LOADING ON EACH TIE SEGMENT =  xxx.xxx kips
                       (SEGMENTS 1-i, ii-ii)
```

For Influence line output only (when INFL CODE “9” entered):

```
              * * * * *  INFLUENCE LINE ORDINATE FOR SECTION nn  * * * * *

   PT.          VV          VH          VM          HV          HH          HM

    ii        xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx

    nn        xxx.xxxx                                        xxx.xxxx

    nn        xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx

    ii        xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx    xxx.xxxx
```

* * * * * ANALYSIS RESULTS * * * * *

F A C T O R E D   V E R T I C A L   L O A D   E F F E C T S

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	THRUST (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

F A C T O R E D   H O R I Z O N T A L   L O A D   E F F E C T S

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	THRUST (kips)	SHEAR (kips)
ii	xxxx.XXX	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.XXX	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.XXX	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.XXX	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

For fixed arches only:

UNFACTORED INTERNAL HORIZONTAL FORCES AT CROWN

RIB SHORTENING			TEMPERATURE CHANGE	
FULL EH (kips)	HALF EH (kips)	SHRINKAGE (kips)	FALL (kips)	RISE (kips)
xxx.xxx	xxx.xxx	xxx.xxx	xxx.xxx	xxx.xxx

TOTAL FACTORED RIB SHORTENING, SHRINKAGE & TEMPERATURE CHANGE EFFECTS

		FULL EARTH PRESSURE			HALF EARTH PRESSURE		
PT.	TEMP.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)
ii	FALL	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
	RISE	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

For reinforcement design only (when REBAR GRADE entered):

G R O U P X

F A C T O R E D V E R T I C A L + H A L F H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	MOMENT STRENGTH (k-ft)	THRUST (kips)	AXIAL STRENGTH (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

F A C T O R E D V E R T I C A L + H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	MOMENT STRENGTH (k-ft)	THRUST (kips)	AXIAL STRENGTH (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

Temperature drop and temperature rise load cases for fixed arches only:

G R O U P X
(TEMPERATURE DROP)

F A C T O R E D V E R T I C A L + H A L F H O R I Z O N T A L

PT.	VERTICAL REACTION	HORIZONTAL REACTION	MOMENT	MOMENT STRENGTH	THRUST	AXIAL STRENGTH	SHEAR
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

F A C T O R E D   V E R T I C A L   +   H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	MOMENT STRENGTH (k-ft)	THRUST (kips)	AXIAL STRENGTH (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

G R O U P X
(TEMPERATURE RISE)

F A C T O R E D   V E R T I C A L   +   H A L F   H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	MOMENT STRENGTH (k-ft)	THRUST (kips)	AXIAL STRENGTH (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

F A C T O R E D   V E R T I C A L   +   H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	MOMENT STRENGTH (k-ft)	THRUST (kips)	AXIAL STRENGTH (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

For no reinforcement design only (when REBAR GRADE not entered) – Strengths not computed:

```
                               G R O U P  X

     F A C T O R E D   V E R T I C A L   +   H A L F   H O R I Z O N T A L

              VERTICAL  HORIZONTAL
          PT. REACTION   REACTION    MOMENT     THRUST      SHEAR
                (kips)     (kips)    (k-ft)     (kips)      (kips)

          ii  xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          nnT xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          nnR xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          ii  xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

         F A C T O R E D   V E R T I C A L   +   H O R I Z O N T A L

              VERTICAL  HORIZONTAL
          PT. REACTION   REACTION    MOMENT     THRUST      SHEAR
                (kips)     (kips)    (k-ft)     (kips)      (kips)

          ii  xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          nnT xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          nnR xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          ii  xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx
```

Temperature drop and temperature rise load cases for fixed arches only:

```
                               G R O U P  X
                            (TEMPERATURE DROP)

     F A C T O R E D   V E R T I C A L   +   H A L F   H O R I Z O N T A L

              VERTICAL  HORIZONTAL
          PT. REACTION   REACTION    MOMENT     THRUST      SHEAR
                (kips)     (kips)    (k-ft)     (kips)      (kips)

          ii  xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          nnT xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          nnR xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx

          ii  xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx   xxxx.xxx
```

F A C T O R E D   V E R T I C A L   +   H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	THRUST (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

G R O U P   X
(TEMPERATURE RISE)

F A C T O R E D   V E R T I C A L   +   H A L F   H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	THRUST (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

F A C T O R E D   V E R T I C A L   +   H O R I Z O N T A L

PT.	VERTICAL REACTION (kips)	HORIZONTAL REACTION (kips)	MOMENT (k-ft)	THRUST (kips)	SHEAR (kips)
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnT	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
nnR	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx
ii	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx	xxxx.xxx

For reinforcement design only (when REBAR GRADE entered):

```
              * * *  DESIGN  STEEL  AREA  AND  SHEARS  * * *

                        EXTRADOS            INTRADOS         FACTORED     SHEAR
PT.  THICKNESS    As req    As min    As req    As min     SHEAR      STRENGTH
       (in)       (in^2)    (in^2)    (in^2)    (in^2)     (kips)      (kips)

ii    xxx.xx      xx.xx*    xx.xx*    xx.xx*    xx.xx*   xxxx.xxx    xxxx.xxx

nnT   xxx.xx      xx.xx*    xx.xx*    xx.xx*    xx.xx*   xxxx.xxx    xxxx.xxx

nnR   xxx.xx      xx.xx*    xx.xx*    xx.xx*    xx.xx*   xxxx.xxx    xxxx.xxx

ii    xxx.xx      xx.xx*    xx.xx*    xx.xx*    xx.xx*   xxxx.xxx    xxxx.xxx

   NOTE THE FOLLOWING FOR STEEL AREAS:

      * GREATER OF REQ OR MIN STEEL USED TO CALCULATE MOMENT STRENGTH

      - OVERSTRESSED SECTION IS INDICATED BY "*******".  SECTION THICKNESS IS
        NOT ADEQUATE.

      - MINIMUM AREA OF STEEL (INTRADOS + EXTRADOS) IS EQUAL TO 1% OF THE GROSS
        AREA OF THE SECTION.

      - SHEAR STRENGTH WAS CALCULATED BASED ON CONCRETE ONLY.
```

For no reinforcement design only (when REBAR GRADE not entered):

```
NOTE:  DESIGN STEEL AREAS AND SHEAR STRENGTHS ARE NOT CALCULATED WHEN THE
       REBAR GRADE IS ENTERED AS ZERO.
```

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7 EXAMPLE PROBLEMS

7.1 GENERAL

This chapter contains four (4) example problems to aid users in preparing data for their problems. A general description and a description of the required input along with completed input forms are given for each example. Refer to Chapter 5 Input Descriptions when preparing data for your specific problem. The following four example problems are included in this chapter.

1. Example Problem 1 - Design of a two-centered fixed arch defined by INTRADOS AND EXTRADOS CENTERS.

2. Example Problem 2 - Analysis of a fixed arch defined by SECTION PROPERTIES input.

3. Example Problem 3 - Design of a two-centered tied arch defined by INTRADOS AND EXTRADOS CENTERS.

4. Example Problem 4 - Design of three-centered fixed arch with a tangent section defined by INTRADOS AND EXTRADOS CENTERS.

The actual input data files and resulting output for the example problems are not listed in this manual, but input files (Ex1.dat, Ex2.dat, etc.) are included electronically with the executable program in the installation directory (default "C:\Program Files\PennDOT\ARCH"). The example problems can be run so that the output can be viewed.

7.2 EXAMPLE PROBLEM 1

PROBLEM DESCRIPTION

Example Problem 1 is the design of a two-centered fixed arch. The intrados and extrados ordinates are known and therefore, the INTRADOS AND EXTRADOS CENTERS input will be used to describe the geometry. Figure 7.1.1 on page 7-3 shows the arch cross-section and input dimensions.

INPUT

The following input lines are entered. Refer to the completed input forms shown in Figure 7.1.2 on page 7-4.

1. Specification Data

   The unit weight of fill is 0.120 k/ft^3. The lateral earth pressure is 0.035 k/ft^3. The temperature rise is 30°F and the temperature fall is 40°F. Default values will be used for the load factors.

2. Geometry and Strength Data

   The arch height measured as the vertical distance from the center of the crown to the point of fixity is 15.917 ft. The arch thickness at the crown is 0.833 ft. The fill height measured from the arch crown is 26 ft. The equivalent uniform live load is 2 k/ft. The concrete strength is 3.0 ksi and the yield strength of the reinforcement steel is 40 ksi. The arch will be divided into 10 segments per half for analysis.

3. Intrados and Extrados Centers

   The intrados ordinates are (0.000, 7.083) for center 1 and (10.000,16.166) for center 2. The extrados ordinates are (0.000, 7.916) for center 1 and (10.000,17.416) for center 2.

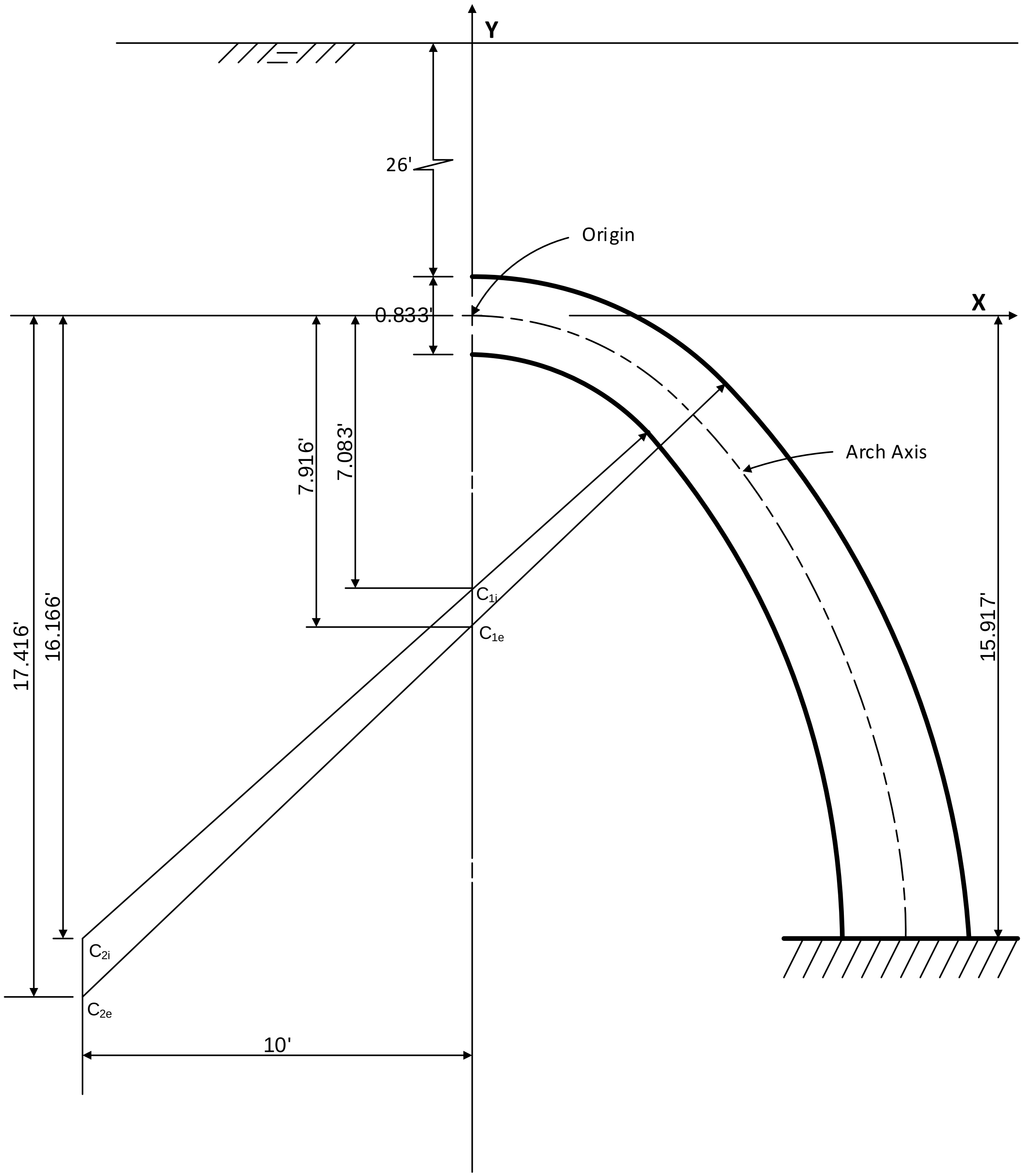

Figure 7.1.1 - Example Problem 1 - Details

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MAY 2002

PROGRAM ARCH
ARCH ANALYSIS AND DESIGN

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PROJECT IDENTIFICATION
*EXAMPLE PROBLEM 1 - 2-CENTERED FIXED ARCH DESIGN
*
*

SPECIFICATION DATA

PROGRAM IDENT	STRUCTURE IDENTIFICATION				DESCRIPTION	LOAD FACTOR						UNIT WT OF EARTH	EQUIV FLUID PRESS	TEMP.	
	COUNTY	STATE ROUTE	SEGMENT	OFFSET		GAMMA	BETA D	BETA L	BETA EV	BETA EH	BETA R			RISE	FALL
1	7	9	13	17	21	45	48	51	54	57	60	63	66	69	71
=SARCH	02	1234	5123	1200		.	.	.	.	.	.	.120	.035	30	40

GEOMETRY AND STRENGTH DATA

CROWN TH	FILL	NO. OF SEGS		INFL CODE	GEOM CODE	YK	SINT	SEXT	ULD	REBAR GRADE	FPC	CORNER TIE TH
		RING	TIE									
1	5	10	12	13	14	15	20	25	30	34	36	40
0.833	260.00	10	0		0	15.917	.	.	2.000	40	3.000	.

INTRADOS AND EXTRADOS CENTERS

YC1i	YC1e	YC2i	XC2i	YC2e	XC2e	YC3i	XC3i	YC3e	XC3e	TIE TH	TIE SL
1	6	11	16	21	26	31	36	41	46	51	55
7.083	7.916	16.166	10.000	17.416	10.000	.	.	.	.	.	.

PREPARED BY ……………………………………. DATE …../…../….. SHEET …..OF…..

Figure 7.1.2 - Example Problem 1 - Input

7.3 EXAMPLE PROBLEM 2

PROBLEM DESCRIPTION

Example Problem 2 is an analysis of a fixed arch. The intrados and extrados ordinates are not known and the geometry is entered using the SECTION PROPERTY input. Figure 7.2.1 on page 7-6 shows the arch cross-section, and the ordinates and thicknesses of the analysis sections.

INPUT

The following input lines are entered. Refer to the completed input forms shown in Figure 7.2.2 on page 7-7.

1. Specification Data

   Default values are used for all items.

2. Geometry and Strength Data

   The arch height measured as the vertical distance from the center of the crown to the point of fixity is 34.37 ft. The arch thickness at the crown is 1.75 ft. The fill height measured from the arch crown is 105 ft. No live load is applied. The concrete strength is 3.0 ksi. The REBAR GRADE input is left blank so that the reinforcement design is not performed. The arch ring will be defined by 10 segments per half.

3. Section Properties

   The X and Y ordinates along with the section thickness are entered for the 10 segments to define the geometry for half the arch ring.

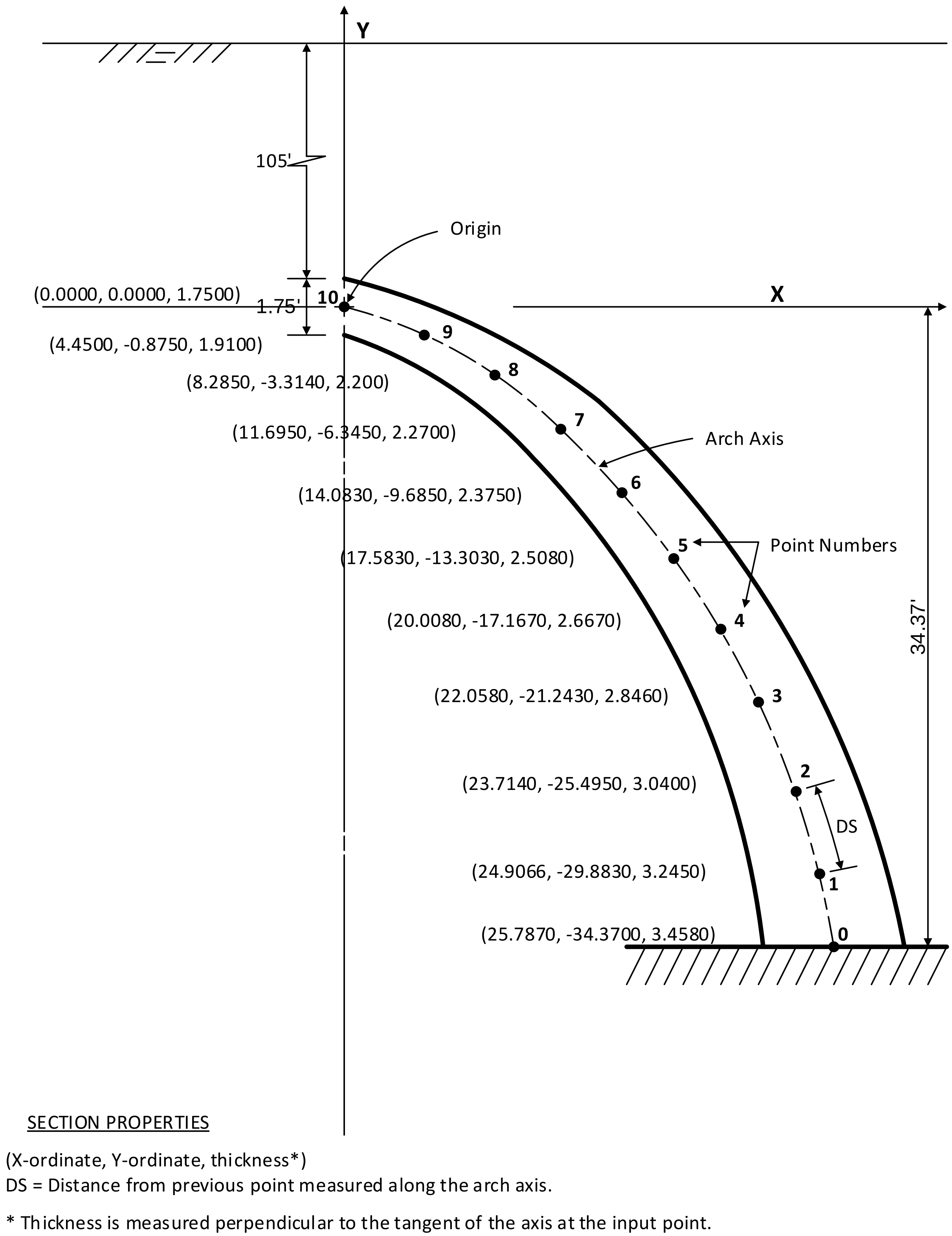

Figure 7.2.1 - Example Problem 2 - Details

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MAY 2002

Form 1 of 2

PROGRAM ARCH
ARCH ANALYSIS AND DESIGN

PROJECT IDENTIFICATION
* EXAMPLE PROBLEM 2 - FIXED ARCH ANALYSIS
*
*

SPECIFICATION DATA

PROGRAM IDENT	STRUCTURE IDENTIFICATION				DESCRIPTION	LOAD FACTOR						UNIT WT OF EARTH	EQUIV FLUID PRESS	TEMP.	
	COUNTY	STATE ROUTE	SEGMENT	OFFSET		GAMMA	BETA D	BETA L	BETA EV	BETA EH	BETA R			RISE	FALL
1	7	9	13	17	21	45	48	51	54	57	60	63	66	69	71
=SARCH	22	0022	0100	0000		.	.	.	.	.	.	.	.		

GEOMETRY AND STRENGTH DATA

CROWN TH	FILL	NO. OF SEGS		INFL CODE	GEOM CODE	YK	SINT	SEXT	ULD	REBAR GRADE	FPC	CORNER TIE TH
		RING	TIE									
1	5	10	12	13	14	15	20	25	30	34	36	40
1.750	105.00	10	0		9	34.370	.	.	.		3.000	.

INTRADOS AND EXTRADOS CENTERS

YC1i	YC1e	YC2i	XC2i	YC2e	XC2e	YC3i	XC3i	YC3e	XC3e	TIE TH	TIE SL
1	6	11	16	21	26	31	36	41	46	51	55
.	.	.	.	.	.	.	.	.	.	.	.

PREPARED BY ………………………………. DATE …../…../….. SHEET …..OF…..

Figure 7.2.2 - Example Problem 2 - Input

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PROGRAM ARCH
ARCH ANALYSIS AND DESIGN

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SECTION PROPERTIES

POINT 0 / 4 / 8 / 12 / 16 / 20 / 24				POINT 1 / 5 / 9 / 13 / 17 / 21 / 25				POINT 2 / 6 / 10 / 14 / 18 / 22				POINT 3 / 7 / 11 / 15 / 19 / 23			
DS	X	Y	T	DS	X	Y	T	DS	X	Y	T	DS	X	Y	T
1	5	10	15	19	23	28	33	37	41	46	51	55	59	64	69
0.000	25.787	34.370	3.458	4.564	24.960	29.883	3.245	4.564	23.714	25.495	3.040	4.564	22.058	21.243	2.846
4.564	20.008	17.167	2.667	4.564	17.583	13.303	2.508	4.564	14.803	9.685	2.375	4.564	11.695	6.345	2.270
4.564	8.285	3.314	2.200	4.564	04.450	00.875	1.910	4.564	00.000	00.000	1.750	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

PREPARED BY ………………………………….   DATE …../…../…..   SHEET …..OF…..

Figure 7.2.2 – Example Problem 2 - Input (cont.)

7.4 EXAMPLE PROBLEM 3

PROBLEM DESCRIPTION

Example Problem 3 is the design of a two-centered tied arch. The intrados and extrados ordinates are known and therefore, the INTRADOS AND EXTRADOS CENTERS input will be used to describe the geometry. Figure 7.3.1 on page 7-10 shows the arch cross-section and input dimensions.

INPUT

The following input lines are entered. Refer to the completed input forms shown in Figure 7.3.2 on page 7-11.

1. Specification Data

   Default values are used for load factor and all other items.

2. Geometry and Strength Data

   The arch height measured as the vertical distance from the center of the crown to the point of fixity is 15.917 ft. The arch thickness at the crown is 0.833 ft. The fill height measured from the arch crown is 19 ft. There is no live load applied. The concrete strength is 3.0 ksi and the yield strength of the reinforcement steel is 40 ksi. The ring portion of the arch is divided into 6 segments per half for analysis and the tie portion is divided into 4 segments.

3. Intrados and Extrados Centers

   The intrados ordinates are (0.000, 7.083) for center 1 and (10.000,16.166) for center 2. The extrados ordinates are (0.000, 7.916) for center 1 and (10.000,17.416) for center 2. The slope of the top surface of the tie slab is 0.04 vertical to 1 horizontal and the thickness of the tie slab at the centerline of the arch is 3 ft.

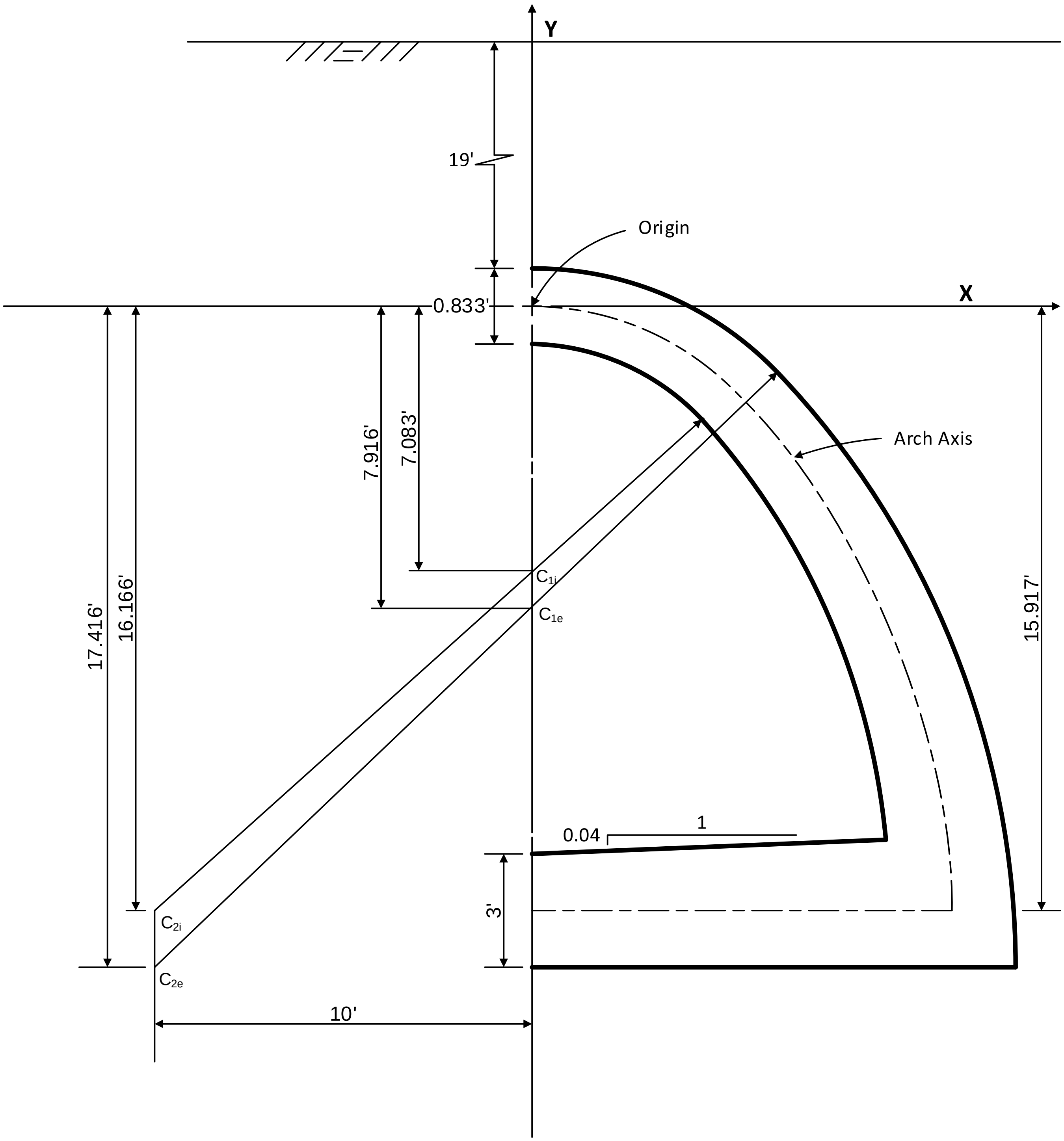

Figure 7.3.1 - Example Problem 3 - Details

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MAY 2002

PROGRAM ARCH
ARCH ANALYSIS AND DESIGN

Form 1 of 2

PROJECT IDENTIFICATION
*EXAMPLE PROBLEM 3 - 2-CENTERED TIED ARCH DESIGN
*
*

SPECIFICATION DATA

PROGRAM IDENT	STRUCTURE IDENTIFICATION				DESCRIPTION	LOAD FACTOR						UNIT WT OF EARTH	EQUIV FLUID PRESS	TEMP.	
	COUNTY	STATE ROUTE	SEGMENT	OFFSET		GAMMA	BETA D	BETA L	BETA EV	BETA EH	BETA R			RISE	FALL
1	7	9	13	17	21	45	48	51	54	57	60	63	66	69	71
=SARCH						.	.	.	.	.	.	.	.		

GEOMETRY AND STRENGTH DATA

CROWN TH	FILL	NO. OF SEGS		INFL CODE	GEOM CODE	YK	SINT	SEXT	ULD	REBAR GRADE	FPC	CORNER TIE TH
		RING	TIE									
1	5	10	12	13	14	15	20	25	30	34	36	40
0.833	019.00	06	4		0	15.917	0.0000	0.0000	0.000	40	3.000	.

INTRADOS AND EXTRADOS CENTERS

YC1i	YC1e	YC2i	XC2i	YC2e	XC2e	YC3i	XC3i	YC3e	XC3e	TIE TH	TIE SL
1	6	11	16	21	26	31	36	41	46	51	55
7.083	7.916	16.166	10.000	17.416	10.000	.	.	.	.	3.000	0.0400

PREPARED BY ………………………………….   DATE …../…../…..   SHEET …..OF…..

Figure 7.3.2 - Example Problem 3 - Input

7.5 EXAMPLE PROBLEM 4

PROBLEM DESCRIPTION

Example Problem 4 is the design of a three-centered fixed arch. The intrados and extrados ordinates are known and therefore, the INTRADOS AND EXTRADOS CENTERS input will be used to describe the geometry. Figure 7.4.1 on page 7-13 shows the arch cross-section and input dimensions.

INPUT

The following input lines are entered. Refer to the completed input forms shown in Figure 7.4.2 on page 7-14.

1. Specification Data

   Load factors for Group X are entered. The unit weight of fill is 0.120 k/ft^3. The lateral earth pressure is 0.085 k/ft^3.

2. Geometry and Strength Data

   The arch height measured as the vertical distance from the center of the crown to the point of fixity is 27'-7". The arch thickness at the crown is 2 ft. There is a tangent potion of the arch. The intrados tangent is vertical and the slope of the extrados tangent is 0.4 horizontal to 1 vertical. The fill height measured from the arch crown is 2 ft. The equivalent uniform live load is 0.139 k/ft. The concrete strength is 3.0 ksi and the yield strength of the reinforcement steel is 60 ksi. The arch will be divided into 23 segments per half for analysis.

3. Intrados and Extrados Centers

   The intrados ordinates are (0.000, 12.583) for center 1, (13.000, 27.166) for center 2, and (4.000, 20.750) for center 3. The extrados only has two centers, which are the same as the intrados centers 1 and 2. Ordinates for extrados center 3 are not required. The program assumes that the arc 2 continues to the tangent portion. However, entering the center 2 ordinates for center 3 has the same effect.

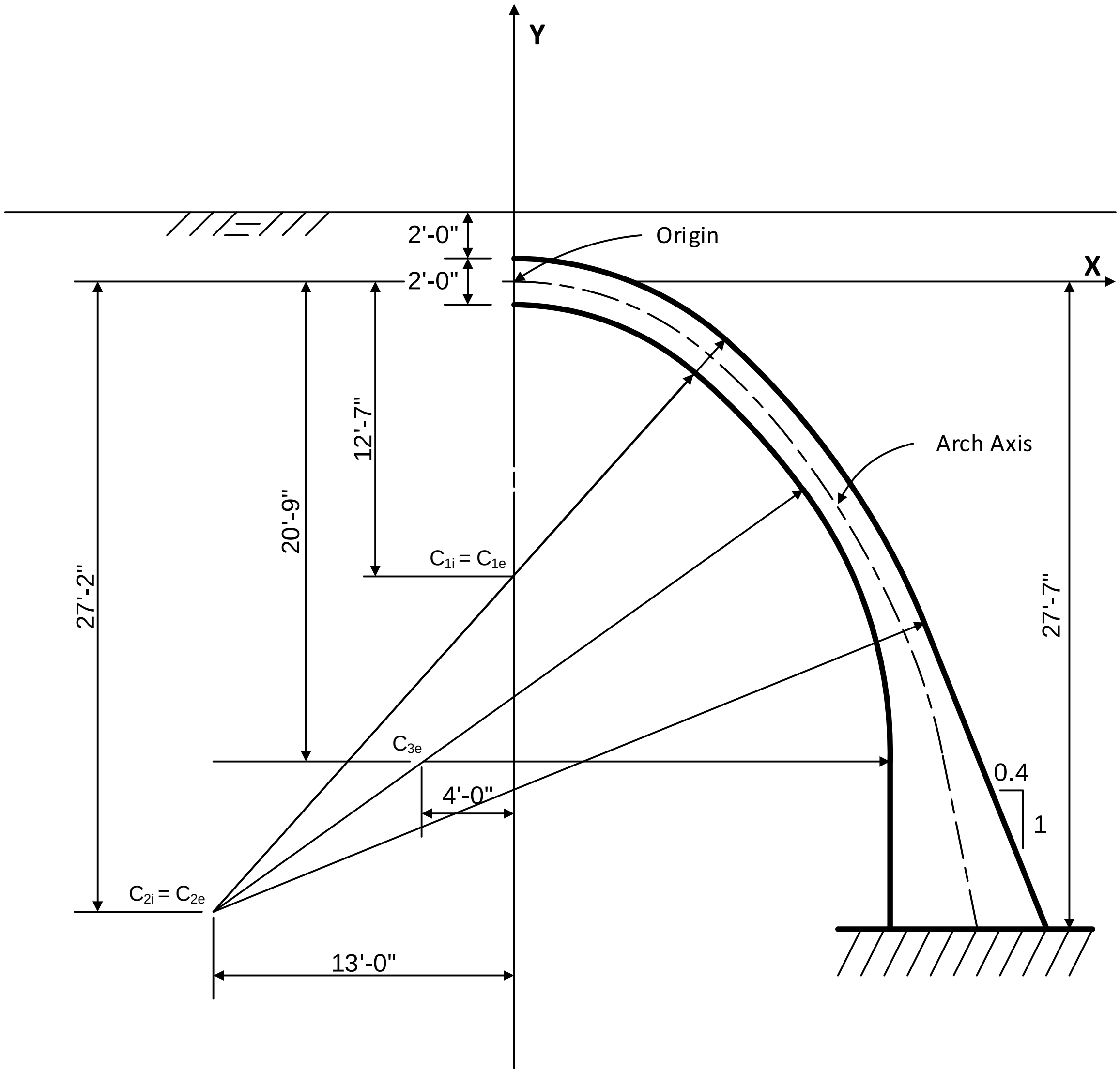

Figure 7.4.1 - Example Problem 4 - Details

PENNSYLVANIA DEPARTMENT OF TRANSPORTATION
MAY 2002

PROGRAM ARCH
ARCH ANALYSIS AND DESIGN

Form 1 of 2

PROJECT IDENTIFICATION
*EXAMPLE PROBLEM 4 - 3-CENTERED FIXED ARCH DESIGN
*
*

SPECIFICATION DATA

PROGRAM IDENT	STRUCTURE IDENTIFICATION				DESCRIPTION	LOAD FACTOR						UNIT WT OF EARTH	EQUIV FLUID PRESS	TEMP.	
	COUNTY	STATE ROUTE	SEGMENT	OFFSET		GAMMA	BETA D	BETA L	BETA EV	BETA EH	BETA R			RISE	FALL
1	7	9	13	17	21	45	48	51	54	57	60	63	66	69	71
=SARCH	36	0283	0010	0000		1.30	1.00	1.67	1.00	1.15	1.00	.120	.085		

GEOMETRY AND STRENGTH DATA

CROWN TH	FILL	NO. OF SEGS		INFL CODE	GEOM CODE	YK	SINT	SEXT	ULD	REBAR GRADE	FPC	CORNER TIE TH
		RING	TIE									
1	5	10	12	13	14	15	20	25	30	34	36	40
2.000	2.00	23	0		0	27.583	0.0000	0.4000	0.139	60	3.000	.

INTRADOS AND EXTRADOS CENTERS

YC1i	YC1e	YC2i	XC2i	YC2e	XC2e	YC3i	XC3i	YC3e	XC3e	TIE TH	TIE SL
1	6	11	16	21	26	31	36	41	46	51	55
12.583	12.583	27.166	13.000	27.166	13.000	20.750	4.000	.	.	.	.

PREPARED BY ……………………………….   DATE …../…../…..   SHEET …..OF…..

Figure 7.4.2 - Example Problem 4 - Input

8 TECHNICAL QUESTIONS AND REQUESTS

This chapter contains reply forms to make it easier for users to convey their questions, problems or comments to the proper unit within the Department. General procedures for using these forms are given. Users should keep the forms in the manual as master copies, which can be reproduced as needed. They are also included as a Word template on the disk that has been provided for the program.

8.1 TECHNICAL QUESTIONS

Technical questions related to the interpretations of the design specifications as implemented in this program, why certain assumptions are made, applicability and limitations of this program, and other questions not related to the operation of this program can be directed to the appropriate person in PennDOT using this form or the information provided on this form. Please review the information provided in this User's Manual and the references given in Chapter 1 before submitting this form for processing or calling for assistance. The completed form should be sent to the Bridge Quality Assurance Division (see form for complete address).

8.2 REVISION REQUESTS

This form is to be used to report suspected program malfunctions that may require revisions to the program. It can also be used to request revisions that may be required due to changes in specifications and for the enhancement of the program. Unexpected or incorrect output, rejection of input data, endless program cycling, and program abortion are examples of program malfunctions. Users are requested to review their input data and the program User's Manual before submitting this form for processing.

This form may also be used to submit suggestions for improving the User's Manual for this program. Suggestions might include typographical error correction, clarification of confusing sections, expansion of certain sections, changes in format, and the inclusion of additional information, diagrams, or examples.

The completed form should be sent to the Engineering Unit via mail, fax, or e-mail.

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ARCH
TECHNICAL QUESTIONS

This form is to be used to ask questions on technical issues related to this engineering program. Questions on the interpretations of the design specifications as implemented in this program, why certain assumptions are made by the program and other questions not related to the operation of this program may be submitted using this form or by calling the telephone number listed in this form. Users are requested to review their input data and read the User's Manual and LRFD Specifications before submitting this form or calling to ask questions.

CONTACT PERSON: ______________________________________ DATE: ____________________
ORGANIZATION: _____________________________________ PHONE: ____________________
E-MAIL ADDRESS: _____________________________________ FAX: ____________________
PROGRAM VERSION: _________

Clearly state your question(s) and attach documentation you feel would be helpful in answering your question(s). If you require more space, use additional 8½ x 11 sheets of plain paper.

FORWARD COMPLETED FORM TO: Pennsylvania Dept. of Transportation
Bridge Design and Technology Division
Commonwealth Keystone Building, 7th Floor
400 North Street
Harrisburg, PA 17120-0094
PHONE: (717) 787-2881
FAX: (717) 787-2882

FOR DEPARTMENT USE ONLY

RECEIVED BY: ________________ ASSIGNED TO: ___________________ DATE: _____________

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ARCH
REVISION REQUEST

This form is to be used to report suspected program malfunctions, or to request revisions to the program or its documentation. Users are requested to review their input data and the program User's Manual before submitting this form.

CONTACT PERSON: ____ DATE: ____________________
ORGANIZATION: ____ PHONE: ____________________
E-MAIL ADDRESS: ____ FAX: ____________________
PROGRAM VERSION: _________

Define your problem and attach samples and/or documentation you feel would be helpful in correcting the problem. If the input data is more than 4 or 5 lines, Licensees should provide the input data file on a diskette. If you require more space, use additional 8½ x 11 sheets of plain paper.

FORWARD COMPLETED FORM TO: Pennsylvania Department of Transportation
Bureau of Business Solutions and Services
Engineering Software Section
Commonwealth Keystone Building, 5th Floor
400 North Street
Harrisburg, PA 17120-0041
PHONE: (717) 787-8407 / (717) 783-8822
FAX: (717) 705-5529
E-MAIL: penndotbisengineer@pa.gov

FOR DEPARTMENT USE ONLY
RECEIVED BY: ________________ ASSIGNED TO: ___________________ DATE: _____________

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