FDOT TRANSPORTATION SYMPOSIUM

2022 Webinar Series

GFRP Reinforced Concrete Design for Pile Bent Caps

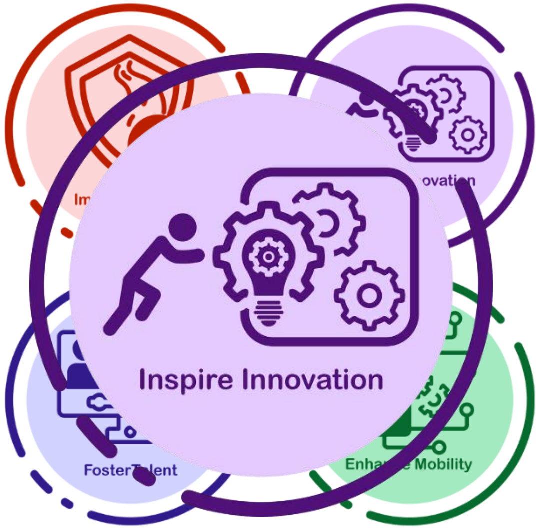
Steven Nolan, P.E. – State Structures Design Office

October 19, 2022

EVERY TRIP BUCKLE UP EVERY TIME

Summary

The ***FDOT Structures Manual*** now encourages the use of Fiber-Reinforced Polymer (FRP) reinforcing for certain concrete bridge elements located in the splash zone of extremely aggressive environments. Pile bent caps are one of the more common bridge elements requiring this design approach. This presentation will summarize the design of Glass FRP reinforced concrete using a typical intermediate pile bent cap example and FDOT's Mathcad Bent Cap Program v1.0.



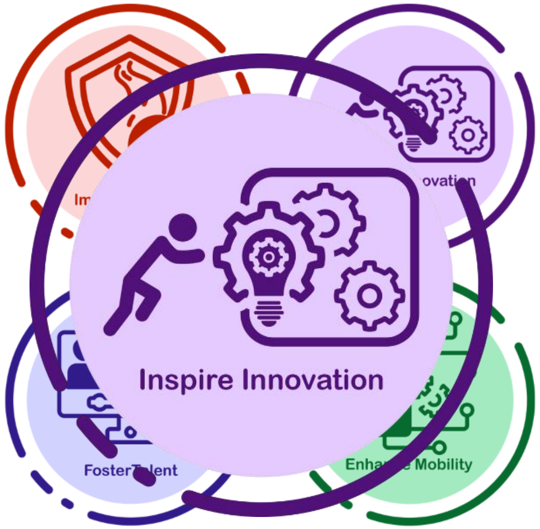
#3 FDOT Vital Few

Learning objectives

- Awareness of FDOT's Mathcad Bent Cap Design Program v1.0 capabilities and limitations.
- Awareness of GFRP reinforced concrete design for Flexural and Shear Limit States.
- Understanding of Pile Bent Cap reinforcing strategies for Glass Fiber-Reinforced Polymer (GFRP) bars.

Outline

- Design Guidance for GFRP-RC
- Design Tools for GFRP-RC
- Flexural Design Limit States:
  - Strength
  - Service – Crack Control
  - Service – Sustained Load
  - Fatigue
- Shrinkage & Temperature Reinforcing Design
- Shear Design
- Review: Design guidance & resources
- Where to find more FRP-RC training

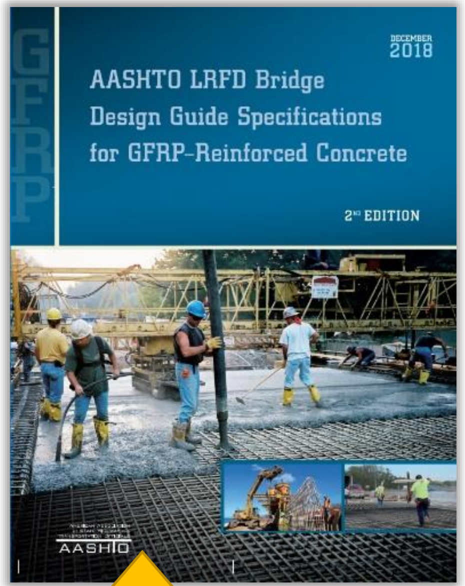


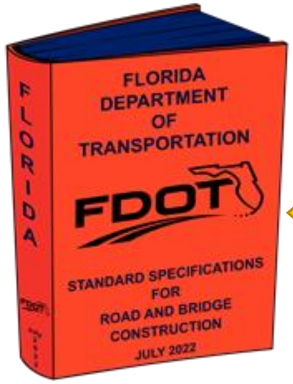
#3 FDOT Vital Few

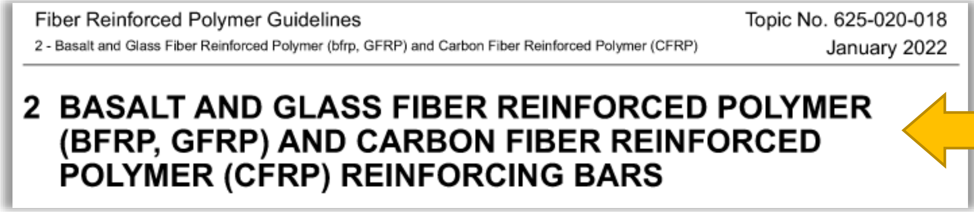
GFRP = Glass Fiber-Reinforced Polymer
BFRP = Basalt Fiber-Reinforced Polymer

Design guidance for Bridges

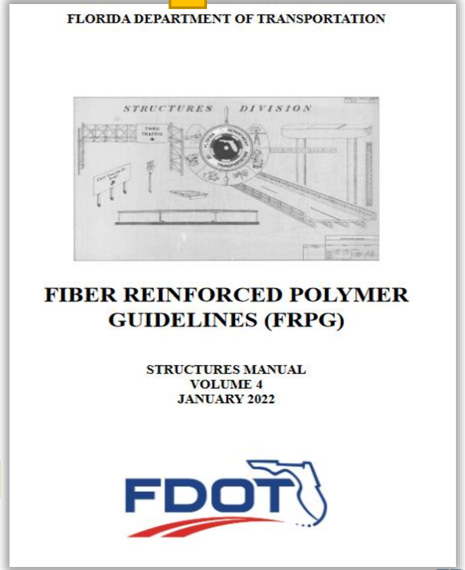
- ***AASHTO*** *LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete, 2nd Edition (2018)*
- *Supplemented by*
  - ***FDOT Structures Manual – Volume 4, FRP Guidelines, Chapter 2*** for BFRP & GFRP Rebar
- *Use associated Material Specifications*
  - ***FDOT Spec 932-3*** for BFRP & GFRP Rebar (Material Specs)
  - *Similar to* ***ASTM D7957*** for GFRP Rebar, *(2017)*





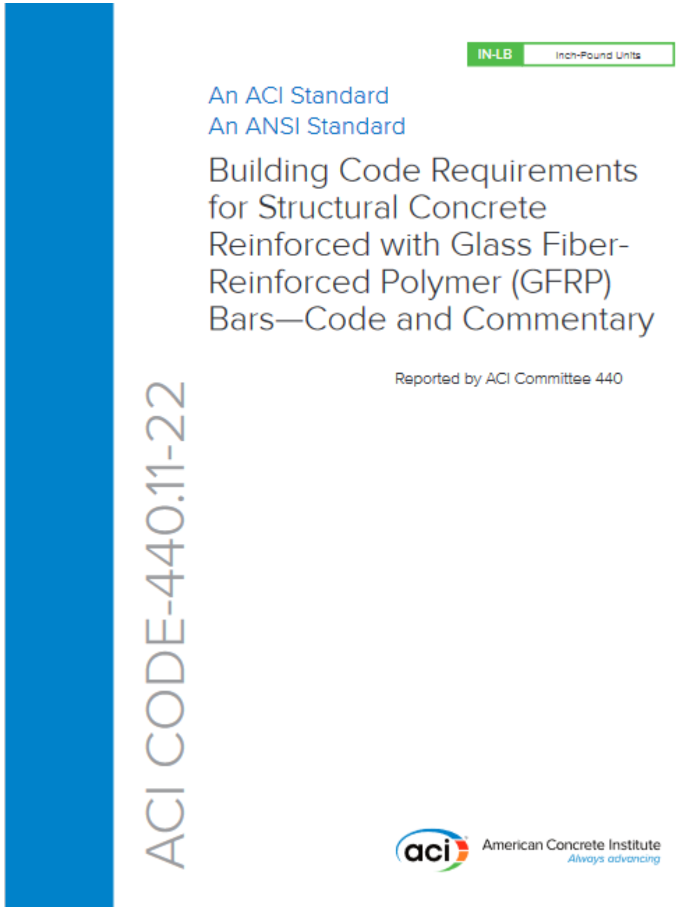

Fiber Reinforced Polymer Guidelines | Topic No. 625-020-018
2 - Basalt and Glass Fiber Reinforced Polymer (bfrp, GFRP) and Carbon Fiber Reinforced Polymer (CFRP) | January 2022

2 BASALT AND GLASS FIBER REINFORCED POLYMER (BFRP, GFRP) AND CARBON FIBER REINFORCED POLYMER (CFRP) REINFORCING BARS



Design guidance for Buildings (FYI only)

- ***ACI CODE-440.11-22:*** *Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary (2022)*
- *Uses associated Material Specifications*
    - ***ASTM D7957*** for GFRP Rebar, *(2017)*



FDOT TRANSPORTATION SYMPOSIUM

Design Tools for GFRP-RC Design

- FDOT Design Software

FDOT OFFICES MAPS & DATA CONTACT ABOUT PROJECTS RESOURCES NEWSROOM

Structures Design

Programs Library

By downloading any programs, you are agreein
No warranty, expressed or implied, is made by the
results they produce, nor shall the fact of distribut
Transportation in any connection therewith.

The Structures Design Office only supports thos

For Mathcad problems, view our Mathcad Frequ

Bent Cap v1.0	11/07/2018	Exe (Zip) (Mathcad 15)	Analyzes and designs fixed or pinned bent caps, including lateral loads, in accordance with the AASHTO LRFD Bridge Design Specifications.
Retaining Wall v4.0	06/01/2020	Zip (Mathcad 15)	Used with FDOT Standard Plan Index 400-010 to design and analyze cast-in-place retaining walls in accordance with the AASHTO LRFD Bridge Design Specification.
Prestressed Beam v6.2	05/31/2022	Zip (Mathcad 15)	Used with FDOT Standard Plan Index 450-010 to 450-299 to design simple span prestressed beams (Florida-I, AASHTO, Florida Bulb-T, Florida-U, Florida Double-T, Flat Slab, Inverted-T, FSB) in accordance with the AASHTO LRFD Bridge Design Specification.
Box Culvert v5.2	09/14/2022	Zip (Mathcad 15)	Used with FDOT Standard Plan Index 400-289 to design concrete box culverts, wingwalls, headwalls, and cutoff walls in accordance with the AASHTO LRFD Bridge Design Specification.

- **Bent Cap v1.0 –** Includes GFRP *11/1/2018*.
- **Retaining Wall v4.0 –** Added GFRP *12/10/2019*.
- **PS Beams v6.2 –** Added CFRP-PC/GFRP in v6.0, *10/1/2021*.
- **Box Culvert v5.2** - Added GFRP in v5.0, *5/26/2022*.

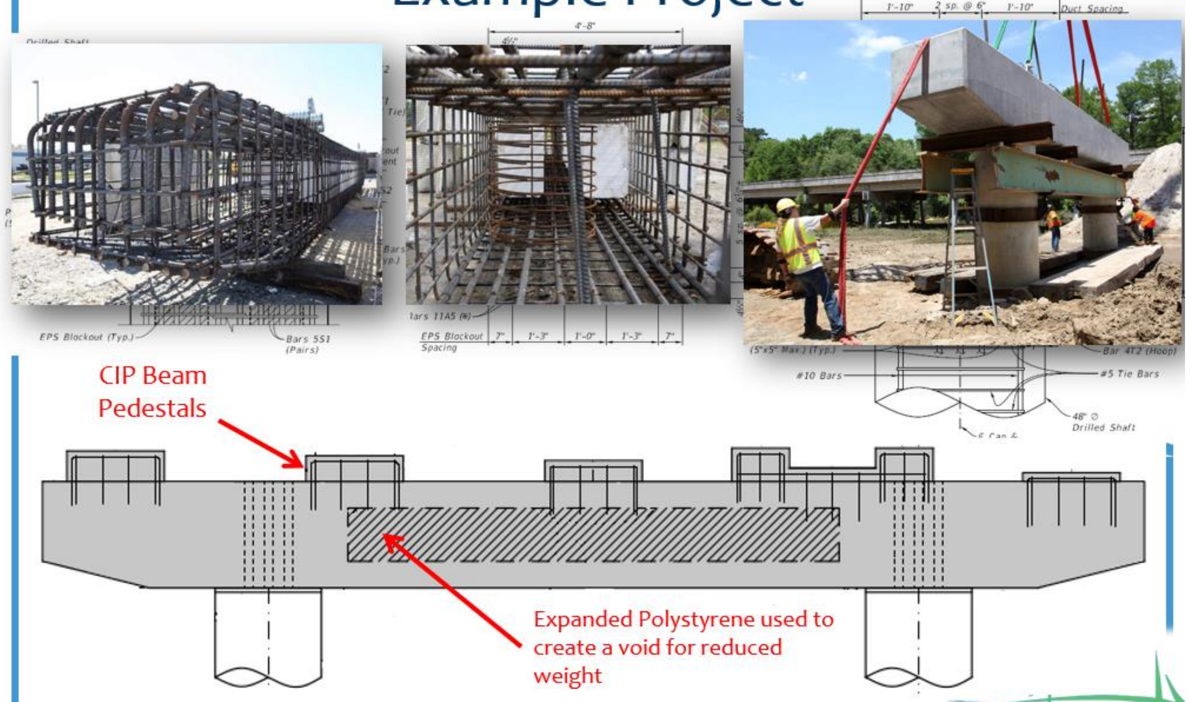
https://www.fdot.gov/structures/proglib.shtm

Design Tool for GFRP-RC Design

- **Bent Cap v1.0**

- **Previously introduced this Mathcad Program at the 2016 FDOT Design Training Expo**

US 90/Little River PBES Demonstration - Example Project -



Mathcad Design Program

US90 Project: 2-Drilled Shaft Cap Design	$Str_I +M_u$ (kip*ft)	$Str_I -M_u$ (kip*ft)	V_u at Int. face of Ext. Col. (kip)	$+M_r$ w/ 18#11 (kip*ft)	$-M_r$ w/ 20#11 (kip*ft)	V_r w/ #5@6" (4 legs) (kip)
EOR's Design	2988	-3255	598	4818	5298	719
FDOT Mathcad (conc.)	3196	-3286	895	4825	5274	687
FDOT Mathcad (distr.)	2947	-3286	798			
Difference (distributed)	1.4%	-0.9%	-25.1%	-0.1%	0.5%	4.7%
RC Pier	3471	-2874	773	4891	4710	715
RC Pier vs. Mathcad Diff.	17.8%	-12.5%	-3.1%	1.4%	-10.7%	4.1%

US90 Project: 6 x Pile Bent Cap	$Str_I +M_u$ (kip*ft)	$Str_I -M_u$ (kip*ft)	Vu (kip)	$+M_r$ w/ 7#9 (kip*ft)	$-M_r$ w/ 8#6 (kip*ft)	V_r w/ #5@7.5" (2 legs) (kip)
EOR's Design	1255	-520	330	1348	921	365
FDOT Mathcad (conc.)	981	-443	467	1347	924	458
FDOT Mathcad (distr.)	753	-421	322			
Difference (distributed)	-21.8%	-14.8%	-2.4%	-0.1%	0.3%	25.5%
RC Pier	590	-495	412	1160	959	453
RC Pier vs. Mathcad Diff.	-21.6%	17.5%	28.1%	-13.9%	3.8%	-1.0%

Comparisons of US 90 Demonstration project designs with new FDOT Mathcad program.

SHRP2 Example 3b: 2-Column Cap Design	$Str_I +M_u$ (kip*ft)	$Str_I -M_u$ (kip*ft)	Vu (kip)	$+M_r$ w/ 10#11 (2 rows) (kip*ft)	$-M_r$ w/ 8#11 (kip*ft)	V_r w/ #6@ 9" (4 legs) (kip)
SHRP2 Example 3b	1901	-2263	354	2823	2396	809
FDOT Matchcad (dist.)	2626	-1799	351	2823	2396	711
Difference	38.2%	-20.5%	-0.9%	0.0%	0.0%	-12.1%
RC Pier	2504	-1613	276	2802	2422	663
RC Pier vs. Mathcad Diff.	-4.6%	-10.3%	-21.3%	-0.7%	1.1%	-6.8%

SHRP2 Example 3b: 2-Column Cap Design	$Str_I +M_u$ (kip*ft)	$Str_I -M_u$ (kip*ft)	Vu (kip)	$+M_r$ w/ 10#11 (2 rows) (kip*ft)	$-M_r$ w/ 8#11 (kip*ft)	V_r w/ #6@ 9" (4 legs) (kip)
SHRP2 Example 3b	1901	-2263	354	2823	2396	809
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Difference	38.2%	-20.5%	-0.9%	0.0%	0.0%	-12.1%
RC Pier	2504	-1613	276	2802	2422	663
RC Pier vs. Mathcad Diff.	-4.6%	-10.3%	-21.3%	-0.7%	1.1%	-6.8%

Comparison with two designs recently completed in-house, a published TxDOT Pile Bent Design Example (June 2010), the SHRP2 R04-RR-1 two-column bent cap design example, and analysis with Bentley's RC Pier software showed good correlation of results. Deviations in the results can be explained by the refinements in modeling and loading assumptions for the different designs.

Comparisons of other design examples with new FDOT Mathcad program

2016 Design Training Expo

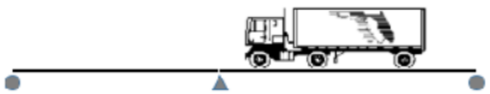
Design Tool for GFRP-RC Design • **Bent Cap v1.0**

State Structures Design Office

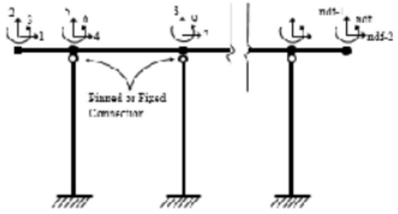
Project =
Designed By =
Checked By =
Back Checked By =

Run the appropriate worksheets by double clicking the icons below. Modify the input data as required & execute <calculate worksheet> (Ctrl + F9) twice to save/view information. When finished, close the worksheet window without saving to return to this screen. Project information is stored in the Project Data File (.dat file), so Mathcad worksheets should not be saved, unless permanent modifications are intended.

PART 1: LOAD GENERATOR

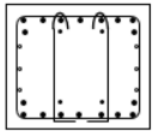


PART 2: FRAME ANALYSIS

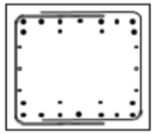


Bent Cap Analysis Model

PART 3: DESIGN & AASHTO BDS CHECKS



Steel Rebar



GFRP

Intermediate Bent-Cap Analysis & Design
Part 1. Load Generator

State Structures Design Office

Project =
Designed By =
Checked By =
Back Checked By =

Data Files Folder

Change Folder

C:\FDOT Structures\Programs\BentCapV1.0test\

Open Existing Data File (optional)

Refresh List

Load Data

US90 DS.dat
US90 Pile.dat

Input Data

Superstructure (Symmetrical)

Girder type

AASHTO Type II
FIB-36
FIB-45
FIB-54

FDOT Structures > Programs > BentCapV1.0

Name

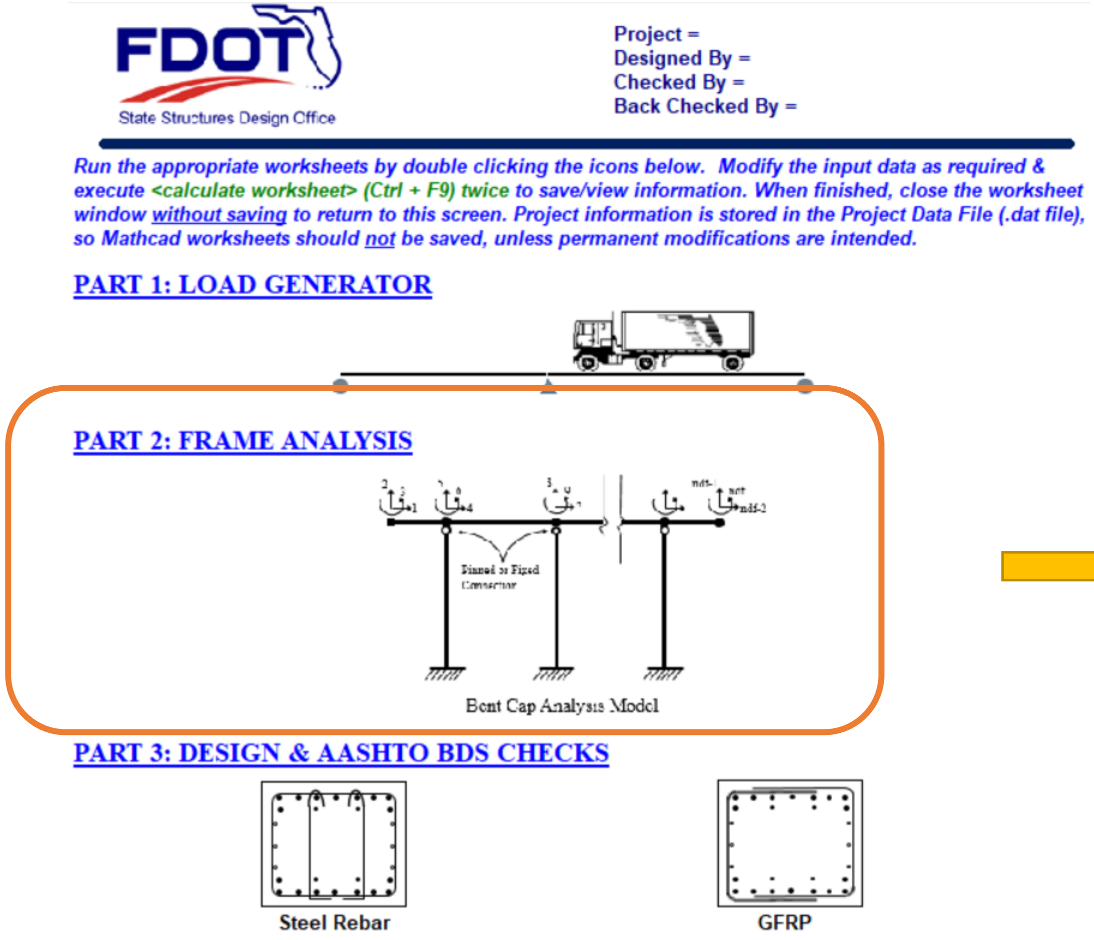
- Data
- Example
- 0-BentCap-FlowChart.xmcd
- 1-BentCap-LoadGenerator.xmcd
- 2-BentCap-FrameAnalysis.xmcd
- 3a-BentCap-CodeChecks.xmcd
- 3b-BentCap-CodeChecks-GFRP.xmcd

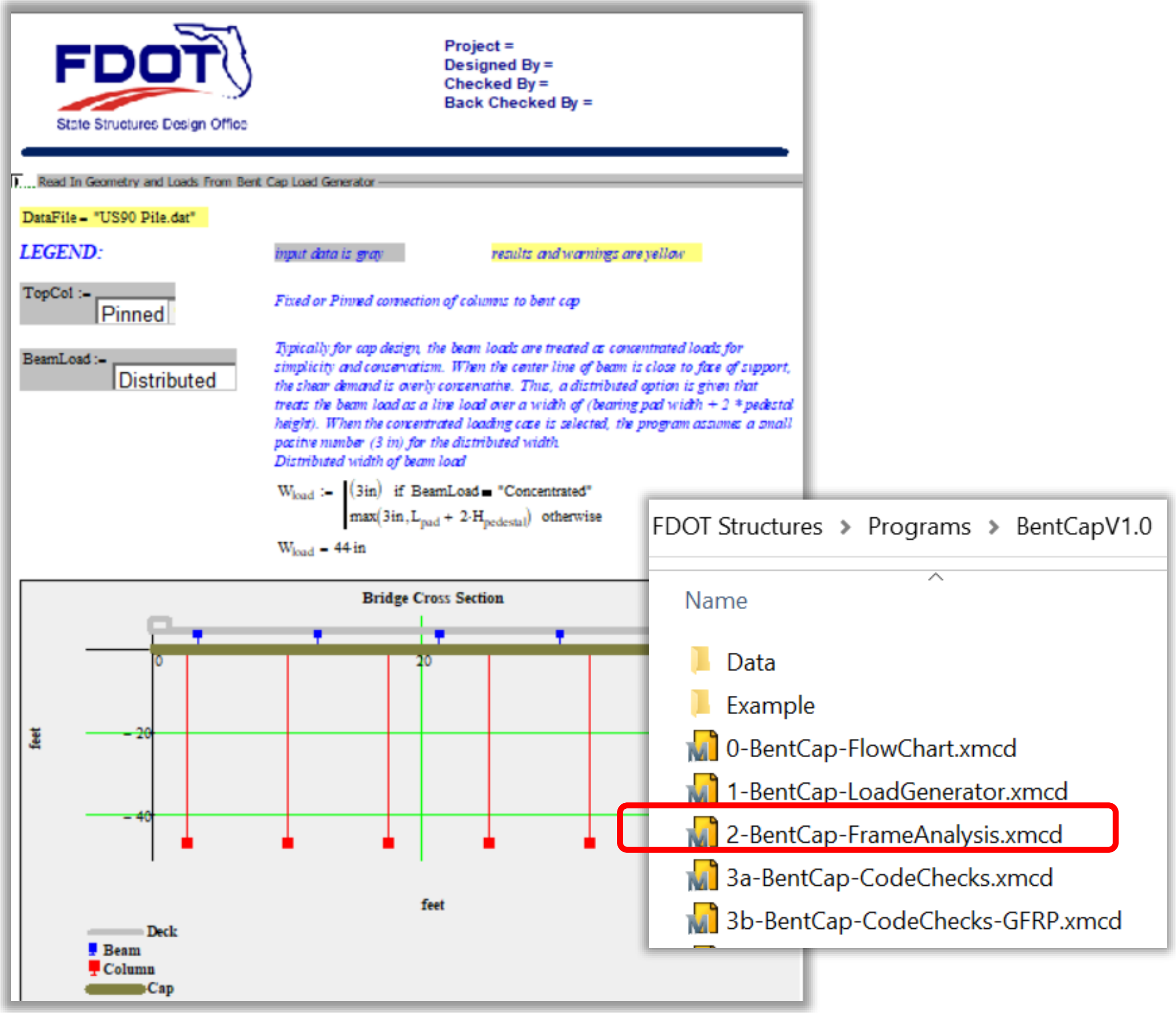
Flow Chart

https://www.fdot.gov/structures/proglib.shtm

Design Tool for GFRP-RC Design

- **Bent Cap v1.0**





Flow Chart

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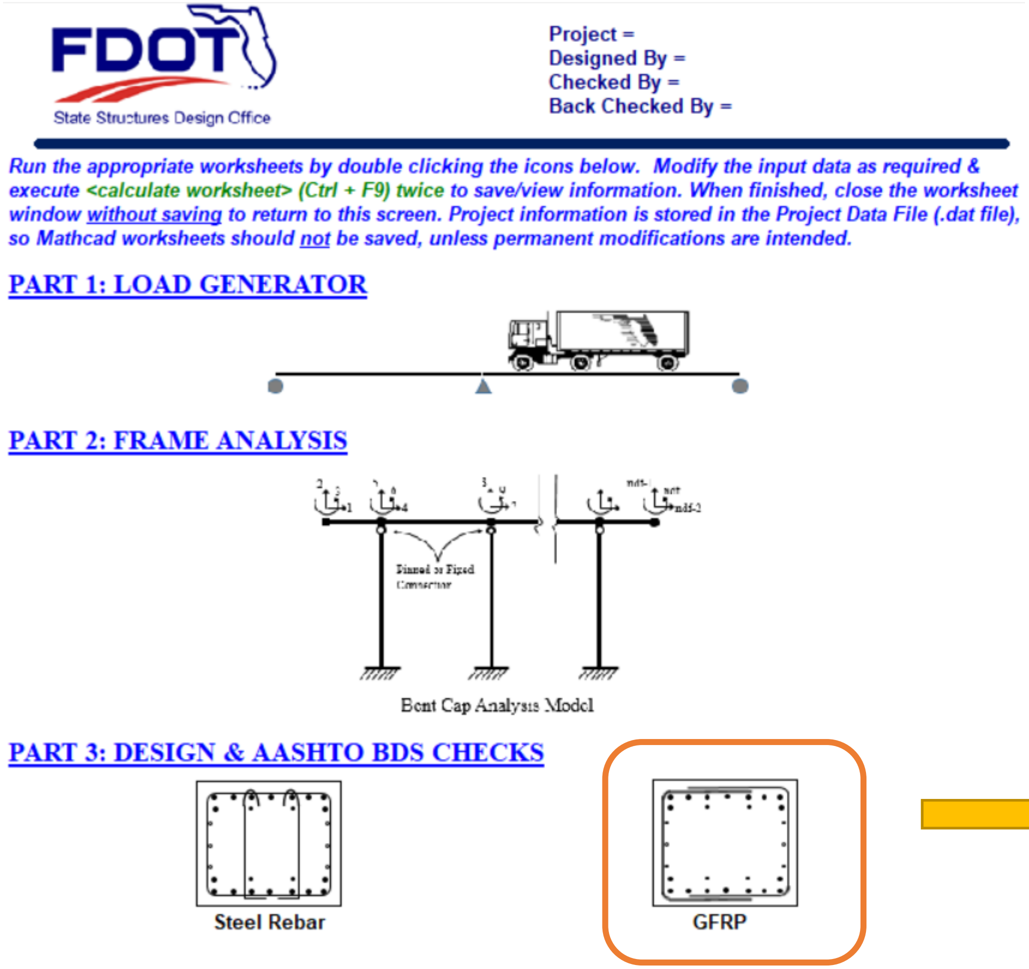
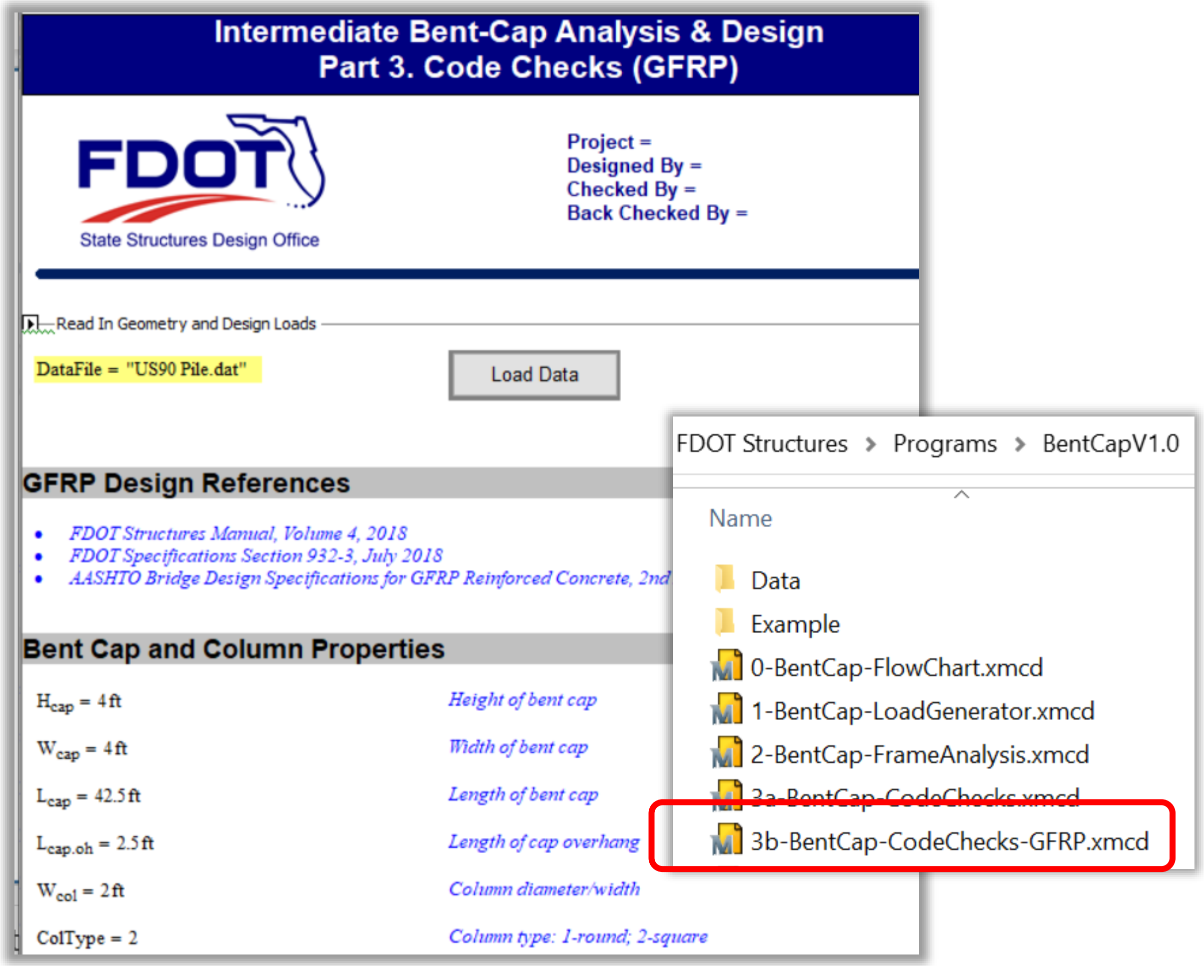
Design Tool for GFRP-RC Design

- **Bent Cap v1.0**



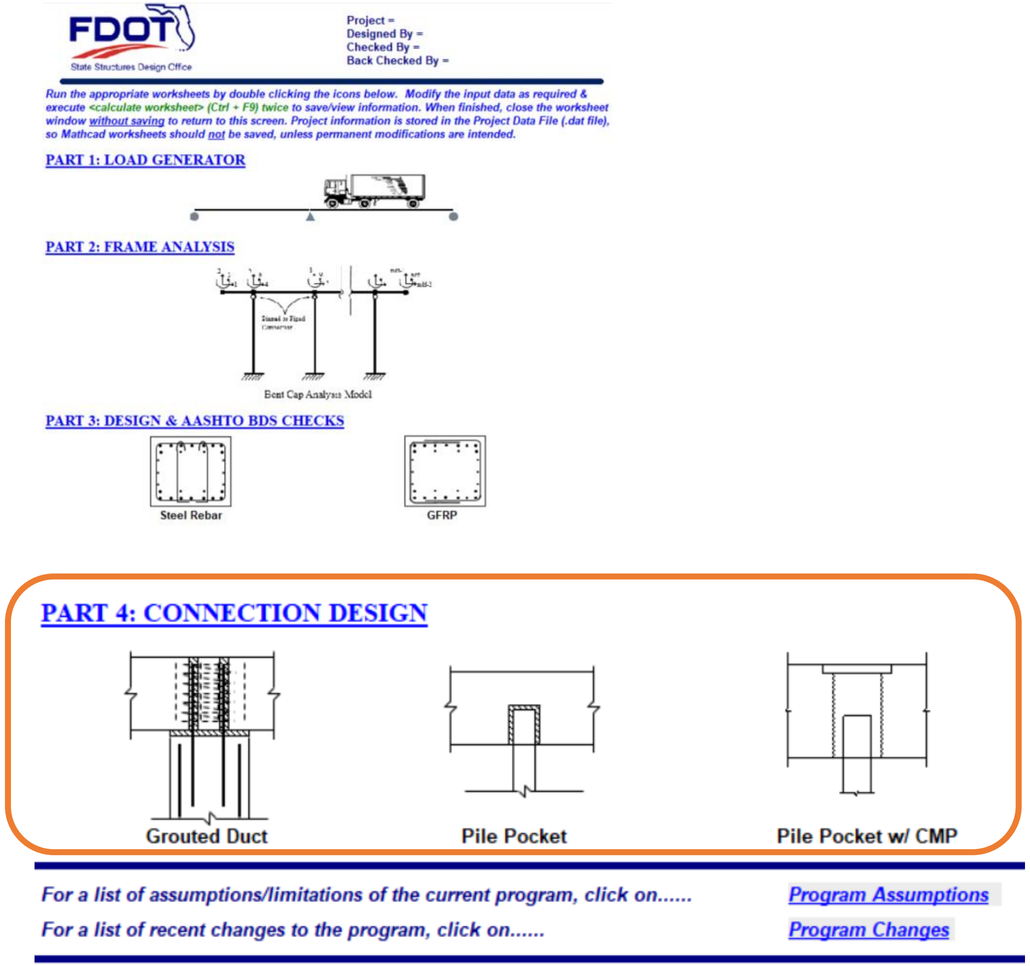


Flow Chart

https://www.fdot.gov/structures/proglib.shtm

Design Tool for GFRP-RC Design

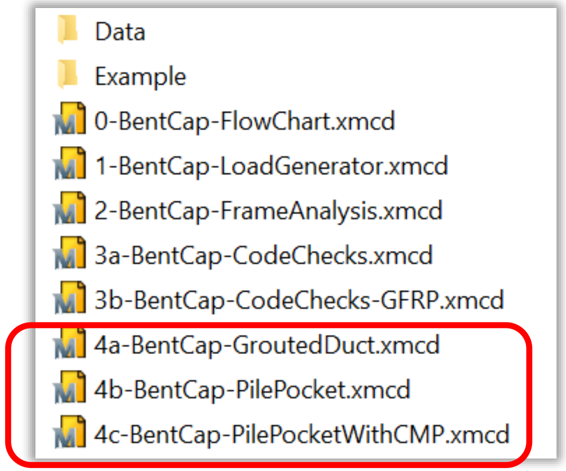
- **Bent Cap v1.0**



Flow Chart

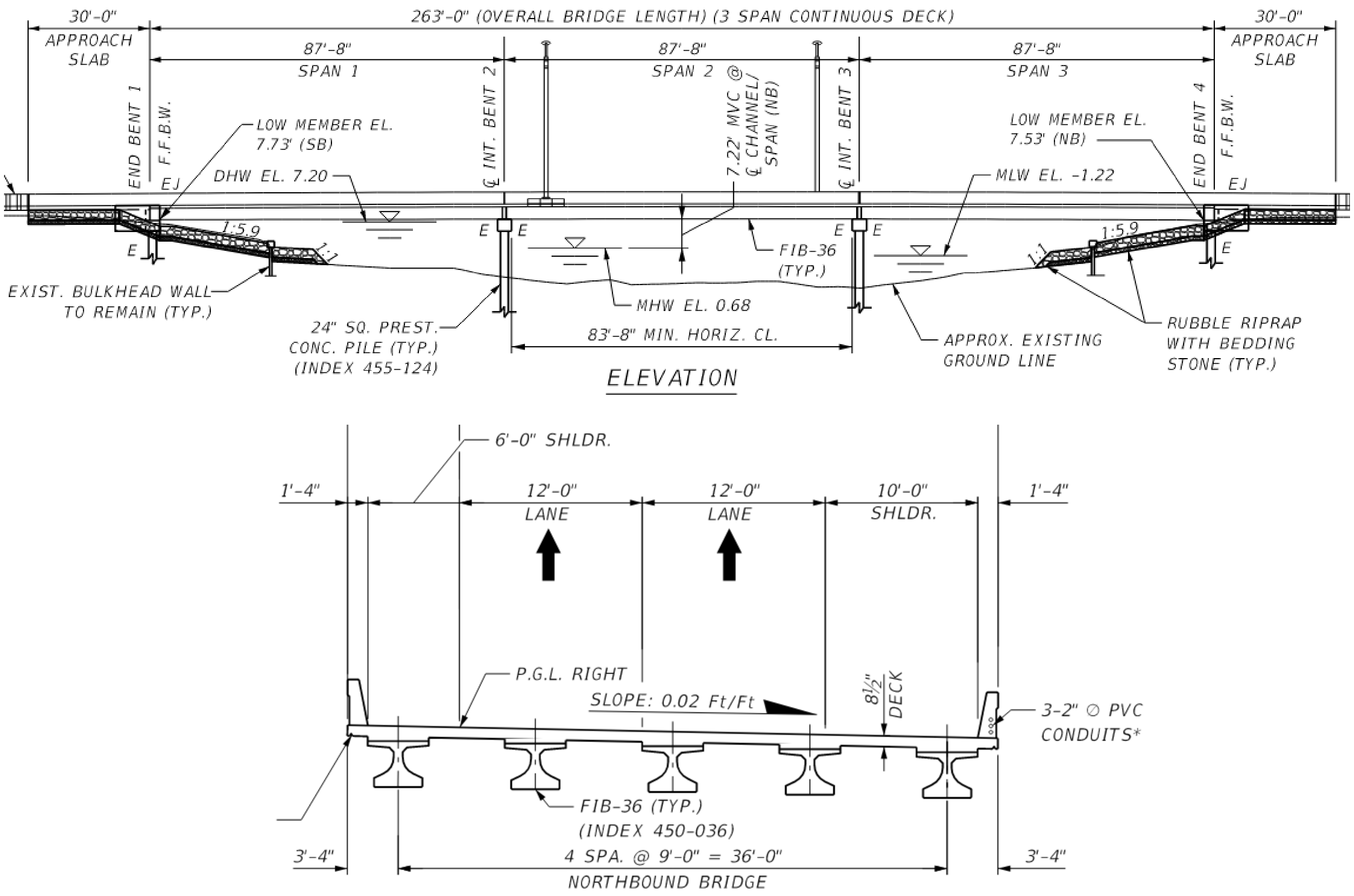
- Part 4 is intended for preliminary design of Precast Bent Cap connections with 3 options.

Part 4 will not be covered in this presentation.



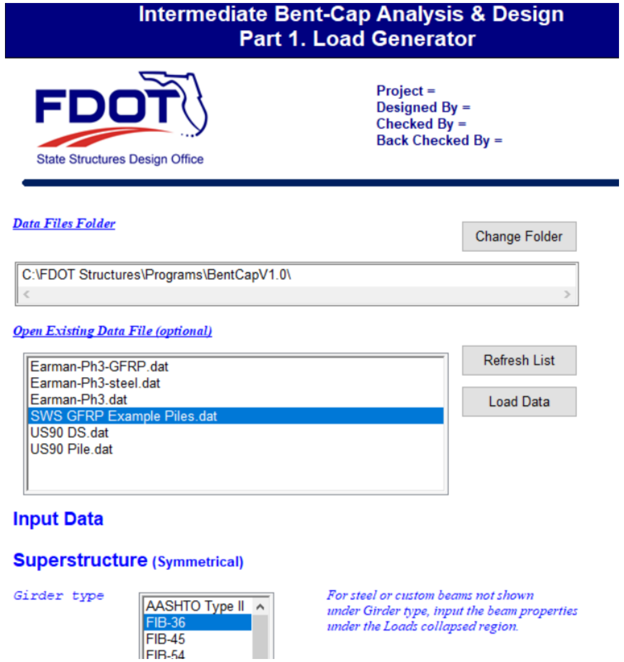
https://www.fdot.gov/structures/proglib.shtm

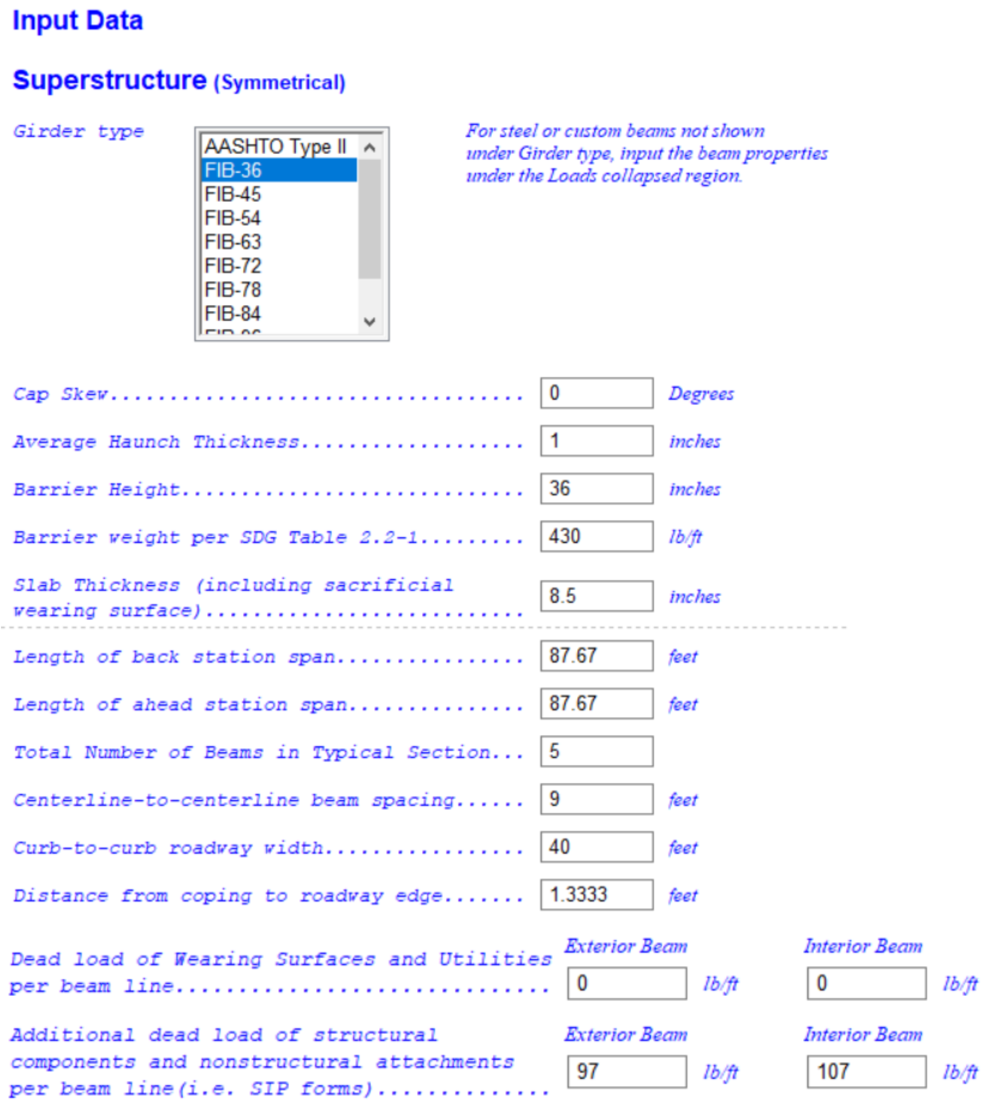
Design Example for Intermediate Pile Bent Cap



- **Inputs - Superstructure**
  - 0 skew
  - Girder = FIB-36 @ 9' spacing (5 total)
  - Haunch 1" (average)
  - Barrier Height = 36" (single-slope) 430 plf
  - Slab = 8.5" (includes 0.5" sacrificial)
  - Back Span = Forward Span = 87.67'
  - Curb-Curb width = 40'
  - Distance Coping to Roadway Edge = 1.333'
  - No Wearing Surface
  - Additional DL (SIP Forms)
    - Int Beam = 100 plf
    - Ext Beam = 50 plf

Design Example for Pile Bent Cap





- **Inputs - Superstructure**
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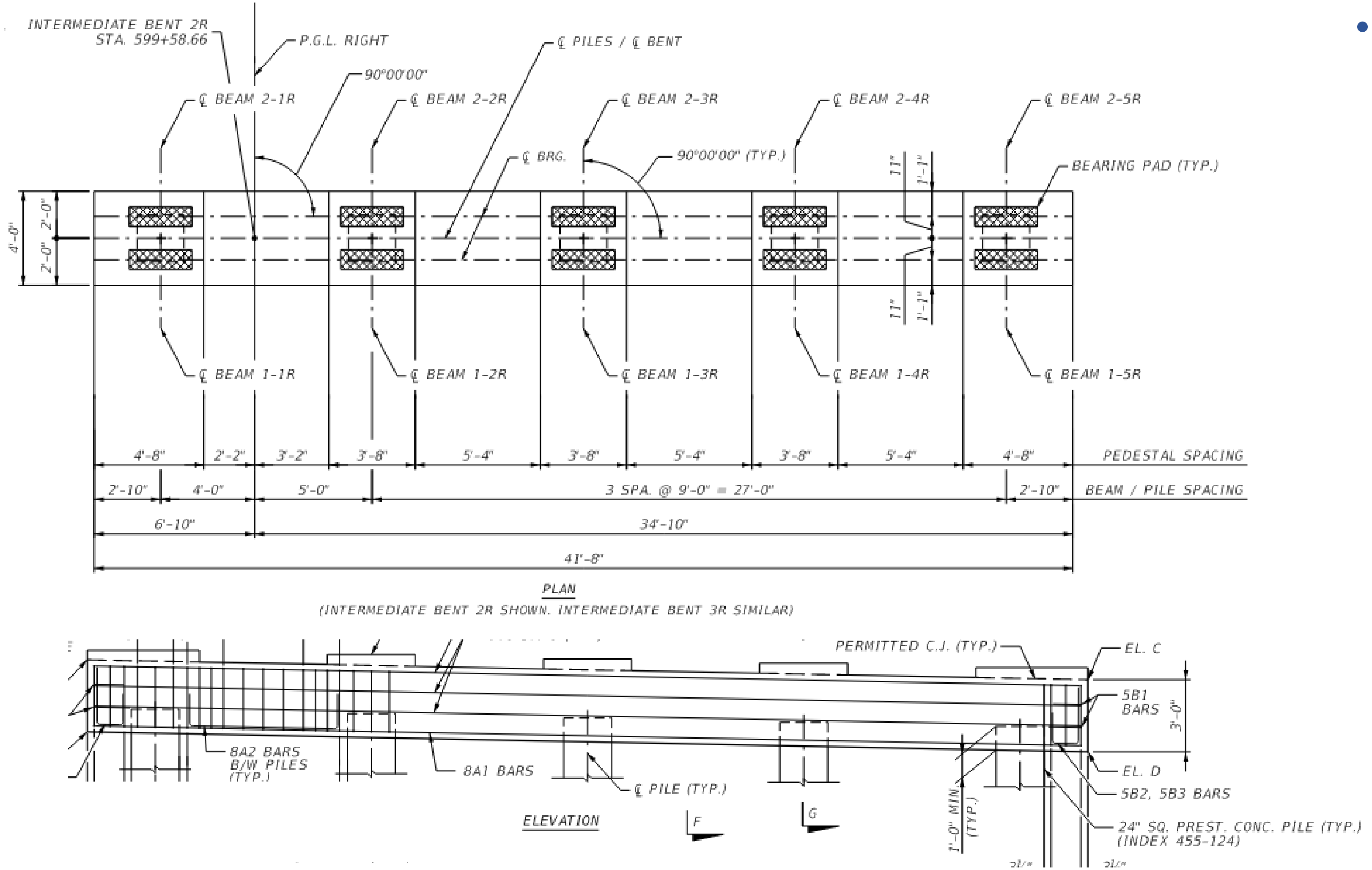
  - Distance Coping to Roadway Edge = 1.333’
  - No Wearing Surface
  - Additional DL (SIP Forms)
    - Int Beam = 100 plf
    - Ext Beam = 50 plf

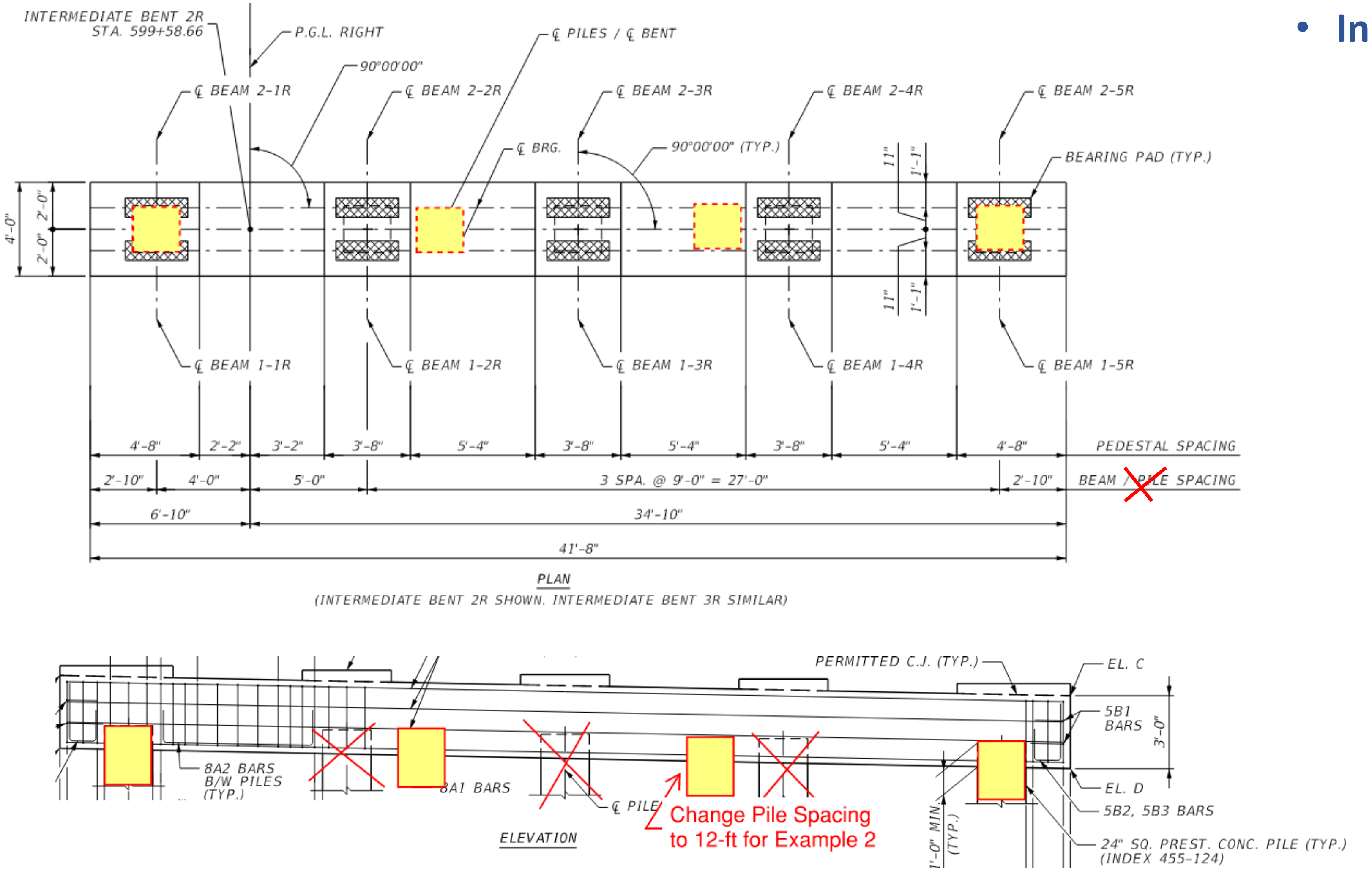
Part 1 - Load Generator

Design Example for Pile Bent Cap



- **Inputs – Substructure Example 1**
  - No. of columns = 5
  - Eff. Length columns = 40’
  - Column Spacing = 9.0’
  - Column Type = 2 (sq.)
  - Column Width = 24”
  - Cap Height = 36”
  - Cap Width = 48”
  - Cap Length = 41.67’
  - Avg. Pedestal Height = 3”
  - Ped. Width = 48”
  - Ped. Length = 44”
  - Bearing Pad Length = 32”
  - f’c Bent Cap = 5.5 ksi
  - f’c Columns = 6.0 ksi
  - Agg. Correction Factor = 1.0
  - Conc. Density for E_c = 0.145 kcf
  - Conc. Density for DL = 0.150 kcf

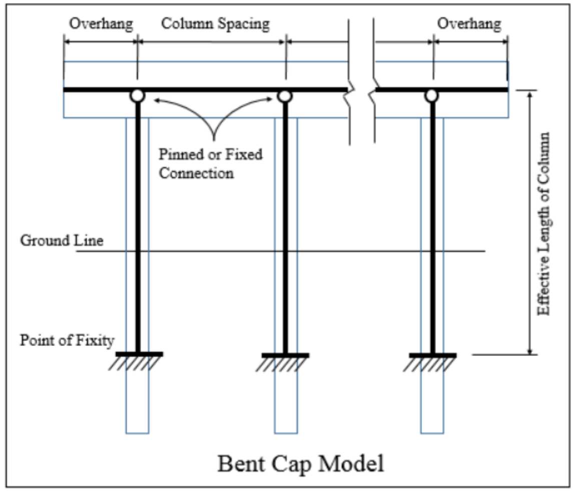
Design Example for Pile Bent Cap



- **Inputs – Substructure Example 2**
  - No. of columns = 4
  - Eff. Length columns = 40'
  - Column Spacing = 12.0'
  - Column Type = 2 (sq.)
  - Column Width = 24"
  - Cap Height = 36"
  - Cap Width = 48"
  - Cap Length = 41.67'
  - Avg. Pedestal Height = 3"
  - Ped. Width = 48"
  - Ped. Length = 44"
  - Bearing Pad Length = 32"
  - f'c Bent Cap = 5.5 ksi
  - f'c Columns = 6.0 ksi
  - Agg. Correction Factor = 1.0
  - Conc. Density for E_c = 0.145 kcf
  - Conc. Density for DL = 0.150 kcf

Design Example for Pile Bent Cap

Substructure (Symmetrical about CL of Superstructure)



Number of columns, minimum of 2 required...	5		
Effective length of columns...............	40	*feet*	*See bent cap model*
Column spacing...........................	9.0	*feet*	
Column type..............................	2	*1 = Round* *2 = Square*	

- **Bent Cap v1.0**

Column Diameter/Width......................	24	*inches*	
Cap Height................................	36	*inches*	
Cap Width.................................	48	*inches*	
Cap Length................................	41.67	*feet*	
Average pedestal height...................	3	*inches*	
Pedestal Width............................	48	*inches*	*In direction of cap width*
Pedestal Length...........................	44	*inches*	*In direction of cap length*
Beam bearing pad Length	32	*inches*	*In direction of cap length*
Min.28-day compressive strength for cap....	5.5	*ksi*	
Min.28-day compressive strength for cols...	6	*ksi*	
Correction factor for source of aggregate..	1.0		*[SDG 1.4.1]*
Concrete unit weight for calculating Ec....	0.145	*kcf*	
Concrete unit weight for calculating dead loads...............................	0.15	*kcf*	*[SDG Table 2.2-1]*

- **Inputs - Substructure**
  - No. of columns = 5 or 4
  - Eff. Length columns = 40.0’
  - Column Spacing = 9.0’ or 12’
  - Column Type = 2 (sq.)
  - Column Width = 24”
  - Cap Height = 36”
  - Cap Width = 48”
  - Cap Length = 41.67’
  - Avg. Pedestal Height = 3”
  - Ped. Width = 48”
  - Ped. Length = 44”
  - Bearing Pad Length = 32”
  - f’c Bent Cap = 5.5 ksi
  - f’c Columns = 6.0 ksi
  - Agg. Correction Factor = 1.0
  - Conc. Density for E_c = 0.145 kcf
  - Conc. Density for DL = 0.150 kcf

Design Example for Pile Bent Cap

Additional Input for Centrifugal Force (CE)

Radius of curvature of traffic lane........ 0 feet *Input a Radius of 0 for bridges with no horizontal curve.*

If the highway design speed is not specified, it should be conservatively taken as the maximum specified in the AASHTO publication, A Policy on Geometric Design of Highways and Streets (70 mph).

Highway design speed....................... 70 mph

The total CE load shall be distributed to bent caps based on the superstructure continuity and the relative stiffness of the bent caps in the direction of CE load.

Distribution Factor for CE load to intermediate bent cap .... 1 *Minimum 0 Maximum 1*

Additional Input for Braking Force (BR)

The total BR load shall be distributed to bent caps based on the superstructure continuity and the relative stiffness of the bent caps in the direction of BR load.

Distribution Factor for BR load to intermediate bent cap .... 0.25 *Minimum 0 Maximum 1*

Length of bridge for BR load calculation (length of lane load)...................... 263 feet *(typically length of continuous deck)*

Additional Input for Wind on Structure (WS)

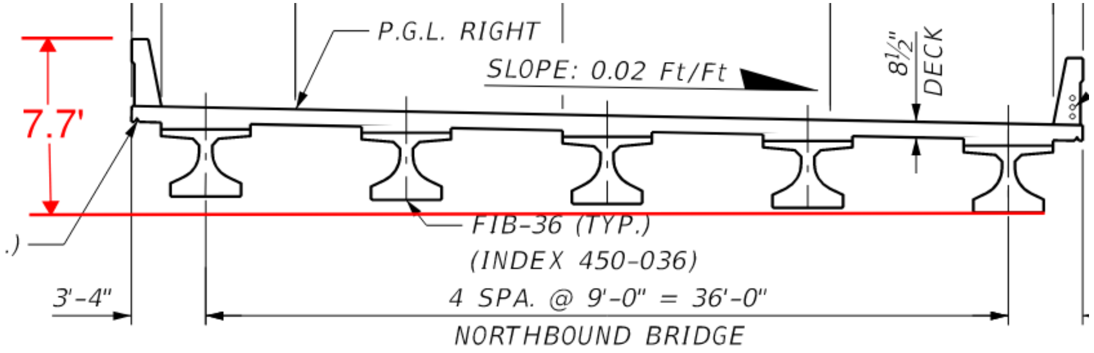
Low Member elevation....................... 7.9 feet

Elevation of low ground or water level..... -1.2 feet

Design Wind Speed (mph) per SDG 2.4.1...... 150 mph

Total depth of superstructure (barrier, deck, haunch, beam and superelevation)..... 8 feet

- **Inputs – Additional (CE, BR, & WS)**
  - Radius of Curvature for CE = 0’
  - Highway Speed for CE = n/a (70 mph)
  - Distribution CE load = n/a (1.0)
  - Distribution BR load = 0.25
  - Length bridge for BR load = 263’
  - Low Member Elev. = EL. +7.9 (avg.)
  - Low Water Level or Ground = EL. -1.2
  - Design Wind Speed = 150 mph
  - Total Depth of Superstructure = 8.0’



Design Example for Pile Bent Cap

Additional Input for Water Load (WA)

NOTES:

- *Current version of Load Generator focuses on design and analysis of Bent-Cap, which is typically controlled by Strength I and Service I, III limit states with water load of 100 year Basic Flood. The flood elevation is typically below the bottom of cap. Thus, calculation of WA is omitted in current version.*
- *To consider WA load (e.g. existing bridges with flood elevation above the bottom of cap), directly input the WA load acting on the bent-cap that is under consideration.*

100 year event: parallel to the bent-cap...	0	kip
100 year event: perpendicular to the bent-cap	0	kip
500 year event: parallel to the bent-cap...	0	kip
500 year event: perpendicular to the bent-cap	0	kip

Additional Input for Force Effect due to Uniform Temperature (TU)

NOTES:

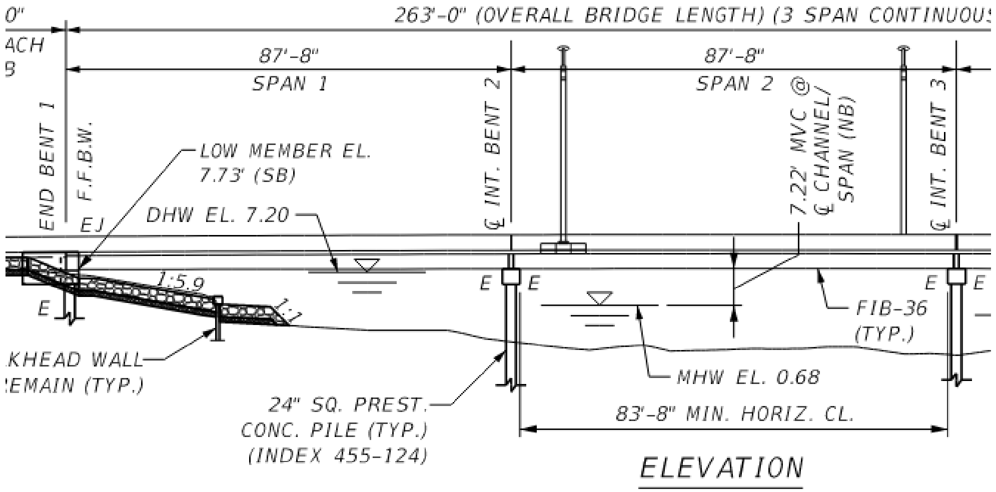
- *TU load is typically perpendicular to the plane of bent-cap and thus resisted by cantilever columns. Calculation of TU is omitted in current version.*
- *To consider TU load (e.g. bridges with big skew), directly input the TU load acting on the bent-cap that is under consideration.*

TU load in the longitudinal direction of the bridge	0	kip

The current version only performs transverse loading analysis. However, there are inputs and place holders for future longitudinal analysis enhancements.

- **Inputs – Additional (WA & TU)**
  - 100-year event: parallel to bent-cap = 0 kips
  - 100-year event: perp. to bent-cap = 0 kips
  - 100-year event: parallel to bent-cap = 0 kips
  - 100-year event: perp. to bent-cap = 0 kips
  - Longitudinal TU load = 0 kips

IGNORE THESE FOR THIS EXAMPLE



Design Example for Pile Bent Cap

Correction needed to Fatigue Load combination:

- Live Load Factor increased from 1.5 to 1.75 in 8th Edition of AASHTO LRFD BDS.

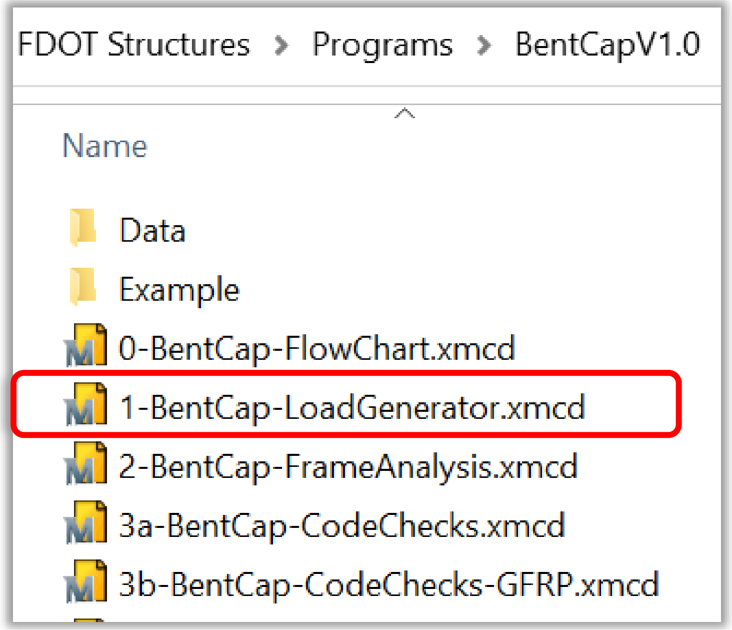
Strength, Service and Extreme Event Limit States

Load factors per LRFD Table 3.4.1-1 and SDG Table 2.4.1-1:

γs :=

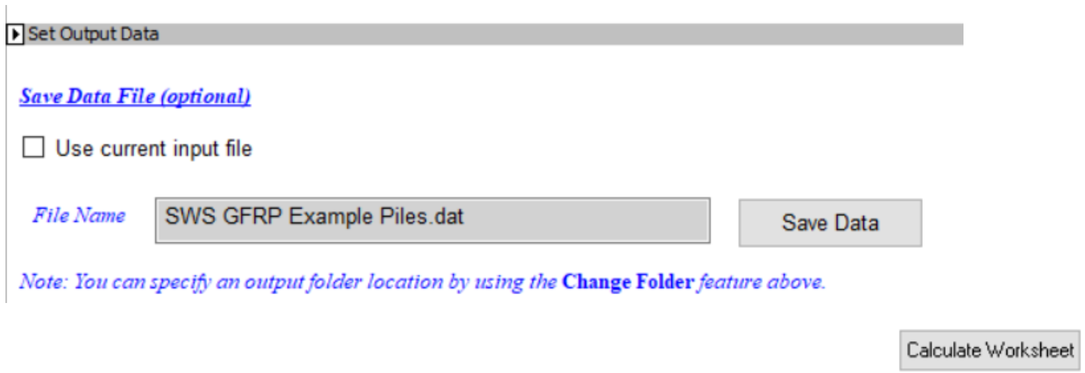
DC	DW	LL	CE	BR	WA	WS	WL	TU	
1.25	1.5	1.75	1.75	1.75	1.0	0.0	0.0	1.2	"Strength I max vertical"
1.25	1.5	0.0	0.0	0.0	1.0	1.0	0.0	1.2	"Strength III max vertical"
1.25	1.5	1.35	1.35	1.35	1.0	1.0	1.0	1.2	"Strength V max vertical"
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2	"Service I"
1.0	1.0	0.8	0.8	0.8	1.0	0.0	0.0	1.2	"Service III"
1.0	1.0	0.2	0	0	0	0	0	0	"Sustained load: DL+0.2LL"
0.9	1.5	1.75	1.75	1.75	1.0	0.0	0.0	1.2	"Strength I min vertical"
0.9	1.5	0.0	0.0	0.0	1.0	1.0	0.0	1.2	"Strength III min vertical"
0.9	1.5	1.35	1.35	1.35	1.0	1.0	1.0	1.2	"Strength V min vertical"
1.0	1.0	1.75	0	0	0	0	0	0	"DL+Fatigue I"

Fatigue I LL factor increased from 1.5 to 1.75 in 8th Edition

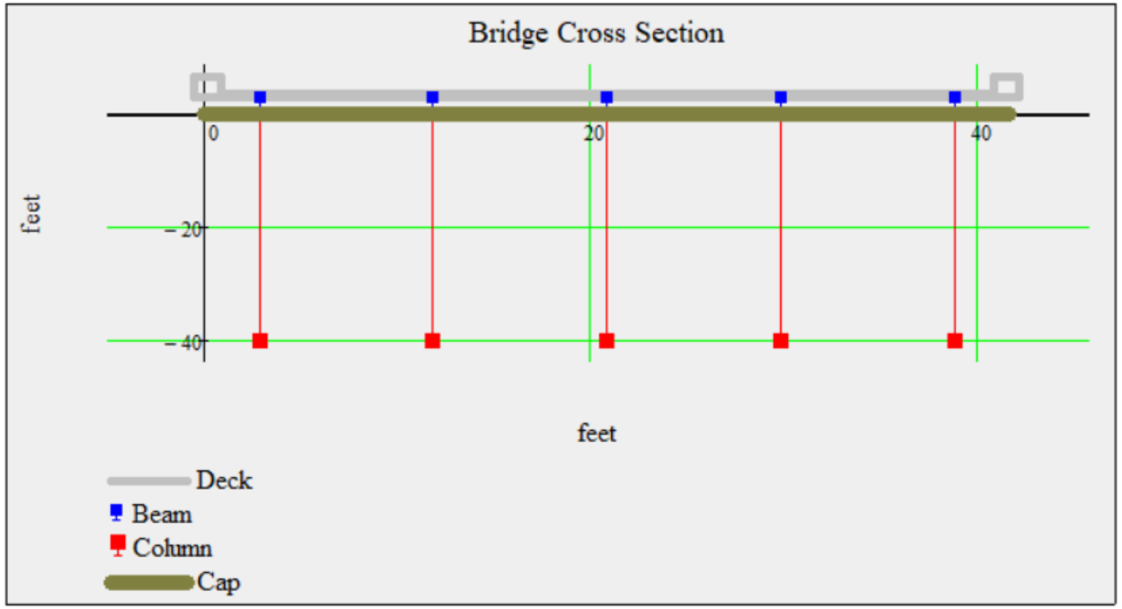


Part 1 - Load Generator

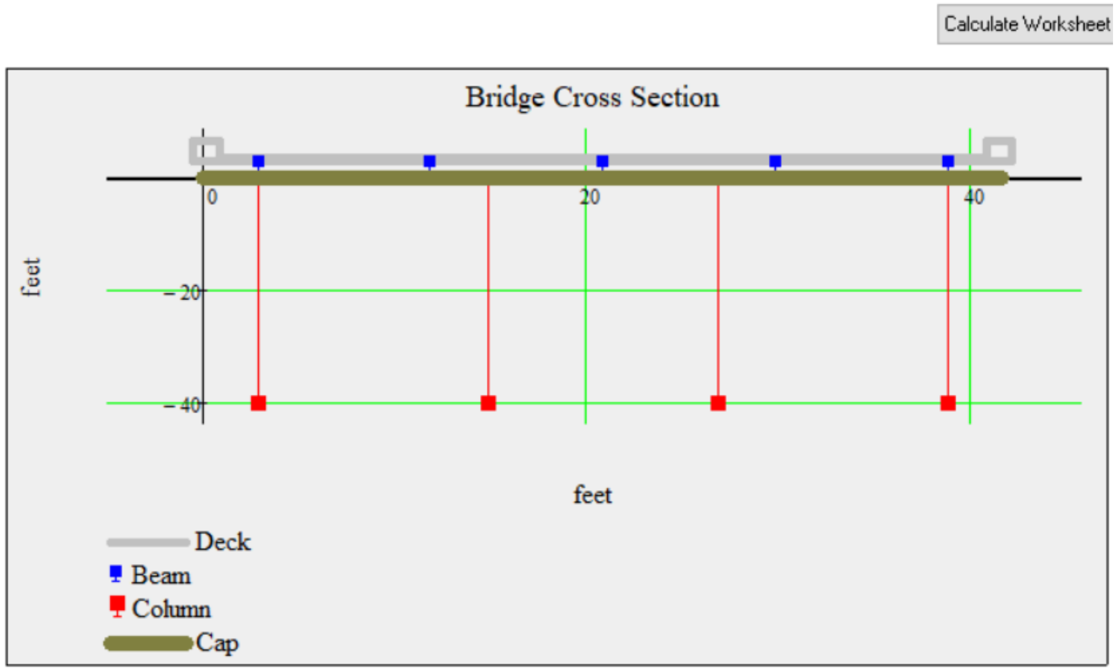
Design Example for Pile Bent Cap



- → **Save Data File**
- → **Calculate Worksheet**
- **Visually Check Inputs** and Wheel load positioning



Example 1 – 5 Piles @ 9' Spacing



Example 2 – 4 Piles @ 12' Spacing

FDOT TRANSPORTATION SYMPOSIUM

Design Example for Pile Bent Cap

Graphical Display of Wheel Loads

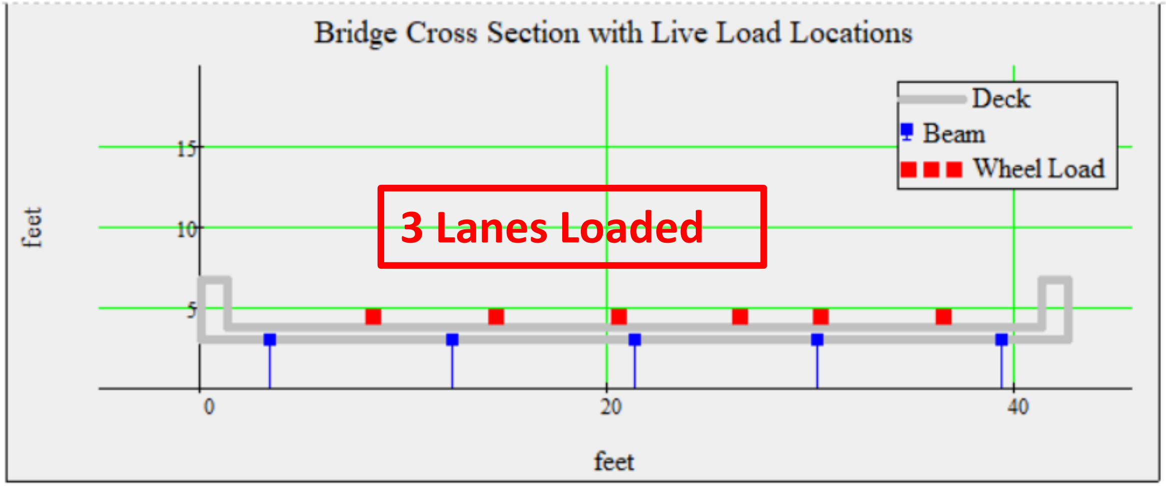
Choose a specific location (increment) to display the wheel load locations

Increment = 54

Choose the number of lanes loaded to display (up to 3 loaded lanes)

#LanesLoaded = 3

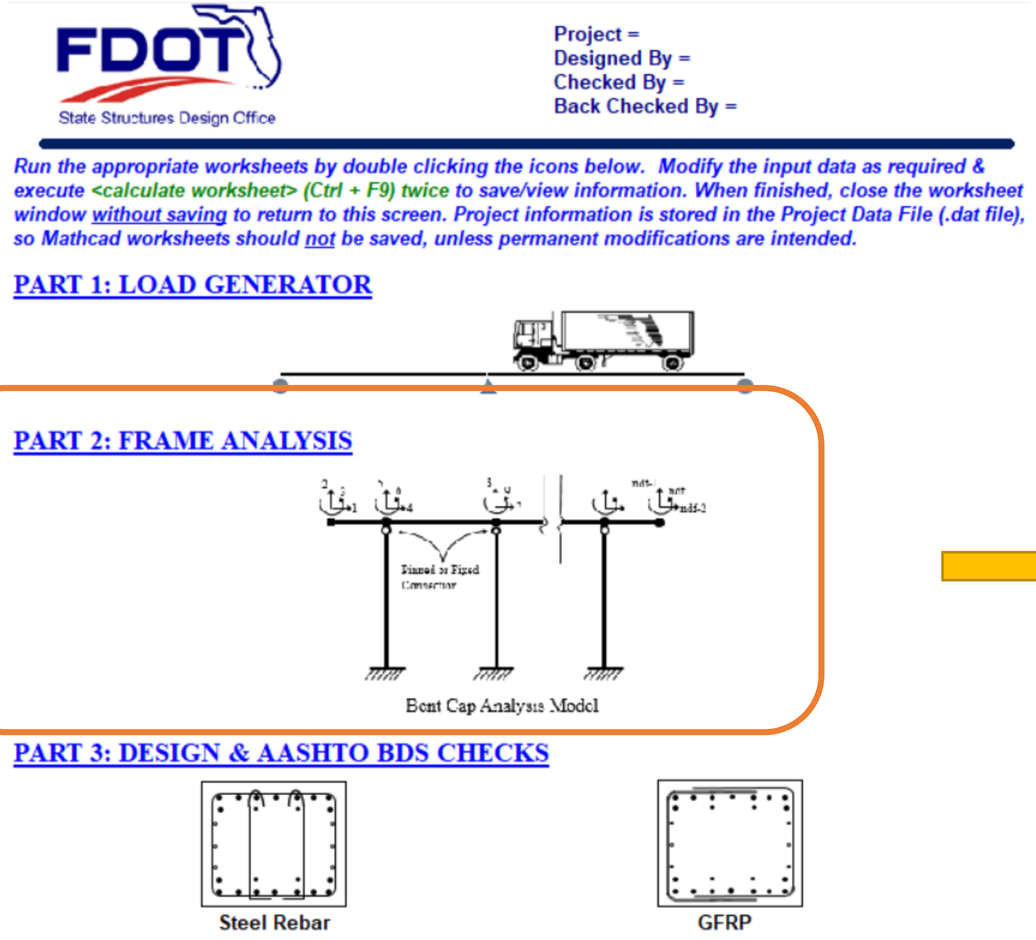
Set Variables to Display LL



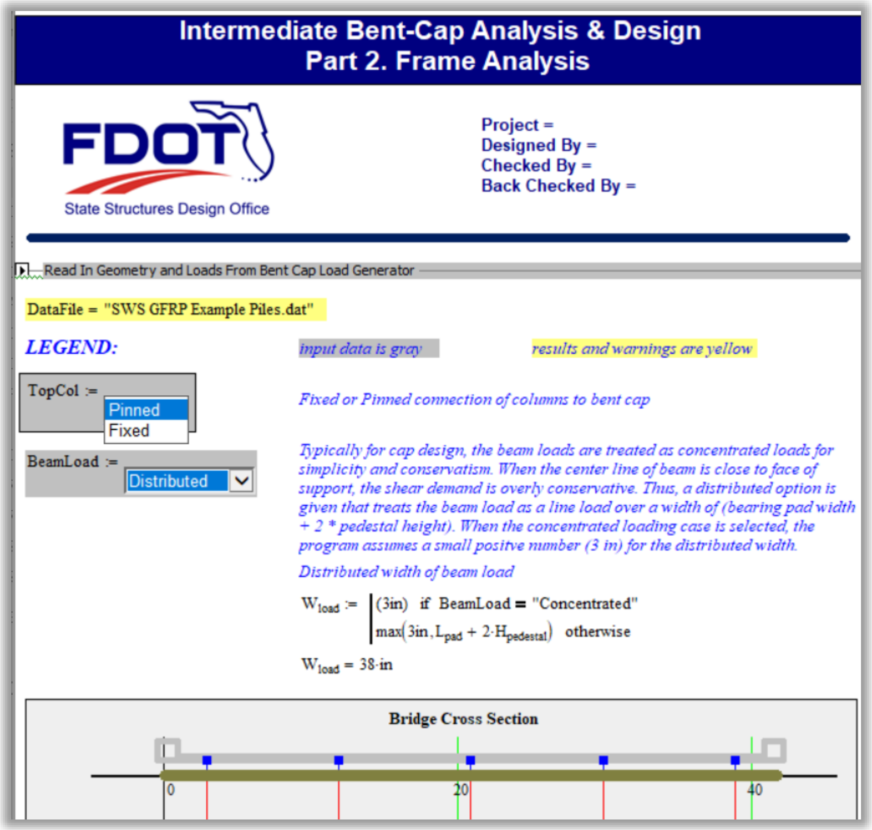
Example 1 – 5 Piles @ 9’ Spacing

- Save Data File
- Calculate Worksheet
- **Visually** Check Inputs and **Wheel load positioning**

Design Example for Pile Bent Cap



- **Inputs – Frame Analysis**
  - Top of Column Connection = **Pinned** or **Fixed**
  - Beam Load Distribution to Cap = **Concentrated** or **Distributed**

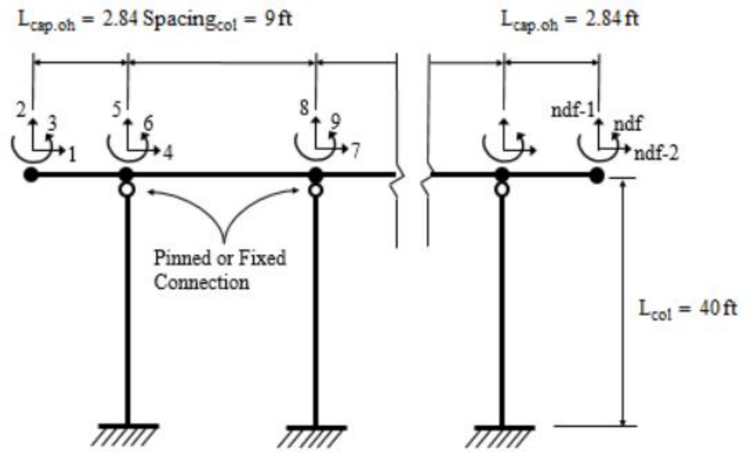


Part 2 – Frame Analysis

FDOT TRANSPORTATION SYMPOSIUM

Design Example for Pile Bent Cap

Model



Bent Cap Analysis Model

$\#Beams = 5$	*Number of beams*
$Spacing_{beam} = 9\,ft$	*Spacing of beams (along length of cap)*
$\#Cols = 5$	*A minimum of two columns required*
$Spacing_{col} = 9\,ft$	*Spacing of columns*
$L_{cap} = 41.67\,ft$	*Length of cap*
$L_{cap.oh} = 2.84\,ft$	*See Bent Cap Model (minimum length is half of column width*
$f_{c.cap} = 5.5 \cdot ksi$	*Min.28-day compressive strength for cap*
$E_{cap} = 4428 \cdot ksi$	*Modulus of elasticity of cap*
$W_{cap} = 4\,ft$	*Width of cap*
$H_{cap} = 3\,ft$	*Height of cap*
$A_{cap} = 1728 \cdot in^2$	*Cross sectional area of cap beam*

- **Frame Analysis - Inputs**
  - Top of Column Connection = **Pinned** or **Fixed**
  - Beam Load Distribution to Cap = **Concentrated** or **Distributed**

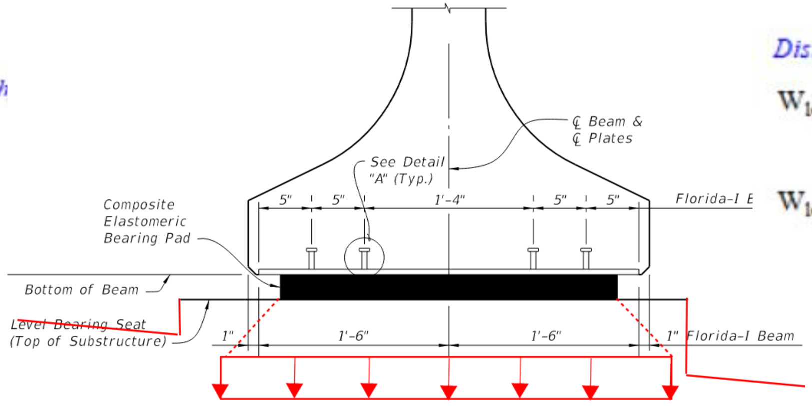
Structures Design Guidelines — Topic No. 625-020-018
3 - Substructure and Retaining, Noise and Perimeter Walls — January 2022

3.5 PILES

3.5.1 Prestressed Concrete Piles (LRFD 5.12.9.4) (Rev. 01/22)

A. For prestressed piling not subjected to significant flexure under service or impact loading, design strand development in accordance with ***LRFD*** 5.9.4.3 and 5.7.2.2. Bending that produces cracking in the pile, such as that resulting from ship impact loading, is considered significant. Comply with the tensile stress limits in ***LRFD*** 5.9.2.3.2b for all piling and apply the "severe corrosive conditions" to substructures with an Extremely Aggressive environment classification.

B. A 1-foot embedment is considered a pinned head condition. For the pinned pile head condition the strand development must be in accordance with ***LRFD*** 5.9.4.3 and 5.7.2.2.



END ELEVATION
WITHOUT BEVELED BEARING PLATE

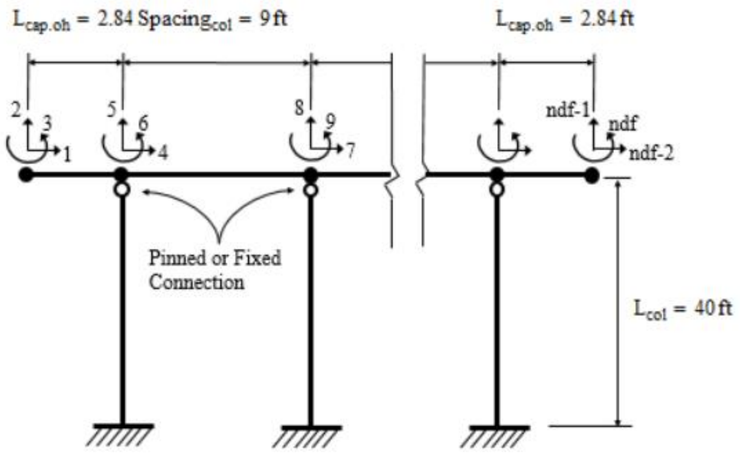
Distributed width of beam load

$$W_{load} := \begin{cases} (3in) & \text{if } BeamLoad = \text{"Concentrated"} \\ \max(3in, L_{pad} + 2 \cdot H_{pedestal}) & \text{otherwise} \end{cases}$$

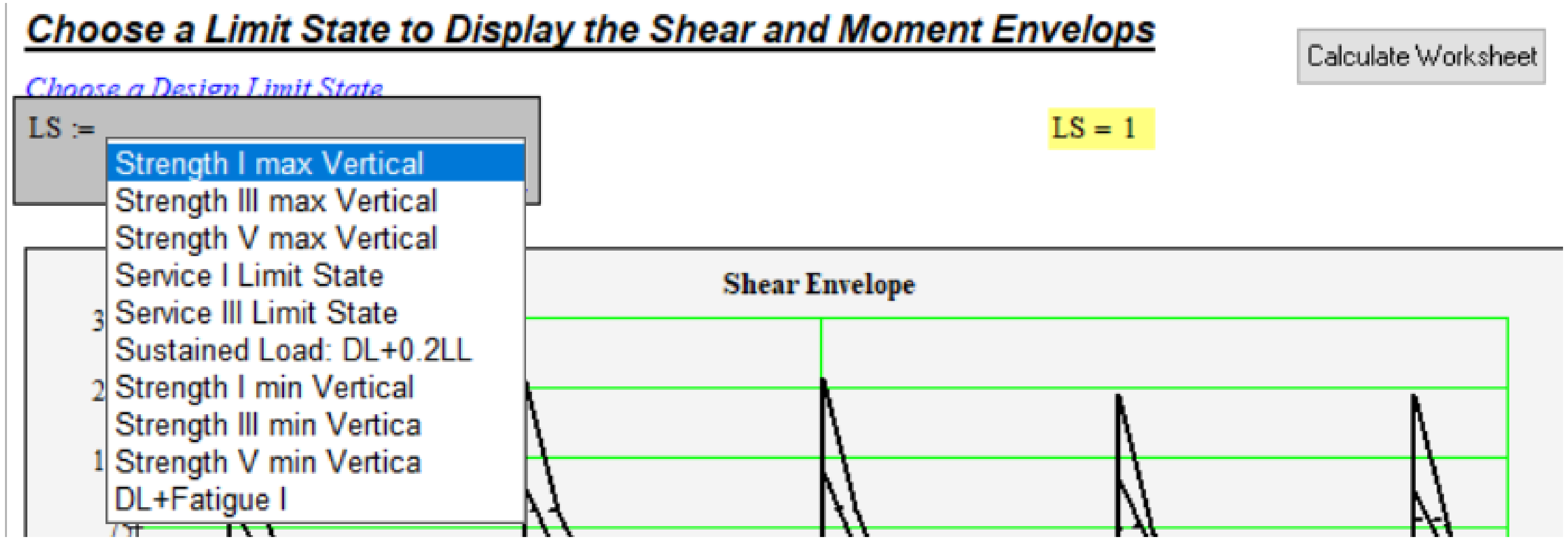
$$W_{load} = 38 \cdot in$$

Design Example for Pile Bent Cap

Model



Bent Cap Analysis Model



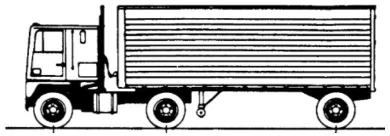
- **Frame Analysis**
  - → **Calculate Worksheet**
  - → Select **Limit State** to view **Shear & Moment Envelopes**

Table 3.4.1-1—Load Combinations and Load Factors

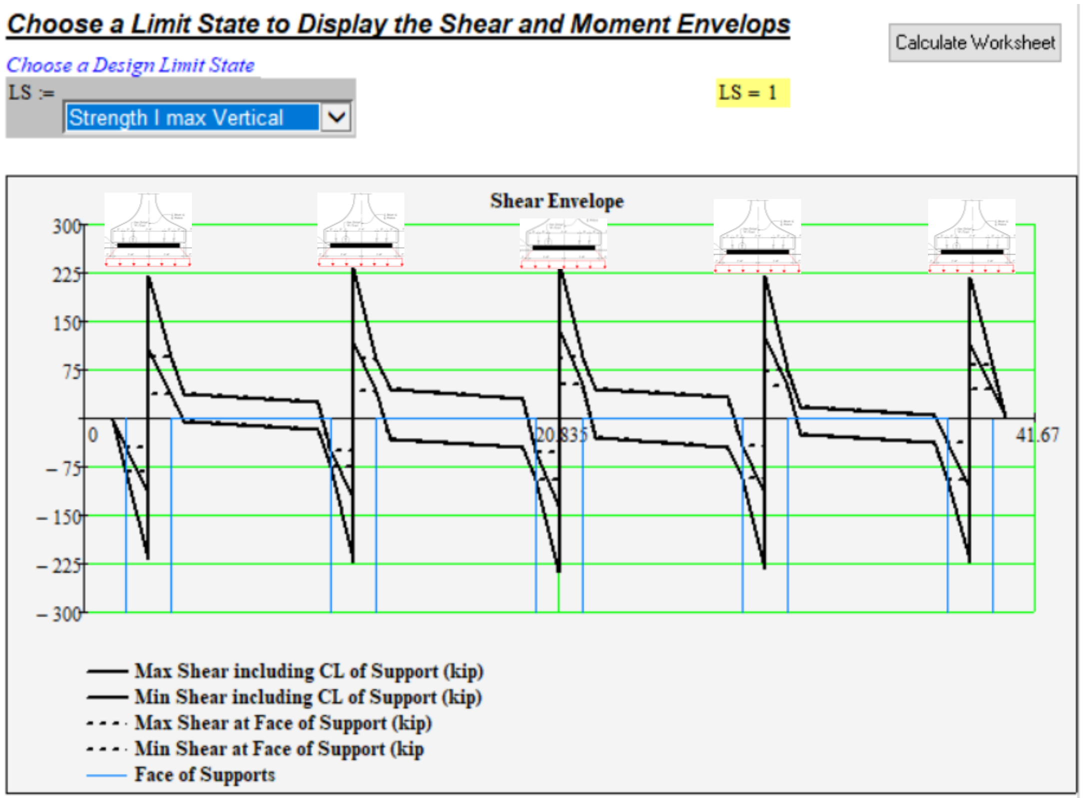
Load Combination Limit State	*DC DD DW EH EV ES EL PS CR SH*	*LL IM CE BR PL LS*	*WA*	*WS*	*WL*
Strength I (unless noted)	γ_p	1.75	1.00	—	—
Strength II	γ_p	1.35	1.00	—	—
Strength III	γ_p	—	1.00	1.00	—
Strength IV	γ_p	—	1.00	—	—
Strength V	γ_p	1.35	1.00	1.00	1.00
Extreme Event I	1.00	γ_{EQ}	1.00	—	—
Extreme Event II	1.00	0.50	1.00	—	—
Service I	1.00	1.00	1.00	1.00	1.00
Service II	1.00	1.30	1.00	—	—
Service III	1.00	γ_{LL}	1.00	—	—
Service IV	1.00	—	1.00	1.00	—
Fatigue I— *LL, IM & CE* ~~only~~	—	1.75	—	—	—

+ DL for GFRP-RC Only

Design Example for Pile Bent Cap

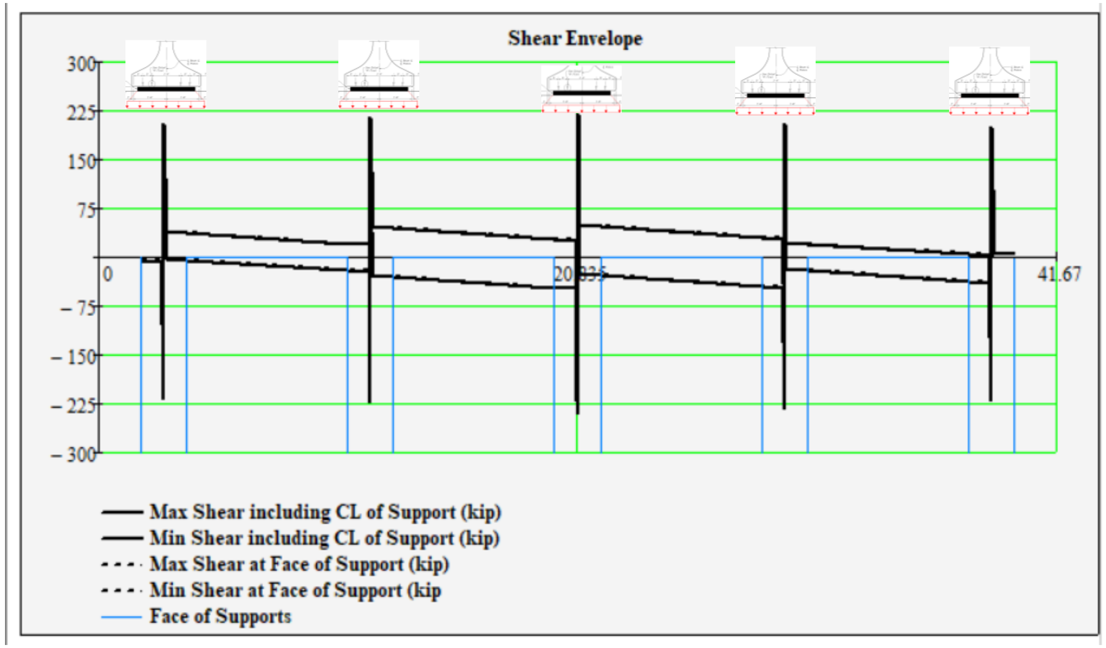


Pinned & Distributed
(Shear: Strength I)



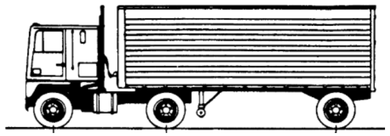
- **Frame Analysis - Inputs**
  - Top of Column Connection = **Pinned** or Fixed
  - Beam Load Distribution to Cap = **Concentrated** or **Distributed**

Pinned & Concentrated
(Shear: Strength I)

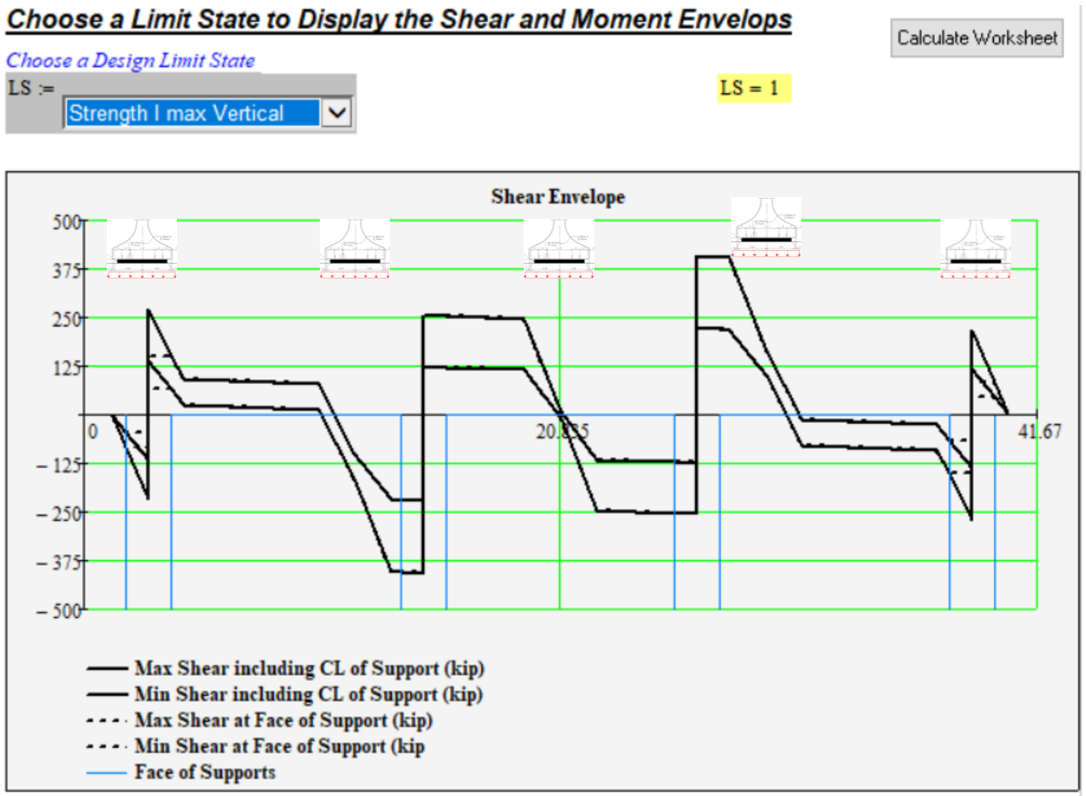


Example 1 – 5 Piles @ 9' Spacing

Design Example for Pile Bent Cap

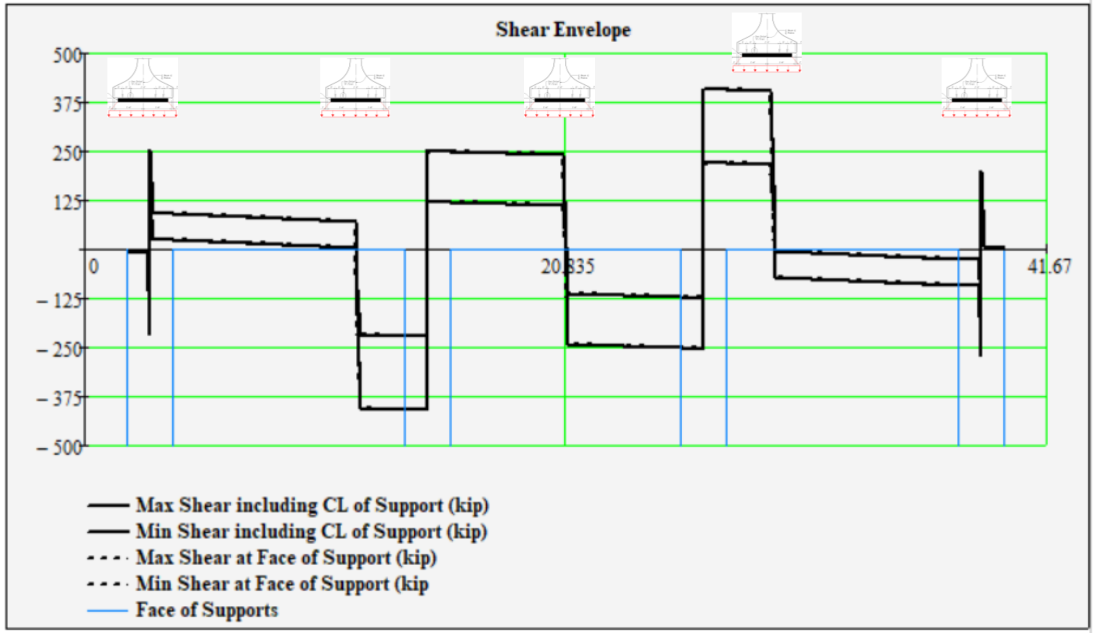


Pinned & Distributed
(Shear: Strength I)



- **Frame Analysis - Inputs**
  - Top of Column Connection = **Pinned** or **Fixed**
  - Beam Load Distribution to Cap = **Concentrated** or **Distributed**

Pinned & Concentrated
(Shear: Strength I)



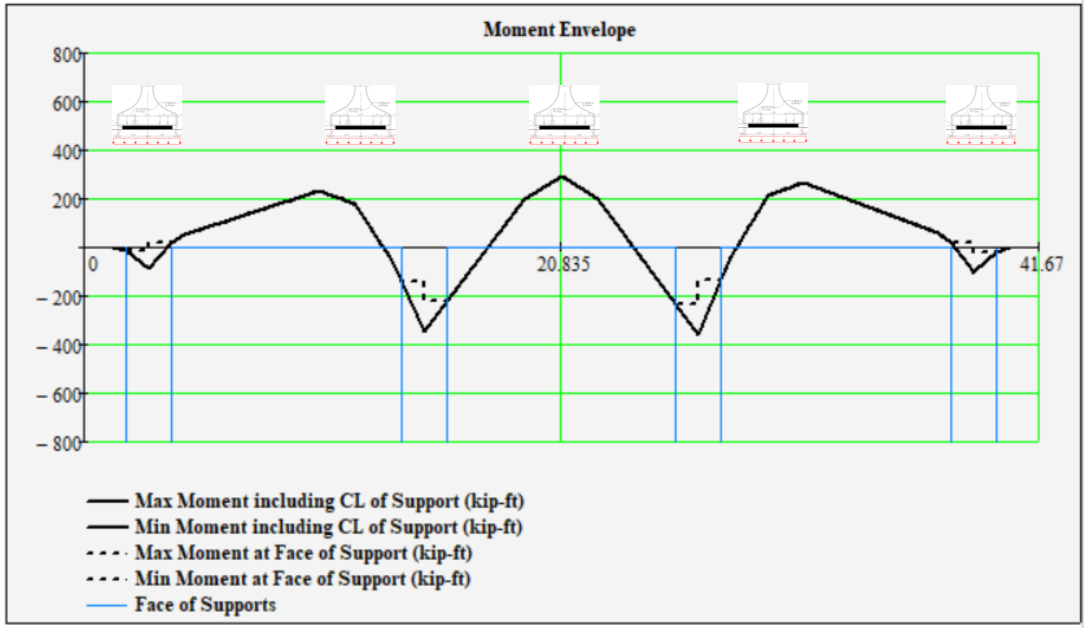
Example 2 – 4 Piles @ 12' Spacing

Design Example for Pile Bent Cap

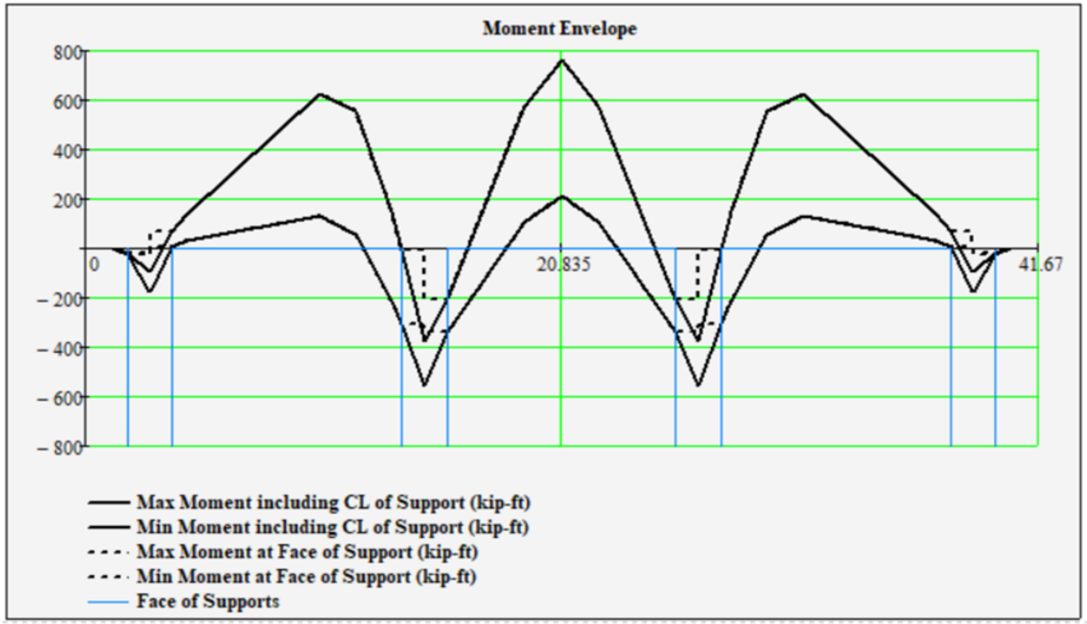
CONTINUE WITH Example 2 – 12' Pile Spacing
Using the conditions

- **Frame Analysis**
  - Top of Column Connection = **Pinned**
  - Beam Load Distribution to Cap = **Distributed**

Pinned & Distributed
(Moment: Strength III)



Pinned & Distributed
(Moment: Strength I)



Example 2 – 4 Piles @ 12' Spacing

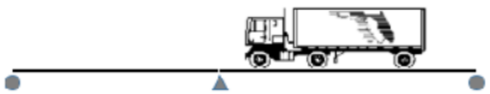
Design Example for Pile Bent Cap

Project =
Designed By =
Checked By =
Back Checked By =

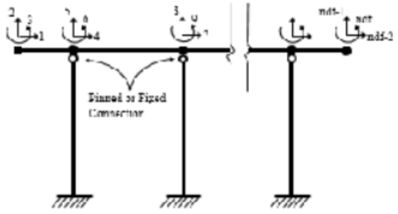
State Structures Design Office

Run the appropriate worksheets by double clicking the icons below. Modify the input data as required & execute <calculate worksheet> (Ctrl + F9) twice to save/view information. When finished, close the worksheet window without saving to return to this screen. Project information is stored in the Project Data File (.dat file), so Mathcad worksheets should not be saved, unless permanent modifications are intended.

PART 1: LOAD GENERATOR

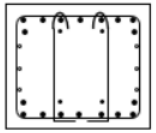


PART 2: FRAME ANALYSIS

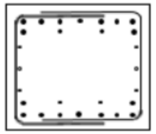


Bent Cap Analysis Model

PART 3: DESIGN & AASHTO BDS CHECKS



Steel Rebar



GFRP

- **Design – GFRP Reinforcing**

  → Load Data

Intermediate Bent-Cap Analysis & Design
Part 3. Code Checks (GFRP)

State Structures Design Office

Project =
Designed By =
Checked By =
Back Checked By =

Read In Geometry and Design Loads

DataFile = "SWS GFRP Example2 Piles.dat"   Load Data

GFRP Design References

- *FDOT Structures Manual, Volume 4, 2018*
- *FDOT Specifications Section 932-3, July 2018*
- *AASHTO Bridge Design Specifications for GFRP Reinforced Concrete, 2nd Edition*

Bent Cap and Column Properties

$H_{cap} = 3\,ft$	*Height of bent cap*
$W_{cap} = 4\,ft$	*Width of bent cap*
$L_{cap} = 41.67\,ft$	*Length of bent cap*
$L_{cap.oh} = 2.84\,ft$	*Length of cap overhang*
$W_{col} = 2\,ft$	*Column diameter/width*
ColType = 2	*Column type: 1-round; 2-square*
#Cols = 4	*Number of columns*

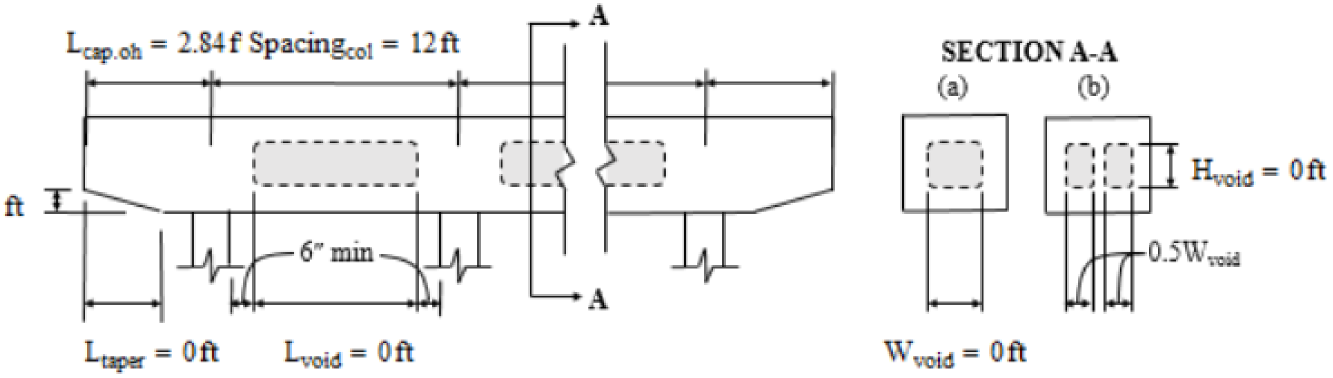
Part 3 – Design & AASHTO Checks

Design Example for Pile Bent Cap

Tapered Ends/Voids in Bent Cap (input 0 if not applicable)

Height of taper..................	0	ft
Length of taper..................	0	ft
Height of void...................	0	ft
Width of void....................	0	ft
Length of void...................	0	ft

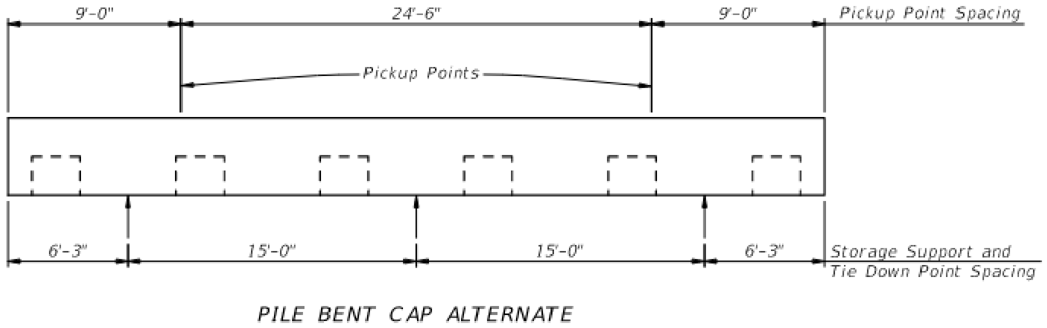
- **Inputs - Tapered Ends and Internal Voids**
  - N/A for Example 2
  - *Internal Voids are only intended for precast bents to reduce handling weights.*



2-Point Support/Pickup Locations (for Precast Bent Cap only, input 0 if not applicable)

Distance of support/pick-up location to cap end...............	0	ft

- **Inputs – Support/Pickup Points**
  - N/A for Example 2 (precast only)



Design Example for Pile Bent Cap

GFRP Material and Design Properties

C_E = Environmental reduction factor ... 0.7 *[AASHTO Table 2.4-1]*

E_f = Tensile modulus of elasticity..... 6500 *ksi* *[FDOT Specs 932]*

Nominal Area of GFRP reinforcing bars [FDOT Spec 932-3]

$$A(Bar) := \begin{cases} 0.049in^2 & \text{if } Bar = 2 \\ 0.11in^2 & \text{if } Bar = 3 \\ 0.20in^2 & \text{if } Bar = 4 \\ 0.31in^2 & \text{if } Bar = 5 \\ 0.44in^2 & \text{if } Bar = 6 \\ 0.60in^2 & \text{if } Bar = 7 \\ 0.79in^2 & \text{if } Bar = 8 \\ 1.00in^2 & \text{if } Bar = 9 \\ 1.27in^2 & \text{if } Bar = 10 \\ 0 & \text{otherwise} \end{cases}$$

Minimum Guaranteed Tensile Load of GFRP reinforcing bars [FDOT Spec 932-3]

$$P_T(Bar) := \begin{cases} 6.1kip & \text{if } Bar = 2 \\ 13.2kip & \text{if } Bar = 3 \\ 21.6kip & \text{if } Bar = 4 \\ 29.1kip & \text{if } Bar = 5 \\ 40.9kip & \text{if } Bar = 6 \\ 54.1kip & \text{if } Bar = 7 \\ 66.8kip & \text{if } Bar = 8 \\ 82.0kip & \text{if } Bar = 9 \\ 98.2kip & \text{if } Bar = 10 \\ 0 & \text{otherwise} \end{cases}$$

Tensile Strength of GFRP reinforcing bars

$$f_{fu}(Bar) := \frac{P_T(Bar)}{A(Bar)}$$

- **Inputs – GFRP Material & Design Properties**
  - Environmental Reduction Factor = 0.7
  - Tensile Modulus of Elasticity = 6,500 ksi
  - Rebar Properties = ***Specification 932-3***

Table 932-6
Sizes and Tensile Loads of FRP Reinforcing Bars

Bar Size Designation	Nominal Bar Diameter (in)	Nominal Cross Sectional Area (in²)	Measured Cross-Sectional Area (in²)		Minimum Guaranteed Tensile Load (kips)		
			Minimum	Maximum	BFRP and GFRP Bars	CFRP (Type II) Single & 7-Wire Strands	CFRP (Type I) Bars
2.1-CFRP	0.21	0.028	0.026	0.042	-	7.1	-
2	0.250	0.049	0.046	0.085	6.1	-	10.3
2.8-CFRP	0.280	0.051	0.048	0.085	-	13.1	-
3	0.375	0.11	0.104	0.161	13.2	-	20.9
3.8-CFRP	0.380	0.09	0.087	0.134	-	23.7	-
4	0.500	0.20	0.185	0.263	21.6	-	33.3
5	0.625	0.31	0.288	0.388	29.1	-	49.1
6	0.750	0.44	0.415	0.539	40.9	-	70.7
6.3-CFRP	0.630	0.19	0.184	0.242	-	49.8	-
7	0.875	0.60	0.565	0.713	54.1	-	-
7.7-CFRP	0.770	0.29	0.274	0.355	-	74.8	-
8	1.000	0.79	0.738	0.913	66.8	-	-
9	1.128	1.00	0.934	1.137	82.0	-	-
10	1.270	1.27	1.154	1.385	98.2	-	-

Design Example for Pile Bent Cap

- **Inputs – Critical Section for Negative Moment**
  - 1 = at Centerline of Support/Pile
  - 2 = at Face of Support/Pile

Design Loads - Moments and Shears (Torques not considered)

Critical section for shear should be at face of support.

Conservatively take design negative moment at the CL of support; Except for bent caps built integrally with supports (full moment connection), design may be based on the moments at face of support.

Critical section for flexural design.. [1] *1 - at center line of support*
2 - at face of support

Reinforcement (Symmetrical to CL of Bent Cap)

A few recommendations on bar size and spacing are available to minimize problems during casting.

- *Use the same size and spacing of reinforcing for both the negative and positive moment regions. This minimizes construction errors where the top steel is mistakenly placed at the bottom or vice versa.*
- *If this arrangement is not possible, give preference to maintaining the same spacing between the top and bottom reinforcement. Same grid pattern allows grouted ducts placement and the concrete vibrator to be more effective in reaching the full depth of the cap, especially for multi-layer reinforcing.*

Design Example for Pile Bent Cap

Correction needed for Bend Radius #2 thru #7 bars

GFRP Material and Design Properties

Diameter of GFRP reinforcing bars [FDOT Specs 932]

d(Bar) := | 1.128·in if Bar = 9
1.27·in if Bar = 10
$\frac{Bar}{8}$·in otherwise

Bend radius of GFRP reinforcing bars [FDOT Developmental Standards D21310]

r(Bar) := | 1.5in if Bar = 2
2.25in if Bar = 3
2.25in if Bar = 4
2.25in if Bar = 5
2.25in if Bar = 6
3in if Bar = 7
3in if Bar = 8
4.5in if Bar = 9
5in if Bar = 10
0 otherwise

Bend radius of GFRP reinforcing bars [FDOT ~~Developmental Standards D21310~~ Standard Plans Index 415-010]

r(Bar) := | 0.75in if Bar = 2
1.125in if Bar = 3
1.5in if Bar = 4
1.875in if Bar = 5
2.25in if Bar = 6
2.75in if Bar = 7
3in if Bar = 8
4.5in if Bar = 9
5in if Bar = 10
0 otherwise

D7957

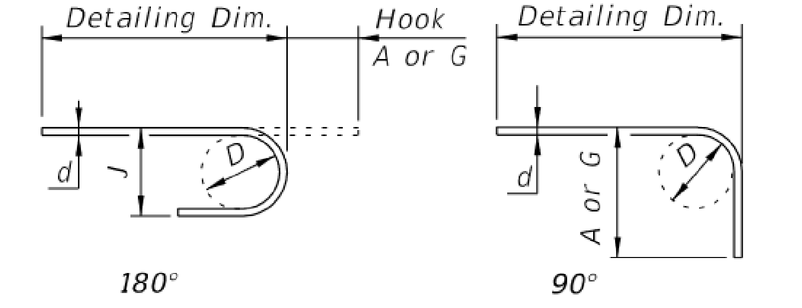
TABLE 4 Minimum Inside Bend Diameter of Bent Bars[A]

Bar Designation, mm [U.S. Standard]	Minimum Bend Diameter mm [in.]
M6 [2]	38 [1.50]
M10 [3]	58 [2.25]
M13 [4]	76 [3.00]
M16 [5]	96 [3.75]
M19 [6]	114 [4.50]
M22 [7]	134 [5.25]
M25 [8]	152 [6.00]

[A]Bent bars of designation M29 [9] and M32 [10] are not included in this specification.

- **Inputs – GFRP Material & Design Properties**
  - Environmental Reduction Factor = 0.7
  - Tensile Modulus of Elasticity = 6500 ksi
  - Rebar Properties = ***Specification 932-3***
  - Rebar Bend Radius = ***Index 415-010***

HOOK DETAILS



BAR SIZE	D	180° HOOKS A OR G	180° HOOKS J	90° HOOKS A OR G
#3	2¼"	5"	3"	6"
#4	3"	6"	4"	8"
#5	3¾"	7"	5"	10"
#6	4½"	8"	6"	1'-0"
#7	5¼"	10"	7"	1'-2"
#8	6"	11"	8"	1'-4"

Design Example for Pile Bent Cap

Flexural reinforcement can be placed up to 2 layers in current version.

Top Reinforcement (Negative Moment)

8	*Size of top reinforcing bars (A, B & C),* $Bar\#_{top}$
3.25	*Distance from c.g. of 1st layer bars to cap top face (in),* t1
0	*Distance from c.g. of 2nd layer bars to c.g. of 1st layer bars (in.),* t2

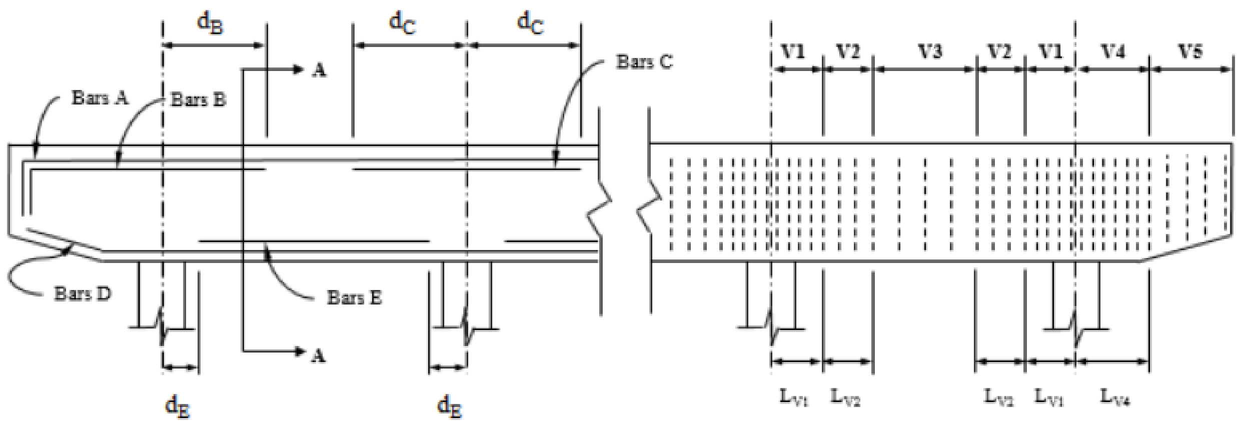
Bottom Reinforcement (Positive Moment)

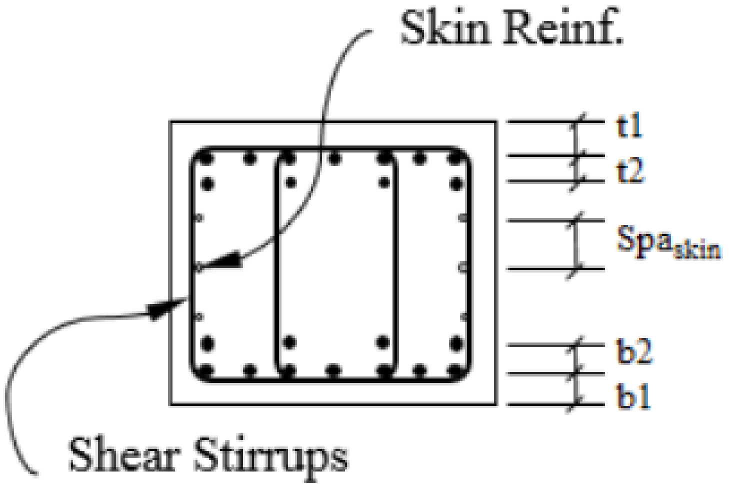
8	*Size of bottom reinforcing bars (D & E),* $Bar\#_{bot}$
3.25	*Distance from c.g. of 1st layer bars to cap bottom face (in.),* b1
4	*Distance from c.g. of 2nd layer bars to c.g. of 1st layer bars (in.),* b2

- **Inputs – Flexural Reinforcement**
  - Bar Size for Top Reinf (#) - *Bars A, B & C*
  - Distance from c.g. 1st layer to top cap face *(t1)*
  - Distance from c.g. 2nd layer to c.g. 1st layer *(t2)*

  - Bar Size for Bottom Reinf (#) - *Bars D & E*
  - Distance from c.g. 1st layer to bottom cap face *(b1)*
  - Distance from c.g. 2nd layer to c.g. 1st layer *(b2)*

Flexural reinforcement





SECTION A-A

Design Example for Pile Bent Cap

Bars A: Continuous Top Reinforcement

Bars A placed in 1st Layer — 10 *Number of bars,* #Bars$_{A1}$

Bars A placed in 2nd Layer — 0 *Number of bars,* #Bars$_{A2}$

Bars B: Supplemental Top Reinforcement over Exterior Columns

0 *Length of Bars B beyond CL of Exterior Column (in.),* d_B

Development Length not considered in current version, input length of portion that is cosidered fully developed.

Bars B placed in 1st Layer — 0 *Number of bars,* #Bars$_{B1}$

Bars B placed in 2nd Layer — 0 *Number of bars,* #Bars$_{B2}$

Bars C: Supplemental Top Reinforcement Centered on CL of Interior Columns

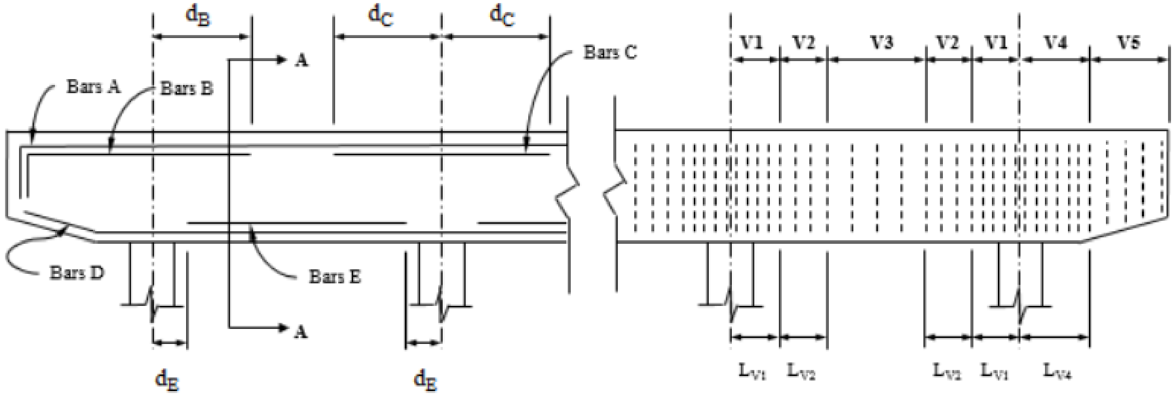
0 *Length of Bars C beyond CL of Interior Column (in.),* d_C

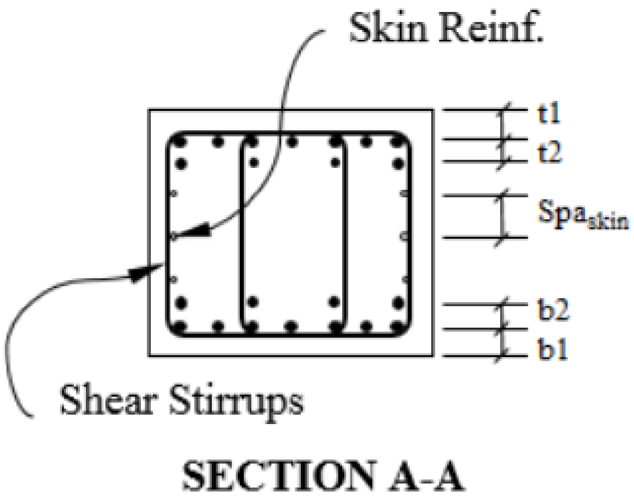
Development Length not considered in current version, input length of portion that is cosidered fully developed.

Bars C placed in 1st Layer — 0 *Number of bars,* #Bars$_{C1}$

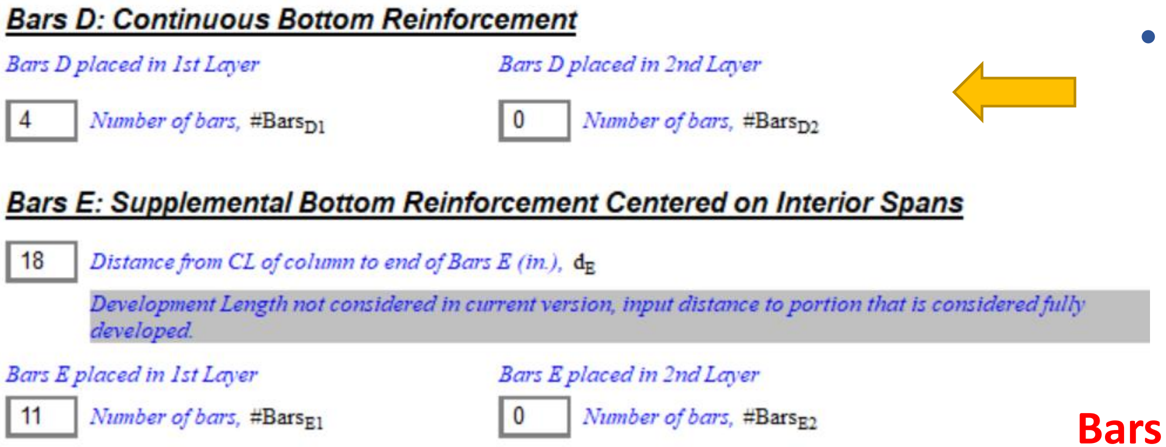
Bars C placed in 2nd Layer — 0 *Number of bars,* #Bars$_{C2}$

- **Inputs – Flexural Top Reinforcement**
  - For simplicity only use Bars A for pile bent caps
  - Bars B and C are intended for large multi-column piers

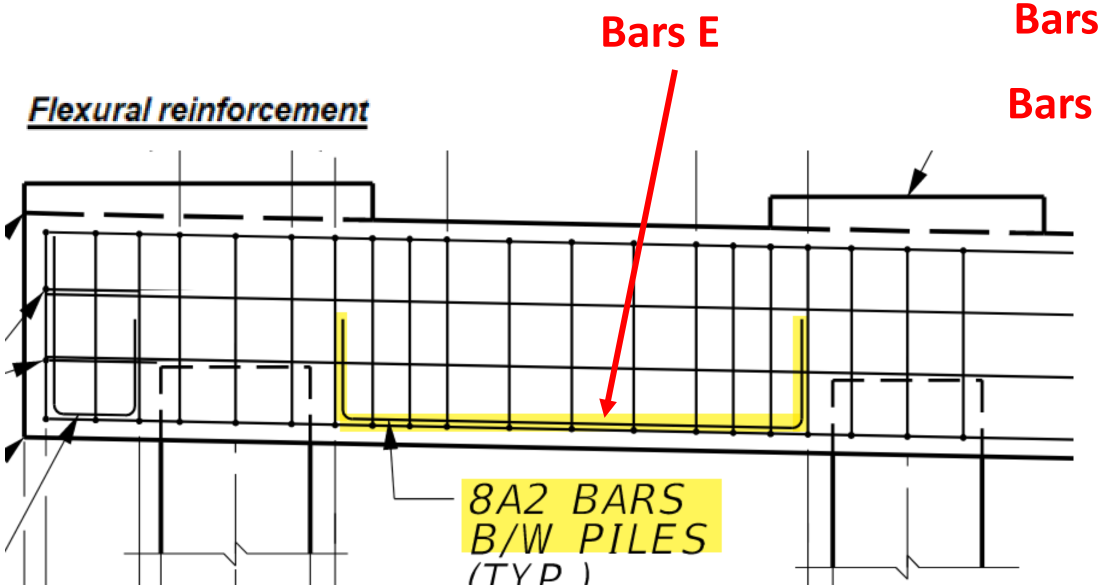


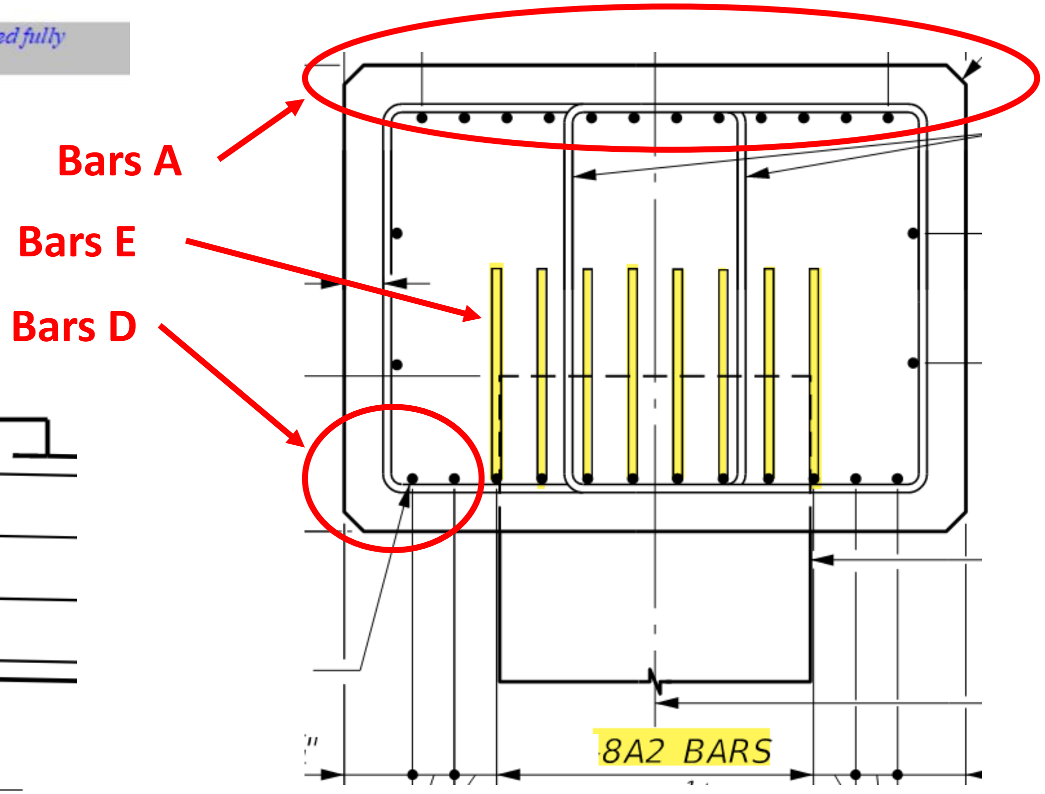


Design Example for Pile Bent Cap



- **Inputs – Flexural Bottom Reinforcement**
  - Bars D – along the outside of piles
  - Bars E – between piles





Design Example for Pile Bent Cap

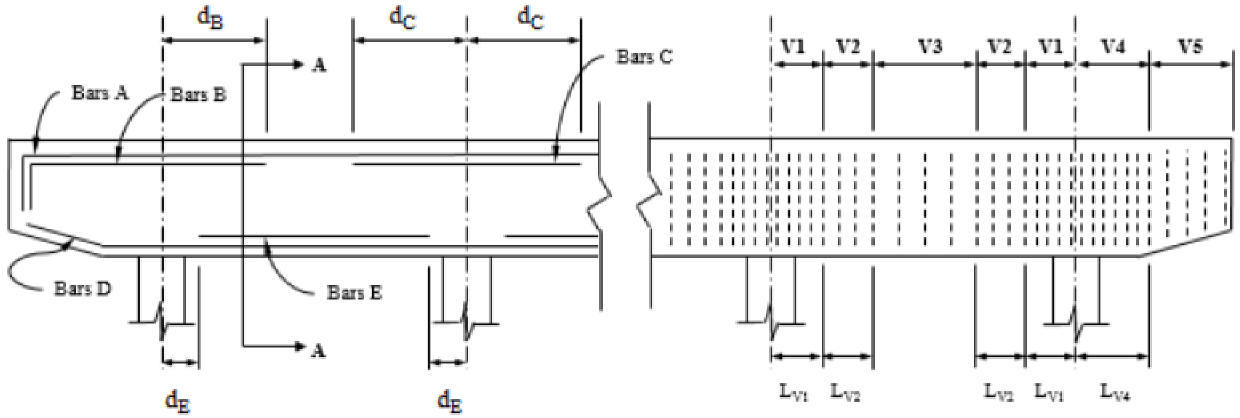
Spacing of Flexural Reinforcement

For crack control check, the bar spacing is calculated assuming a uniform distribution of bars on the 1st layer. Designer/user to calculate the actual spacing of bars if bars are not evenly distributed or bundled together. The maximum allowable spacing is plotted along the cap under the "Crack Control" section and the maximum allowable spacing at the most critical cap section is reported at the end of the program.

2	*Concrete cover on the two sides (in.)*

- **Inputs – Concrete Cover**
  - See ***Structures Manual, Vol.4*** - ***FRPG 2.3.E***
  - Side Concrete Cover = 2”
  - Bottom & Top cover previously set by “1st layer c.g.”

Flexural reinforcement



Fiber Reinforced Polymer Guidelines — Topic No. 625-020-018
2 - Basalt and Glass Fiber Reinforced Polymer (bfrp, GFRP) and Carbon Fiber Reinforced Polymer (CFRP) — January 2022

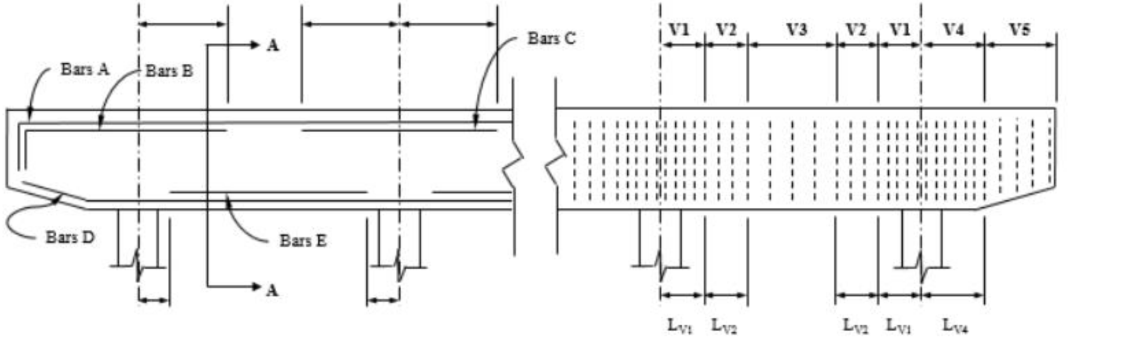
E. Use the following minimum concrete covers:

FRP Reinforced Component (Precast and Cast-in-Place)	Environment: S[1] M[1] E[1] — Concrete Cover (inches)
Superstructure Components	
Cast-in-Place Beams	2
Top deck surfaces of Short Bridges[2]	1.5
Top deck surfaces of Long Bridges[2]	2[3]
Front and back surfaces of Pedestrian/Bicycle Railings constructed using the slip form method	2.5
Wall copings and all other bridge superstructure surfaces and components not listed above	1.5
Noise Wall Posts	2
Precast Concrete Perimeter Wall Posts	1.75
Precast Noise and Perimeter Wall Panels	1.5
Substructure Components	
External surfaces cast against earth	3
Exterior formed surfaces, columns, and tops of footings	2
Exterior formed surfaces of Approach Slabs other than the bottom surface	2
Beam/Girder Pedestals No. 5 bars and smaller	1.5
Beam/Girder Pedestals No 6 bar thru no. 10 bars	2
Prestressed Piles	3[4]
Cast-in-Place Cantilever Retaining Walls and Gravity Walls	2
MSE Walls No. 5 bars and smaller	1.5
MSE Walls No 6 bar thru. no. 10 bars	2
Box and Three-sided Culverts	2
Bulkheads and Sheet Pile Wall Caps	2
Sheet Piles	Front and Back Faces - 3[5] Sides - 2

Design Example for Pile Bent Cap

Shear Reinforcement

In order to maintain a level of flexibility for modeling and to allow for multiple spacings for shear reinforcement along the cap, the spacing of the stirrups over the pile (non-critical fo shear) is assumed to be the same as the first zone beyond the face of the pile.



Zone V1

0	*Size of stirrup bar,* $Bar\#_{V1}$
0	*No. of bar legs,* $\#Legs_{V1}$
0	*Spacing (in.),* Spa_{V1}
0	*Length of Zone V1 (in.),* L_{V1}

Zone V2

0	*Size of stirrup bar,* $Bar\#_{V2}$
0	*No. of bar legs,* $\#Legs_{V2}$
0	*Spacing (in.),* Spa_{V2}
0	*Length of Zone V2 (in.),* L_{V2}

Zone V3

5	*Size of stirrup bar,* $Bar\#_{V3}$
4	*No. of bar legs,* $\#Legs_{V3}$
6	*Spacing (in.),* Spa_{V3}

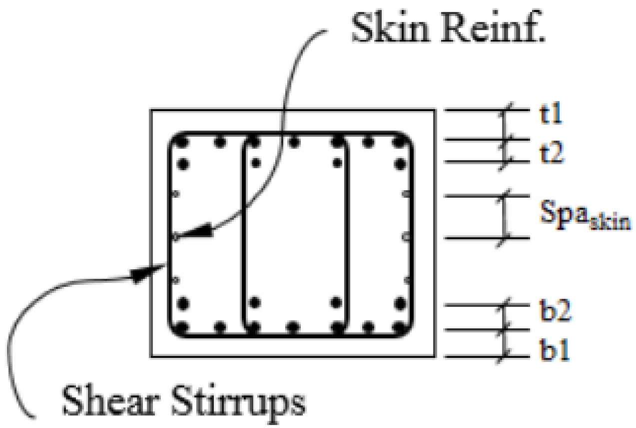
Zone V4 (Cap overhang)

0	*Size of stirrup bar,* $Bar\#_{V4}$
0	*No. of bar legs,* $\#Legs_{V4}$
0	*Spacing (in.),* Spa_{V4}
0	*Length of Zone V1 (in.),* L_{V4}

Zone V5 (Cap overhang)

5	*Size of stirrup bar,* $Bar\#_{V5}$
4	*No. of bar legs,* $\#Legs_{V5}$
6	*Spacing (in.),* Spa_{V5}

- **Inputs Shear Reinforcement**
  - Only use Zone 3 spacing for simplicity b/w piles
  - Only use Zone 5 spacing for simplicity b/w piles



SECTION A-A

FDOT TRANSPORTATION SYMPOSIUM

Design Example for Pile Bent Cap

Summary of LRFD and SDG Checks

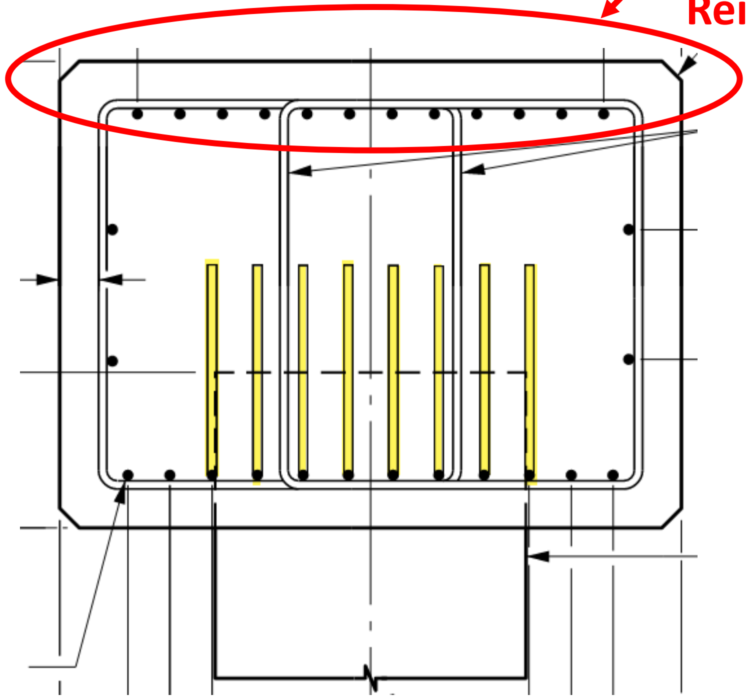
Save Data

Positive Moment	***Negative Moment***	
$Check_{M.r.pos}$ = "OK"	$Check_{M.r.neg}$ = "OK"	
$\max(DCR_{M.pos}) = 0.80$	$\max(DCR_{M.neg}) = 0.88$	*The maximum demand to capacity ratio*
$Check_{minAf.bot}$ = "OK"	$Check_{minAf.top}$ = "NG"	
$Check_{crack.control.bot}$ = "OK"	$Check_{crack.control.top}$ = "NG, bar spacing exceeds maximum"	
$\max(CrackW_{SerI.bot}) = 0.024 \cdot in$	$\max(CrackW_{SerI.top}) = 0.032 \cdot in$	*The maximum crack width*
$Check_{creep.bot}$ = "OK"	$Check_{creep.top}$ = "OK"	
$\max(f_{f.SL.bot}) = 9.36 \cdot ksi$	$\max(f_{f.SL.top}) = 14.74 \cdot ksi$	*The maximum stress under sustained load (DL+0.2LL)*
$Check_{fatigue.bot}$ = "OK"	$Check_{fatigue.top}$ = "NG"	
$\max(f_{f.Fat.bot}) = 12.97 \cdot ksi$	$\max(f_{f.Fat.top}) = 16.3 \cdot ksi$	*The maximum stress under fatigue (DL+1.75LL.fatigue)*
$C_f \cdot f_{fl.pos} = 14.8 \cdot ksi$	$C_f \cdot f_{fl.neg} = 14.8 \cdot ksi$	*Fatigue stress limit*

- **Output – Flexure (Pos. & Neg. Moment)**
  - Neg. for Min. Cracking Moment – *No Good*
  - Neg. for Service I Crack Control – *No Good*
  - Neg. for Fatigue Check – *No Good*

→ **Need to Revise Input**

Negative Moment Reinf.

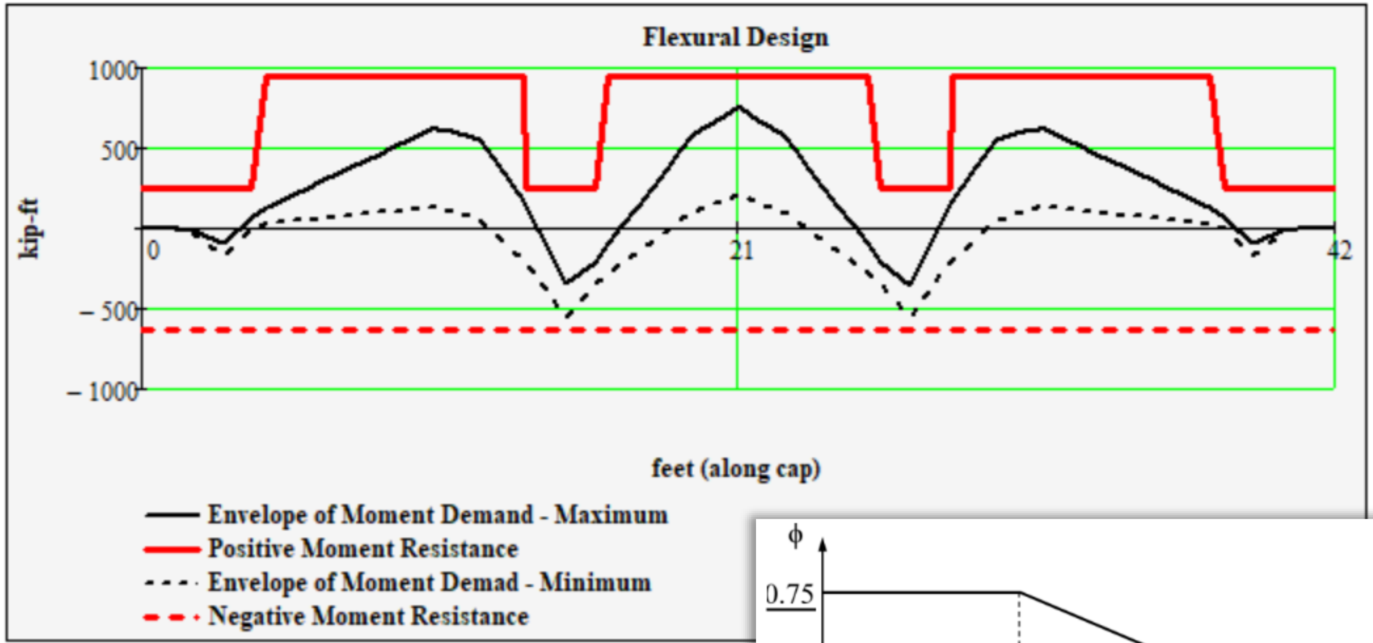


Design Example for Pile Bent Cap

Flexural Resistance [AASHTO BDS for GFRP 2.6]

Maximum demand to capacity ratio

$\max(DCR_{M.pos}) = 0.80$ $\max(DCR_{M.neg}) = 0.88$



2.6.3.2.1—Factored Flexural Resistance

The factored flexural resistance, M_r, shall be taken as:

$$M_r = \phi M_n \quad (2.6.3.2.1\text{-}1)$$

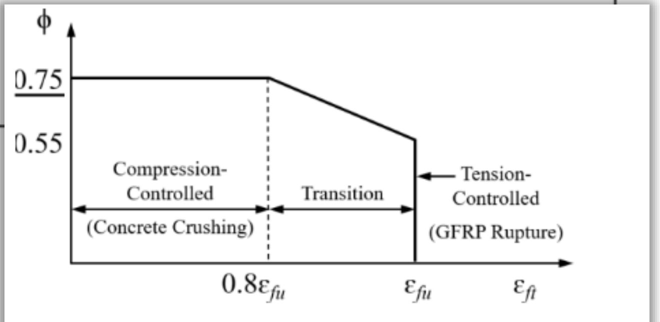


Figure C2.5.5.2-1—Variation of ϕ with Tensile Strain at Failure, ε_{ft}, in GFRP Reinforcement

- **Output – Flexure (Pos. & Neg. Moment)**
  - Strength Limit State OK for loading.
  - *ØMn.pos* = 952 kip-ft
  - *ØMn.neg* = 634 kip-ft

<u>Compression-Controlled (Concrete Crushing)</u>

$$f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f'_c}{\rho_f} E_f \varepsilon_{cu}} - 0.5 E_f \varepsilon_{cu} \le f_{fd} \quad (2.6.3.1\text{-}1)$$

$$M_n = A_f f_f \left(d - \frac{a}{2}\right) \quad (2.6.3.2.2\text{-}1)$$

in which:

$$a = \frac{A_f f_f}{0.85 f'_c b} \quad (2.6.3.2.2\text{-}2)$$

<u>Tension-Controlled (GFRP Bar Rupture)</u>

$$M_n = A_f f_{fd} \left(d - \frac{\beta_1 c_b}{2}\right) \quad (2.6.3.2.2\text{-}3)$$

in which:

$$c_b = \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fd}}\right) d \quad (2.6.3.2.2\text{-}4)$$

Design Example for Pile Bent Cap

Cracking Moment

$f_r := 7.5 \cdot \sqrt{f_{c.cap} \cdot psi} = 556 \cdot psi$ — *Modulus of Rupture*

$S_{cap} :=$ | for $i \in 1..\#AllSections$ — *Section modulus of cap*

$M_{cr} := f_r \cdot S_{cap}$ — *Cracking moment*

$\max(M_{cr}) = 480.57 \cdot kip \cdot ft$ — *Maximum cracking moment along the cap*

Minimum GFRP Reinforcement [AASHTO BDS for GFRP 2.6.3.3]

Required flexural resistance for minimum reinforcement

$M_{minAfbot_i} := \min(1.33 \cdot maxM_{u_i}, 1.6 \cdot M_{cr_i})$

$\max(M_{minAfbot}) = 768.91 \cdot kip \cdot ft$

$M_{minAftop_i} := \min(-1.33 \cdot minM_{u_i}, 1.6 \cdot M_{cr_i})$

$\max(M_{minAftop}) = 739.24 \cdot kip \cdot ft$

Check minimum GFRP reinforcement

$Check_{minAfbot} :=$ | Check ← "OK"
for $i \in 1..\#AllSections$
  Check ← "NG" if $M_{r.pos_i} < M_{minAfbo}$
Check

$Check_{minAftop} :=$ | Check ← "OK"
for $i \in 1..\#AllSections$
  Check ← "NG" if $M_{r.neg_i} < M_{minAftop_i}$
Check

$Check_{minAfbot} =$ "OK"

$Check_{minAftop} =$ "NG"

- **Output – Flexure (Pos. & Neg. Moment)**
  - Negative Cracking Moment – No Good
  - 1.33*Mu = 1013 kip-ft
  - 1.6*Mcr = 739 kip-ft ← *controls*
  - ØM.neg = 634 kip-ft < *min.(1.33Mu, 1.6Mcr), NG*
    - *Add approx. 20% more reinforcing*

2.6.3.3—Limits for Reinforcement

There is no maximum reinforcement limit.

Unless otherwise specified by the Owner, at any section of a noncompression-controlled flexural component, the amount of tensile reinforcement shall be adequate to develop a factored flexural resistance, M_r, greater than or equal to the lesser of the following:

- 1.33 times the factored moment required by the applicable strength load combination specified in Table 3.4.1-1 of the *AASHTO LRFD Bridge Design Specifications*.
- $1.6 f_r S_c - M_{dnc}\left(\frac{S_c}{S_{nc}} - 1\right)$ (2.6.3.3-1)

Design Example for Pile Bent Cap

Crack Control [AASHTO BDS for GFRP 2.6.7]

$CrackLimit := 0.028in$ — *limiting crack width*

$C_b := 0.83$ — *the bond reduction factor*

$$s_{max.bot_i} := \min\left[1.15\cdot\frac{C_b\cdot E_f\cdot CrackLimit}{\left(f_{f.SerI.bot_i} + 0.0001ksi\right)} - 2.5c_{c.bot}, 0.92\cdot\frac{C_b\cdot E_f\cdot CrackLimit}{\left(f_{f.SerI.bot_i} + 0.0001ksi\right)}\right]$$

maximum spacing for crack control

$\min(s_{max.bot}) = 3.79\cdot in$

$$s_{max.top_i} := \min\left[1.15\cdot\frac{C_b\cdot E_f\cdot CrackLimit}{\left(f_{f.SerI.top_i} + 0.0001ksi\right)} - 2.5c_{c.top}, 0.92\cdot\frac{C_b\cdot E_f\cdot CrackLimit}{\left(f_{f.SerI.top_i} + 0.0001ksi\right)}\right]$$

maximum spacing for crack control

$\min(s_{max.top}) = 2.15\cdot in$

```
Checksmax.bot := | Check ← "OK"
                 | for i ∈ 1..#AllSections
                 |   Check ← "NG" if Spabar.bot_i > smax.bot_i
                 | Check

Checksmax.top := | Check ← "OK"
                 | for i ∈ 1..#AllSections
                 |   Check ← "NG" if Spabar.top_i > s
                 | Check
```

$Check_{smax.bot}$ = "OK" $\min(Spa_{bar.bot}) = 2.96in$ $Check_{smax.top}$ = "NG" $\min(Spa_{bar.top}) = 4.61in$

- **Output – Flexure (Pos. & Neg. Moment)**
  - Service I Limit State (Crack Control):
  - Max. Allowed Bot. Bar Spacing = 3.79 in.
  - Bot. Spacing (b/w piles) = 2.96 in. ← *OK*
  - Max. Allowed Top Bar Spacing = 2.15 in.
  - Top Spacing = 4.61 in. ← *NG*
    - *AASHTO & ACI provides this check in terms of bar spacing, but it is easier to visualize & graph by converting to crack width.*

2.6.7—Control of Cracking by Distribution of Reinforcement

Except for deck slabs designed in accordance with Article 3.7.2, the provisions specified herein shall apply

The spacing, *s*, of the longitudinal GFRP reinforcing bars in the layer closest to the tension face shall satisfy Eq. 2.6.7-1:

$$s \le \min\left(1.15\frac{C_b E_f w}{f_{fs}} - 2.5c_c;\ 0.92\frac{C_b E_f w}{f_{fs}}\right) \quad (2.6.7\text{-}1)$$

Equation 2.6.7-1 is based on ***ACI 440.1R*** which uses a simplified conversion of the 1999 Frosch crack width equation.

Design Example for Pile Bent Cap

Crack Control [AASHTO BDS for GFRP 2.6.7]

$CrackLimit := 0.028in$ *limiting crack width*

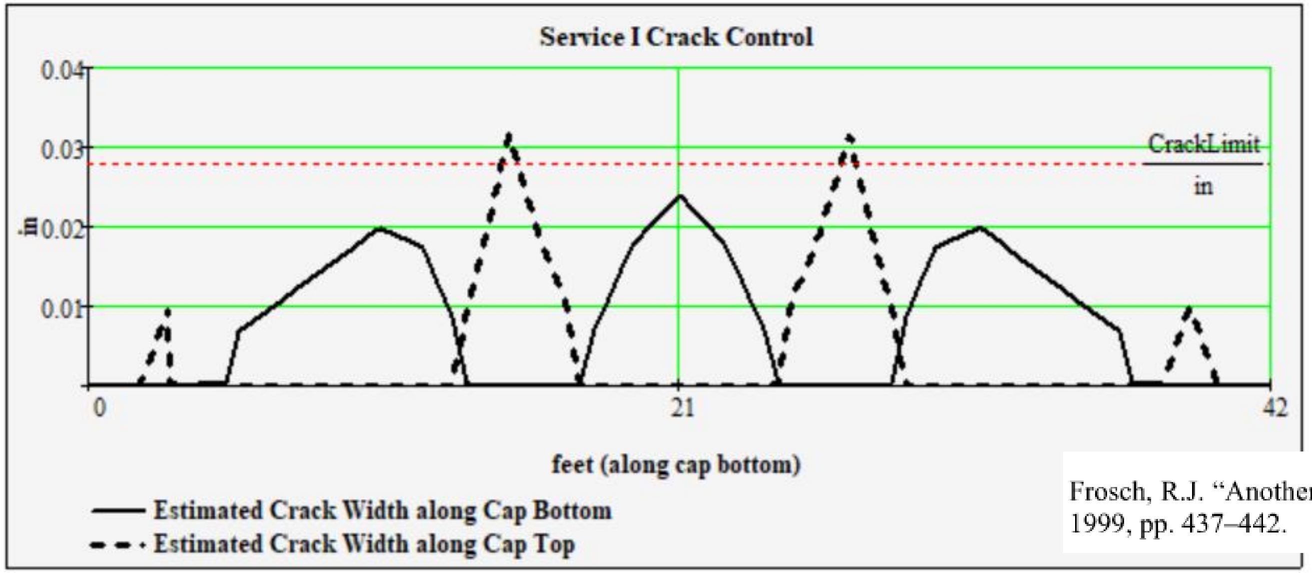
Estimated Service I crack width

$$CrackW_{SerI.bot_i} := 2\frac{f_{f.SerI.bot_i}}{C_b \cdot E_f}\cdot \zeta_{pos_i}\cdot\sqrt{{d_{c.bot}}^2 + \left(\frac{Spa_{bar.bot_i}}{2}\right)^2}$$

$$CrackW_{SerI.top_i} := 2\frac{f_{f.SerI.top_i}}{C_b \cdot E_f}\cdot \zeta_{neg_i}\cdot\sqrt{{d_{c.top}}^2 + \left(\frac{Spa_{bar.top_i}}{2}\right)^2}$$

Maximum Service I crack width

$\max(CrackW_{SerI.bot}) = 0.024 \cdot in$ $\max(CrackW_{SerI.top}) = 0.032 \cdot in$



- **Output – Flexure (Pos. & Neg. Moment)**
  - Service I Limit State (Crack Control) cont.:
  - Max. allowed crack width = 0.28 in.
  - Bot. Crack Width (max) = 0.024 in. ← *OK*
  - Top Crack Width (max) = 0.032 in. ← *NG*
    - *Provide closer spacing or increase area of reinforcing for top reinforcing to reduce tensile stress.*

A NEW CRACK WIDTH EQUATION

Frosch[4] observed that a significant shortcoming of the Gergely-Lutz and Kaar-Mattock equations is that they were both developed empirically using statistical analysis techniques on experimental data that was limited in the range of concrete covers investigated. In fact, he noted that only three test specimens had concrete covers greater than 2.5 inches.

Frosch developed the following simple, theoretically-derived equation to predict crack widths that could be used regardless of the actual concrete cover:

$$w_c = 2\frac{f_s}{E_s}\beta\sqrt{(d_c)^2 + \left(\frac{s}{2}\right)^2} \qquad (4)$$

Frosch, R.J. "Another Look at Cracking and Crack Control in Reinforced Concrete." *ACI Structural Journal*, 96(3), 1999, pp. 437–442.

Design Example for Pile Bent Cap

Crack Control [AASHTO BDS for GFRP 2.6.7]

$CrackLimit := 0.028in$ *limiting crack width*

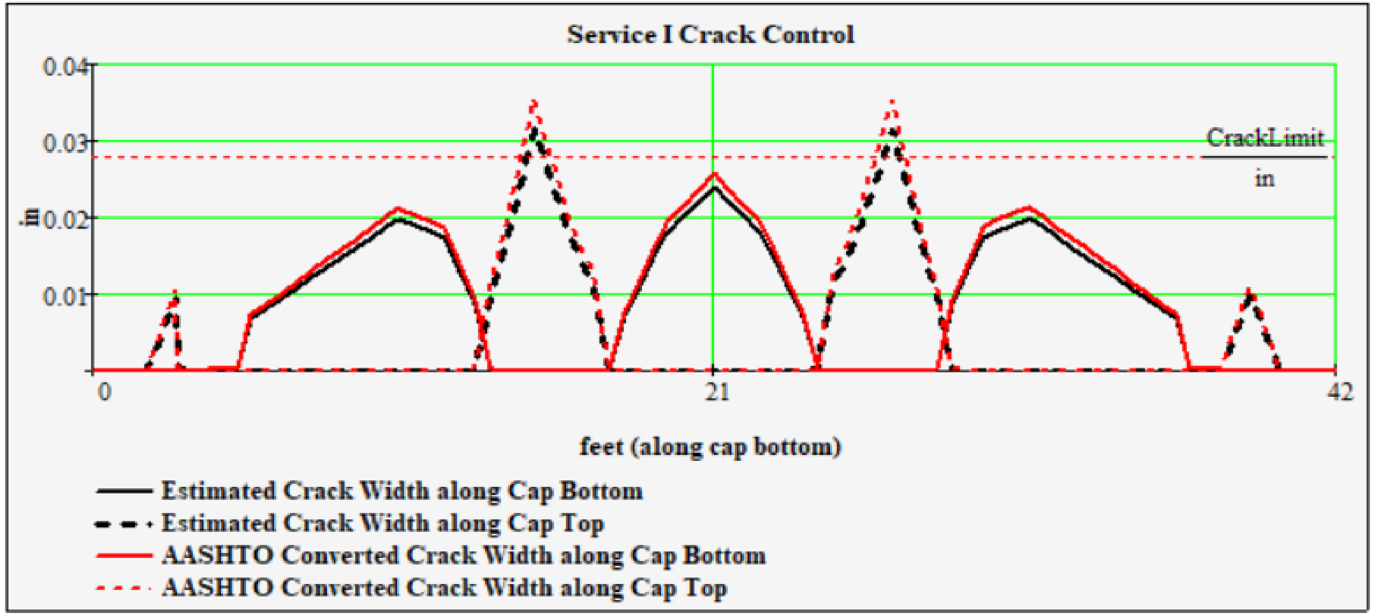
Estimated Service I crack width

$$CrackW_{SerI.bot_i} := 2\frac{f_{f.SerI.bot_i}}{C_b \cdot E_f} \cdot \zeta_{pos_i} \cdot \sqrt{{d_{c.bot}}^2 + \left(\frac{Spa_{bar.bot_i}}{2}\right)^2}$$

$$CrackW_{SerI.top_i} := 2\frac{f_{f.SerI.top_i}}{C_b \cdot E_f} \cdot \zeta_{neg_i} \cdot \sqrt{{d_{c.top}}^2 + \left(\frac{Spa_{bar.top_i}}{2}\right)^2}$$

Maximum Service I crack width

$max(CrackW_{SerI.bot}) = 0.024 \cdot in$ $max(CrackW_{SerI.top}) = 0.032 \cdot in$



- **Output – Flexure (Pos. & Neg. Moment)**
  - Service I Limit State (Crack Control) cont.:
  - Max. allowed crack width = 0.28 in.
  - Bot. Crack Width (max) = 0.024 in. ← *OK*
  - Top Crack Width (max) = 0.032 in. ← *NG*

A direct conversion of ***AASHTO Guide Spec Eq. 2.6.7-1***, provides slightly more conservative widths as shown by the red plot lines in this graph.

$$s \le \min\left(1.15\frac{C_b E_f w}{f_{fs}} - 2.5c_c;\ 0.92\frac{C_b E_f w}{f_{fs}}\right) \qquad (2.6.7\text{-}1)$$

$$CrackWgs115_{Top_i} := \frac{f_{f.SerI.top_i}}{1.15 \cdot C_b \cdot E_f} \cdot \left(Spa_{bar.top_i} + 2.5c_{c.top}\right)$$

Design Example for Pile Bent Cap

Creep Rupture Limit State [AASHTO BDS for GFRP 2.5.3]

To avoid creep ruptureof the FRP reinforcement under sustained stresses or failure due to cyclic stresses and fatigue of th FRP reinforcement, the stress levels in the FRP under these stress conditions should be limited.

$C_c := 0.30$ *Creep rupture reduction factor*

Creep rupture stress limit of GFRP

$CreepLimit_{pos_i} := C_c \cdot f_{fd.pos}$ $CreepLimit_{neg_i} := C_c \cdot f_{fd.neg}$

$\max(CreepLimit_{pos}) = 17.76 \cdot ksi$ $\max(CreepLimit_{neg}) = 17.76 \cdot ksi$

Stress in the bottom reinforcing due to sustained load (DL+0.2LL)

$f_{f.SL.bot_i} := ff_f(maxM_{SL_i}, d_{f.pos_i}, d_{cap_i}, S_{cap_i}, k_{pos_i}, I_{cr.pos_i}, M_{cr_i})$

$\max(f_{f.SL.bot}) = 9.36 \cdot ksi$

Stress in the top reinforcing due to sustained load (DL+0.2LL)

$f_{f.SL.top_i} := ff_f(-minM_{SL_i}, d_{f.neg_i}, d_{cap_i}, S_{cap_i}, k_{neg_i}, I_{cr.neg_i}, M_{cr_i})$

$\max(f_{f.SL.top}) = 12.33 \cdot ksi$

$Check_{creep.bot} :=$
Check ← "OK"
for i ∈ 1..#AllSections
  Check ← "NG" if $f_{f.SL.bot_i} > C_c \cdot f_{fd.pos}$
Check

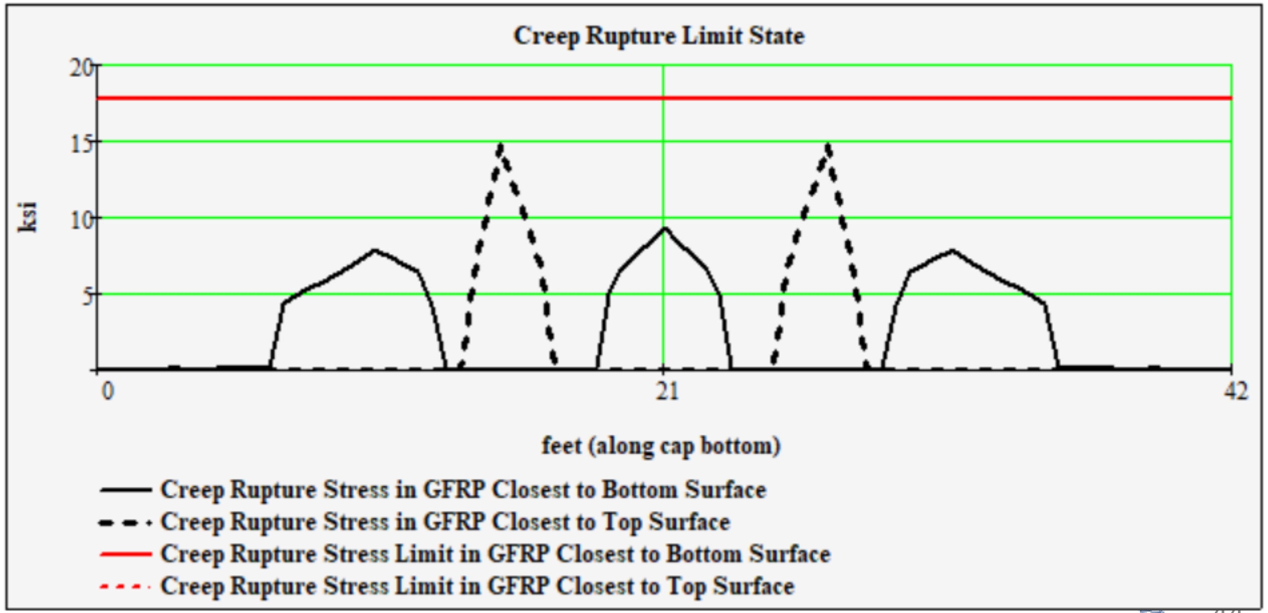
$Check_{creep.top} :=$
Check ← "OK"
for i ∈ 1..#AllSections
  Check ← "NG" if $f_{f.SL.top}$
Check

$Check_{creep.bot} =$ "OK" $Check_{creep.top} =$ "OK"

- **Output – Flexure (Pos. & Neg. Moment)**
  - Service Limit State (Creep Rupture):

$$f_{f,s} \le C_c f_{fd} \qquad (2.5.3\text{-}1)$$

  - Max. allowed bar stress = 17.8 ksi
  - Bot. Stress (max) = 9.4 ksi ← *OK*
  - Top Stress (max) = 12.3 ksi ← *OK*



Design Example for Pile Bent Cap

Fatigue Limit State [AASHTO BDS for GFRP 2.5.4]

$C_f := 0.25$ *Fatigue rupture reduction factor*

Fatigue rupture stress limit of GFRP

$FatigueLimit_{pos_i} := C_f \cdot f_{fd.pos}$ $FatigueLimit_{neg_i} := C_f \cdot f_{fd.neg}$

$\max(FatigueLimit_{pos}) = 14.8 \cdot ksi$ $\max(FatigueLimit_{neg}) = 14.8 \cdot ksi$

Stress in the bottom reinforcing due to sustained load (DL+1.5FatigueLL)

$f_{fFat.bot_i} := ff_f\left(maxM_{FatI_i}, d_{fpos_i}, d_{cap_i}, S_{cap_i}, k_{pos_i}, I_{cr.pos_i}, M_{cr_i}\right)$

$\max(f_{fFat.bot}) = 12.97 \cdot ksi$

Stress in the top reinforcing due to sustained load (DL+1.5FatigueLL)

$f_{fFat.top_i} := ff_f\left(-minM_{FatI_i}, d_{fneg_i}, d_{cap_i}, S_{cap_i}, k_{neg_i}, I_{cr.neg_i}, M_{cr_i}\right)$

$\max(f_{fFat.top}) = 16.3 \cdot ksi$

$Check_{fatigue.bot} :=$
- Check ← "OK"
- for $i \in 1..\#AllSections$
  - Check ← "NG" if $f_{fFat.bot_i} > C_f \cdot f_{fd.pos}$
- Check

$Check_{fatigue.top} :=$
- Check ← "OK"
- for $i \in 1..\#AllSections$
  - Check ← "NG" if $f_{fFat.top_i} >$ (
- Check

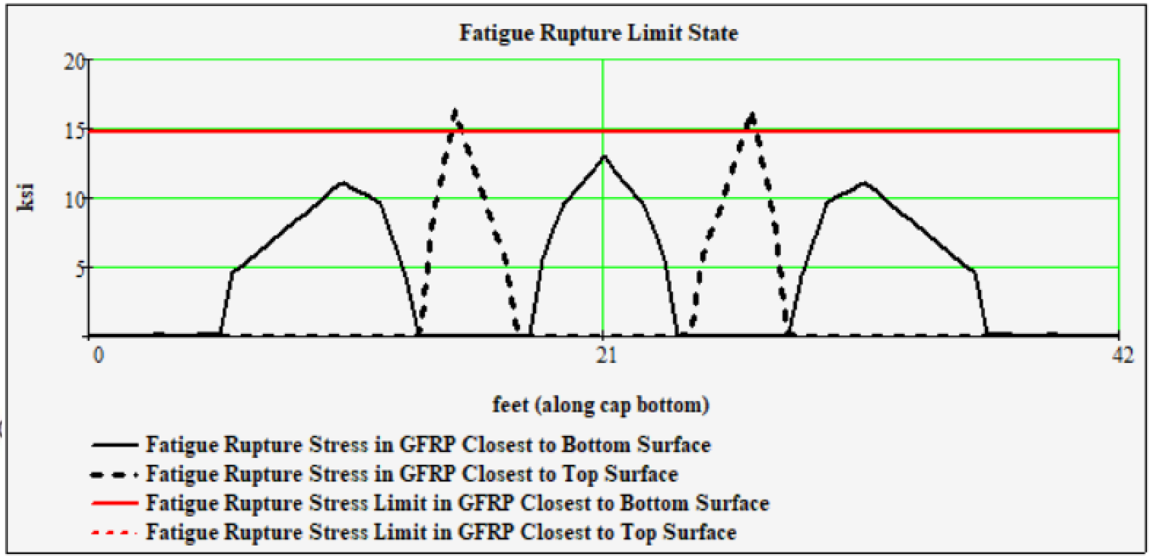
$Check_{fatigue.bot} =$ "OK" $Check_{fatigue.top} =$ "NG"

- **Output – Flexure (Pos. & Neg. Moment)**

  Fatigue Limit State:

$$f_{f,f} \le C_f f_{fd} \qquad (2.5.4\text{-}1)$$

  - Max. allowed bar stress = 14.8 ksi
  - Bot. Stress (max) = 13.0 ksi ← *OK*
  - Top Stress (max) = 16.3 ksi ← *NG*



Design Example for Pile Bent Cap

Skin Reinforcement [LRFD 5.7.3.4]

$d_{t.pos} := H_{cap} - b1 = 2.73\,ft$

$d_{t.neg} := H_{cap} - t1 = 2.73\,ft$

Distance from the extreme compression fiber to the centroid of extreme tension steel element

$Check_{skin.reinf.reqd} := if(d_{t.pos} \geq 3ft \vee d_{t.neg} \geq 3ft, \text{"Skin Reinf Required"}, \text{"Skin Reinf Not Required"})$

$Check_{skin.reinf.reqd} = \text{"Skin Reinf Not Required"}$

$Bar\#_{skin} = 5$ — *Size of bar*

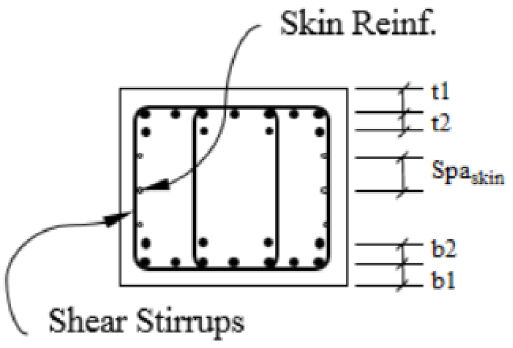
$\#Bars_{skin} = 4$ — *Number of bars on each side face*

If d_ℓ of nonprestressed members exceeds 3.0 ft, longitudinal skin reinforcement shall be uniformly distributed along both side faces of the component for a distance $d_\ell/2$ nearest the flexural tension reinforcement. The area of skin reinforcement, A_{sk}, in in.^{2}/ft of height on each side face shall satisfy:

$$A_{sk} \geq 0.012\,(d_\ell - 30) \qquad (5.6.7\text{-}3)$$

where:

d_ℓ = distance from the extreme compression fiber to the centroid of extreme tension steel element (in.)

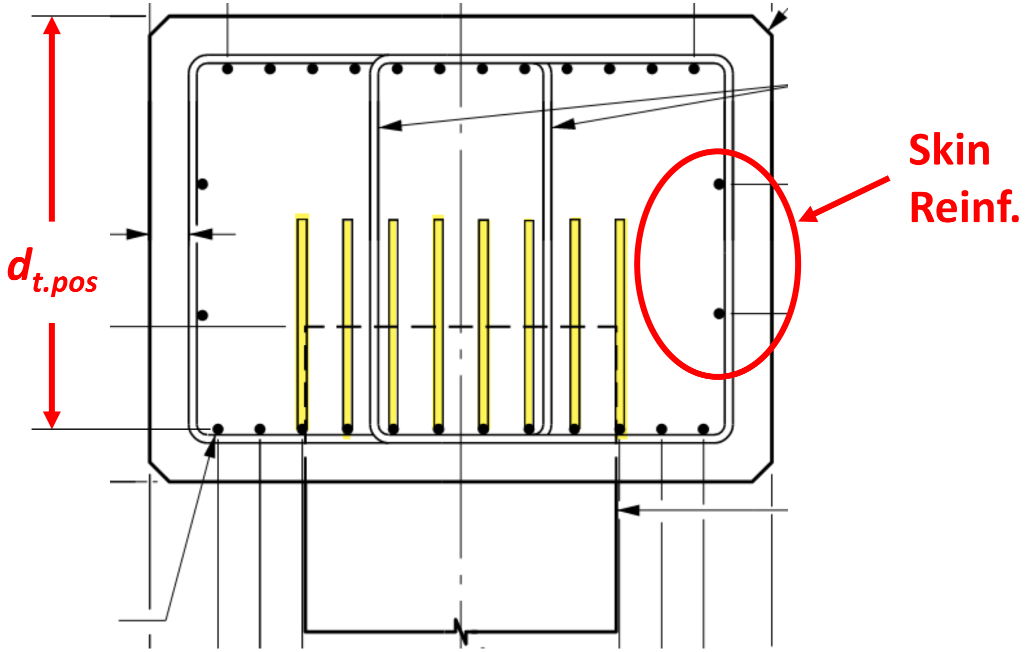


SECTION A-A

- **Output – Flexure (Pos. & Neg. Moment)**

  Skin Reinforcement (based on ***LRFD BDS***):

  - Not Required, since d_t < 3-ft
  - *Provide anyway #5's, need for Shrinkage & Temperature reinforcing on side face.*



Design Example for Pile Bent Cap

Shrinkage and Temperature Reinforcement [AASHTO BDS for GFRP 2.9.6]

For conservatism, use the lowest f_{fs} for the calculation of the minimum shrinkage and temperature reinforcement ratio

$f_{fd.pos} = 57.4 \cdot ksi$ — *Strength of Positive Reinforcement*

$f_{fd.neg} = 59.19 \cdot ksi$ — *Strength of Negative Reinforcement*

$f_{fd.skin} := f_{fd}(Bar\#_{skin}) = 65.71 \cdot ksi$ — *Strength of Skin Reinforcement*

$maxVbar := \max(Bar\#_{V1}, Bar\#_{V2}, Bar\#_{V3}, Bar\#_{V4}, Bar\#_{V5}) = 5$ — *Maximum bar size of Shear Reinforcement*

$f_{fd.shear} := f_{fd}(maxVbar) = 65.71 \cdot ksi$ — *Lowest Strength of Shear Reinforcement*

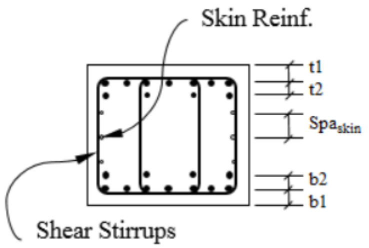
$f_{fd.ts} := \min(f_{fd.pos}, f_{fd.neg}, f_{fd.skin}, f_{fd.shear}) = 57.4 \cdot ksi$ — *Design strength for calculation of Shrinkage and Temperature Reinforcement Ratio (Lowest Strength of All Reinforcement for conservatism)*

$$\rho_{f.ts} := 0.0018 \cdot \frac{60ksi}{f_{fd.ts}} \cdot \frac{29000ksi}{E_f} = 0.0084$$

$$\rho_{f.ts} := \max(0.0014, \min(\rho_{f.ts}, 0.0036)) = 0.0036$$

$$A_{shrink.reqd} := \frac{\rho_{f.ts} \cdot W_{cap} \cdot H_{cap}}{2(W_{cap} + H_{cap})} = 0.44 \cdot \frac{in^2}{ft}$$

Area of required minimum shrinkage and temperature reinforcement per foot [LRFD 5.10.8]



SECTION A-A

$$A_{shrink.top} := \frac{A(Bar\#_{top}) \cdot \#Bars_{A1}}{W_{cap}} = 1.98 \cdot \frac{in^2}{ft}$$

Area of reinforcement near top surface

$$A_{shrink.bot} := \frac{A(Bar\#_{bot}) \cdot \#Bars_{D1}}{W_{cap}} = 1 \cdot \frac{in^2}{ft}$$

Area of reinforcement near bottom surface

$$A_{shrink.side} := \frac{A(Bar\#_{skin}) \cdot \#Bars_{skin} + A(Bar\#_{top}) + A(Bar\#_{bot})}{H_{cap}} = 0.8 \cdot \frac{in^2}{ft}$$

Area of reinforcement near side surface

- **Output –**

Shrinkage & Temp. Reinforcement Area:

- Min. Required = 0.44 sq.in/ft
- Min. Provided = 0.80 sq.in/ft (on side face)

and not less than 0.0014 (ACI, 2014). These provisions are modified accounting for the tensile modulus of elasticity and strength of shrinkage and temperature GFRP reinforcement:

$$\rho_{f,st} = 0.0018 \times \frac{60}{f_{fd}} \frac{29,000}{E_f} \geq 0.0014 \qquad \text{(C2.9.6-1)}$$

Design Example for Pile Bent Cap

Shrinkage and Temperature Reinforcement [AASHTO BDS for GFRP 2.9.6]

… continued

$Check_{AreaShrinkReinf}$ = "OK"

$Spa_{shrink.reqd} := 12in$ — *Maximum spacing of shrinkage and temperature reinforcement*

$Spa_{shrink.top} := \frac{W_{cap}}{\#Bars_{A1}} = 4.8 \cdot in$ — *Spacing of reinforcement near top surface*

$Spa_{shrink.bot} := \frac{W_{cap}}{\#Bars_{D1}} = 12 \cdot in$ — *Spacing of reinforcement near bottom surface*

$Spa_{shrink.side} := Spa_{skin} = 10 \cdot in$ — *Spacing of reinforcement near side surface*

$Spa_{shrink.shear} := \max(Spa_{fv}) = 6 \cdot in$ — *Spacing of shear reinforcement (max along the cap)*

$Spa_{shrink} := \max(Spa_{shrink.top}, Spa_{shrink.bot}, Spa_{shrink.side}, Spa_{shrink.shear}) = 12 \cdot in$ — *Critical spacing*

$SpaR_{shrink} := \frac{Spa_{shrink}}{Spa_{shrink.reqd}} = 1.00$ — *Spacing Ratio of Shrinkage Reinforcement - Provided to Required*

$Check_{SpaShrinkReinf} :=$ | "NG" if $SpaR_{shrink} > 1.005$
"OK" otherwise

$Check_{SpaShrinkReinf}$ = "OK"

- **Output –**

  Shrinkage & Temp. Reinforcement Spacing:
  - Min. Required = 12 in.
  - Min. Provided = 12 in. (on bottom face)

    or is 6" due to effect of pile embedment??

The spacing of GFRP reinforcing bars used as shrinkage and temperature reinforcement shall not exceed three times the slab thickness or 12 in., whichever is less.

$$\rho_{f,st} = \max\left(\frac{3,132}{E_f f_{fd}}; 0.0014\right) \leq 0.0036 \qquad (2.9.6\text{-}1)$$

and not less than 0.0014 (ACI, 2014). These provisions are modified accounting for the tensile modulus of elasticity and strength of shrinkage and temperature GFRP reinforcement:

$$\rho_{f,st} = 0.0018 \times \frac{60}{f_{fd}} \frac{29,000}{E_f} \geq 0.0014 \qquad (C2.9.6\text{-}1)$$

Design Example for Pile Bent Cap

Recall from our Initial Design attempt:

Summary of LRFD and SDG Checks

Save Data

Positive Moment

$Check_{M.r.pos}$ = "OK"

$\max(DCR_{M.pos}) = 0.80$

$Check_{minAf.bot}$ = "OK"

$Check_{crack.control.bot}$ = "OK"

$\max(CrackW_{SerI.bot}) = 0.024 \cdot in$

$Check_{creep.bot}$ = "OK"

$\max(f_{f.SL.bot}) = 9.36 \cdot ksi$

$Check_{fatigue.bot}$ = "OK"

$\max(f_{f.Fat.bot}) = 12.97 \cdot ksi$

$C_f \cdot f_{fd.pos} = 14.8 \cdot ksi$

Negative Moment

$Check_{M.r.neg}$ = "OK"

$\max(DCR_{M.neg}) = 0.88$ *The maximum demand to capacity ratio*

$Check_{minAf.top}$ = "NG"

$Check_{crack.control.top}$ = "NG, bar spacing exceeds maximum"

$\max(CrackW_{SerI.top}) = 0.032 \cdot in$ *The maximum crack width*

$Check_{creep.top}$ = "OK"

$\max(f_{f.SL.top}) = 14.74 \cdot ksi$ *The maximum stress under sustained load (DL+0.2LL)*

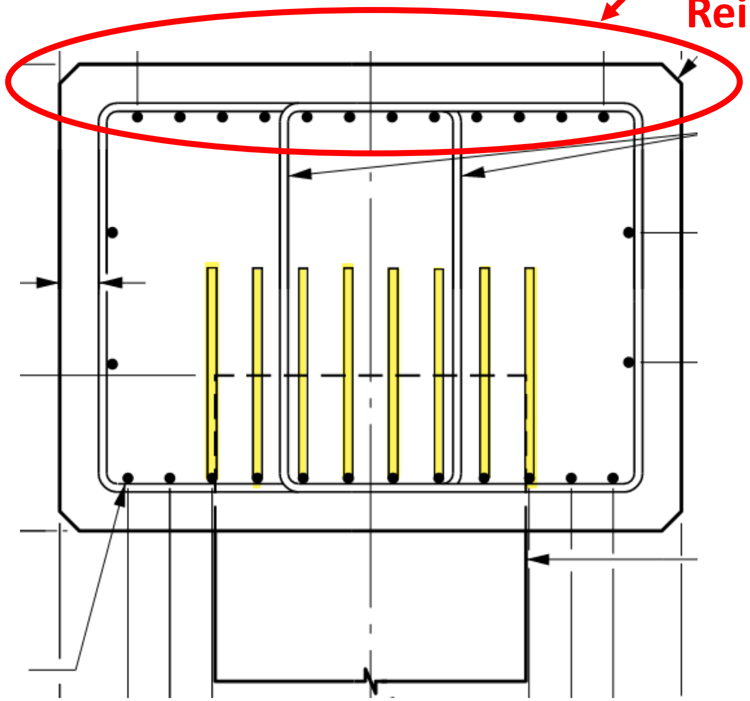
$Check_{fatigue.top}$ = "NG"

$\max(f_{f.Fat.top}) = 16.3 \cdot ksi$ *The maximum stress under fatigue (DL+1.75LL.fatigue)*

$C_f \cdot f_{fd.neg} = 14.8 \cdot ksi$ *Fatigue stress limit*

- **Output – Flexure (Pos. & Neg. Moment)**
  - Neg. for Min. Cracking Moment – *No Good*
  - Neg. for Service I Crack Control – *No Good*
  - Neg. for Fatigue Check – *No Good*

→ **Revise Input**



Design Example for Pile Bent Cap

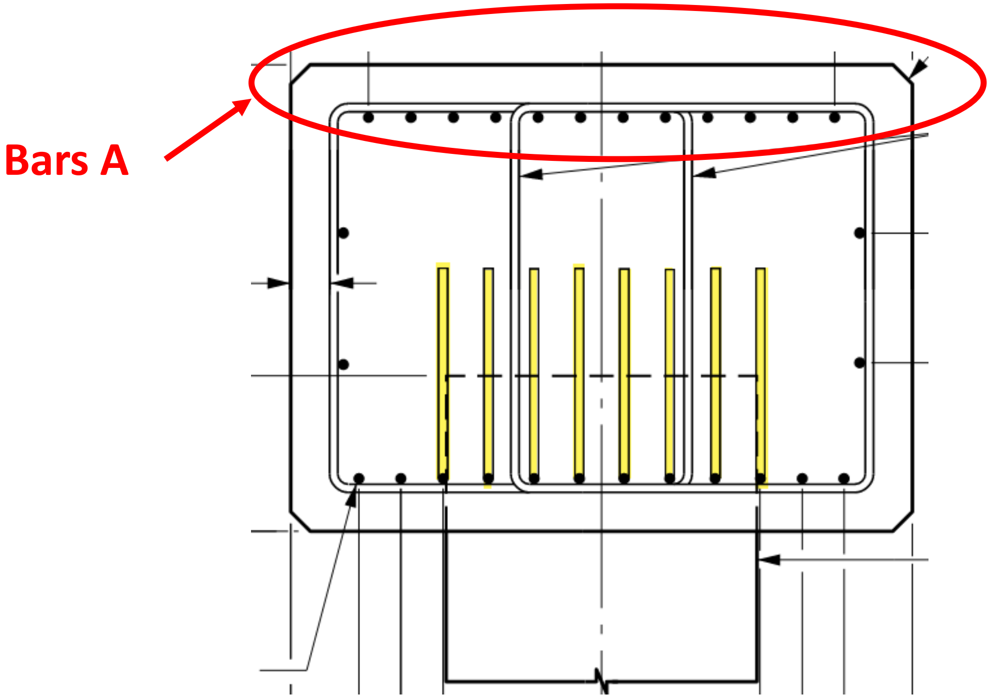
- **Revise Inputs – Flexural Top Reinforcement**
  - Number of Bars A: change from 10 to 12

Bars A: Continuous Top Reinforcement

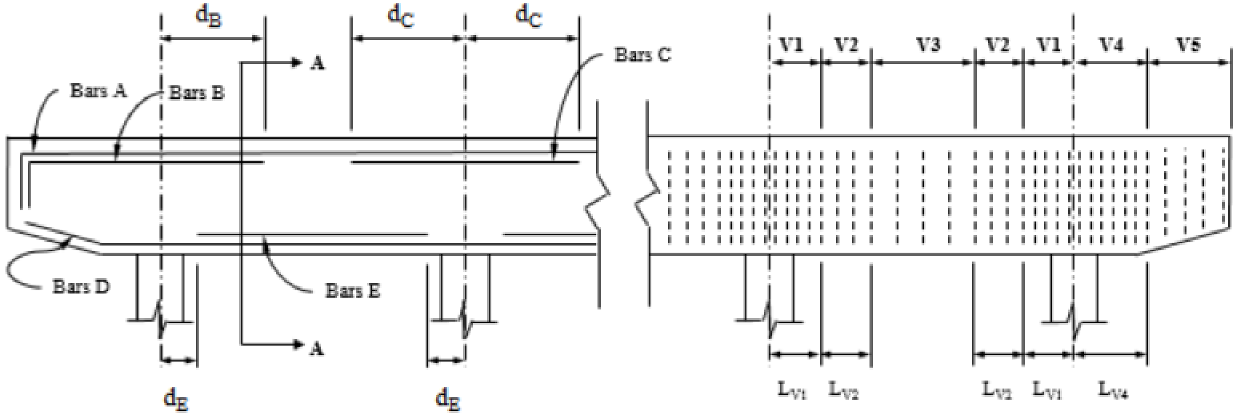
Bars A placed in 1st Layer	*Bars A placed in 2nd Layer*
10 *Number of bars,* $\#Bars_{A1}$	0 *Number of bars,* $\#Bars_{A2}$

Bars A: Continuous Top Reinforcement

Bars A placed in 1st Layer	*Bars A placed in 2nd Layer*
12 *Number of bars,* $\#Bars_{A1}$	0 *Number of bars,* $\#Bars_{A2}$



Flexural reinforcement



Design Example for Pile Bent Cap

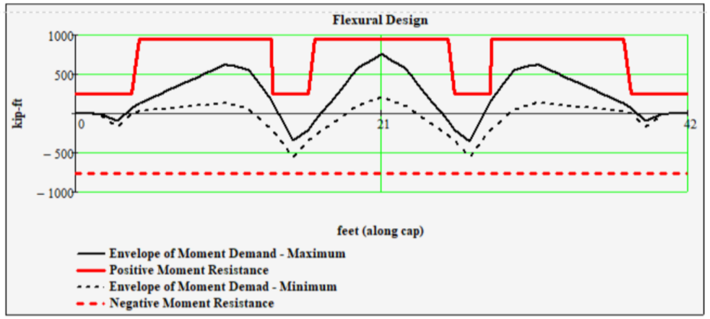
From Revised Design:

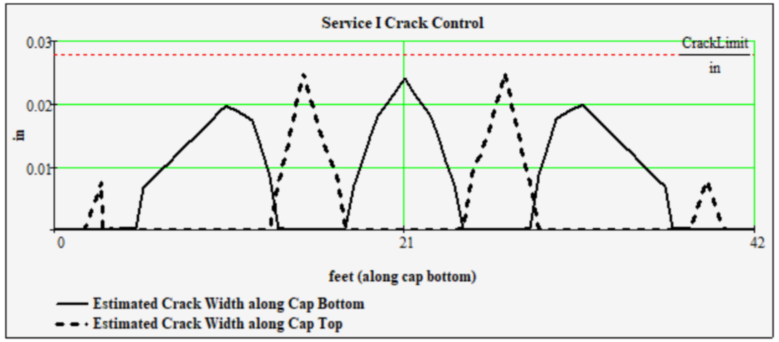
Summary of LRFD and SDG Checks

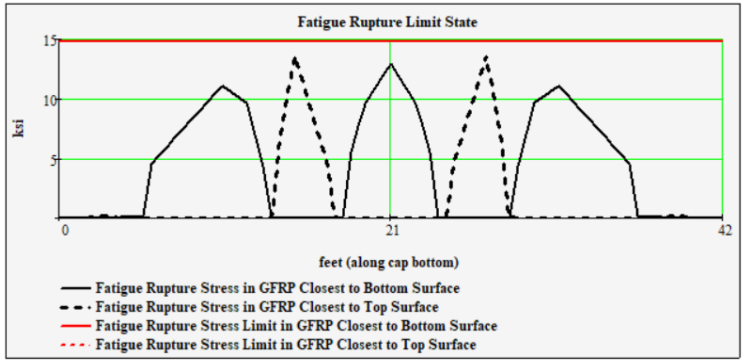
Save Data

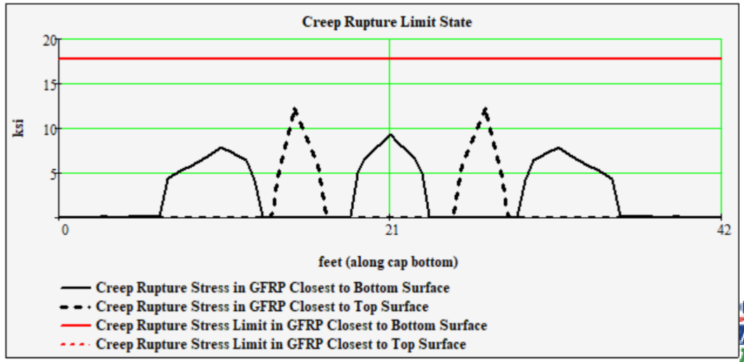
Positive Moment	***Negative Moment***	
$Check_{M.r.pos}$ = "OK"	$Check_{M.r.neg}$ = "OK"	
$\max(DCR_{M.pos}) = 0.80$	$\max(DCR_{M.neg}) = 0.73$	*The maximum demand to capacity ratio*
$Check_{minAf.bot}$ = "OK"	$Check_{minAf.top}$ = "OK"	
$Check_{crack.control.bot}$ = "OK"	$Check_{crack.control.top}$ = "OK"	
$\max(CrackW_{SerI.bot}) = 0.024 \cdot in$	$\max(CrackW_{SerI.top}) = 0.025 \cdot in$	*The maximum crack width*
$Check_{creep.bot}$ = "OK"	$Check_{creep.top}$ = "OK"	
$\max(f_{f.SL.bot}) = 9.36 \cdot ksi$	$\max(f_{f.SL.top}) = 12.33 \cdot ksi$	*The maximum stress under sustained load (DL+0.2LL)*
$Check_{fatigue.bot}$ = "OK"	$Check_{fatigue.top}$ = "OK"	
$\max(f_{f.Fat.bot}) = 12.97 \cdot ksi$	$\max(f_{f.Fat.top}) = 13.63 \cdot ksi$	*The maximum stress under fatigue (DL+1.75LL.fatigue)*
$C_f \cdot f_{fd.pos} = 14.8 \cdot ksi$	$C_f \cdot f_{fd.neg} = 14.8 \cdot ksi$	*Fatigue stress limit*

- **Revised Output – Flexure (Pos. & Neg. Moment)**
  - All OK!









Design Example for Pile Bent Cap

Summary of LRFD and SDG Checks

Positive Moment ***Negative Moment*** Save Data

Shear Checks

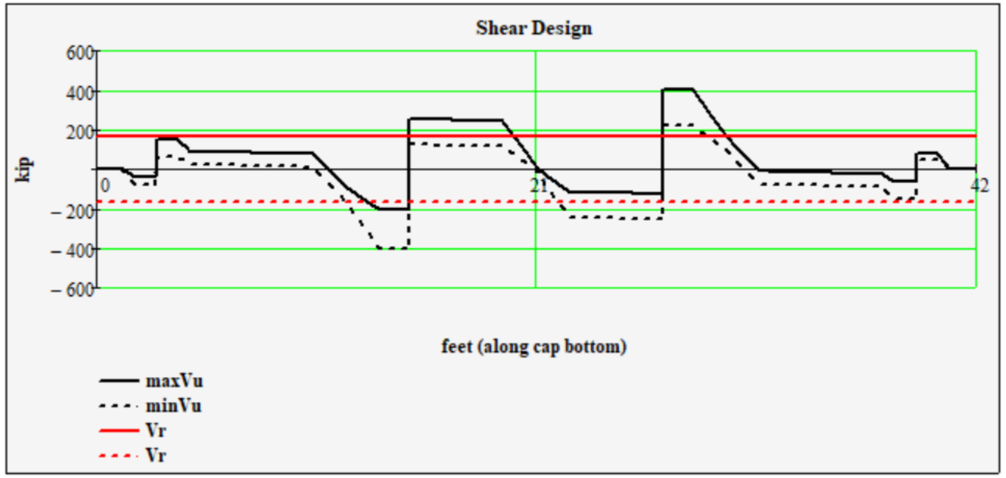
$Check_{V.r}$ = "NG"

$\max(DCR_V) = 2.40$ *The maximum demand to capacity ratio*

$Check_{A.v.min}$ = "OK"

$Check_{shear.spa}$ = "OK"

$CriticalSpa_{reqd.shear} = 14.8 \cdot in$ *The allowable spacing for shear reinforcement at the most critical cap section*



- **Check Output – Shear Reinforcement**
  - DCR = 2.40 ← *No Good!*
  - Revise
- Shear resistance is lower for both V_c & V_f than steel-RC design.

2.7.3.3—Nominal Shear Resistance

The nominal shear resistance, V_n, shall be determined as:

$$V_n = V_c + V_f \qquad (2.7.3.3\text{-}1)$$

Using Simplified Method for determining β *and* θ

$$V_c = 0.0316\,\beta\,\sqrt{f'_c}\,b_v d_v \qquad (2.7.3.4\text{-}1)$$

- $\beta = 5.0k$

where the ratio of depth of neutral axis to reinforcement depth, k, may be calculated using Eq. 2.5.3-4.

- $\theta = 45°$

Design Example for Pile Bent Cap

Summary of LRFD and SDG Checks

Positive Moment ***Negative Moment*** Save Data

Shear Checks

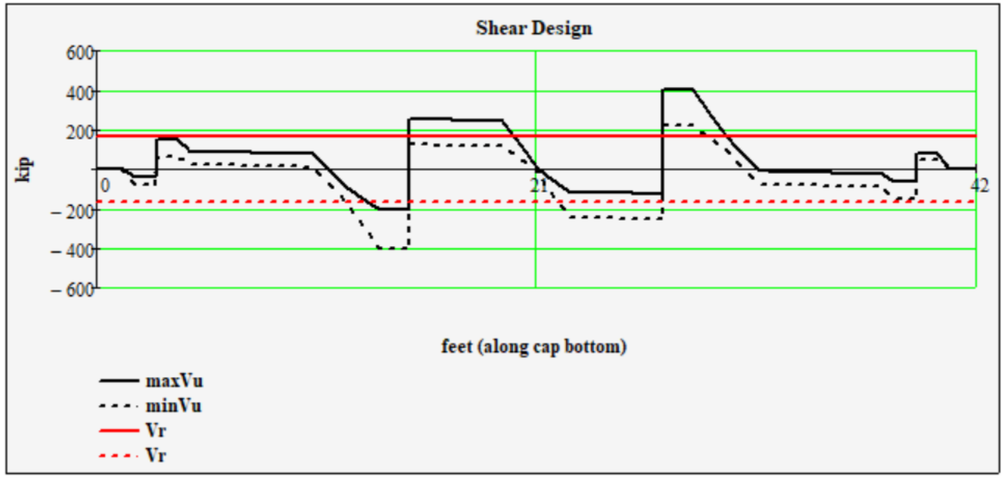
$\text{Check}_{V.r}$ = "NG"

$\max(\text{DCR}_V) = 2.40$ *The maximum demand to capacity ratio*

$\text{Check}_{A.v.min}$ = "OK"

$\text{Check}_{shear.spa}$ = "OK"

$\text{CriticalSpa}_{reqd.shear} = 14.8 \cdot in$ *The allowable spacing for shear reinforcement at the most critical cap section*



- **Check Output – Shear Reinforcement**
  - DCR = 2.40 ← *No Good!*
  - Revise Spacing or Size
- Shear Reinf. Design Stress is Limited by Elastic Modulus not Bent Bar Strength
  - $0.004E_f$ = 26 ksi ← *Governs!*
  - $(0.05r_b/d_b + 0.3)f_{fd}$ = 31.5 ksi

2.7.3.5—Procedure for Determining Shear Resistance Provided by Transverse Reinforcement

When using stirrups or hoops perpendicular to the longitudinal axis of the member, the nominal shear resistance provided by the transverse reinforcement, V_f, shall be calculated as:

$$V_f = \frac{A_{fv} f_{fv} d_v \cot\theta}{s} \quad (2.7.3.5\text{-}1)$$

in which:

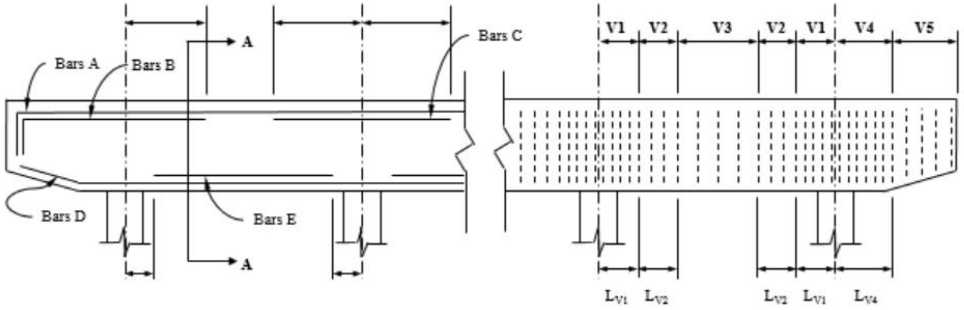
$$f_{fv} = 0.004E_f \le f_{fb} \quad (2.7.3.5\text{-}2)$$

$$f_{fb} = \left(0.05\frac{r_b}{d_b} + 0.3\right) f_{fd} \le f_{fd} \quad (2.7.3.5\text{-}3)$$

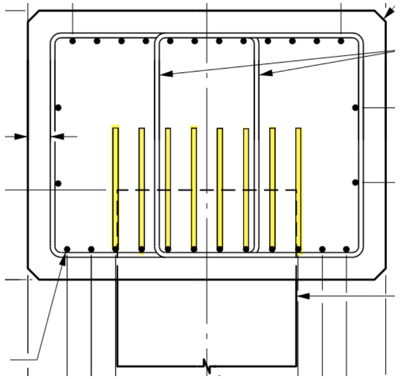
Design Example for Pile Bent Cap

Shear Reinforcement

In order to maintain a level of flexibility for modeling and to allow for multiple spacings for shear reinforcement along the cap, the spacing of the stirrups over the pile (non-critical fo shear) is assumed to be the same as the first zone beyond the face of the pile.

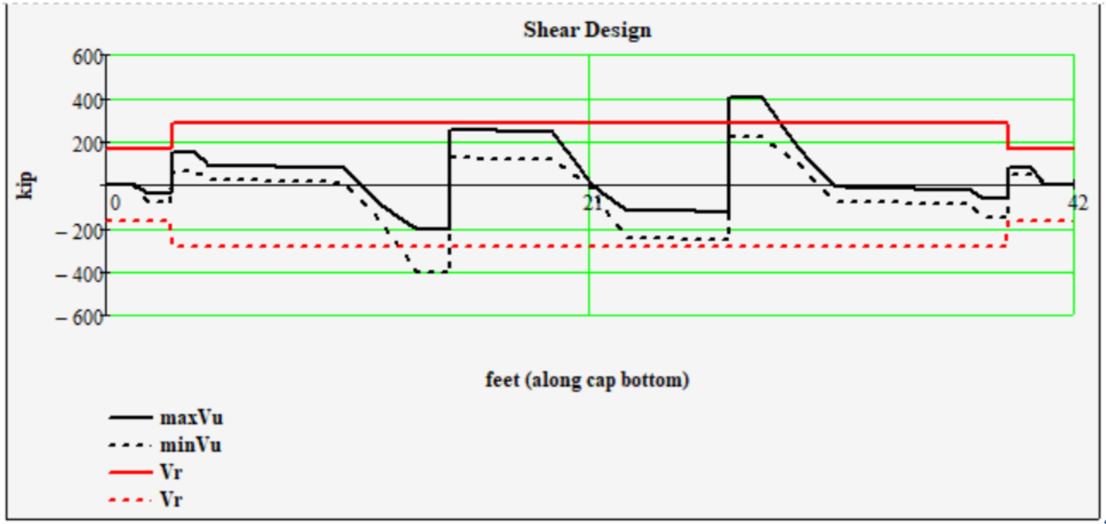


Zone V1		*Zone V2*		*Zone V3*	
0	*Size of stirrup bar,* $Bar\#_{V1}$	0	*Size of stirrup bar,* $Bar\#_{V2}$	5	*Size of stirrup bar,* $Bar\#_{V3}$
0	*No. of bar legs,* $\#Legs_{V1}$	0	*No. of bar legs,* $\#Legs_{V2}$	4	*No. of bar legs,* $\#Legs_{V3}$
0	*Spacing (in.),* Spa_{V1}	0	*Spacing (in.),* Spa_{V2}	3	*Spacing (in.),* Spa_{V3}
0	*Length of Zone V1 (in.),* L_{V1}	0	*Length of Zone V2 (in.),* L_{V2}		



- **Recall Original Inputs for Shear Reinforcement**
  - Zone V3 - #5 @ 6” sp. (4 legs) ← *No Good*
  - Zone V5 - #5 @ 6” sp. (4 legs) ← *OK*
- **Revision-1 Inputs Shear Reinforcement - Zone 3**
  - Try Zone V3 - #5 @ 3” sp. (4 legs)
  - DCR = 1.41 ← *still No Good*

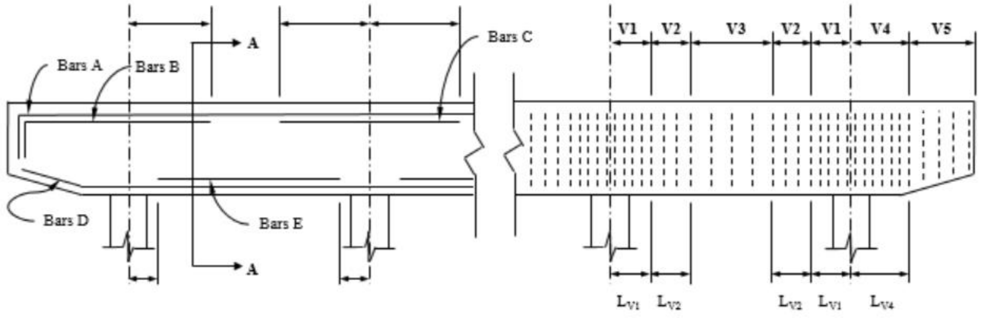
$\max(DCR_V) = 1.41$ *The maximum demand to capacity ratio*



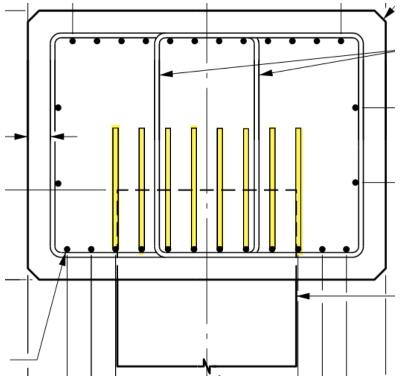
Design Example for Pile Bent Cap

Shear Reinforcement

In order to maintain a level of flexibility for modeling and to allow for multiple spacings for shear reinforcement along the cap, the spacing of the stirrups over the pile (non-critical fo shear) is assumed to be the same as the first zone beyond the face of the pile.

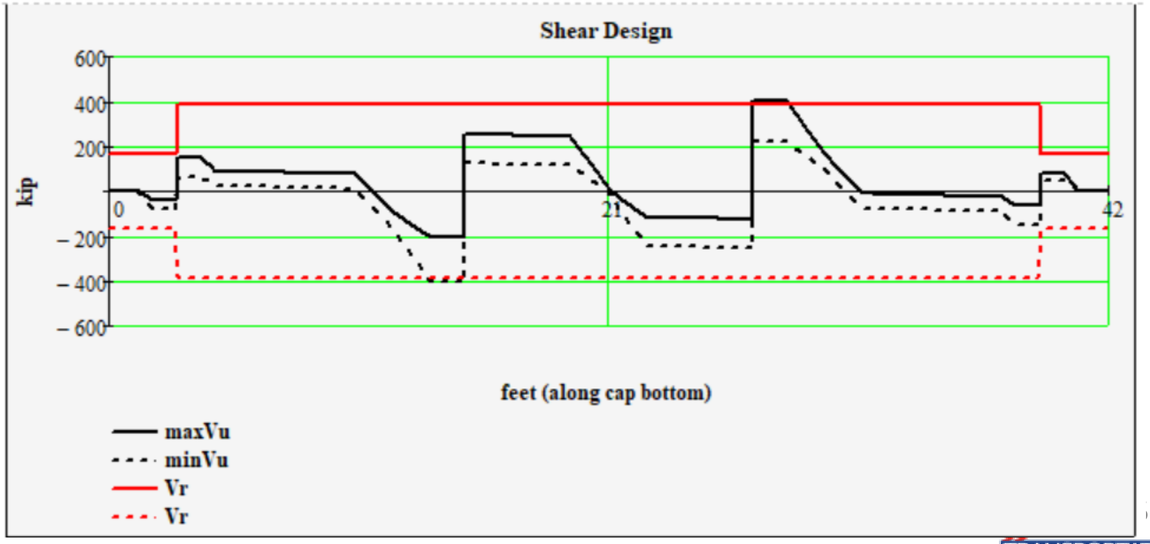


Zone V1		*Zone V2*		*Zone V3*	
0	*Size of stirrup bar,* $Bar\#_{V1}$	0	*Size of stirrup bar,* $Bar\#_{V2}$	6	*Size of stirrup bar,* $Bar\#_{V3}$
0	*No. of bar legs,* $\#Legs_{V1}$	0	*No. of bar legs,* $\#Legs_{V2}$	4	*No. of bar legs,* $\#Legs_{V3}$
0	*Spacing (in.),* Spa_{V1}	0	*Spacing (in.),* Spa_{V2}	3	*Spacing (in.),* Spa_{V3}
0	*Length of Zone V1 (in.),* L_{V1}	0	*Length of Zone V2 (in.),* L_{V2}		



- **Recall Revision-1 Inputs for Shear Reinforcement**
  - Zone V3 - #5 @ 3” sp. (4 legs) ← *No Good*
  - Zone V5 - #5 @ 6” sp. (4 legs) ← *OK*
- **Revision-2 Inputs Shear Reinforcement - Zone 3**
  - Try Zone V3 - #6 @ 3” sp. (4 legs)
  - DCR = 1.04 ← *Still No Good* & too congested!

$\max(DCR_V) = 1.04$ *The maximum demand to capacity ratio*

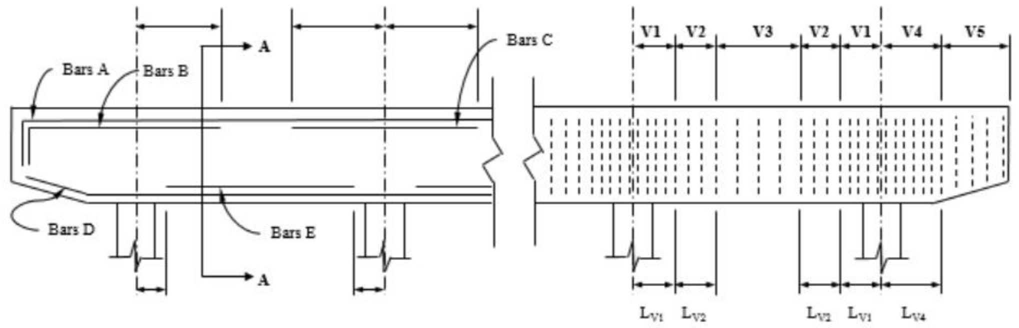


TRANSPORTATION SYMPOSIUM

Design Example for Pile Bent Cap (3-ft height cap)

Shear Reinforcement

In order to maintain a level of flexibility for modeling and to allow for multiple spacings for shear reinforcement along the cap, the spacing of the stirrups over the pile (non-critical fo shear) is assumed to be the same as the first zone beyond the face of the pile.



Zone V1

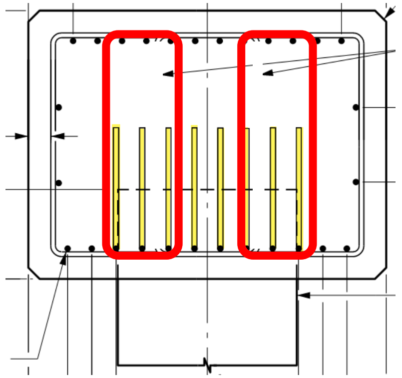
0	*Size of stirrup bar,* $Bar\#_{V1}$
0	*No. of bar legs,* $\#Legs_{V1}$
0	*Spacing (in.),* Spa_{V1}
0	*Length of Zone V1 (in.),* L_{V1}

Zone V2

0	*Size of stirrup bar,* $Bar\#_{V2}$
0	*No. of bar legs,* $\#Legs_{V2}$
0	*Spacing (in.),* Spa_{V2}
0	*Length of Zone V2 (in.),* L_{V2}

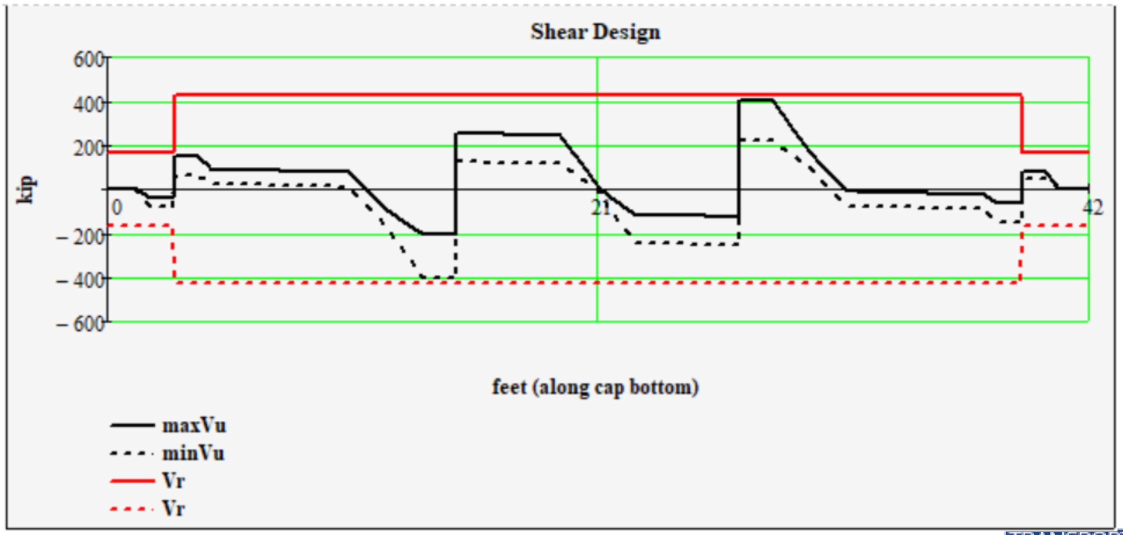
Zone V3

6	*Size of stirrup bar,* $Bar\#_{V3}$
6	*No. of bar legs,* $\#Legs_{V3}$
4	*Spacing (in.),* Spa_{V3}



- **Recall Revision-2 Inputs for Shear Reinforcement**
  - Zone V3 - #6 @ 3" sp. (4 legs) ← *No Good*
  - Zone V5 - #5 @ 6" sp. (4 legs) ← *OK*
- **Revision-3 Inputs Shear Reinforcement - Zone 3**
  - Try Zone V3 - #6 @ 4" sp. (6 legs)
  - DCR = 0.94 ← *OK, however a better design approach would be to thicken the bent cap to 4-ft.*

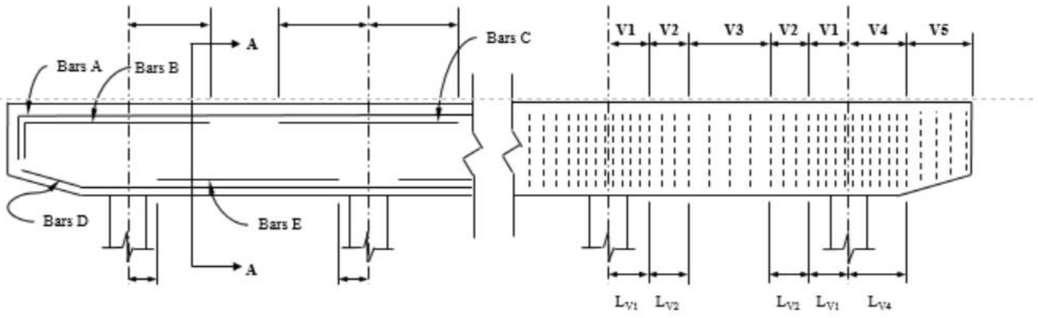
$\max(DCR_V) = 0.94$ *The maximum demand to capacity ratio*



Design Example for Pile Bent Cap (4-ft height cap)

Shear Reinforcement

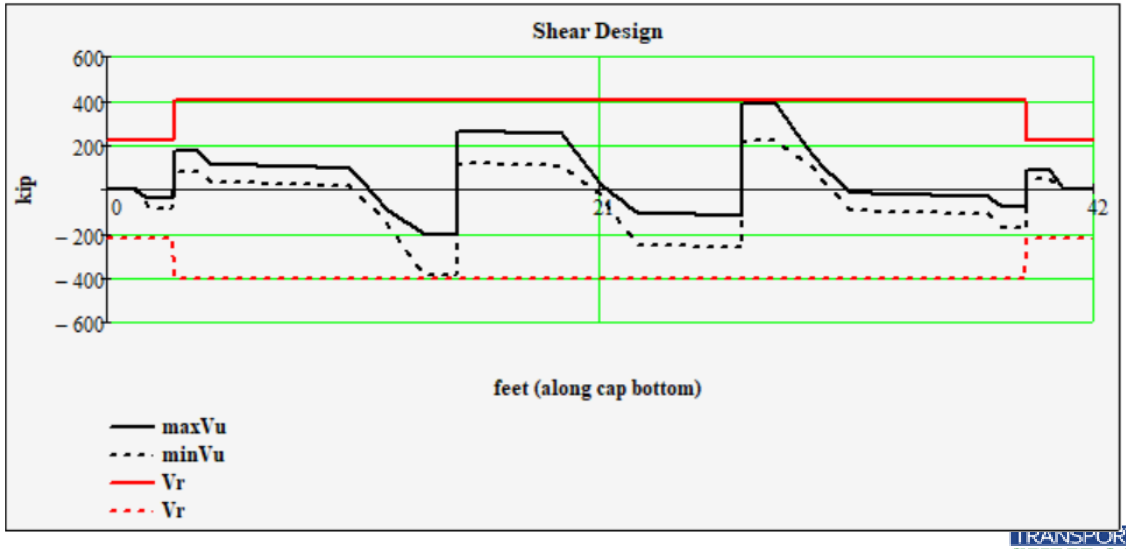
In order to maintain a level of flexibility for modeling and to allow for multiple spacings for shear reinforcement along the cap, the spacing of the stirrups over the pile (non-critical fo shear) is assumed to be the same as the first zone beyond the face of the pile.



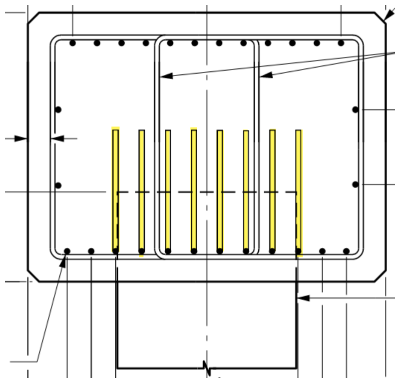
Zone V1		*Zone V2*		*Zone V3*	
0	*Size of stirrup bar,* $Bar\#_{V1}$	0	*Size of stirrup bar,* $Bar\#_{V2}$	6	*Size of stirrup bar,* $Bar\#_{V3}$
0	*No. of bar legs,* $\#Legs_{V1}$	0	*No. of bar legs,* $\#Legs_{V2}$	4	*No. of bar legs,* $\#Legs_{V3}$
0	*Spacing (in.),* Spa_{V1}	0	*Spacing (in.),* Spa_{V2}	4	*Spacing (in.),* Spa_{V3}
0	*Length of Zone V1 (in.),* L_{V1}	0	*Length of Zone V2 (in.),* L_{V2}		

- **Recall 3-ft Cap Inputs for Shear Reinforcement**
  - Zone V3 - #6 @ 4” sp. (6 legs) ← *OK*
  - Zone V5 - #5 @ 6” sp. (4 legs) ← *OK*
- **Revise 4-ft Cap Shear Reinforcement - Zone 3**
  - Try Zone V3 - #6 @ 4” sp. (4 legs)
  - DCR = 0.96 ← *OK*

$\max(DCR_V) = 0.96$ *The maximum demand to capacity ratio*



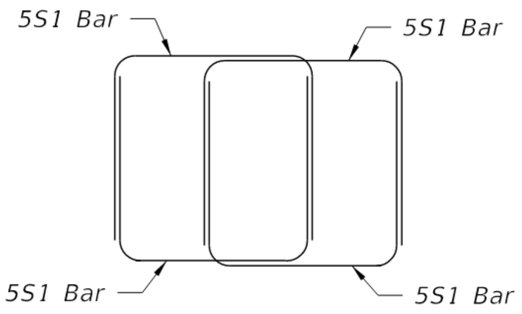
You should also be able to reduce some of the flexural reinforcing with the deeper cap!



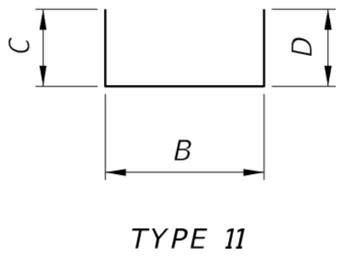
TRANSPORTATION SYMPOSIUM

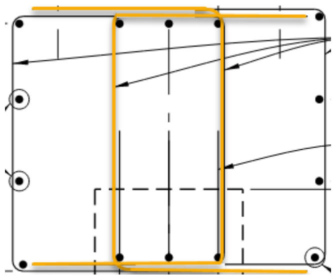
Design Example for Pile Bent Cap (Shear Stirrups)

- **Shear Stirrup Configurations (2 or 4-Leg)**

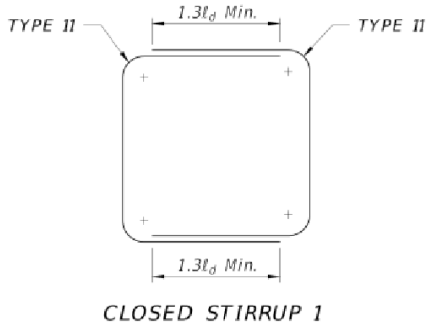


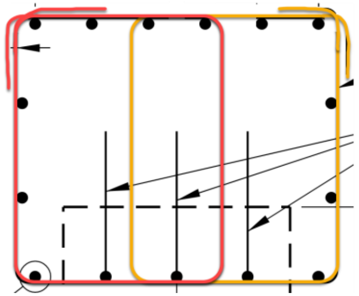
Initial FDOT project details (used Side Lap-Splice with pairs of U-Bars – “Type 11” FDOT Bar Bend)





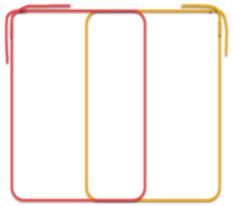
Better Detail uses Top & Bottom laps. Better anchorage, but results in congestion in 4-leg stirrups due to 4 bar overlap). Similar to ***SPI 415-010 “Design Aid”***

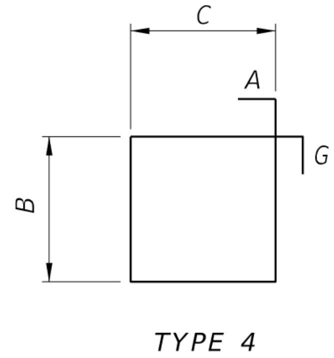




4 -Leg Stirrups

Now Recommend using “Type 4” FDOT Bar Bend. Being added to ***FY 2023-24*** ***Standard Plans*** ***Index 415-010***



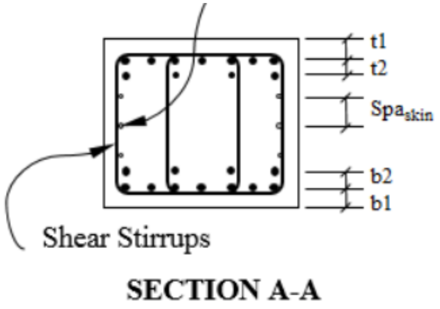


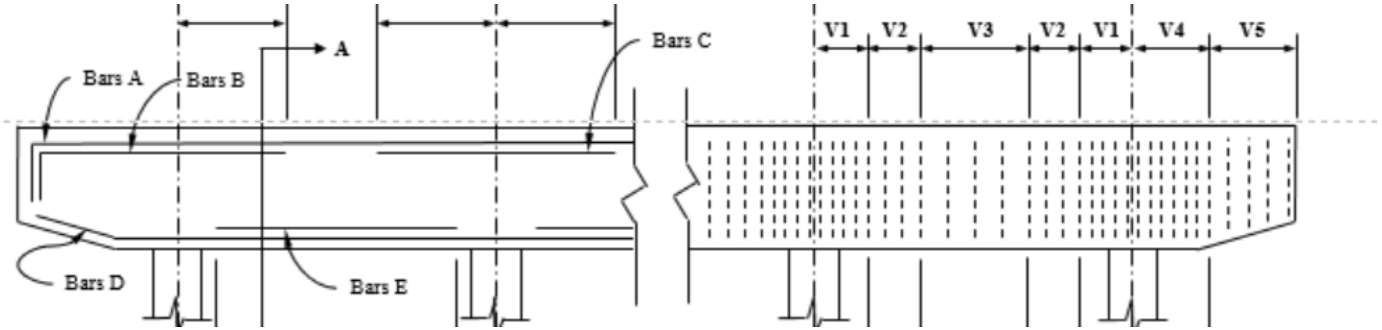
Part 3 – Design & AASHTO Checks

Design Example for Pile Bent Cap (Summary)

- **Comparison of different design alternates for 4-piles @ 12-ft spacing (Example 2)**

Rebar Location	GFRP-RC 3-ft Deep Cap	GFRP-RC 4-ft Deep Cap	Steel-RC 3-ft Deep Cap
Bars A - Flexural Top	**12 ~ #8's** (A_f = 9.5 in^2)	**9 ~ #8's** (A_f = 7.1 in^2)	**7 ~ #8's** (A_s = 5.5 in^2)
Bars D & E - Flexural Bottom	**15 ~ #8's** (A_f = 11.9 in^2)	**16 ~ #8's** (A_f = 12.6 in^2)	**8 ~ #8's** (A_s = 6.3 in^2)
Bars V3 - Shear Stirrups	**6-legs #6 at 4" sp.** (A_f = 7.9 in^2/ft)	**4-legs #6 at 4" sp.** (A_f = 5.3 in^2)	**4-legs #5 at 9" sp.** (A_s = 1.7 in^2)

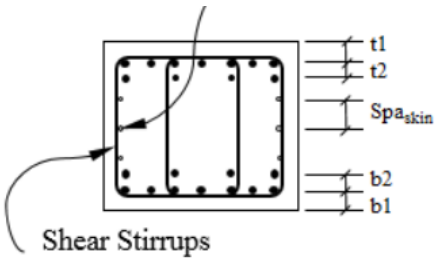




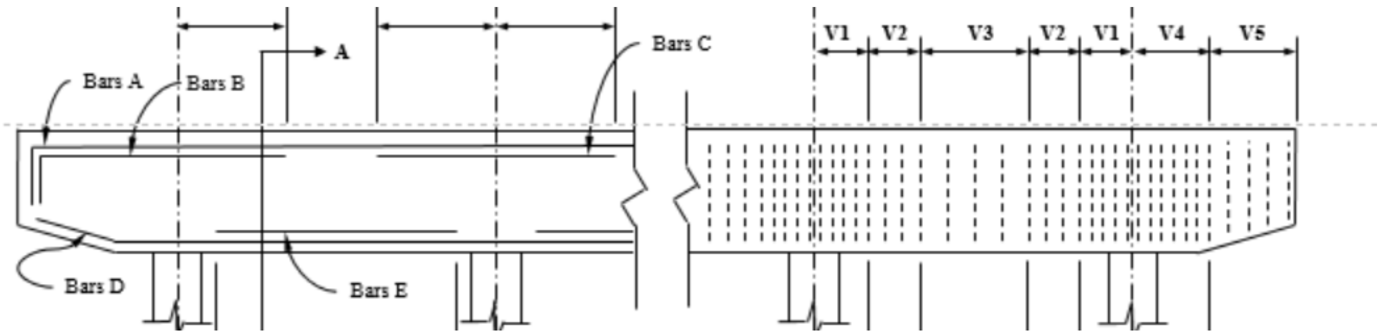
Design Example for Pile Bent Cap (Summary)

- **Comparison of different design alternates for 5-piles @ 9-ft spacing (Example 1)**

Rebar Location	GFRP-RC 3-ft Deep Cap		Steel-RC 3-ft Deep Cap
Bars A - Flexural Top	**6 ~ #8's** (A_f = 4.7 in^2)		**6 ~ #6's** (A_s = 2.6 in^2)
Bars D & E - Flexural Bottom	**8 ~ #8's** (A_f = 6.3 in^2)		**7 ~ #7's** (A_s = 4.2 in^2)
Bars V3 - Shear Stirrups	**4-legs #5 at 11" sp.** (A_f = 1.4 in^2/ft)		**4-legs #4 at 12" sp.** (A_s = 0.8 in^2)



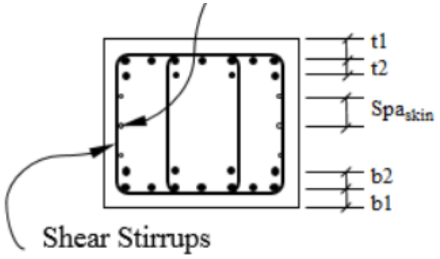
SECTION A-A



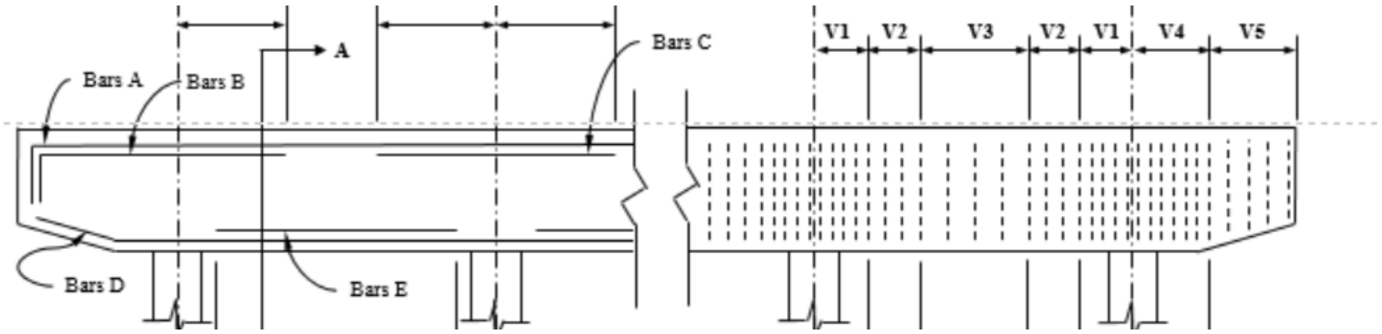
Design Example for Pile Bent Cap (Summary)

- **Comparison of different design alternates for 5-piles @ 9-ft spacing (Example 1) – Higher Modulus GFRP Rebar (Ef = 6,500 psi to 8,700 psi for future enhancements to ASTM D7957)**

Rebar Location	**GFRP-RC 3-ft Deep Cap** (E_f = 6500 ksi)	**GFRP-RC 3-ft Deep Cap** (E_f = 7250 ksi)	**GFRP-RC 3-ft Deep Cap** (E_f = 8700 ksi)
Bars A - Flexural Top	**6 ~ #8's** (A_f = 4.7 in^2)	**7 ~ #7's** (A_f = 4.2 in^2)	**6 ~ #7's** (A_f = 3.6 in^2)
Bars D & E - Flexural Bottom	**8 ~ #8's** (A_f = 6.3 in^2)	**7 ~ #8's** (A_f = 5.5 in^2)	**6 ~ #8's** (A_f = 4.7 in^2)
Bars V3 - Shear Stirrups	**4-legs #5 at 11" sp.** (A_f = 1.4 in^2/ft)	**4-legs #5 at 13" sp.** (A_f = 1.1 in^2/ft)	**4-legs #4 at 10" sp.** (A_f = 1.0 in^2/ft)

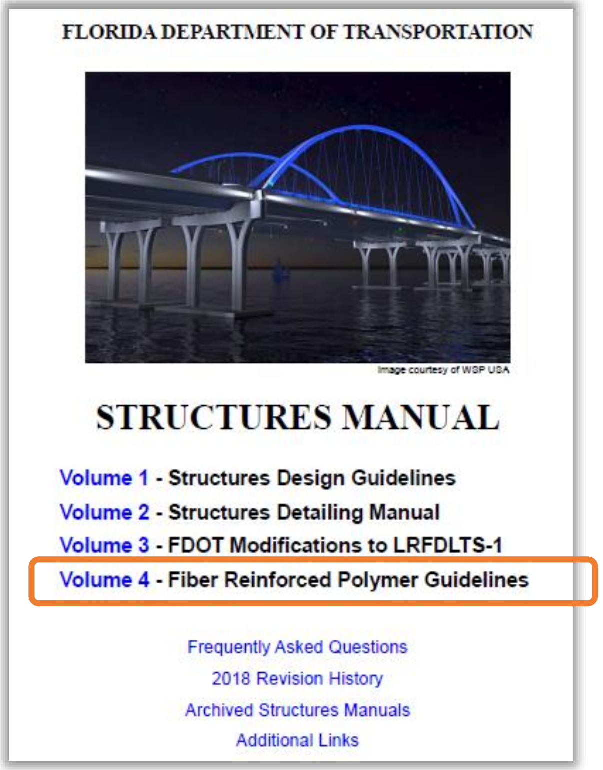


SECTION A-A

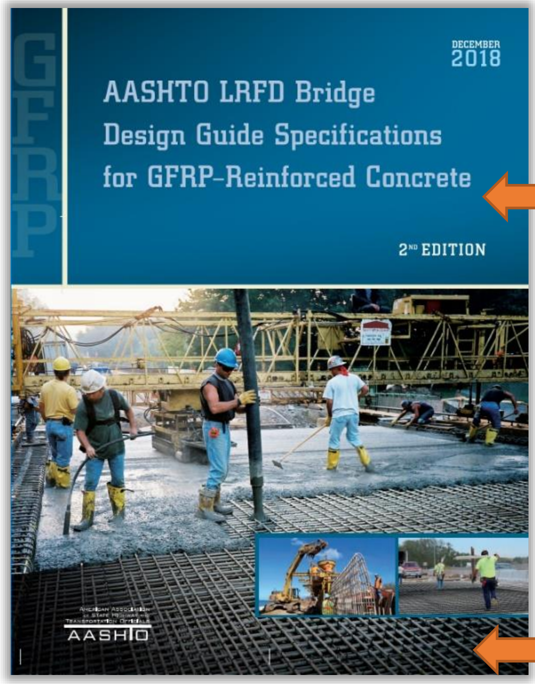


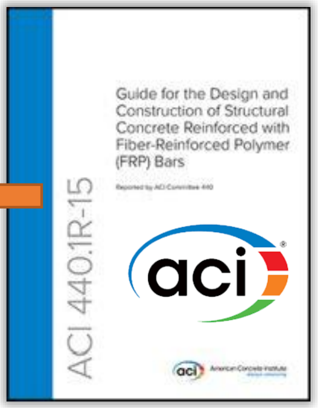
Review: Design guidance & resources

- FDOT Design Guidance – *FRPG Chapter 2*



- AASHTO Design Guide Specifications for GFRP-RC





https://www.fdot.gov/structures/structuresmanual/currentrelease/structuresmanual.shtm

Review: Design guidance & resources

- Materials & Construction

MAC Materials Acceptance and Certification System

elect Report to View

Production Facility

Aggregate Production Facility Listing	Lists all Aggregate Production Facilities
All Producers (Excel)	Lists all non-expired Production Facilities in an Excel file
Approved Aggregate Products For Friction Course	Lists all Aggregate Friction Course Products by Geological
Approved Aggregate Products From Mines or Terminals Listing	Lists Approved Aggregate Products for Mines or Terminals
Approved Products at Expired Mines or Terminals	A summary report to identify Approved Products at Expired Terminals Expired at Mine
Asphalt Production Facility Listing	Lists all Asphalt Production Facilities
Asphalt Recycled Products	Approved Asphalt Recycled Products Report by Plant
Asphalt Targets	A listing of the asphalt gradation and gravity (Gsb) data for
Cementitious Materials Production Facility Listing	Lists Cementitious Materials Production Facilities
Coatings Production Facility Listing	Lists all Coatings Production Facilities
Fiber Reinforced Polymer Production Facility Listing	Lists all Fiber Reinforced Polymer Production Facilities

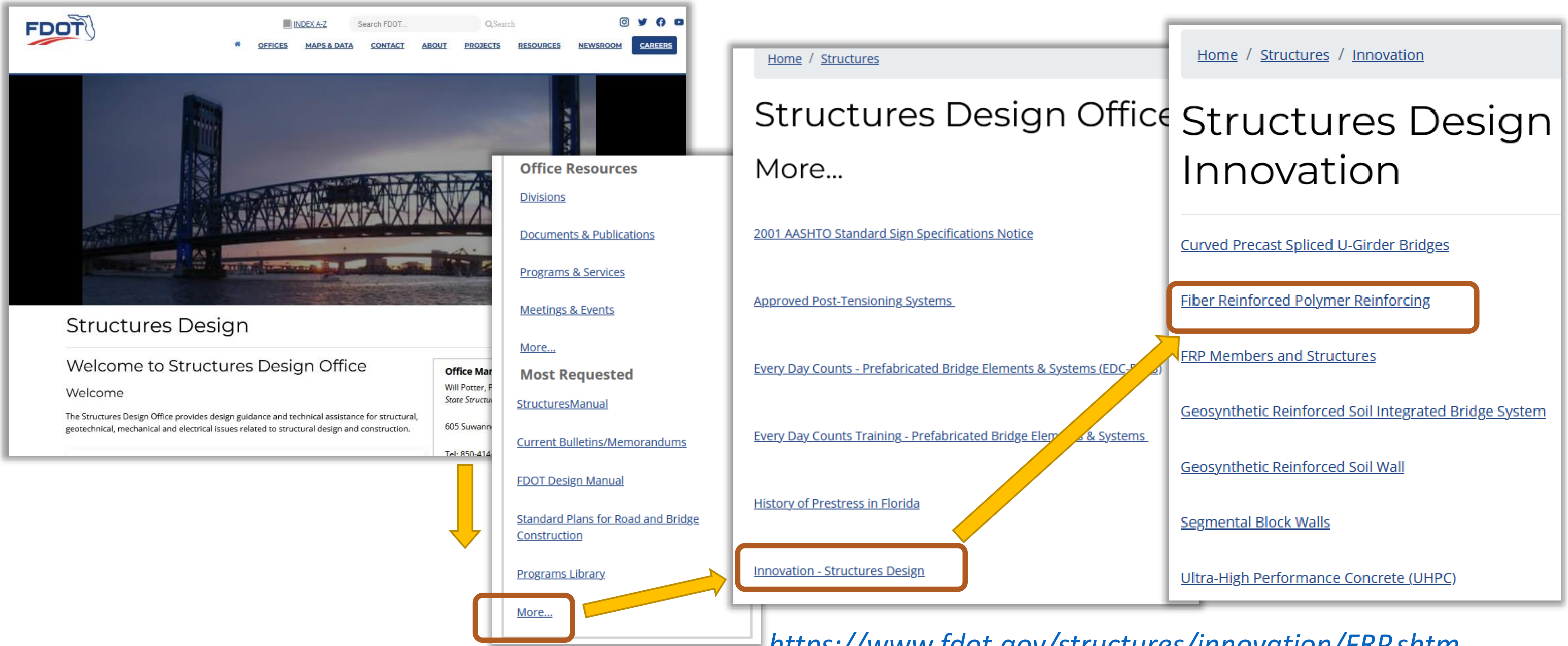
https://mac.fdot.gov/smoreports

Sections 415, 450, 932-3 & 933

https://www.fdot.gov/programmanagement/Implemented/SpecBooks/default.shtm

Where to find more FRP-RC info & training

https://www.fdot.gov/structures



https://www.fdot.gov/structures/innovation/FRP.shtm

Where to find more FRP-RC training

Structures Design

Structures Design / Design Innovation

Fiber Reinforced Polymer Reinforcing

Structures Design - Transportation Innovation
Fiber Reinforced Polymer (FRP)
Reinforcing Bars and Strands

- **Overview**
- **Usage Restrictions / Parameters**
- **Design Criteria**
- **Specifications**
- **Standards**
- **Producer Quality Control Program**
- **Projects**
- **Technology Transfer (T^2)**
- **FDOT Research**
- **Contact**

Overview

The deterioration of reinforcing and prestressing stee... structures. In addition to being exposed to weather, con... aggressive environments such as marine locations and inla... create paths for the agents of the aggressive environments... corrosive oxidation process. An innovative approach to com... reinforcement with Fiber Reinforced Polymer (FRP) reinforc... from filaments or fibers held in a polymeric resin matrix bind... glass (GFRP), basalt (BFRP) or carbon (CFRP). A surface t... reinforcing and the concrete.

2020

- TRB 2020 Workshop 1063 (Jan 12, 2020):
  - **Externally Bonded Wraps**
  - **FRP Design Tools, CBB Implementation & Pedestrian Bridges**
- **FDOT Executive Workshop** (January 15, 2020)
- FTS2020 **"FRP Reinforced and Prestressed Concrete Designer Training Int...**
- **FDOT/FRP Industry 4th RC/PC Workshop** (August 4, 2020)
- **FDOT GFRP-RC Designer Training for Bridges & Structures** (August 10, 2020)
- **FDOT CFRP-PC Designer Training for Bridges & Structures** (September 9, 2020)
- CAMX 2020 - Infrastructure Education Presentation: **Advancements in composite infrastr...**

Structures Design Office

FDOT 2020 GFRP-RC Design Training Course

Meeting Information

Dates
August 10, 2020

Location
FDOT - Hosted Online via GoTo Webinar

Video Recording - AASHTO GFRP-RC Designer Training for Bridges and Structures (GoTo Stage)

Presentation Slides:

- Introduction & Materials
- Flexure Response
- Shear Response
- Axial Response
- Case Studies & Field Applications

https://www.fdot.gov/structures/innovation/FRP.shtm

Florida Department of TRANSPORTATION

FDOT 2020 GFRP-RC Design Training Course

6-Hour Recorded Webinar Course

https://www.fdot.gov/structures/innovation/fdot-2020-gfrp-rc-design-course

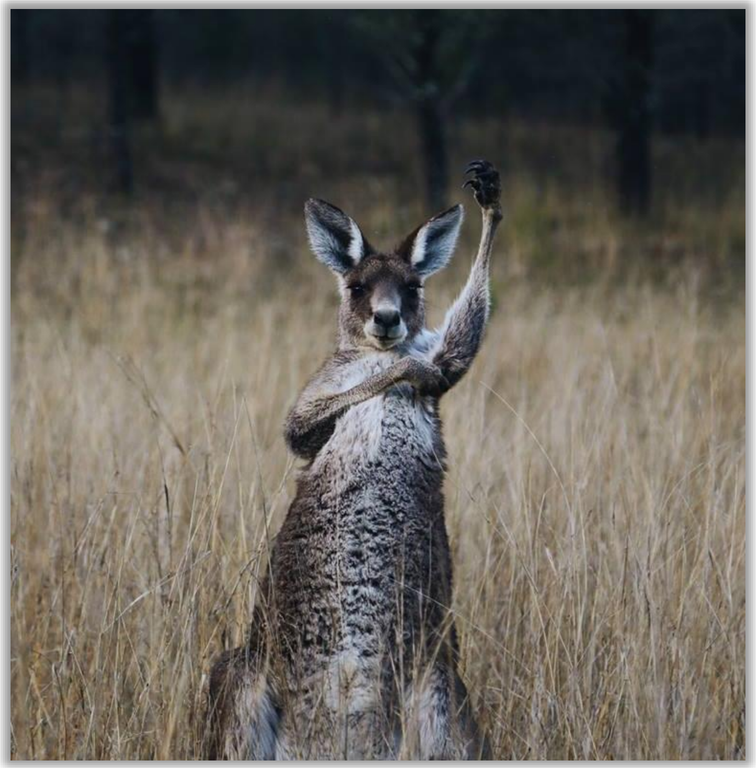
GFRP-Reinforced Concrete Design for Bridges

Lead Speaker: Prof. Antonio Nanni
Co-Speaker: Dr. Francisco De Caso

Department of Civil, Architectural &
Environmental Engineering
University of Miami

UNIVERSITY OF MIAMI

Questions



NO text.
NO call.
NOTHING
is worth losing a life over.

PUT IT DOWN
IT'S THE LAW

Contact Information

Steven Nolan, P.E.
FDOT State Structures Design Office,
605 Suwannee St, Tallahassee, FL. 32399
Steven.Nolan@dot.state.fl.us

Ge Wan, P.E.
FDOT State Structures Design Office,
605 Suwannee St, Tallahassee, FL. 32399
Ge.Wan@dot.state.fl.us