ASCE TEXAS
CECON2023
CIVIL ENGINEERING CONFERENCE

# Shallow Foundation Design: PTI vs Finite Element Method of Design and Performance for a Typical 40x70 Slab-On-Ground Foundation Design

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Presented by Anna Olveda with Wafflemat

PT-Structures

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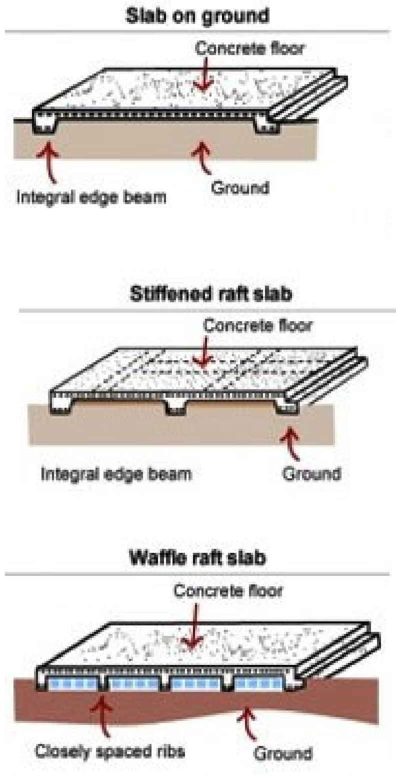
# Shallow Foundation Design Introduction

The design of shallow, slab-on-grade foundation design is a widely favored approach for creating foundations for low- to mid-rise buildings. This preference is driven by its cost-effectiveness, construction simplicity, and the engineer’s capability to expedite the foundation design process.

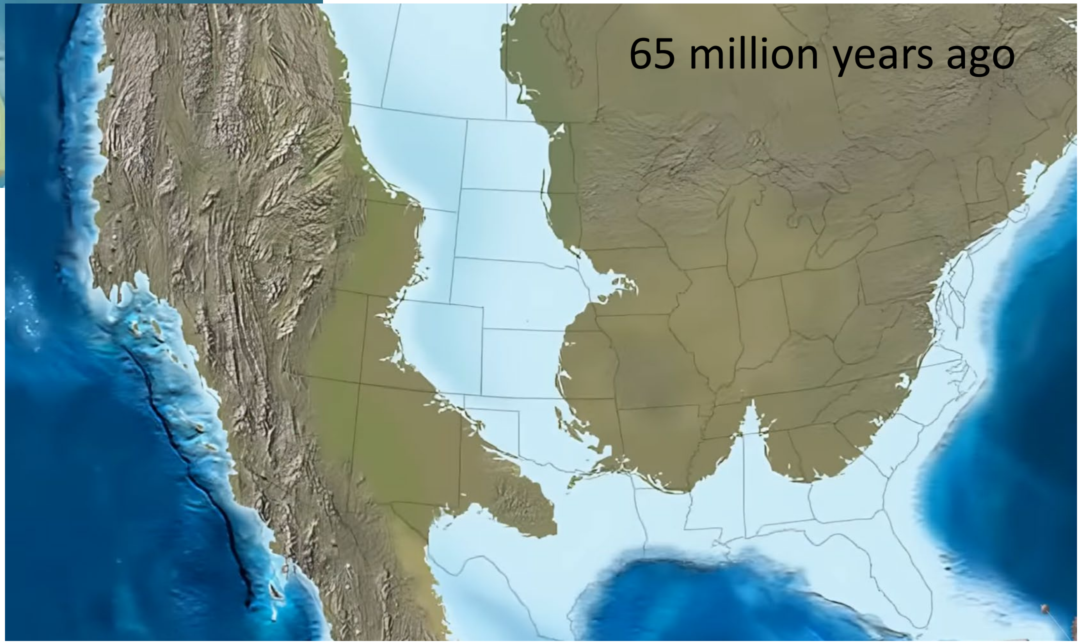


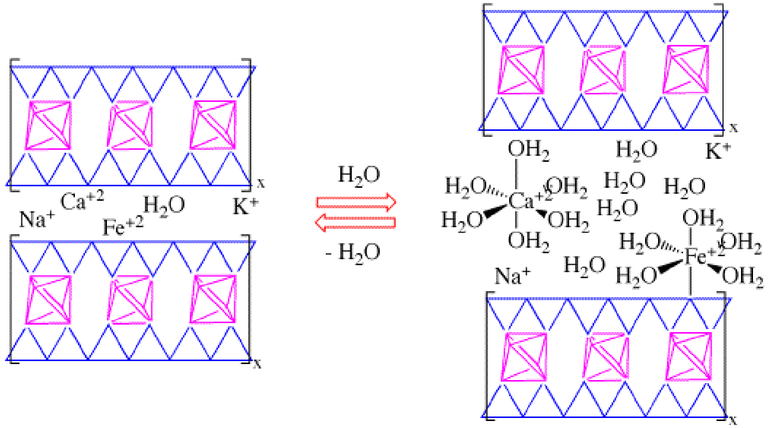
*Source: https://theconstructor.org/practical-guide/concrete-slab-construction-cost/28153/*

Stiffened Slab

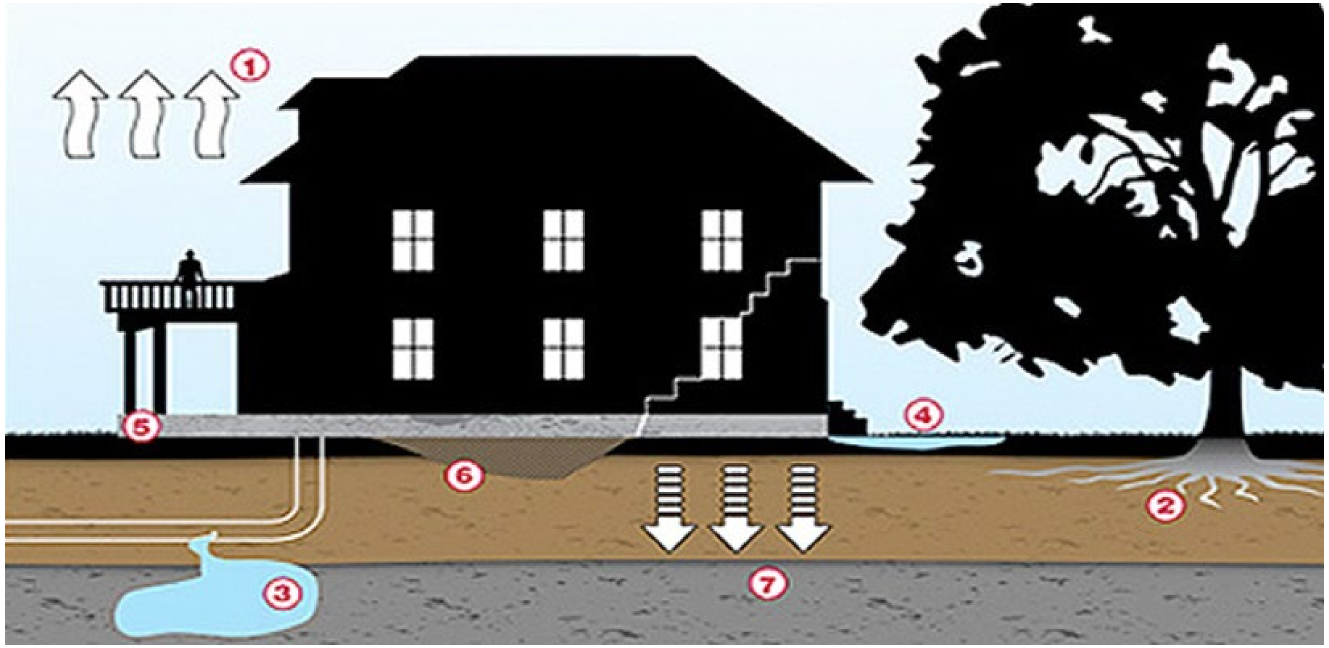
Waffle Slab

# Expansive Clays: Macro to Micro Views





Source: Retention of Water in Clay Minerals – Atomic Structure
http://butane.chem.uiuc.edu/pshapley/Environmental/L28/2.html



# Reasons for Heave

Primary Causes of Differential Heave:

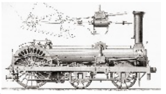
- Nonuniform changes in soil moisture
- Variation in thickness and composition of the expansive foundation soil
- Nonuniform structural loads
- Geometry of the structure

Early Settlements & Colonial Periods

1600s to 1700s

In the early day of the United States, foundation design for buildings were rudimentary. European settlers used simple shallow foundations, such as stone or brick footings to support their structures.

Industrial Revolution & Early Engineering Principles



1700s

Industrial Revolution & the growth of cities, the need more sophistacated foundation design became apparent. Engineers introduced improved foundation systems for important structures.

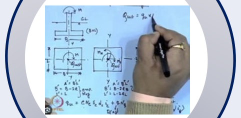
American Society of Civil Engineers Established

ASCE

11/5/1852

Structural engineering became a recognized discipline & professional organization ASCE was established. The establishment of building codes and standards brought uniformity & safety to shallow foundation design practices.

Development of Structural Analysis & Load Calculations



1800s to 1900s

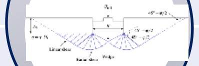
Engineers contributed to the understanding of soil mechanics and the determination of bearing capacity. This knowledge provided a scientific basis for shallow foundation design.

1900

Start of World War II

1939

Advancements in Soil Investigation & Testing

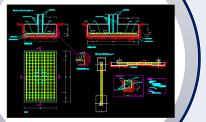


mid 1900s

1970s - Significant progress in soil investigation & testing techniques. The development of standard penetration tests, cone penetration tests, & other geo investigations allowed engineers to gather more accurate data of soil properties, enabling better designs.

Only build on good dirt

Computer Aided Design & Analysis



late 1900s to 2000s

Engineers could now create 2D and 3D models, perform structural anaylsis, and simulate soil-structure interaction more efficiently and accurately.

2000

2023

All the good dirt is taken

The Future is Now

# Current Design Codes/Guides

**1808.6.2 Slab-on-ground foundations.**

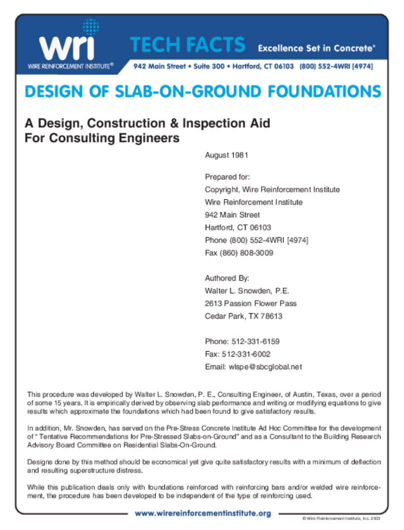
Moments, shears and deflections for use in designing slab-on-ground, mat or raft foundations on expansive soils shall be determined in accordance with WRI/CRSI *Design of Slab-on-Ground Foundations* or PTI DC 10.5. Using the moments, shears and deflections determined above, nonprestressed slabs-on-ground, mat or raft foundations on expansive soils shall be designed in accordance with WRI/CRSI *Design of Slab-on-Ground Foundations* and post-tensioned slab-on-ground, mat or raft foundations on expansive soils shall be designed in accordance with PTI DC 10.5. It shall be permitted to analyze and design such slabs by other methods that account for soil-structure interaction, the deformed shape of the soil support, the plate or stiffened plate action of the slab as well as both center lift and edge lift conditions. Such alternative methods shall be rational and the basis for all aspects and parameters of the method shall be available for peer review.


TENTH EDITION

CRSI

DESIGN HANDBOOK 2008

CRSI CONCRETE REINFORCING STEEL INSTITUTE


wri WIRE REINFORCEMENT INSTITUTE® TECH FACTS Excellence Set in Concrete®

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DESIGN OF SLAB-ON-GROUND FOUNDATIONS

A Design, Construction & Inspection Aid
For Consulting Engineers

August 1981

Prepared for:
Copyright, Wire Reinforcement Institute
Wire Reinforcement Institute
942 Main Street
Hartford, CT 06103
Phone (800) 552-4WRI [4974]
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Authored By:
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2613 Passion Flower Pass
Cedar Park, TX 78613

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Email: wlspe@sbcglobal.net

This procedure was developed by Walter L. Snowden, P. E., Consulting Engineer, of Austin, Texas, over a period of some 15 years. It is empirically derived by observing slab performance and writing or modifying equations to give results which approximate the foundations which had been found to give satisfactory results.

In addition, Mr. Snowden, has served on the Pre-Stress Concrete Institute Ad Hoc Committee for the development of " Tentative Recommendations for Pre-Stressed Slabs-on-Ground" and as a Consultant to the Building Research Advisory Board Committee on Residential Slabs-On-Ground.

Designs done by this method should be economical yet give quite satisfactory results with a minimum of deflection and resulting superstructure distress.

While this publication deals only with foundations reinforced with reinforcing bars and/or welded wire reinforcement, the procedure has been developed to be independent of the type of reinforcing used.

www.wirereinforcementinstitute.org

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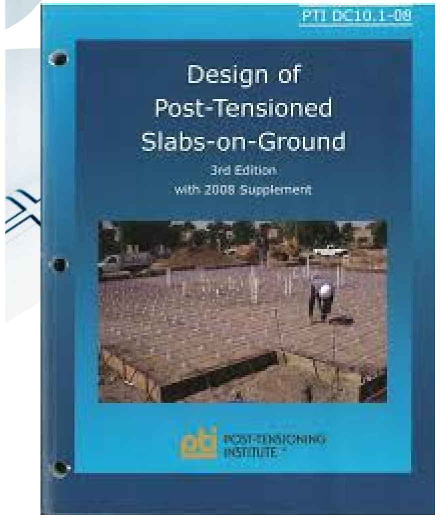
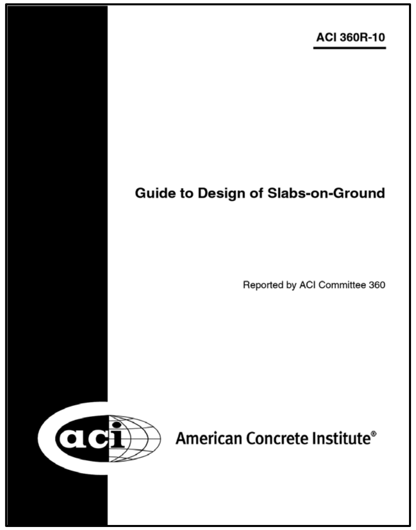

PTI DC10.1-08

Design of
Post-Tensioned
Slabs-on-Ground

3rd Edition
with 2008 Supplement

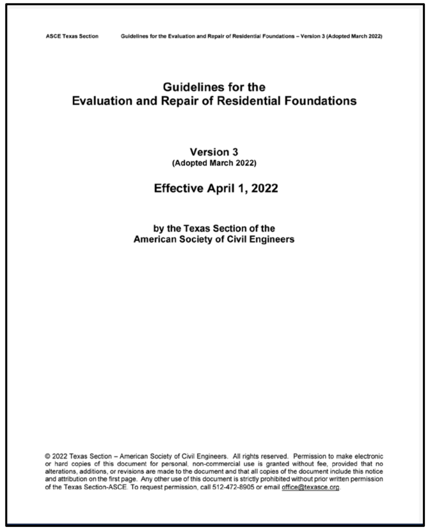
pti POST-TENSIONING INSTITUTE


ACI 360R-10

Guide to Design of Slabs-on-Ground

Reported by ACI Committee 360

aci American Concrete Institute®


ASCE Texas Section Guidelines for the Evaluation and Repair of Residential Foundations – Version 3 (Adopted March 2022)

Guidelines for the
Evaluation and Repair of Residential Foundations

Version 3
(Adopted March 2022)

Effective April 1, 2022

by the Texas Section of the
American Society of Civil Engineers

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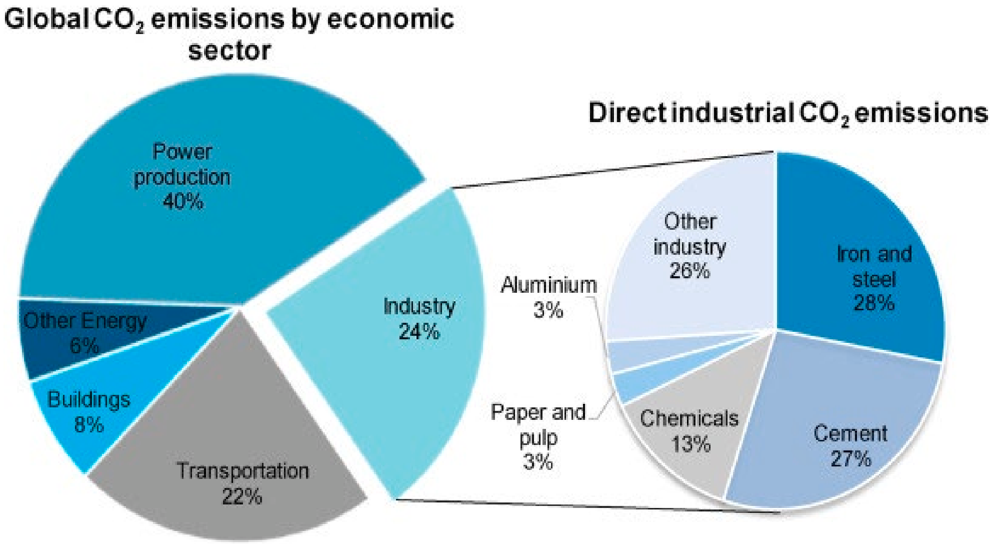
# Shallow Foundation Design Fun Facts

- Shallow foundation failures occur more often than earthquakes, floods, hurricanes, and tornadoes damages combined in the United States
- After water, concrete is the 2nd most consumed material on the planet
- Concrete production accounts for more than 8% of all green house gas emissions in 2021
- Demand for cost-effective and well performing foundations on expansive soils is very high, however, the existing PTI method of design is very restrictive and does not allow for the implementation of innovative foundation solutions.



*Source: https://www.sciencedirect.com/science/article/pii/S136403212100318X*

# Why Should We Care?

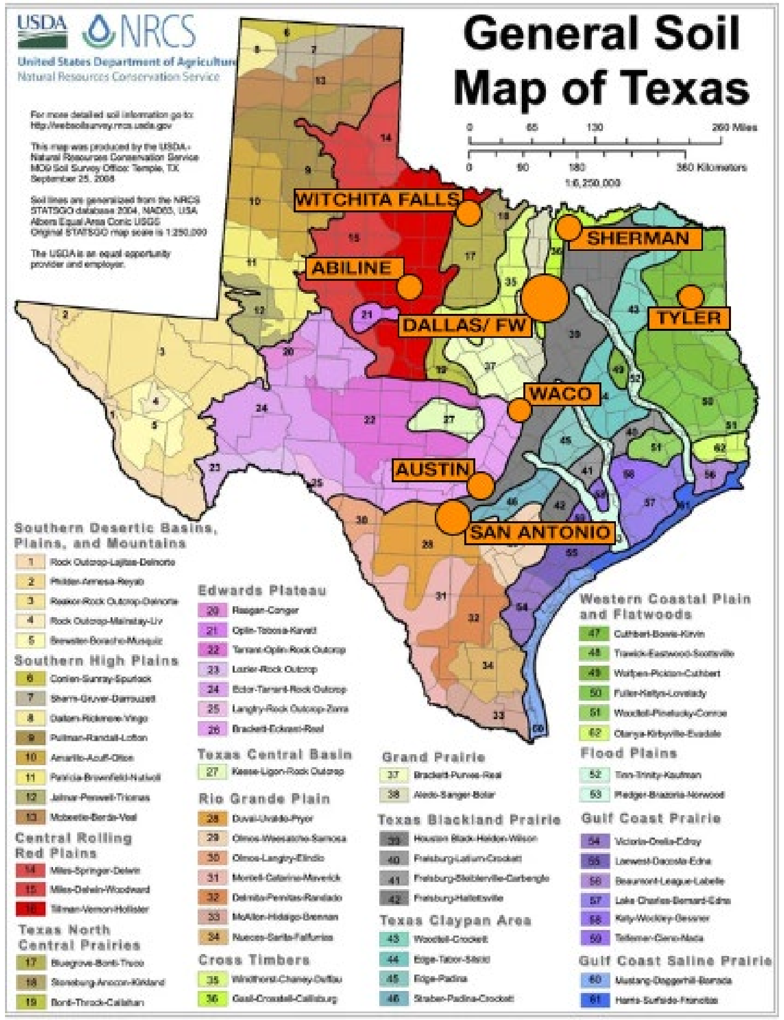
**Top 15 Metro Areas with Foundation Issues**

1 Sherman, TX – Ada, OK
2 San Antonio, TX
3 Dallas-Fort Worth, TX
4 Tyler-Longview, TX
5 Kansas City, MO
6 Grand Junction-Montrose, CO
7 Wichita Falls, TX – Lawton, OK
8 Waco-Temple-Bryan, TX
9 Columbia-Jefferson City, MO
10 Jackson, MS
11 St. Louis, MO
12 Abilene-Sweetwater, TX
13 Shreveport, LA
14 Austin, TX
15 Roanoke-Lynchburg, VA

*Top 15 US Metros with Foundation Issues in 2019 – list produced by Groundworks*

Foundation Repair Companies

#1 Sherman, TX – 466
#2 San Antonio, TX – 192
#3 Dalls-Fort Worth, TX – 488
#4 Tyler-Longview, TX – 472
#5 Wichita Falls, TX - 417
#6 Waco-Temple-Bryan, TX – 621
#7 Abilene-Sweetwater, TX – 129
#8 Austin, TX - 271

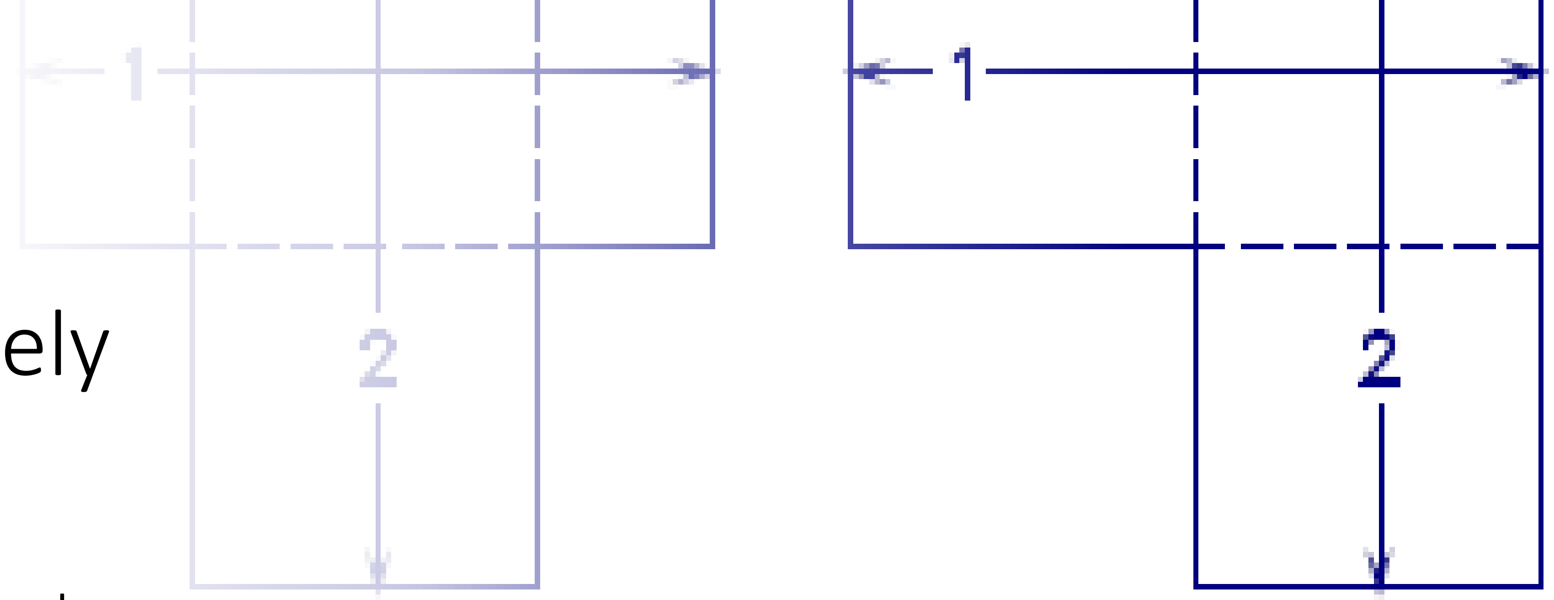


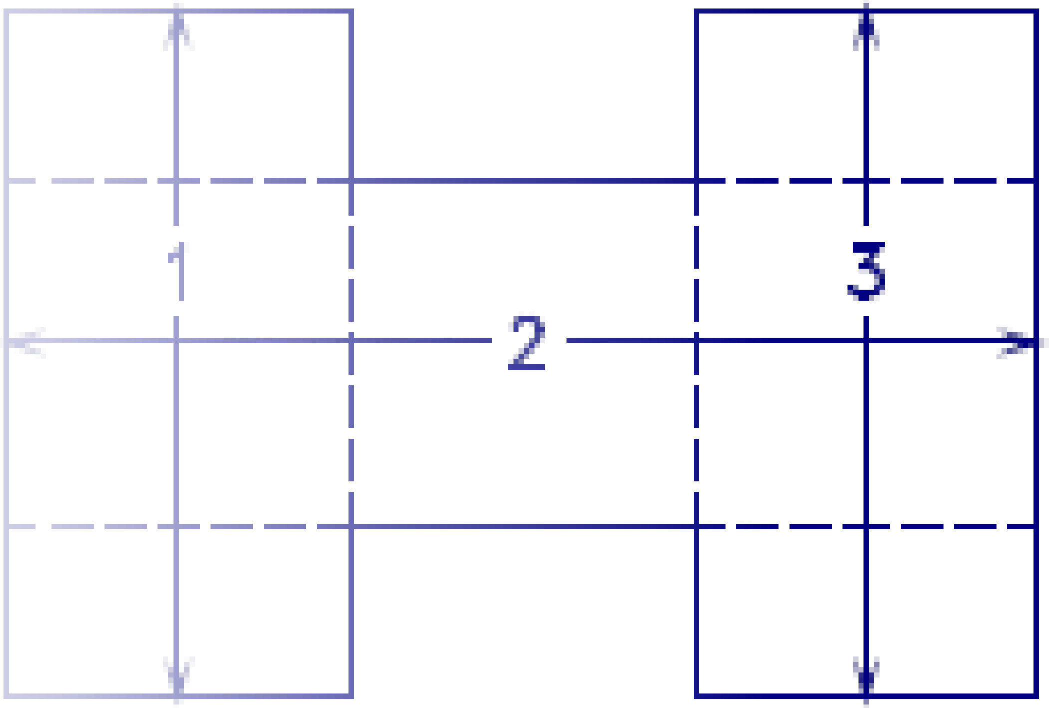
*Source: https://i.imgur.com/yrDkF4h.jpg*

*"This again is the paradox of design. Things that succeed teach us little beyond the fact that they have been successful; things that fail provide us with incontrovertible evidence that the limits of design have been exceeded. Emulating success risks failure; studying failures increases our chances of success. The simple principle that is seldom explicitly stated is that the most successful designs are based on the best and most complete assumptions about failure." ~Petroski 1985*

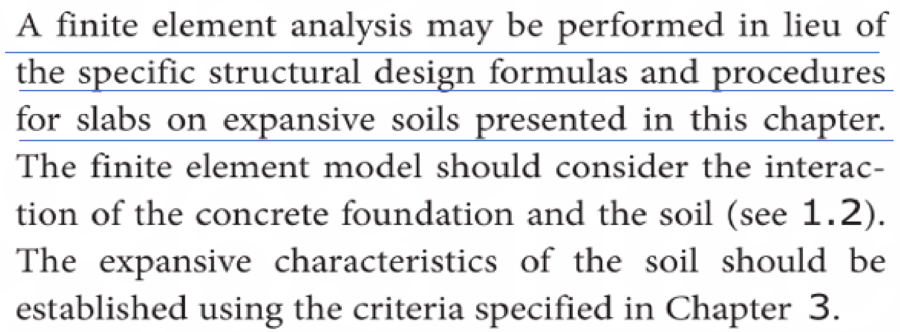
# Existing Design Methodology Extremely Limited

- Prescriptive and not performance-based
- Limited to rectangular shapes
- Overly conservative – worst-case rectangle governs
- Maximum allowable difference in beam depths not greater than 1.2
- Moment calculation discontinuity for Center Lift $e_m > 5$ ft
- Is not set up to analyze and check any other configuration



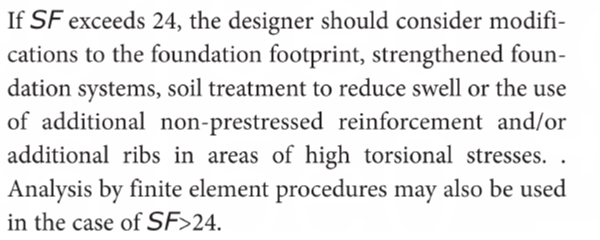


# Leveraging Capabilities of Advanced Finite Element Analysis



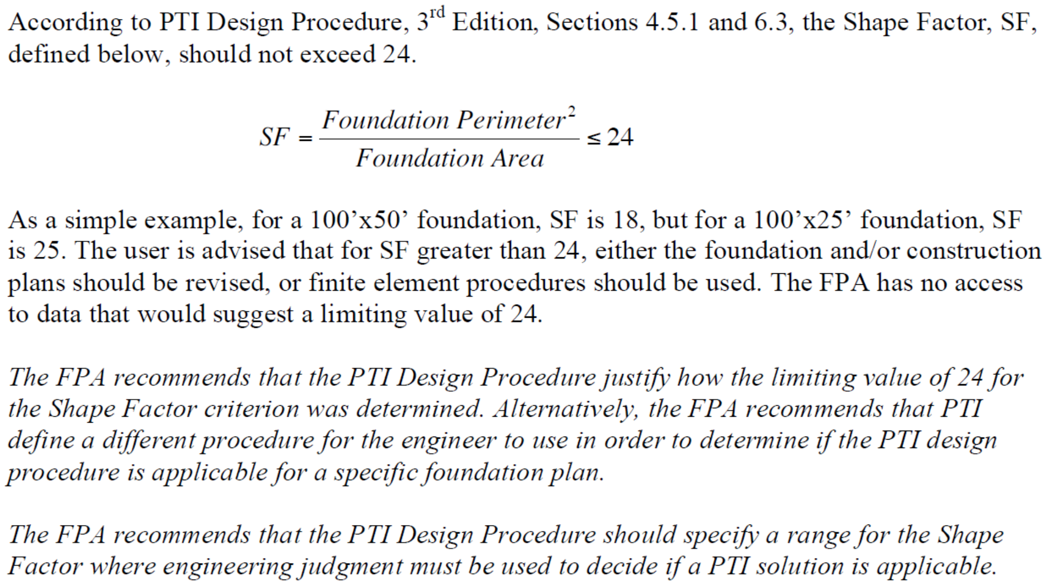
A finite element analysis may be performed in lieu of the specific structural design formulas and procedures for slabs on expansive soils presented in this chapter. The finite element model should consider the interaction of the concrete foundation and the soil (see 1.2). The expansive characteristics of the soil should be established using the criteria specified in Chapter 3.

PTI Section 6.1.13



If *SF* exceeds 24, the designer should consider modifications to the foundation footprint, strengthened foundation systems, soil treatment to reduce swell or the use of additional non-prestressed reinforcement and/or additional ribs in areas of high torsional stresses. . Analysis by finite element procedures may also be used in the case of *SF*>24.

PTI Section 4.5.1



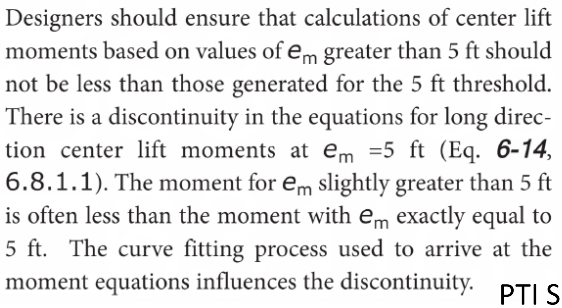
According to PTI Design Procedure, 3$^{rd}$ Edition, Sections 4.5.1 and 6.3, the Shape Factor, SF, defined below, should not exceed 24.

$$SF = \frac{Foundation\ Perimeter^2}{Foundation\ Area} \leq 24$$

As a simple example, for a 100'x50' foundation, SF is 18, but for a 100'x25' foundation, SF is 25. The user is advised that for SF greater than 24, either the foundation and/or construction plans should be revised, or finite element procedures should be used. The FPA has no access to data that would suggest a limiting value of 24.

*The FPA recommends that the PTI Design Procedure justify how the limiting value of 24 for the Shape Factor criterion was determined. Alternatively, the FPA recommends that PTI define a different procedure for the engineer to use in order to determine if the PTI design procedure is applicable for a specific foundation plan.*

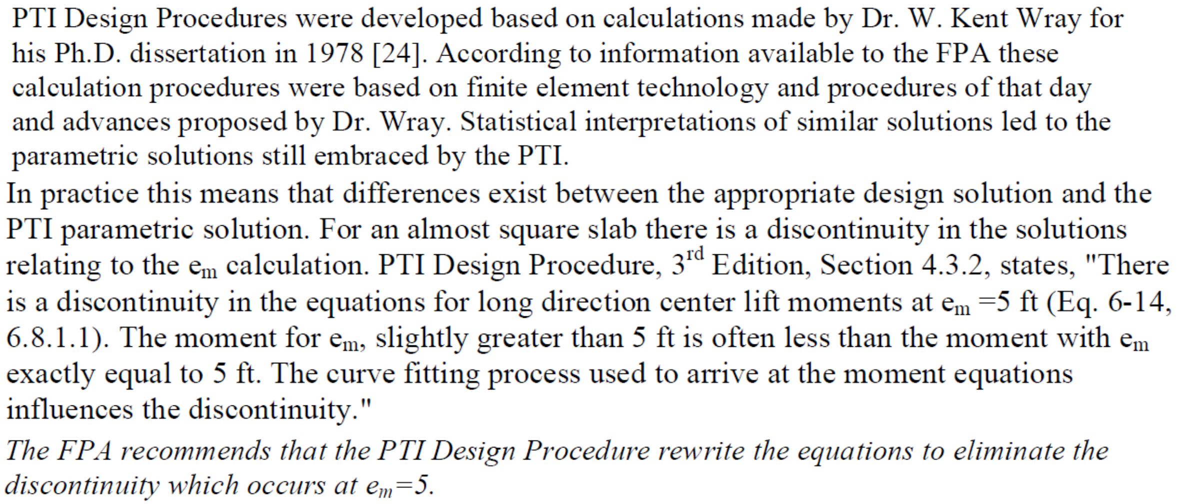
*The FPA recommends that the PTI Design Procedure should specify a range for the Shape Factor where engineering judgment must be used to decide if a PTI solution is applicable.*



Designers should ensure that calculations of center lift moments based on values of $e_m$ greater than 5 ft should not be less than those generated for the 5 ft threshold. There is a discontinuity in the equations for long direction center lift moments at $e_m$ =5 ft (Eq. **6-14**, 6.8.1.1). The moment for $e_m$ slightly greater than 5 ft is often less than the moment with $e_m$ exactly equal to 5 ft. The curve fitting process used to arrive at the moment equations influences the discontinuity.

PTI Section 4.3.2

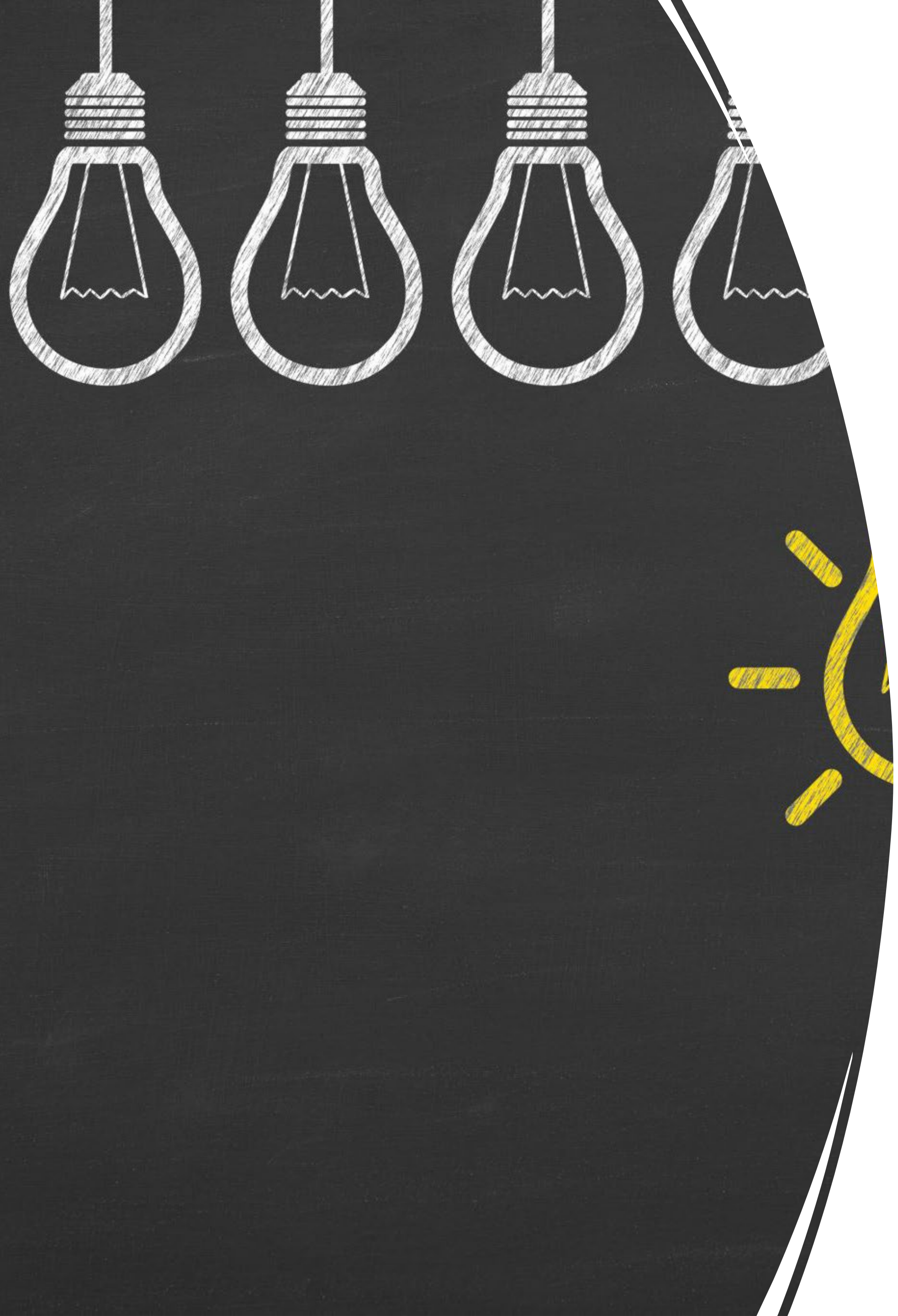
## FPA Comments by Structural Committee June 28, 2006



PTI Design Procedures were developed based on calculations made by Dr. W. Kent Wray for his Ph.D. dissertation in 1978 [24]. According to information available to the FPA these calculation procedures were based on finite element technology and procedures of that day and advances proposed by Dr. Wray. Statistical interpretations of similar solutions led to the parametric solutions still embraced by the PTI.

In practice this means that differences exist between the appropriate design solution and the PTI parametric solution. For an almost square slab there is a discontinuity in the solutions relating to the $e_m$ calculation. PTI Design Procedure, 3$^{rd}$ Edition, Section 4.3.2, states, "There is a discontinuity in the equations for long direction center lift moments at $e_m$ =5 ft (Eq. 6-14, 6.8.1.1). The moment for $e_m$, slightly greater than 5 ft is often less than the moment with $e_m$ exactly equal to 5 ft. The curve fitting process used to arrive at the moment equations influences the discontinuity."

*The FPA recommends that the PTI Design Procedure rewrite the equations to eliminate the discontinuity which occurs at $e_m$=5.*

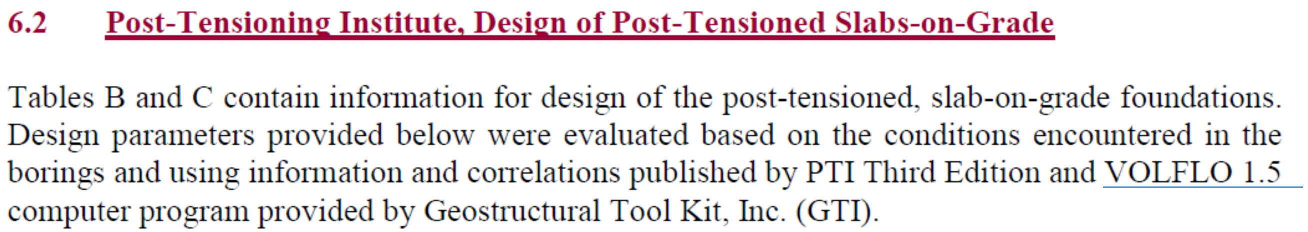


# Learning Objectives

At the end of this presentation, you will be able to:

- Assess differences between traditional PTI and FEM design methods for slab-on-ground foundations
- Understand FEM design approach
- Evaluate a Wafflemat design
- Confidently apply FEM-based design method to non-traditional slabs

# Case Study Project: 40x70 Foundation



**6.2 Post-Tensioning Institute, Design of Post-Tensioned Slabs-on-Grade**

Tables B and C contain information for design of the post-tensioned, slab-on-grade foundations. Design parameters provided below were evaluated based on the conditions encountered in the borings and using information and correlations published by PTI Third Edition and VOLFLO 1.5 computer program provided by Geostructural Tool Kit, Inc. (GTI).

Registered T
Serial Number :

PTISlab 3.5

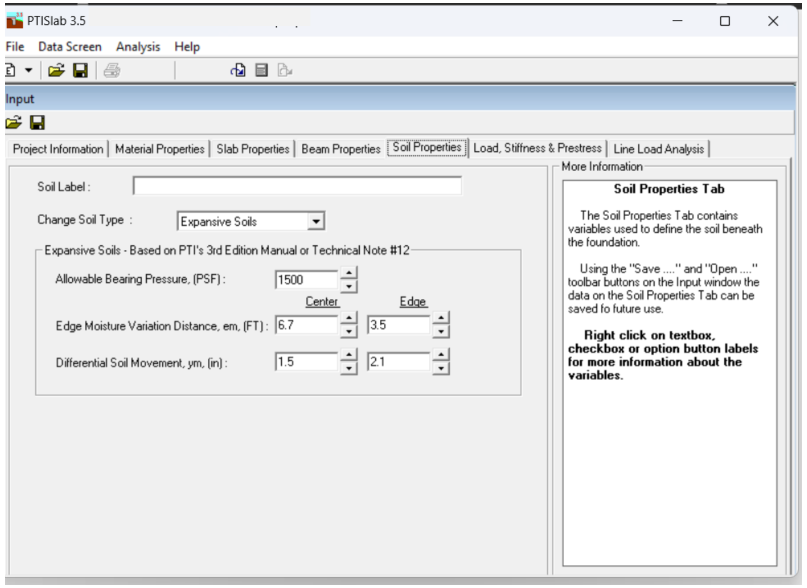
Build 011313

GTK
Geostructural Tool Kit, Inc.

pti
MEMBER

Copyright © 2013 Geostructural Tool Kit, Inc.

Warning: This computer program is protected by copyright law and international treaties. Unauthorized reproduction or distribution of this program, or any portion of it, may result in severe civil and criminal penalties, and will be prosecuted to the maximum extent possible under law.



Soil Label :

Change Soil Type : Expansive Soils

Expansive Soils - Based on PTI's 3rd Edition Manual or Technical Note #12

| | Center | Edge |
|---|---|---|
| Allowable Bearing Pressure, (PSF) : | 1500 | |
| Edge Moisture Variation Distance, em, (FT) : | 6.7 | 3.5 |
| Differential Soil Movement, ym, (in) : | 1.5 | 2.1 |

**Soil Properties Tab**

The Soil Properties Tab contains variables used to define the soil beneath the foundation.

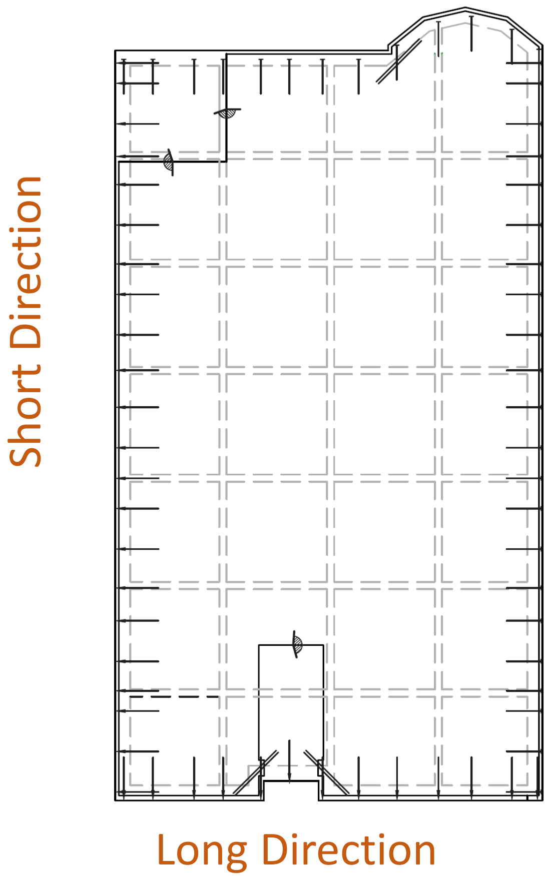
Using the "Save ...." and "Open ...." toolbar buttons on the Input window the data on the Soil Properties Tab can be saved fo future use.

**Right click on textbox, checkbox or option button labels for more information about the variables.**

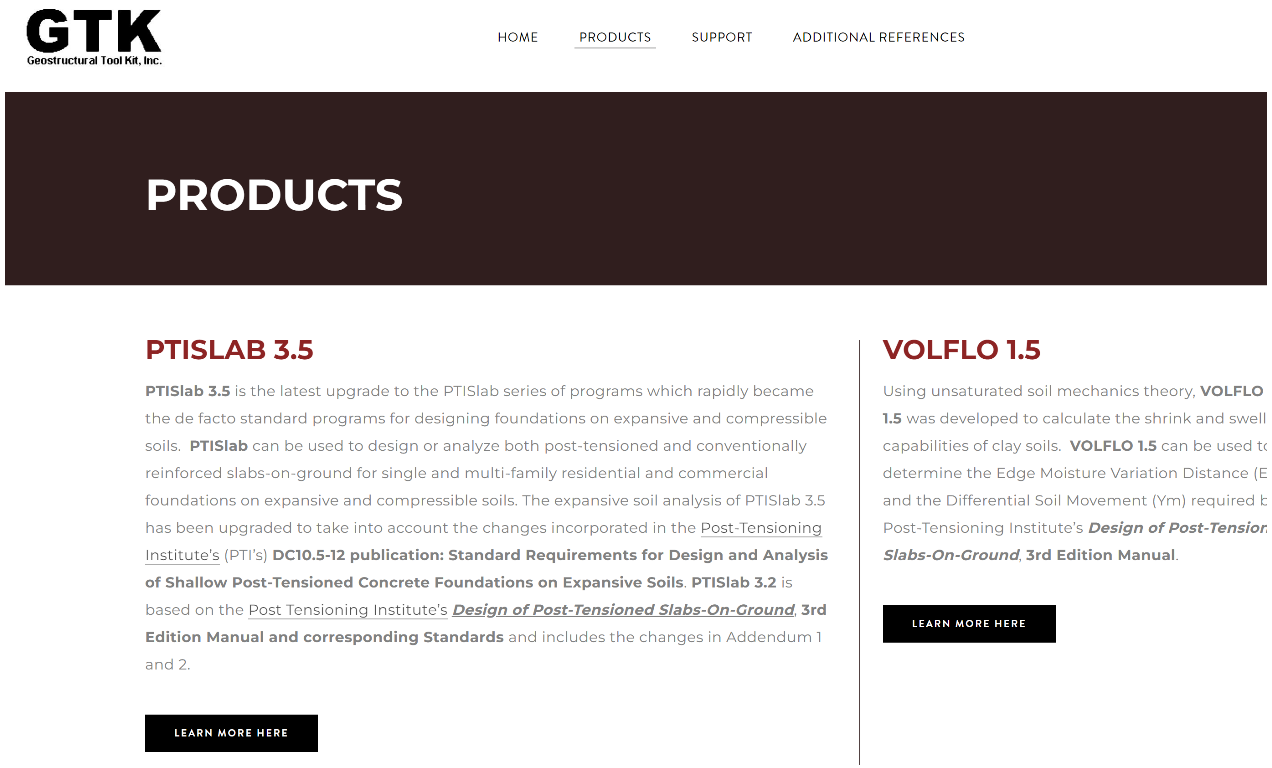
PVR 4.5" with a 2ft embedment depth

| Select Soil Parameters: | Edge Lift | Center Lift |
|---|---|---|
| Edge Moisture Distance, ft (em) | 3.5 | 6.7 |
| Differential Soil Movement, inches (ym) | 2.1 | 1.5 |

Traditional Ribbed Layout



# Outline of Design Procedure using GTK PTISlab Software



**GTK**
Geostructural Tool Kit, Inc.

## PRODUCTS

### PTISLAB 3.5

**PTISlab 3.5** is the latest upgrade to the PTISlab series of programs which rapidly became the de facto standard programs for designing foundations on expansive and compressible soils. **PTISlab** can be used to design or analyze both post-tensioned and conventionally reinforced slabs-on-ground for single and multi-family residential and commercial foundations on expansive and compressible soils. The expansive soil analysis of PTISlab 3.5 has been upgraded to take into account the changes incorporated in the Post-Tensioning Institute's (PTI's) **DC10.5-12 publication: Standard Requirements for Design and Analysis of Shallow Post-Tensioned Concrete Foundations on Expansive Soils**. **PTISlab 3.2** is based on the Post Tensioning Institute's ***Design of Post-Tensioned Slabs-On-Ground*, 3rd Edition Manual and corresponding Standards** and includes the changes in Addendum 1 and 2.

### VOLFLO 1.5

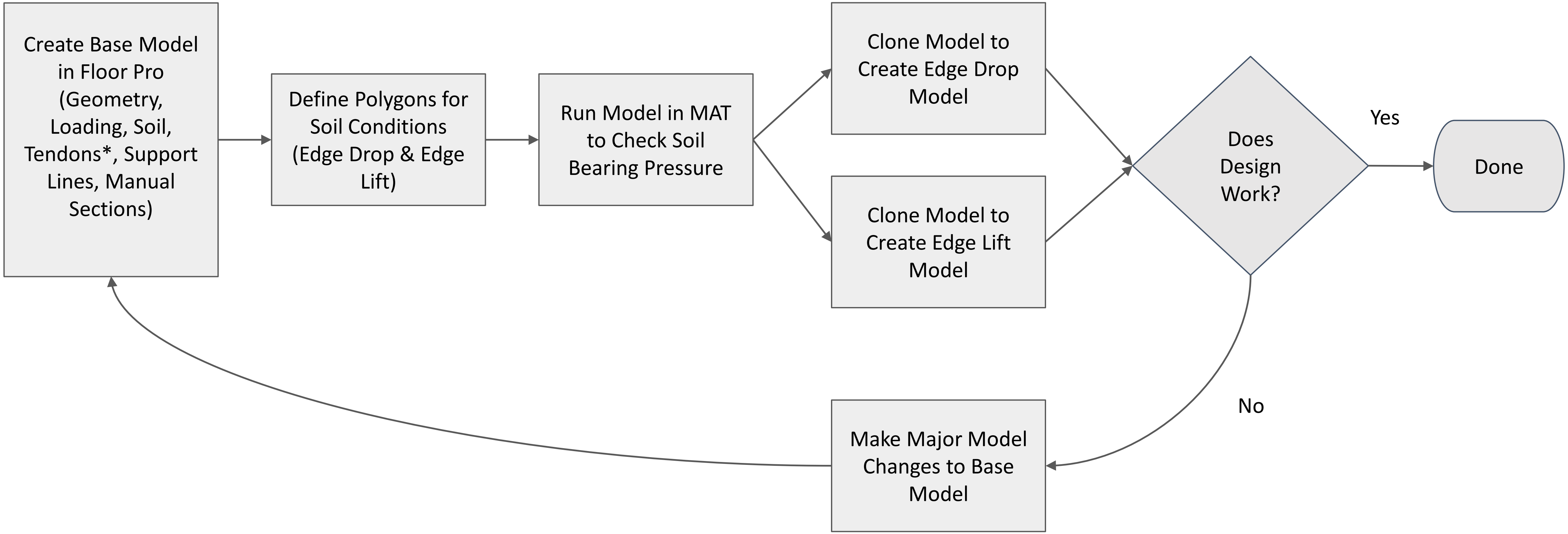
Using unsaturated soil mechanics theory, **VOLFLO 1.5** was developed to calculate the shrink and swell capabilities of clay soils. **VOLFLO 1.5** can be used t
determine the Edge Moisture Variation Distance (E
and the Differential Soil Movement (Ym) required b
Post-Tensioning Institute's ***Design of Post-Tension***
***Slabs-On-Ground*, 3rd Edition Manual**.

- Soil bearing pressure check
  - Based on Load/Area
- Center lift design checks
  - Bending stress
  - Stiffness
  - Shear stress
  - Cracked moment capacity
- Edge lift design checks
  - Bending stress
  - Stiffness
  - Shear stress
  - Cracked moment capacity

# PTISlab 3.5 Software Limitations

- Can only model rectangular slabs
- Cannot model beams spaced closer than 6 ft apart
- No flexibility in tendon profiling or placement
- No flexibility in detailed load modeling

# Overall Design Workflow Using Finite Element Analysis



Create Base Model in Floor Pro (Geometry, Loading, Soil, Tendons*, Support Lines, Manual Sections)

Define Polygons for Soil Conditions (Edge Drop & Edge Lift)

Run Model in MAT to Check Soil Bearing Pressure

Clone Model to Create Edge Drop Model

Clone Model to Create Edge Lift Model

Does Design Work?

Yes

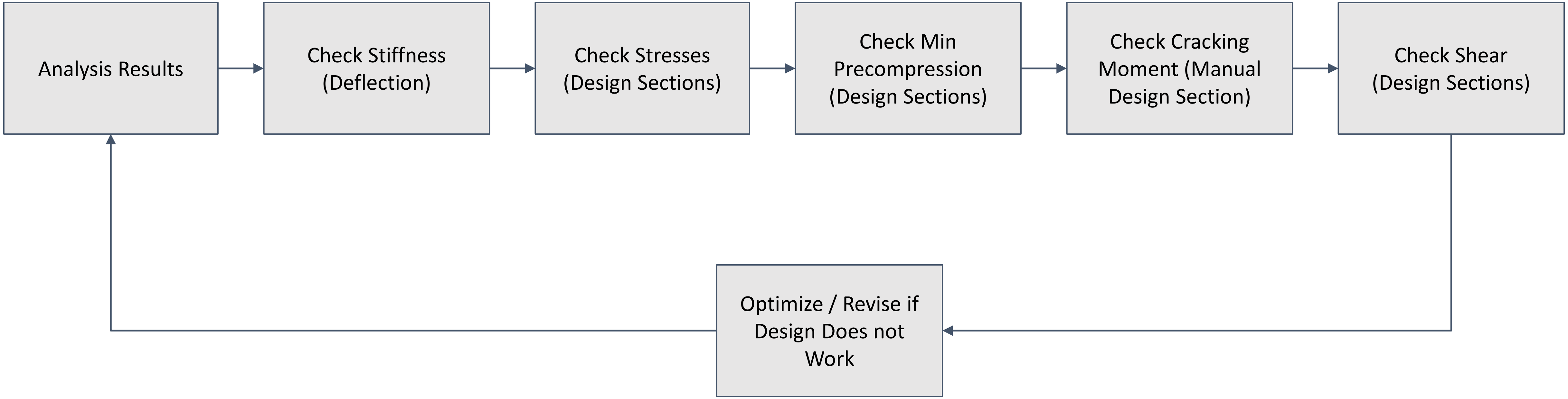
Done

No

Make Major Model Changes to Base Model

* To account for soil friction losses, model tendons with Effective Force = 26.7 (default value) - max soil friction loss

# Check PTI Code Compliance of Design Iteration



Analysis Results

Check Stiffness (Deflection)

Check Stresses (Design Sections)

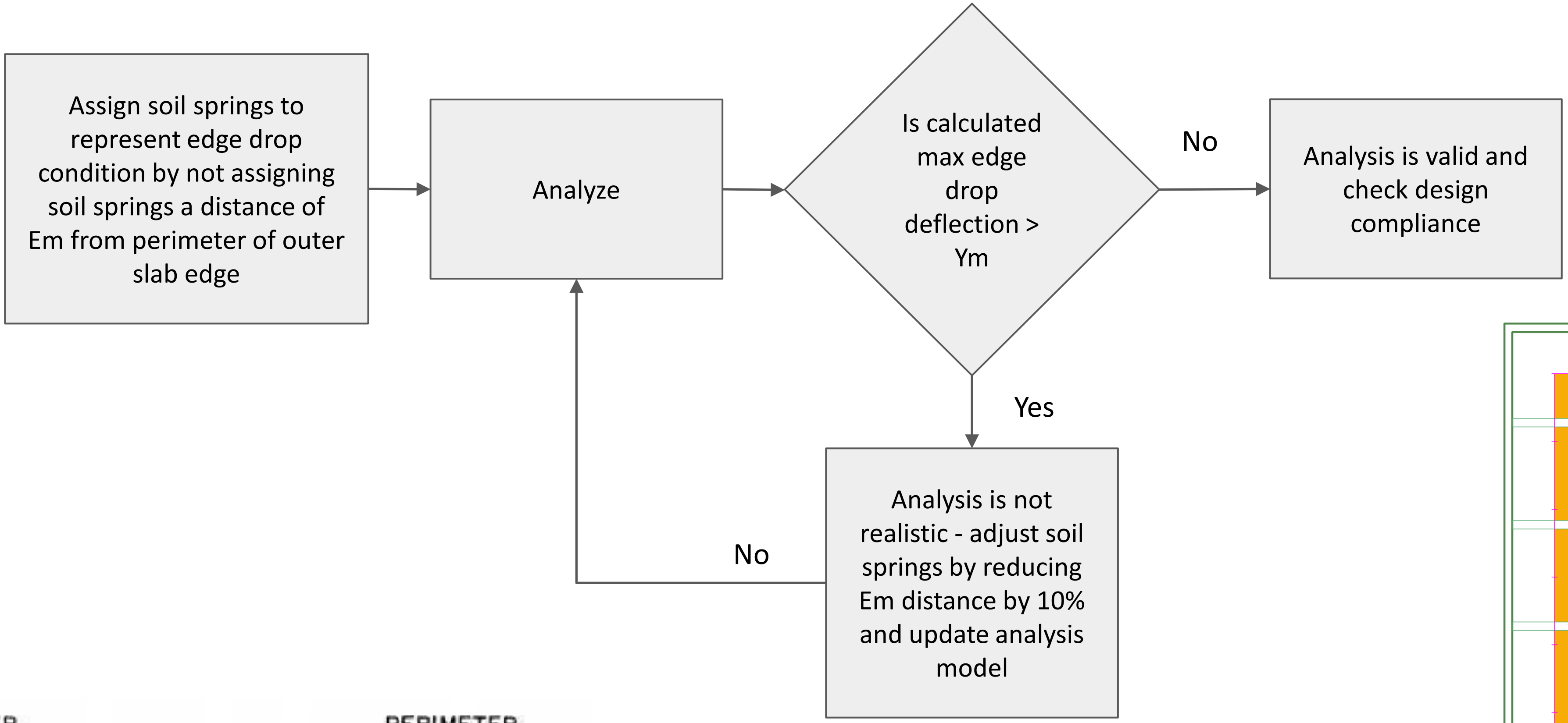
Check Min Precompression (Design Sections)

Check Cracking Moment (Manual Design Section)

Check Shear (Design Sections)

Optimize / Revise if Design Does not Work

# Edge Drop Analysis *(formerly Center Lift)*



Assign soil springs to represent edge drop condition by not assigning soil springs a distance of Em from perimeter of outer slab edge

Analyze

Is calculated max edge drop deflection > Ym

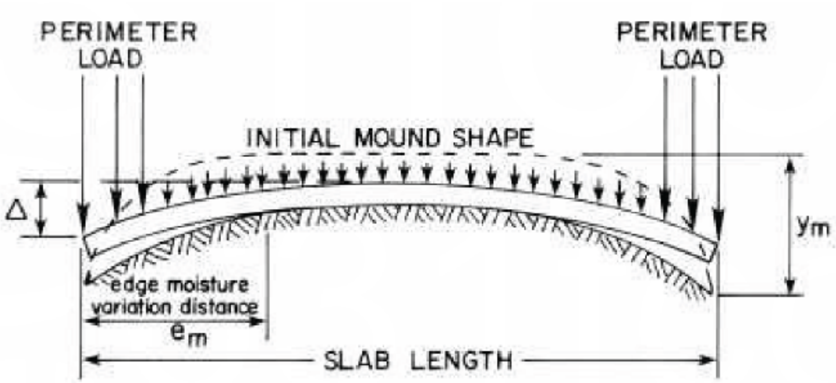
No

Analysis is valid and check design compliance

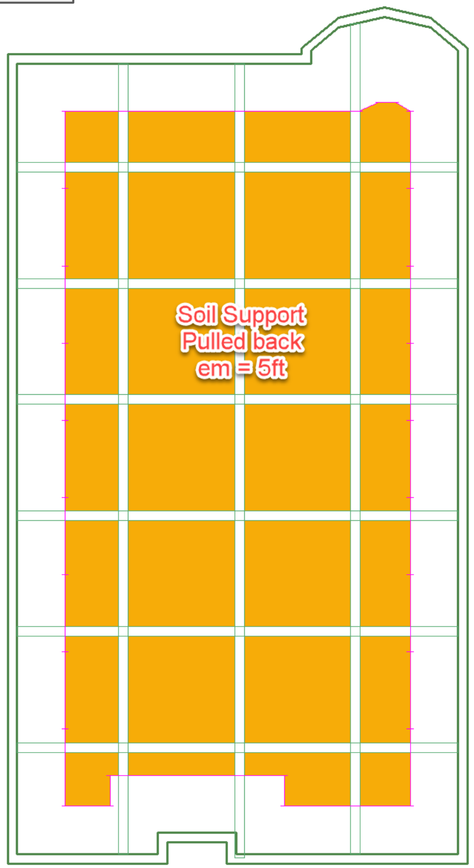
Yes

Analysis is not realistic - adjust soil springs by reducing Em distance by 10% and update analysis model

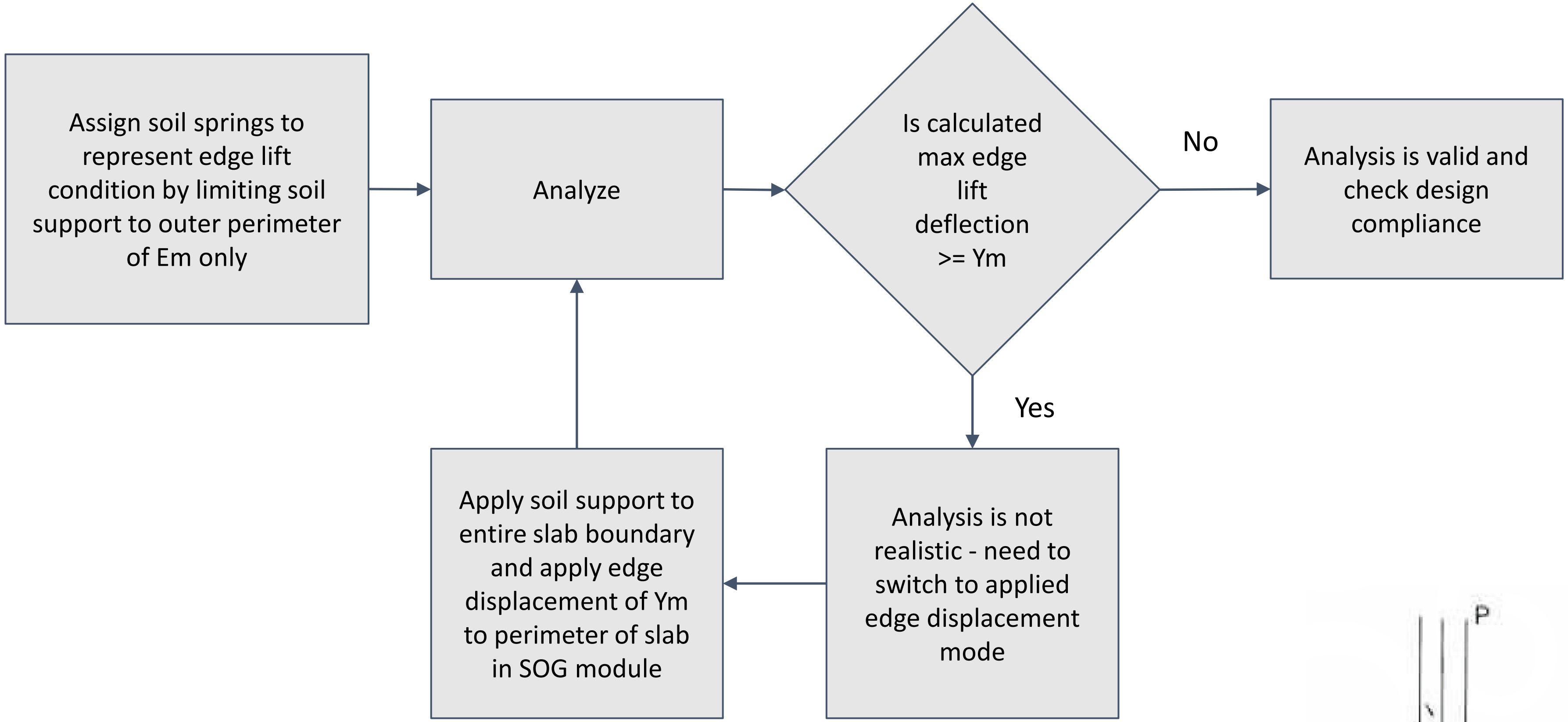
No



PTI Figure 3.5



# Edge Lift Analysis



Assign soil springs to represent edge lift condition by limiting soil support to outer perimeter of Em only

Analyze

Is calculated max edge lift deflection >= Ym

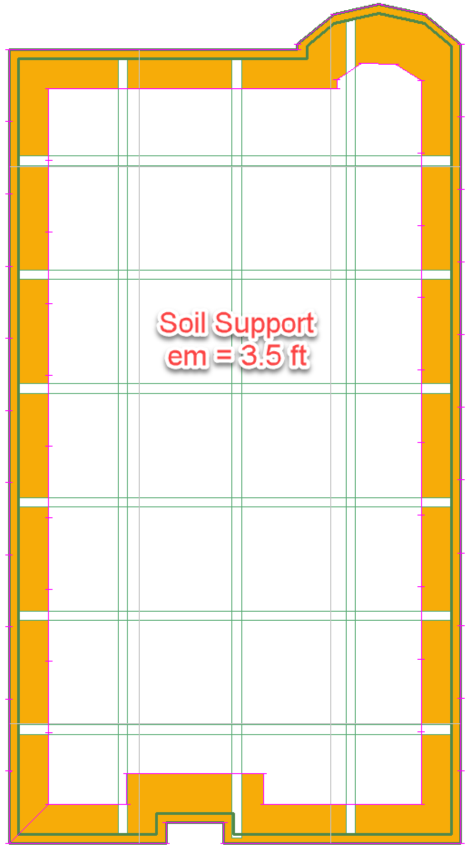
No

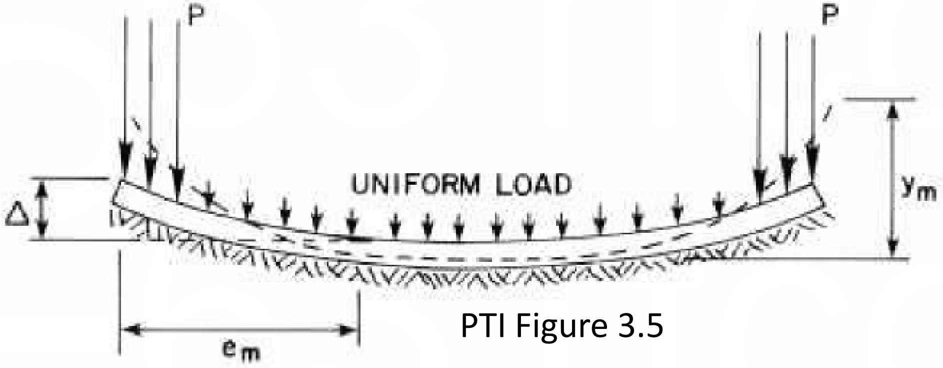
Analysis is valid and check design compliance

Yes

Analysis is not realistic - need to switch to applied edge displacement mode

Apply soil support to entire slab boundary and apply edge displacement of Ym to perimeter of slab in SOG module

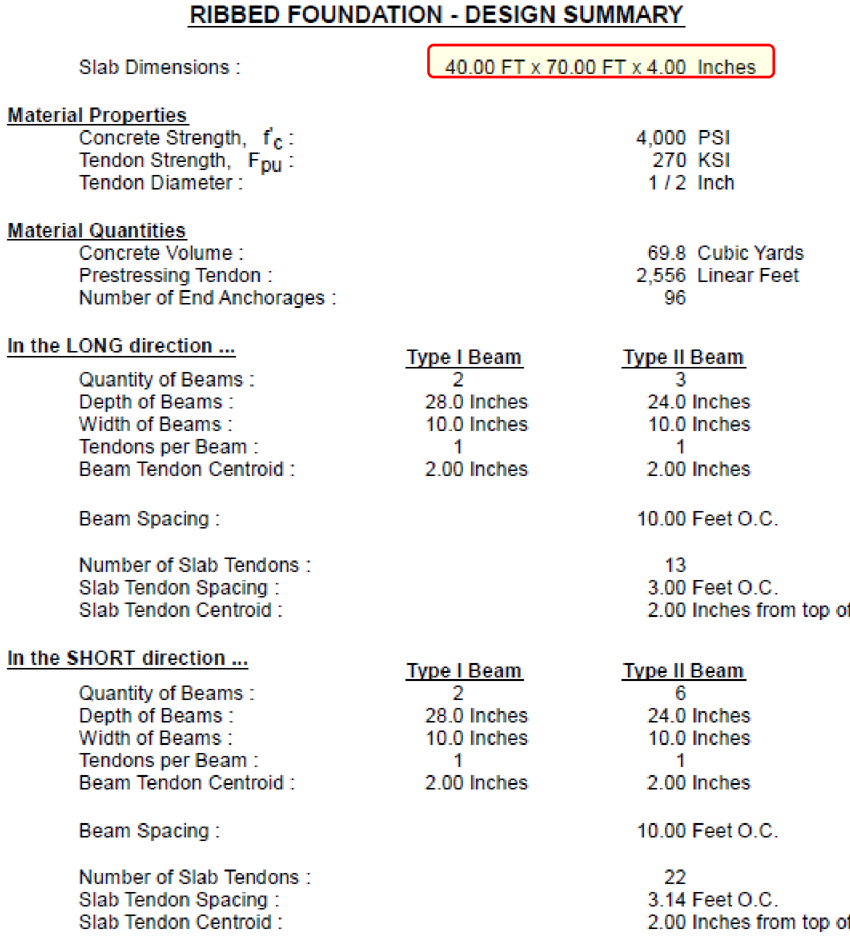




PTI Figure 3.5

**Note on applying edge displacements:** Applying edge displacements along the entire length of a foundation, in particular, irregular foundations with re-entrant corners can lead to unrealistic high stress concentrations at the corners. It is advised to only apply the edge displacement along the primary outer edges and a distance away from the corners.

# Input Data: Ribbed Foundation Analysis Model



## RIBBED FOUNDATION - DESIGN SUMMARY

| | |
|---|---|
| Slab Dimensions : | 40.00 FT x 70.00 FT x 4.00 Inches |

**Material Properties**

| | |
|---|---|
| Concrete Strength, $f'_c$ : | 4,000 PSI |
| Tendon Strength, $F_{pu}$ : | 270 KSI |
| Tendon Diameter : | 1 / 2 Inch |

**Material Quantities**

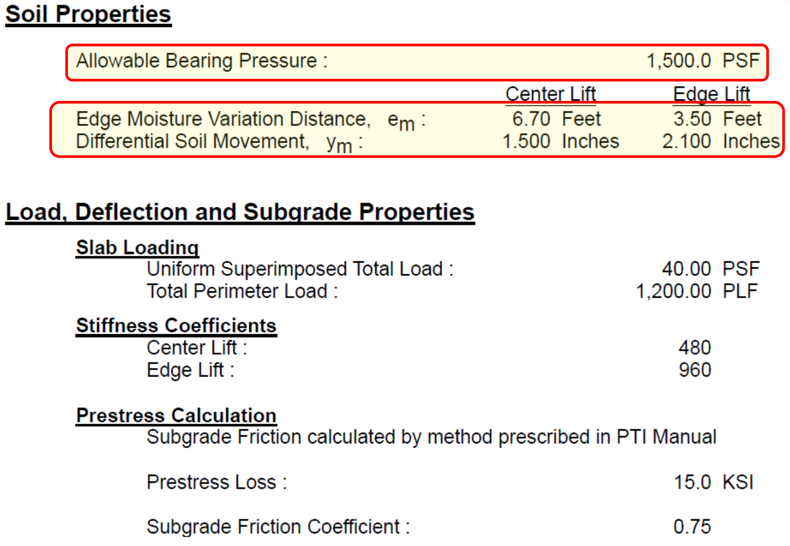
| | |
|---|---|
| Concrete Volume : | 69.8 Cubic Yards |
| Prestressing Tendon : | 2,556 Linear Feet |
| Number of End Anchorages : | 96 |

**In the LONG direction ...**

| | Type I Beam | Type II Beam |
|---|---|---|
| Quantity of Beams : | 2 | 3 |
| Depth of Beams : | 28.0 Inches | 24.0 Inches |
| Width of Beams : | 10.0 Inches | 10.0 Inches |
| Tendons per Beam : | 1 | 1 |
| Beam Tendon Centroid : | 2.00 Inches | 2.00 Inches |
| Beam Spacing : | | 10.00 Feet O.C. |
| Number of Slab Tendons : | | 13 |
| Slab Tendon Spacing : | | 3.00 Feet O.C. |
| Slab Tendon Centroid : | | 2.00 Inches from top of slab |

**In the SHORT direction ...**

| | Type I Beam | Type II Beam |
|---|---|---|
| Quantity of Beams : | 2 | 6 |
| Depth of Beams : | 28.0 Inches | 24.0 Inches |
| Width of Beams : | 10.0 Inches | 10.0 Inches |
| Tendons per Beam : | 1 | 1 |
| Beam Tendon Centroid : | 2.00 Inches | 2.00 Inches |
| Beam Spacing : | | 10.00 Feet O.C. |
| Number of Slab Tendons : | | 22 |
| Slab Tendon Spacing : | | 3.14 Feet O.C. |
| Slab Tendon Centroid : | | 2.00 Inches from top of slab |



## Soil Properties

| | Center Lift | Edge Lift |
|---|---|---|
| Allowable Bearing Pressure : | 1,500.0 PSF | |
| Edge Moisture Variation Distance, $e_m$ : | 6.70 Feet | 3.50 Feet |
| Differential Soil Movement, $y_m$ : | 1.500 Inches | 2.100 Inches |

## Load, Deflection and Subgrade Properties

**Slab Loading**

| | |
|---|---|
| Uniform Superimposed Total Load : | 40.00 PSF |
| Total Perimeter Load : | 1,200.00 PLF |

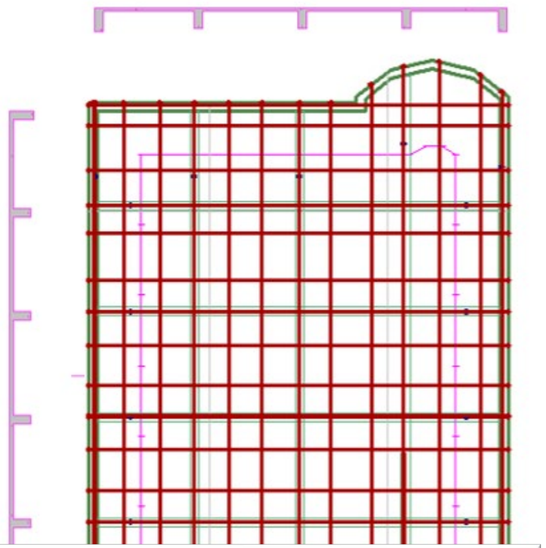
**Stiffness Coefficients**

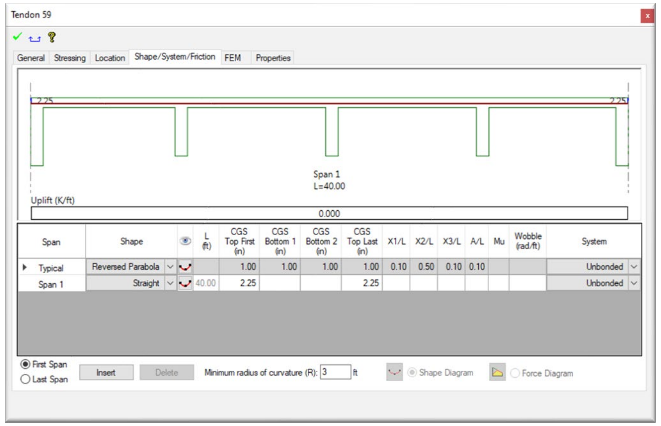
| | |
|---|---|
| Center Lift : | 480 |
| Edge Lift : | 960 |

**Prestress Calculation**

Subgrade Friction calculated by method prescribed in PTI Manual

| | |
|---|---|
| Prestress Loss : | 15.0 KSI |
| Subgrade Friction Coefficient : | 0.75 |



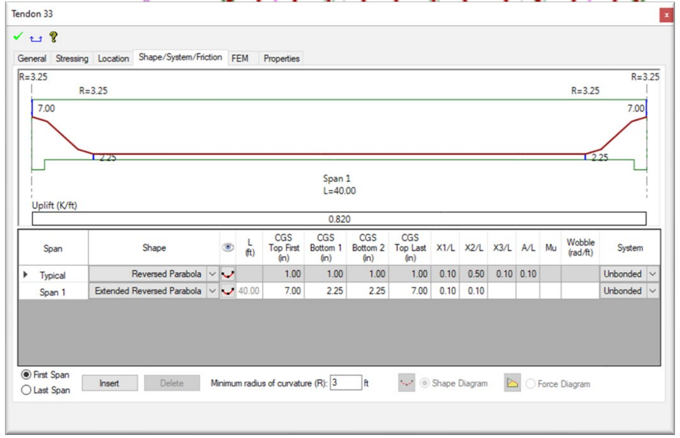


Tendon 59

| Span | Shape | | L (ft) | CGS Top First (in) | CGS Bottom 1 (in) | CGS Bottom 2 (in) | CGS Top Last (in) | X1/L | X2/L | X3/L | A/L | Mu | Wobble (rad/ft) | System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Typical | Reversed Parabola | | | 1.00 | 1.00 | 1.00 | 1.00 | 0.10 | 0.50 | 0.10 | 0.10 | | | Unbonded |
| Span 1 | Straight | | 40.00 | 2.25 | | | 2.25 | | | | | | | Unbonded |

● First Span
○ Last Span

Minimum radius of curvature (R): 3 ft



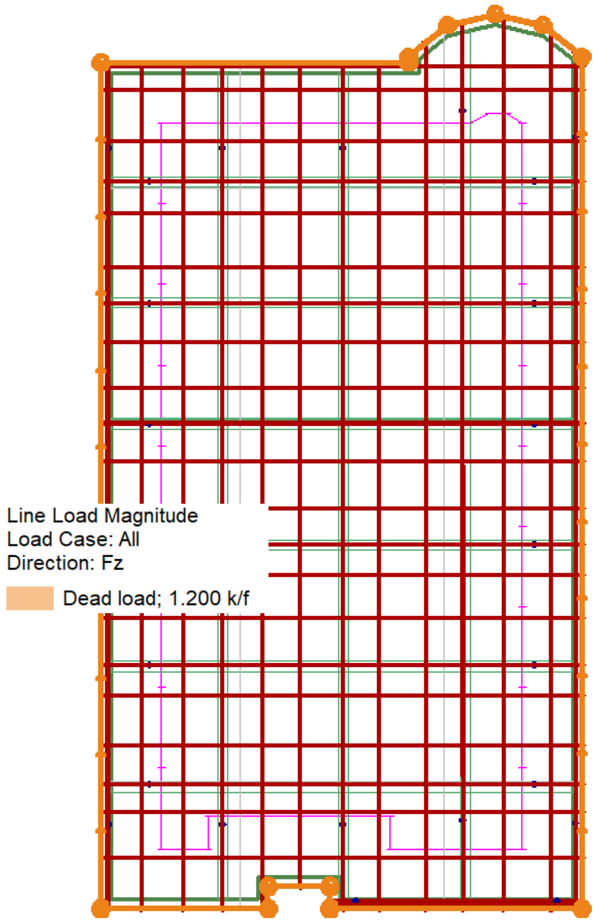
Tendon 33

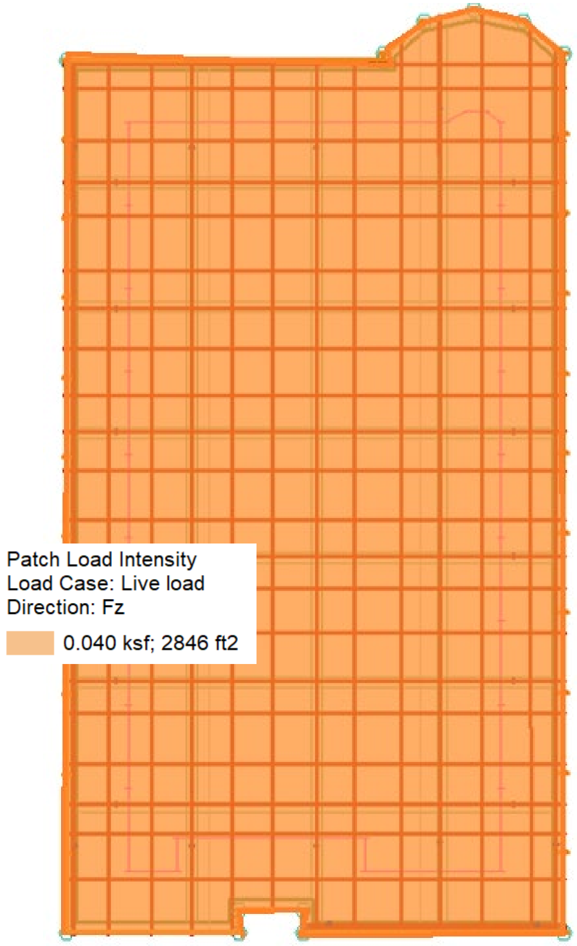
| Span | Shape | | L (ft) | CGS Top First (in) | CGS Bottom 1 (in) | CGS Bottom 2 (in) | CGS Top Last (in) | X1/L | X2/L | X3/L | A/L | Mu | Wobble (rad/ft) | System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Typical | Reversed Parabola | | | 1.00 | 1.00 | 1.00 | 1.00 | 0.10 | 0.50 | 0.10 | 0.10 | | | Unbonded |
| Span 1 | Extended Reversed Parabola | | 40.00 | 7.00 | 2.25 | 2.25 | 7.00 | 0.10 | 0.10 | | | | | Unbonded |

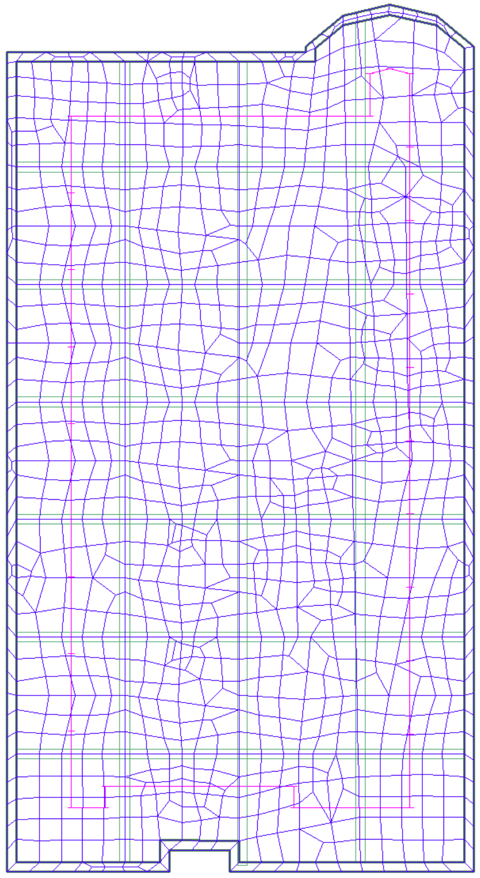
● First Span
○ Last Span

Minimum radius of curvature (R): 3 ft

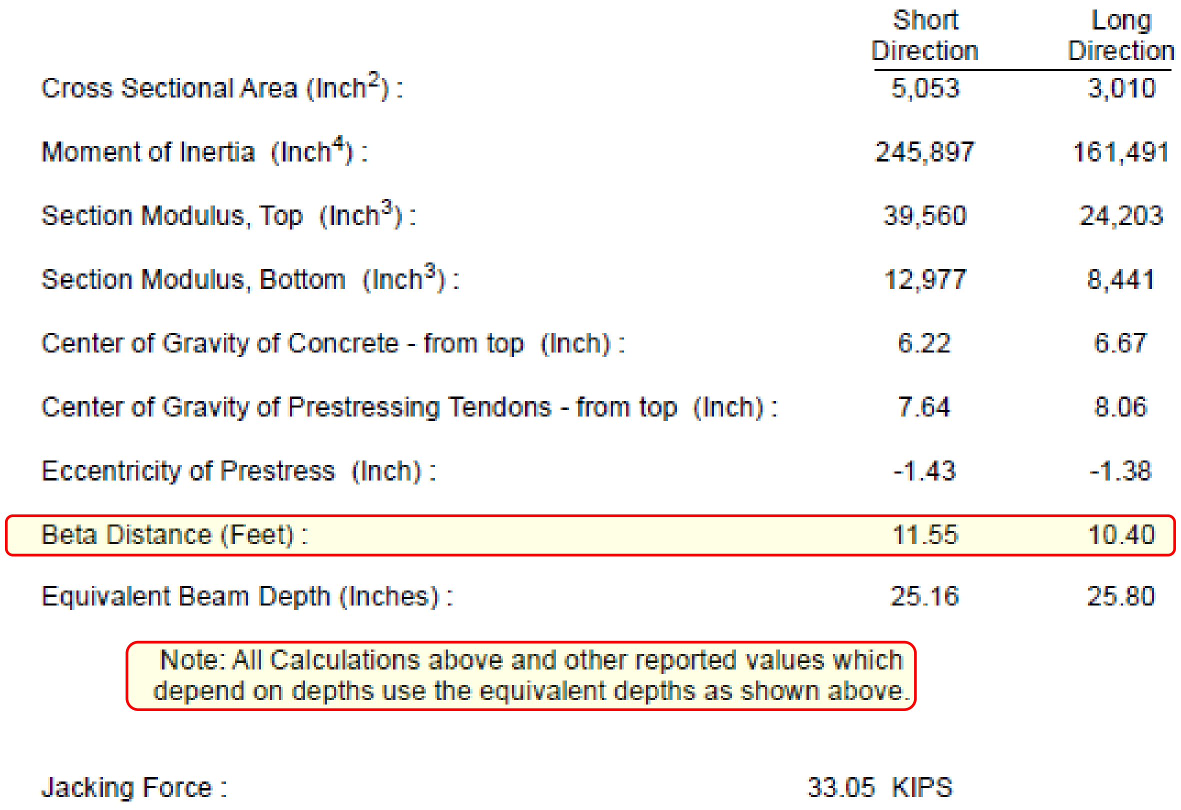
# 3D Finite Element Ribbed Foundation Analysis Model







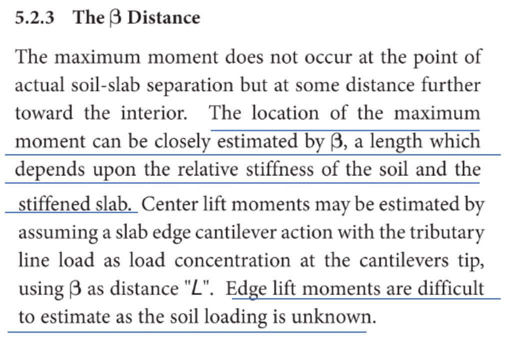
# PTISlab 3.5 Analysis Parameters: Ribbed Foundation Analysis Model



| | Short Direction | Long Direction |
|---|---|---|
| Cross Sectional Area (Inch$^2$) : | 5,053 | 3,010 |
| Moment of Inertia (Inch$^4$) : | 245,897 | 161,491 |
| Section Modulus, Top (Inch$^3$) : | 39,560 | 24,203 |
| Section Modulus, Bottom (Inch$^3$) : | 12,977 | 8,441 |
| Center of Gravity of Concrete - from top (Inch) : | 6.22 | 6.67 |
| Center of Gravity of Prestressing Tendons - from top (Inch) : | 7.64 | 8.06 |
| Eccentricity of Prestress (Inch) : | -1.43 | -1.38 |
| Beta Distance (Feet) : | 11.55 | 10.40 |
| Equivalent Beam Depth (Inches) : | 25.16 | 25.80 |

Note: All Calculations above and other reported values which depend on depths use the equivalent depths as shown above.

Jacking Force : 33.05 KIPS



**5.2.3 The β Distance**

The maximum moment does not occur at the point of actual soil-slab separation but at some distance further toward the interior. The location of the maximum moment can be closely estimated by β, a length which depends upon the relative stiffness of the soil and the stiffened slab. Center lift moments may be estimated by assuming a slab edge cantilever action with the tributary line load as load concentration at the cantilevers tip, using β as distance "*L*". Edge lift moments are difficult to estimate as the soil loading is unknown.

# Soil Bearing Analysis

## PTI 3.5 Soil Bearing Analysis

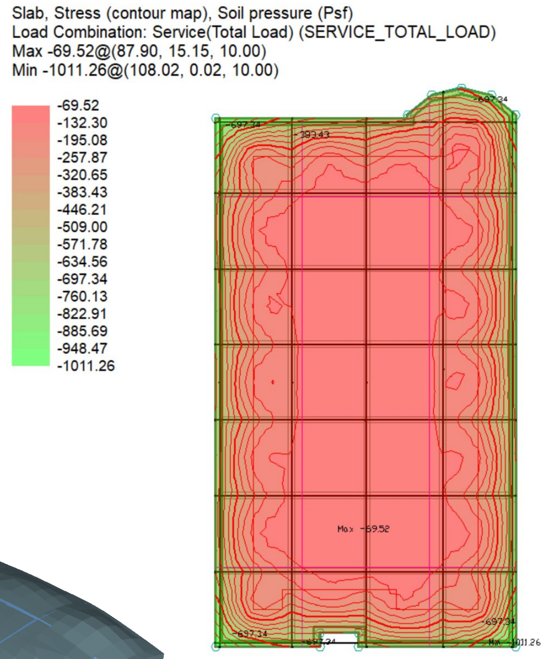
- Assumes uniform soil support
- Equally distributes all load to supporting soil
- Max pressure on soil 163 PSF << allowable 1,500 PSF

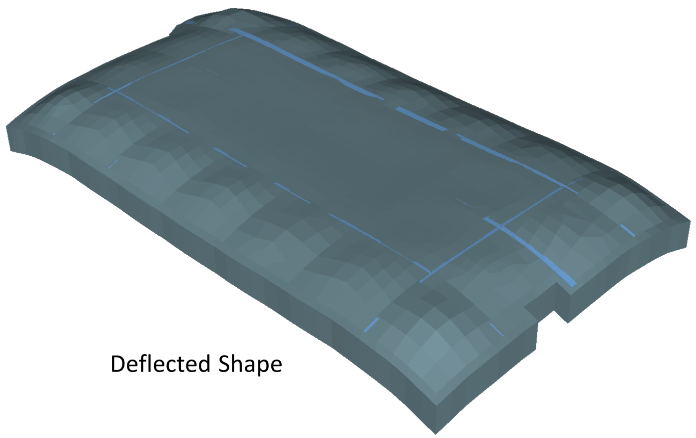
**Soil Bearing Analysis**

| | | |
|---|---|---|
| Total Applied Load | 385,266 | LB |
| Bearing Area | 2,367 | $FT^2$ |
| Applied Pressure on Soil | 163 | PSF |
| Soil Pressure Safety Factor | 0.00 | |

## FEM Soil Bearing Analysis

- Assumes uniform soil support
- Max pressure on soil 1,011 PSF < allowable 1,500 PSF



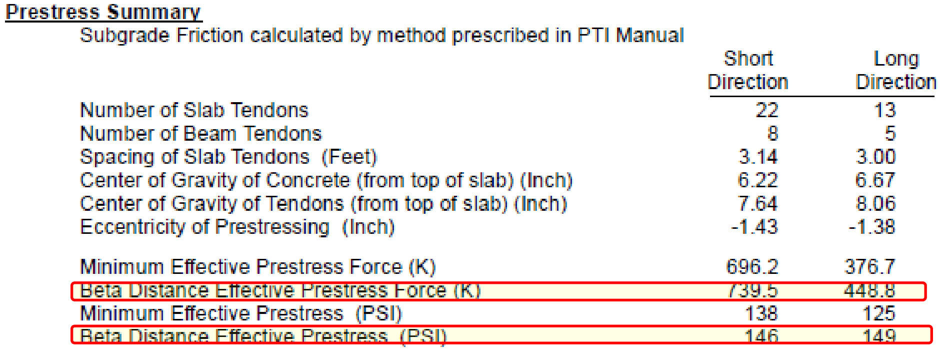


Deflected Shape

# Effective Prestress Calculations

## PTISlab

- Effective PT force/tendon at Beta distance
  - Short direction: **24.65 kips**
  - Long direction: **24.93 kips**
  - We assume the same valued in the FEM model

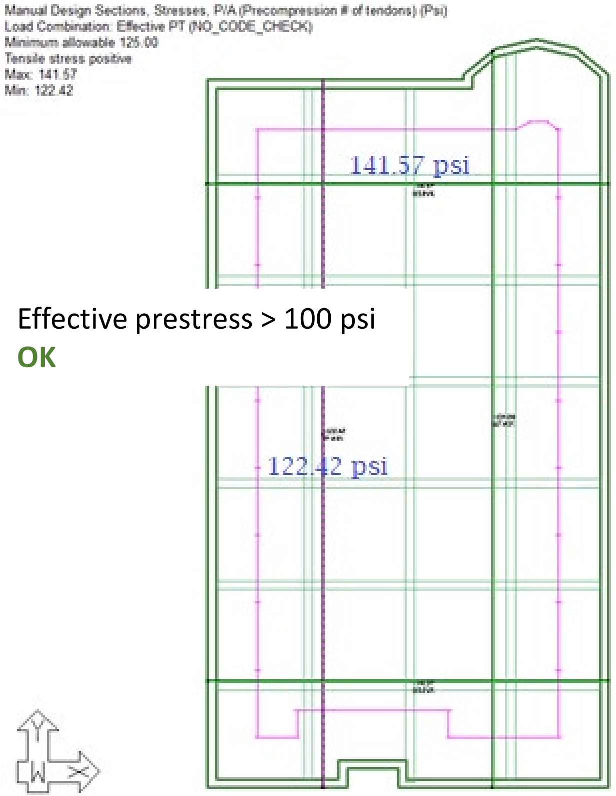


**Prestress Summary**

Subgrade Friction calculated by method prescribed in PTI Manual

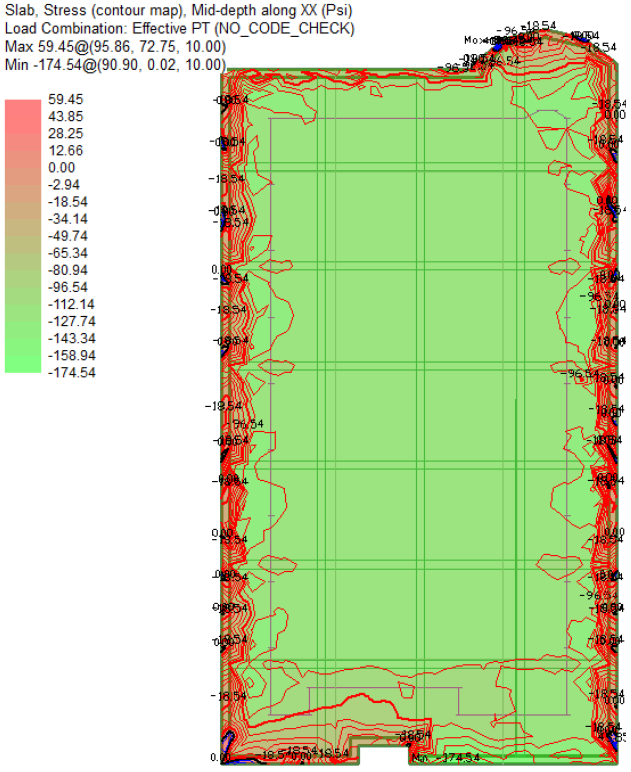
| | Short Direction | Long Direction |
|---|---|---|
| Number of Slab Tendons | 22 | 13 |
| Number of Beam Tendons | 8 | 5 |
| Spacing of Slab Tendons (Feet) | 3.14 | 3.00 |
| Center of Gravity of Concrete (from top of slab) (Inch) | 6.22 | 6.67 |
| Center of Gravity of Tendons (from top of slab) (Inch) | 7.64 | 8.06 |
| Eccentricity of Prestressing (Inch) | -1.43 | -1.38 |
| Minimum Effective Prestress Force (K) | 696.2 | 376.7 |
| Beta Distance Effective Prestress Force (K) | 739.5 | 448.8 |
| Minimum Effective Prestress (PSI) | 138 | 125 |
| Beta Distance Effective Prestress (PSI) | 146 | 149 |

## FEM

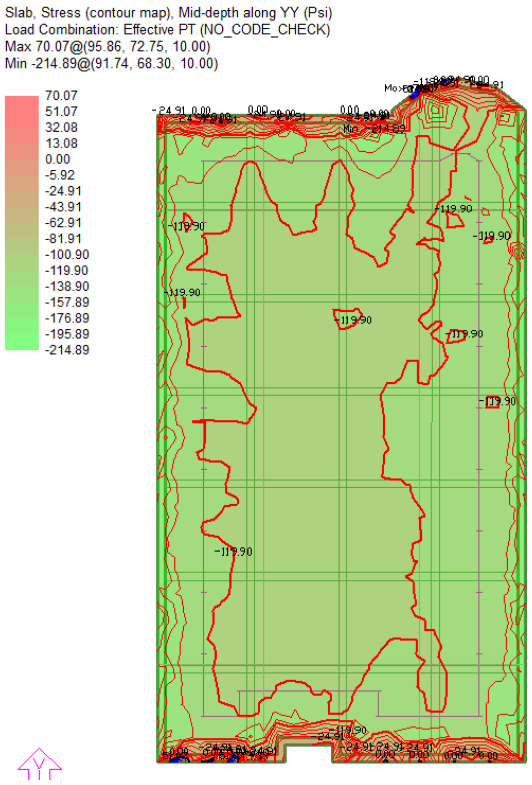


Manual Design Sections, Stresses, P/A (Precompression # of tendons) (Psi)
Load Combination: Effective PT (NO_CODE_CHECK)
Minimum allowable 125.00
Tensile stress positive
Max: 141.57
Min: 122.42

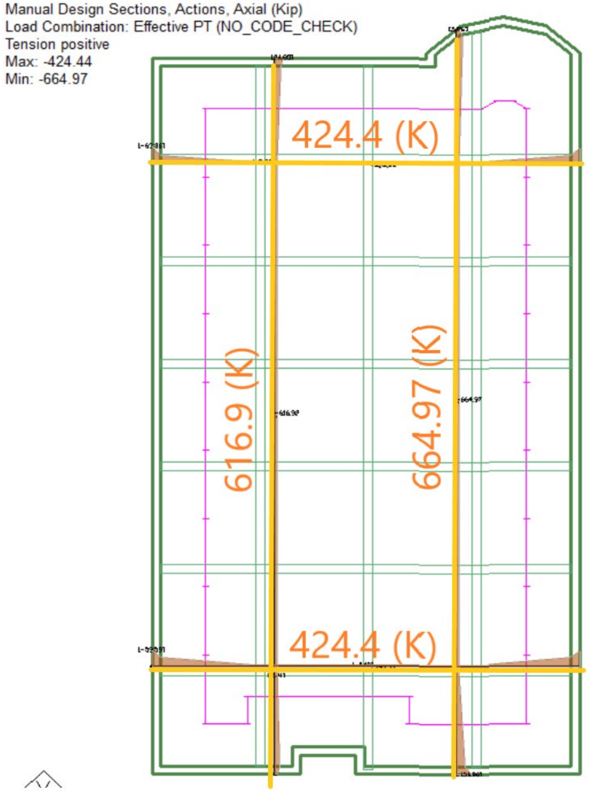
Effective prestress > 100 psi
**OK**



Slab, Stress (contour map), Mid-depth along XX (Psi)
Load Combination: Effective PT (NO_CODE_CHECK)
Max 59.45@(95.86, 72.75, 10.00)
Min -174.54@(90.90, 0.02, 10.00)



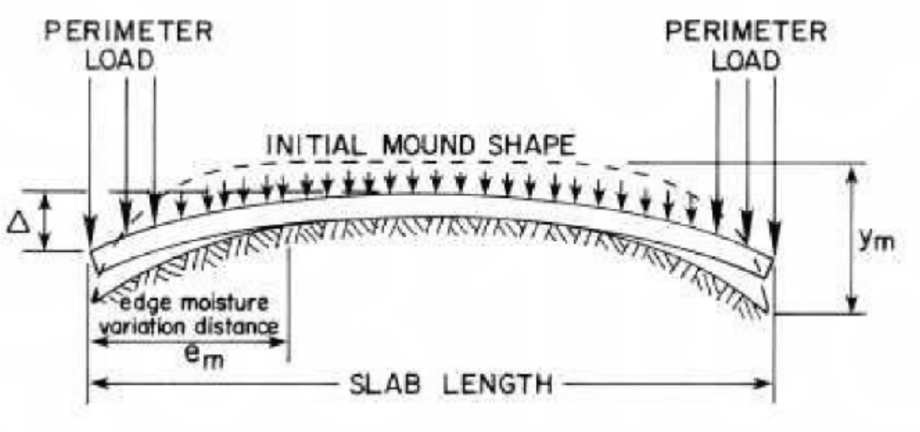
Slab, Stress (contour map), Mid-depth along YY (Psi)
Load Combination: Effective PT (NO_CODE_CHECK)
Max 70.07@(95.86, 72.75, 10.00)
Min -214.89@(91.74, 68.30, 10.00)



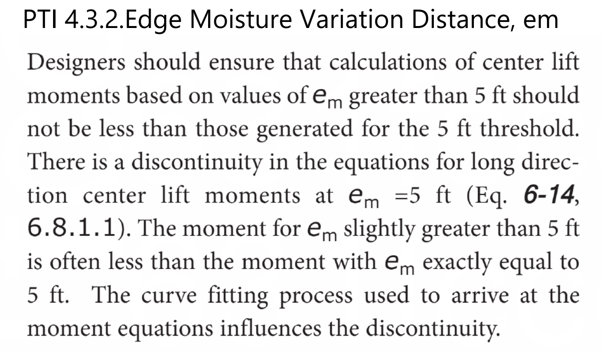
Manual Design Sections, Actions, Axial (Kip)
Load Combination: Effective PT (NO_CODE_CHECK)
Tension positive
Max: -424.44
Min: -664.97

Exact same PT force applied to FEM model as in PTSlab.

# Edge Drop/Center Lift

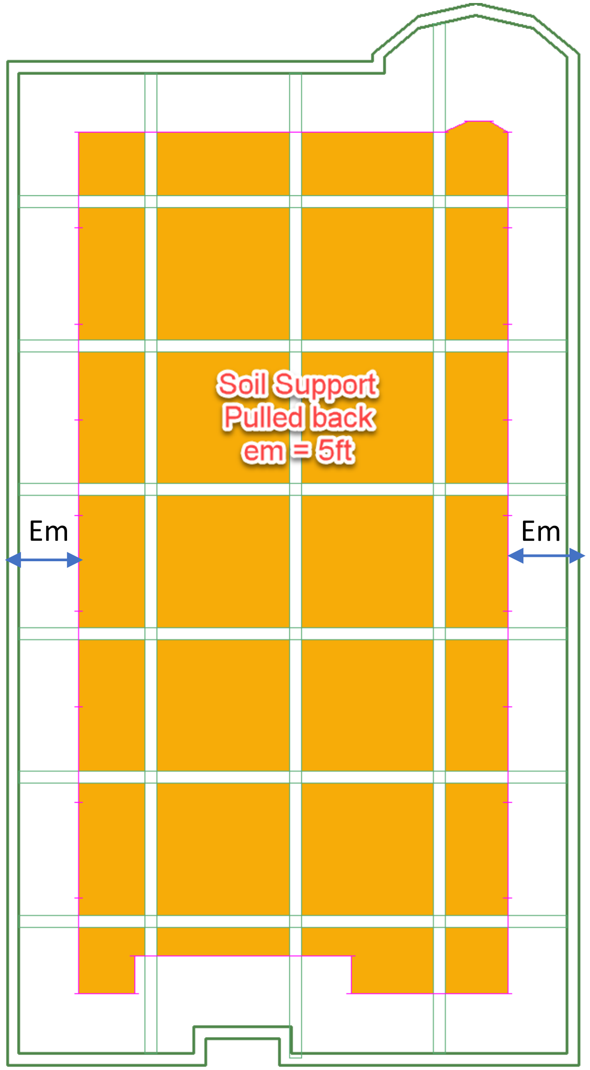


PTI Figure 3.5



PTI 4.3.2.Edge Moisture Variation Distance, em

Designers should ensure that calculations of center lift moments based on values of $e_m$ greater than 5 ft should not be less than those generated for the 5 ft threshold. There is a discontinuity in the equations for long direction center lift moments at $e_m$ =5 ft (Eq. ***6-14***, 6.8.1.1). The moment for $e_m$ slightly greater than 5 ft is often less than the moment with $e_m$ exactly equal to 5 ft. The curve fitting process used to arrive at the moment equations influences the discontinuity.



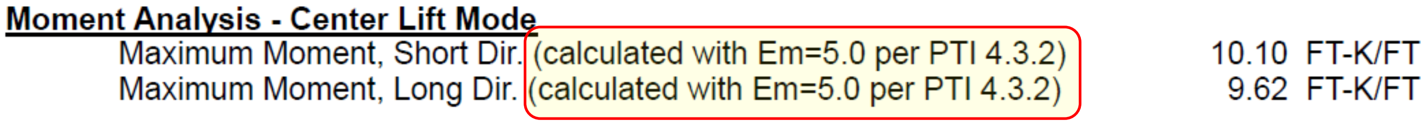
Select Soil Parameters:

| | Edge Lift | Center Lift |
|---|---|---|
| Edge Moisture Distance, ft (em) | 3.5 | 6.7 |
| Differential Soil Movement, inches (ym) | 2.1 | 1.5 |

*To simulate Center Lift Mode, soil support is removed the distance of em (5ft) around the perimeter of the slab.*

# Edge Drop/Center Lift Moment Analysis

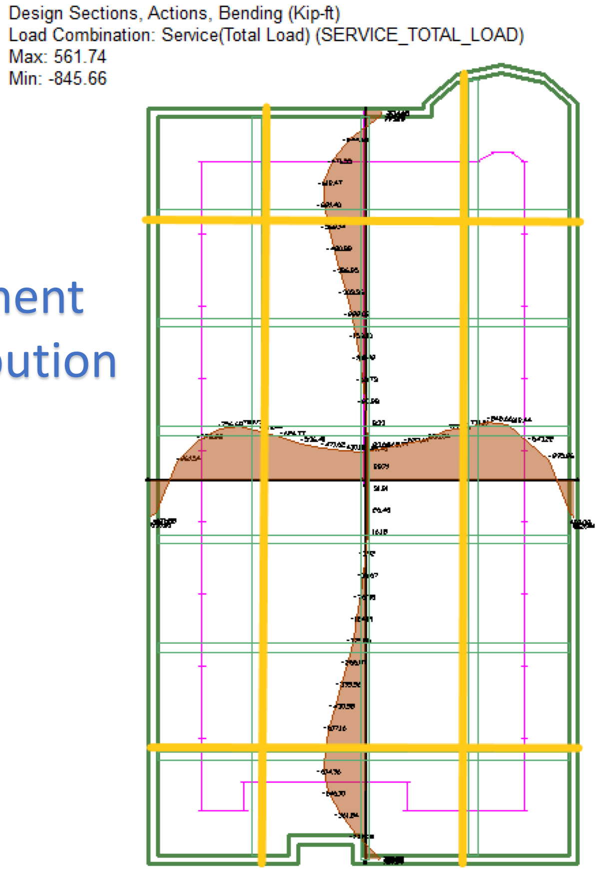
**PTISlab**



**Moment Analysis - Center Lift Mode**

Maximum Moment, Short Dir. (calculated with Em=5.0 per PTI 4.3.2) 10.10 FT-K/FT
Maximum Moment, Long Dir. (calculated with Em=5.0 per PTI 4.3.2) 9.62 FT-K/FT

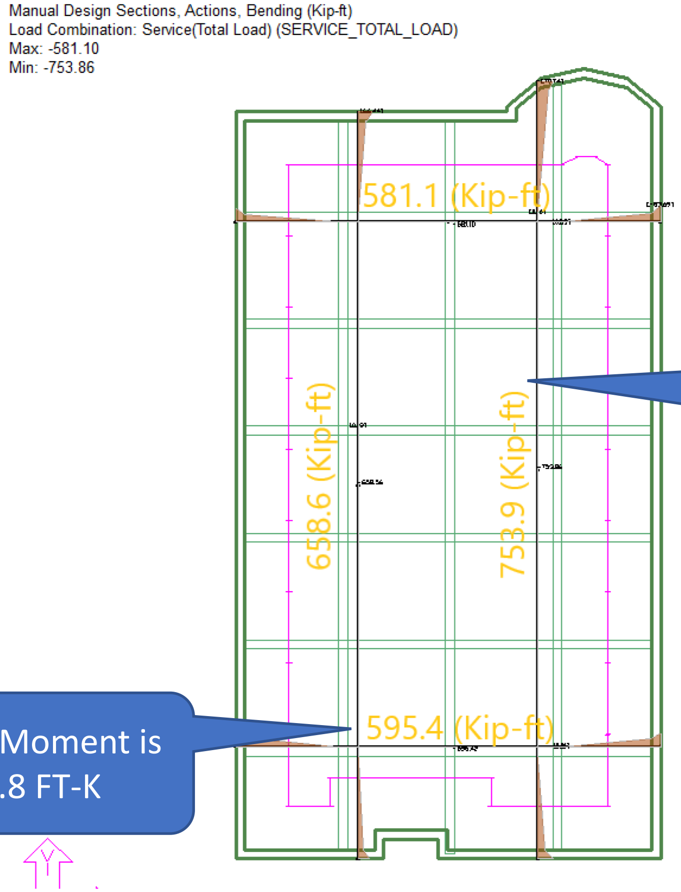
**FEM**



Design Sections, Actions, Bending (Kip-ft)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 561.74
Min: -845.66

Moment Distribution

Stresses @ beta distance pass.



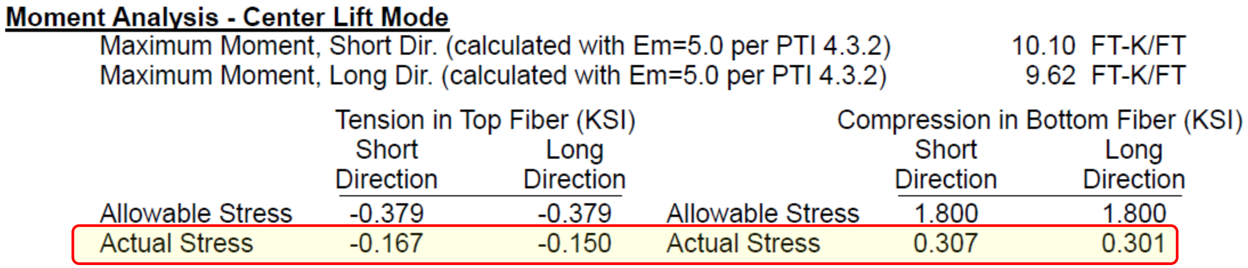
Manual Design Sections, Actions, Bending (Kip-ft)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: -581.10
Min: -753.86

PTISlab Moment is 707 FT-K

PTISlab Moment is 384.8 FT-K

# Edge Drop/Center Lift Moment Stress Analysis

PTISlab



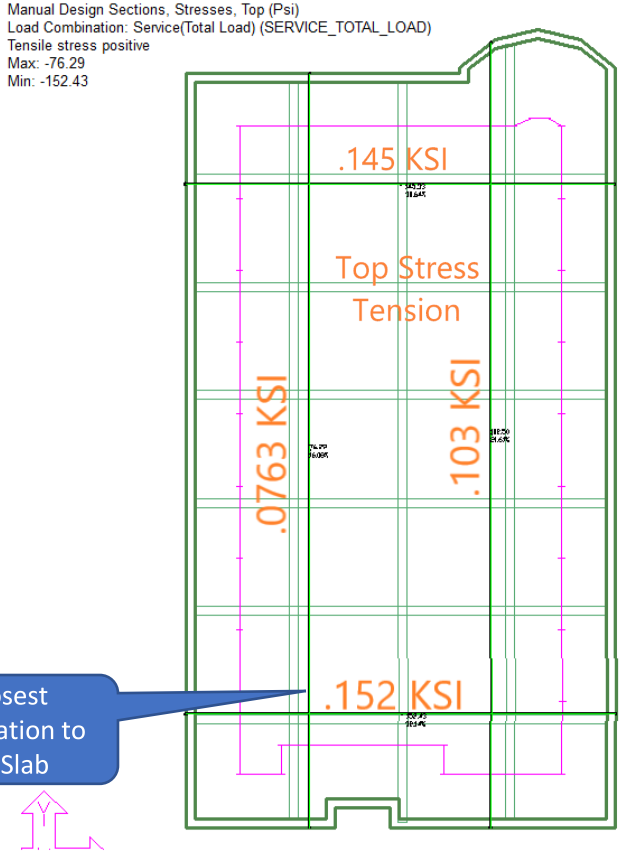
**Moment Analysis - Center Lift Mode**

Maximum Moment, Short Dir. (calculated with Em=5.0 per PTI 4.3.2) 10.10 FT-K/FT

Maximum Moment, Long Dir. (calculated with Em=5.0 per PTI 4.3.2) 9.62 FT-K/FT

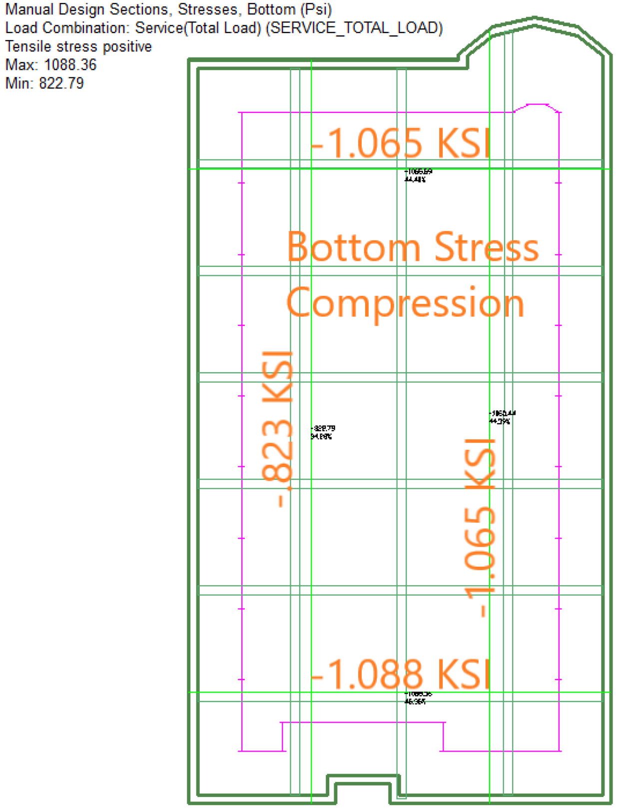
| | Tension in Top Fiber (KSI) | | | Compression in Bottom Fiber (KSI) | |
|---|---|---|---|---|---|
| | Short Direction | Long Direction | | Short Direction | Long Direction |
| Allowable Stress | -0.379 | -0.379 | Allowable Stress | 1.800 | 1.800 |
| Actual Stress | -0.167 | -0.150 | Actual Stress | 0.307 | 0.301 |

FEM



Manual Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: -76.29
Min: -152.43

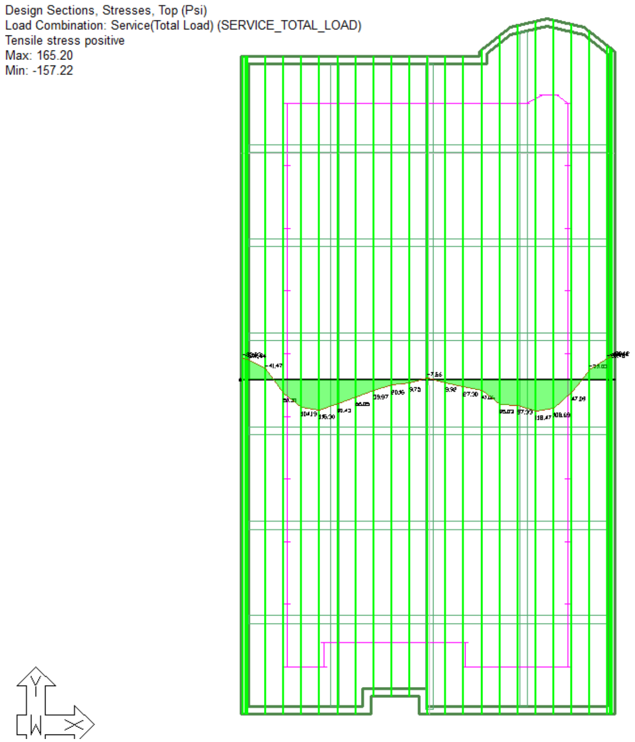
Closest correlation to PTISlab



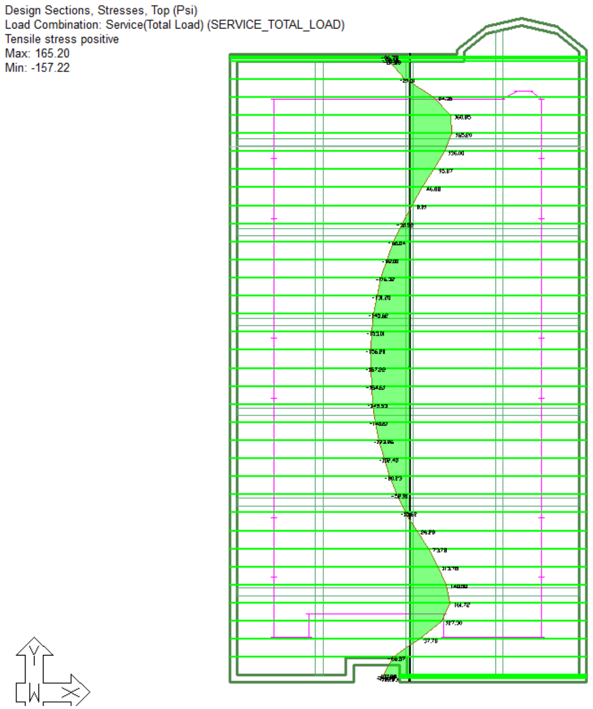
Manual Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 1088.36
Min: 822.79

# FEM – Moment Analysis @ All Sections – Center Lift Mode

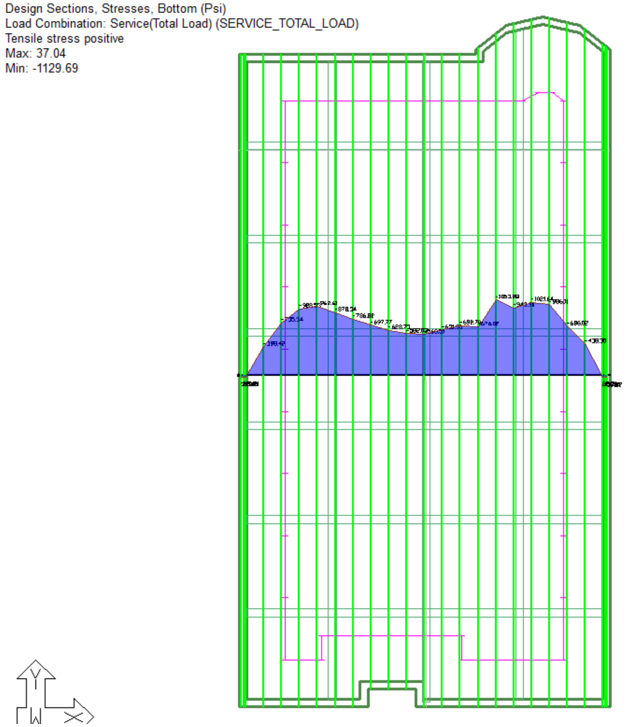
All slab stresses are within allowable limits if integrated over entire slab width.



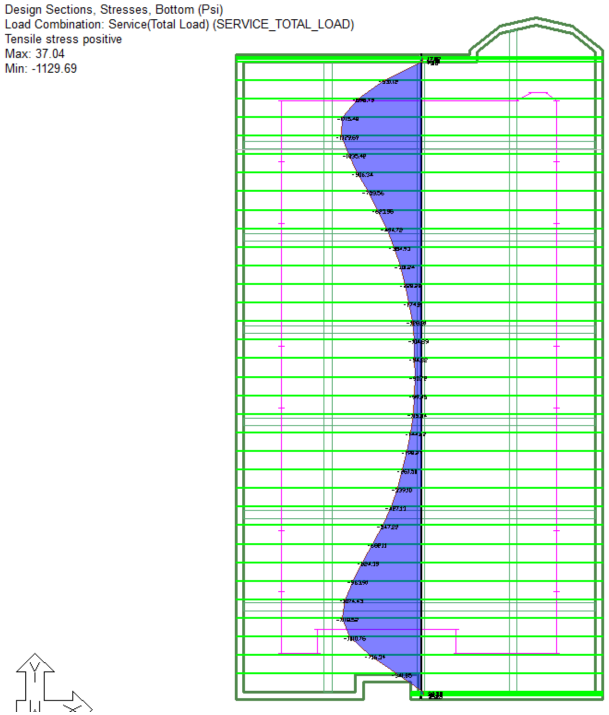
Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 165.20
Min: -157.22



Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 165.20
Min: -157.22



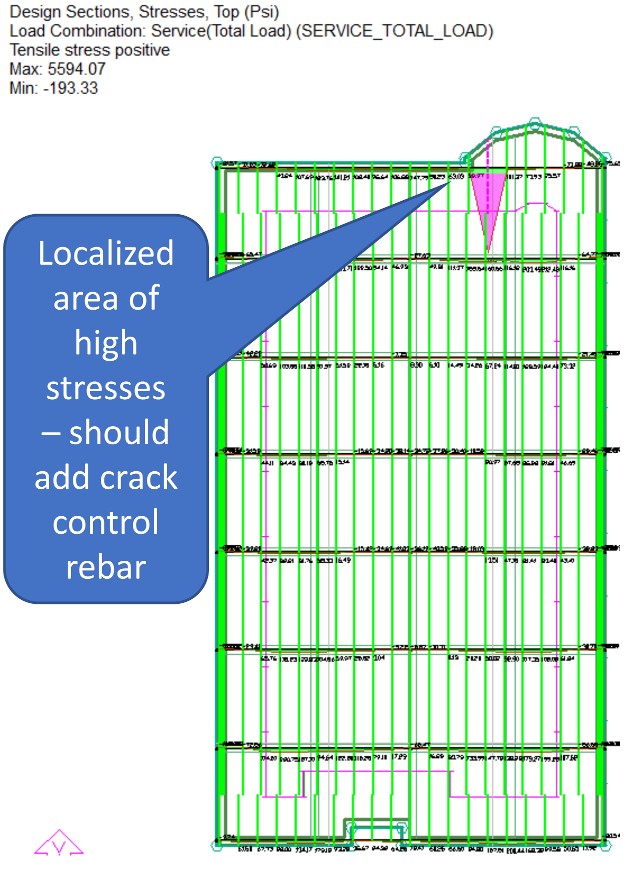
Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 37.04
Min: -1129.69



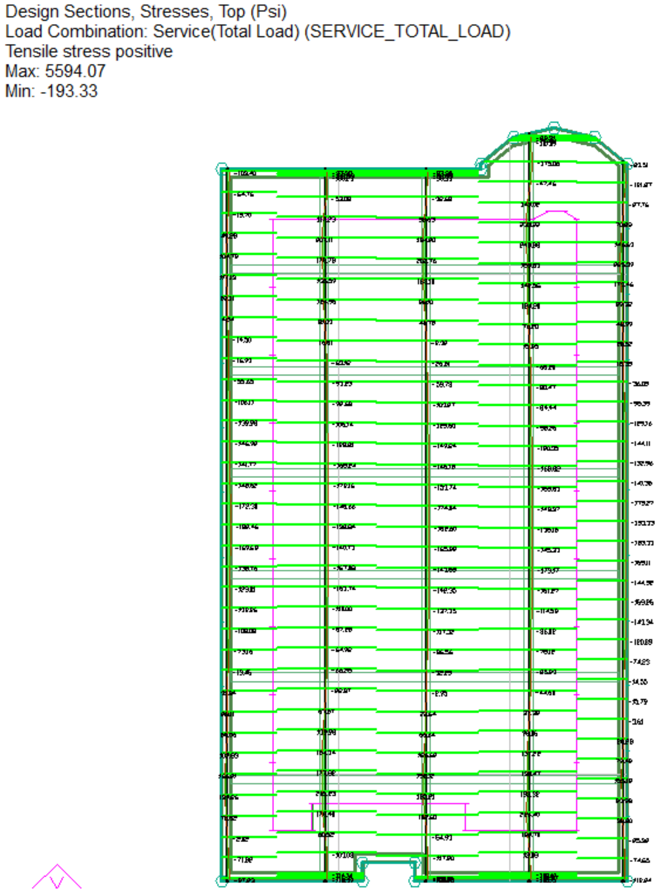
Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 37.04
Min: -1129.69

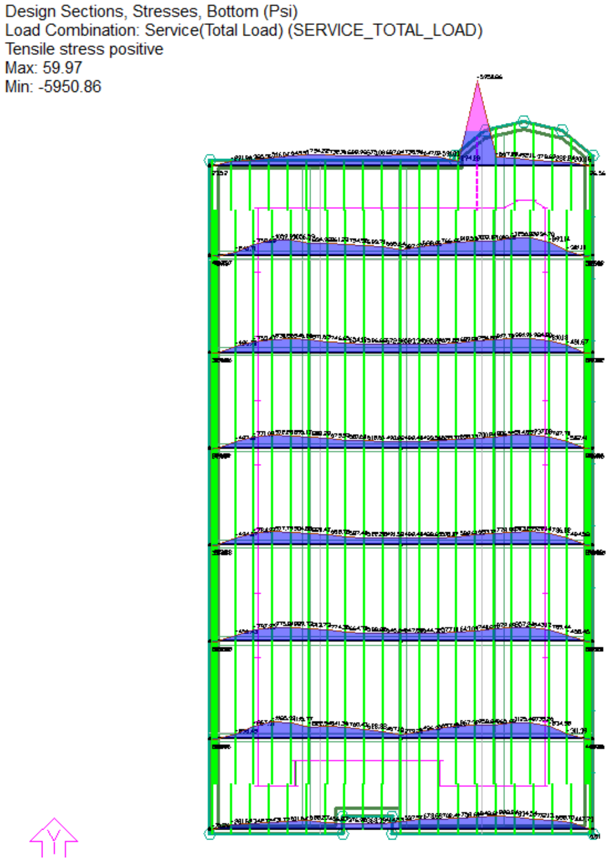
# FEM – Moment Analysis @ Detailed – Center Lift Mode

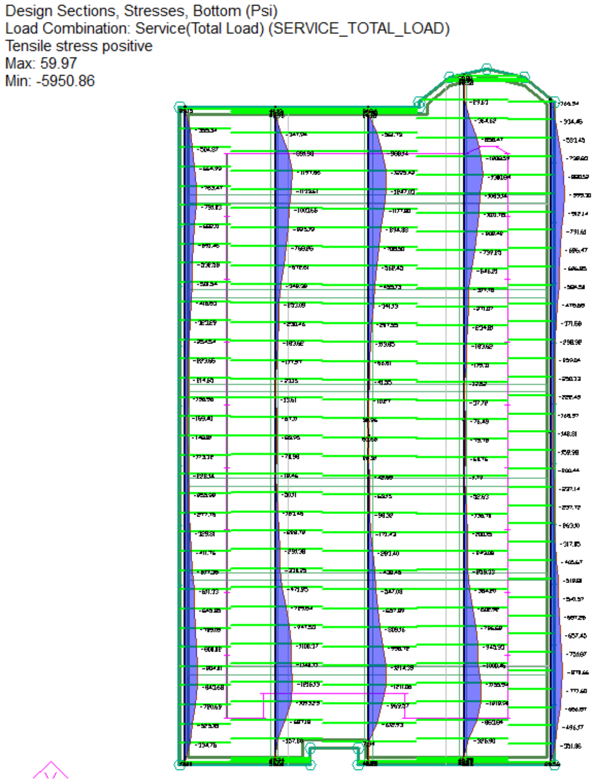
FEM can provide more detailed and localized stress distribution, a useful guide for added rebar placement.


Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 5594.07
Min: -193.33

Localized area of high stresses – should add crack control rebar

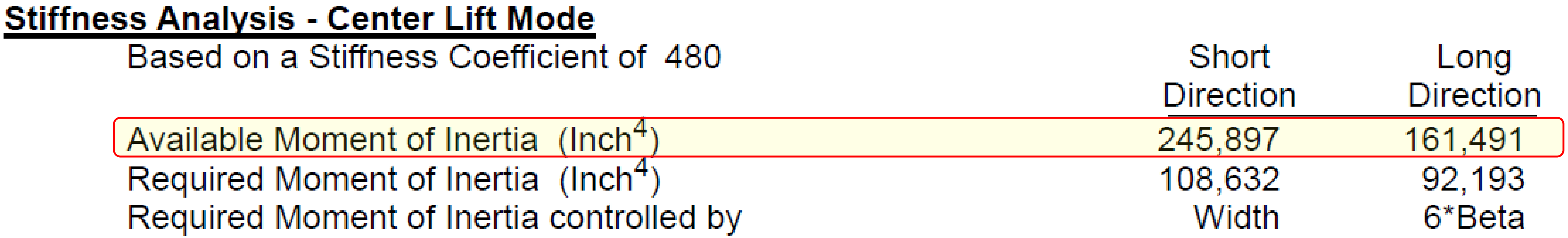

Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 5594.07
Min: -193.33


Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 59.97
Min: -5950.86


Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 59.97
Min: -5950.86

# Stiffness Analysis – Edge Drop/Center Lift Mode

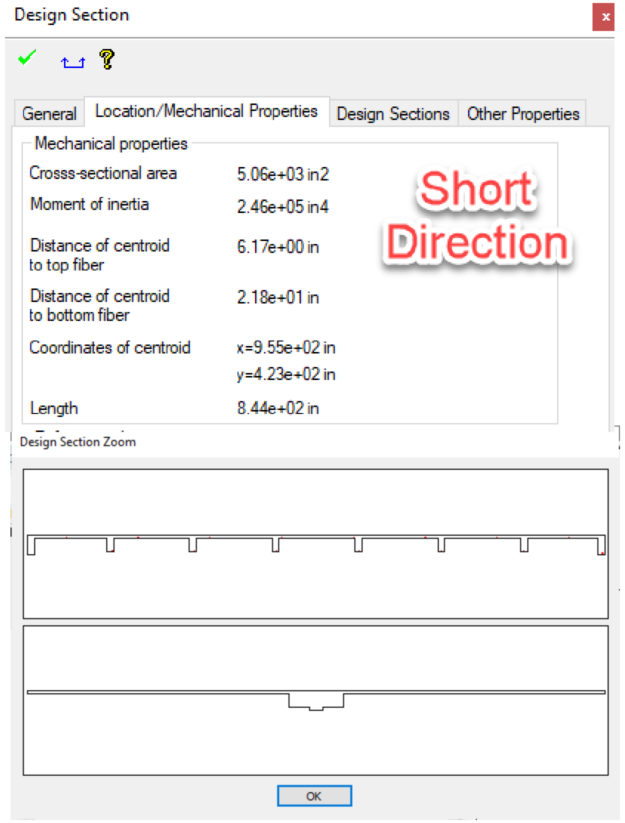
**PTISlab**



**Stiffness Analysis - Center Lift Mode**

| Based on a Stiffness Coefficient of 480 | Short Direction | Long Direction |
|---|---|---|
| Available Moment of Inertia (Inch$^4$) | 245,897 | 161,491 |
| Required Moment of Inertia (Inch$^4$) | 108,632 | 92,193 |
| Required Moment of Inertia controlled by | Width | 6*Beta |

**FEM**



Design Section

| Mechanical properties | |
|---|---|
| Crosss-sectional area | 5.06e+03 in2 |
| Moment of inertia | 2.46e+05 in4 |
| Distance of centroid to top fiber | 6.17e+00 in |
| Distance of centroid to bottom fiber | 2.18e+01 in |
| Coordinates of centroid | x=9.55e+02 in<br>y=4.23e+02 in |
| Length | 8.44e+02 in |

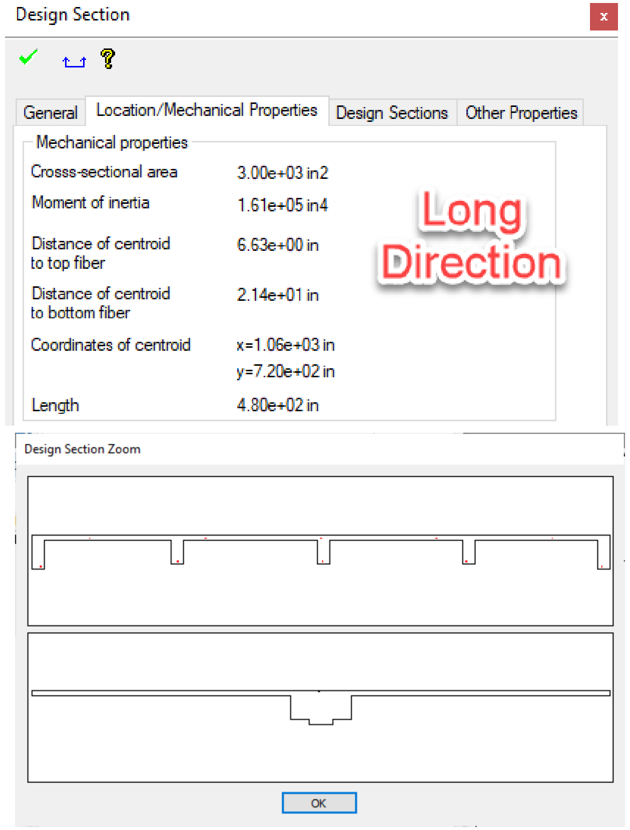
Short Direction

Short direction:

- Required 108,632 (in4)
- Available 246,000 (in4)
- OK

Long direction:

- Required 92,193 (in4)
- Available 161,000 (in4)
- OK

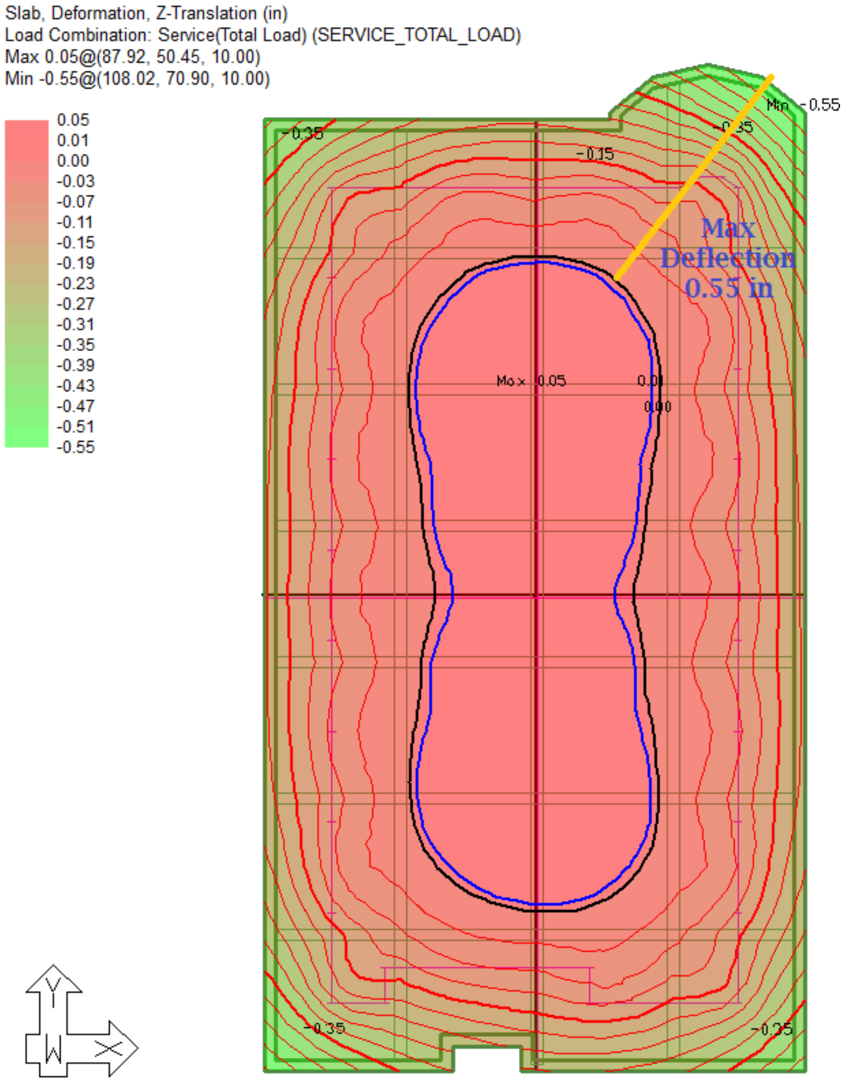


Design Section

| Mechanical properties | |
|---|---|
| Crosss-sectional area | 3.00e+03 in2 |
| Moment of inertia | 1.61e+05 in4 |
| Distance of centroid to top fiber | 6.63e+00 in |
| Distance of centroid to bottom fiber | 2.14e+01 in |
| Coordinates of centroid | x=1.06e+03 in<br>y=7.20e+02 in |
| Length | 4.80e+02 in |

Long Direction

# Stiffness Analysis – Edge Drop/Center Lift Mode



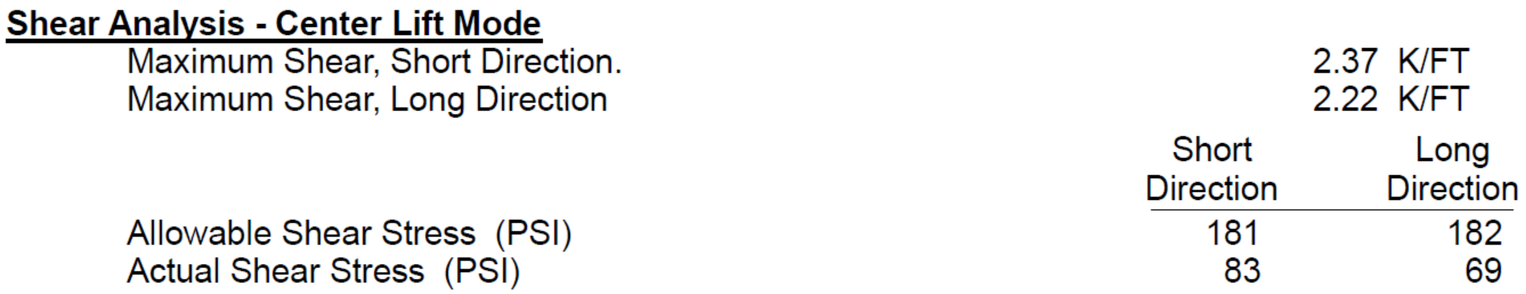
Slab, Deformation, Z-Translation (in)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max 0.05@(87.92, 50.45, 10.00)
Min -0.55@(108.02, 70.90, 10.00)

Can use actual deflection to check deflection criteria.

| | |
|---|---|
| • Stiffness coefficient | 480 |
| • Max allowable deflection | 0.9 in |
| (based on 18 ft cantilever deflection) | |
| • Max deflection | 0.55 in **OK** |

# Shear Analysis – Edge Drop/Center Lift Mode

**PTISlab**

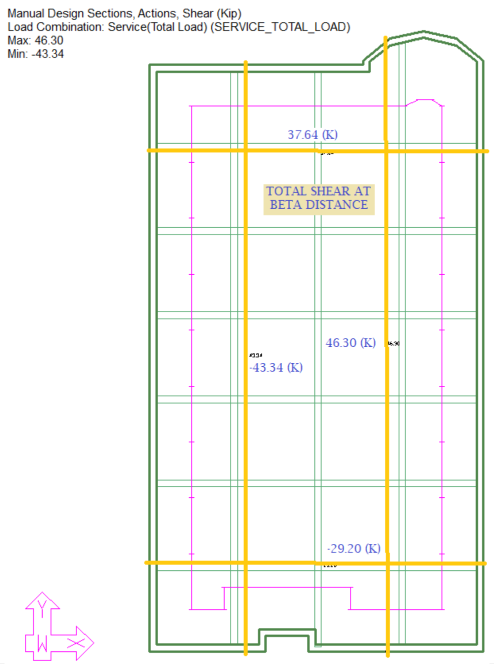


**Shear Analysis - Center Lift Mode**

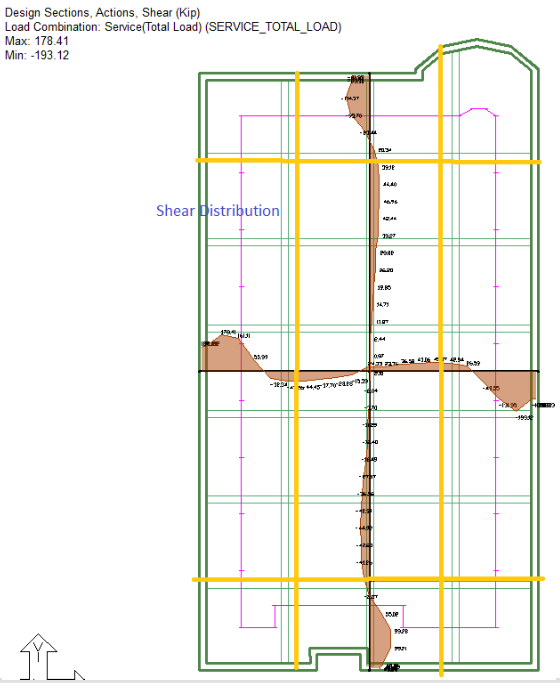
| | |
|---|---|
| Maximum Shear, Short Direction. | 2.37 K/FT |
| Maximum Shear, Long Direction | 2.22 K/FT |

| | Short Direction | Long Direction |
|---|---|---|
| Allowable Shear Stress (PSI) | 181 | 182 |
| Actual Shear Stress (PSI) | 83 | 69 |

**FEM**



Manual Design Sections, Actions, Shear (Kip)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 46.30
Min: -43.34

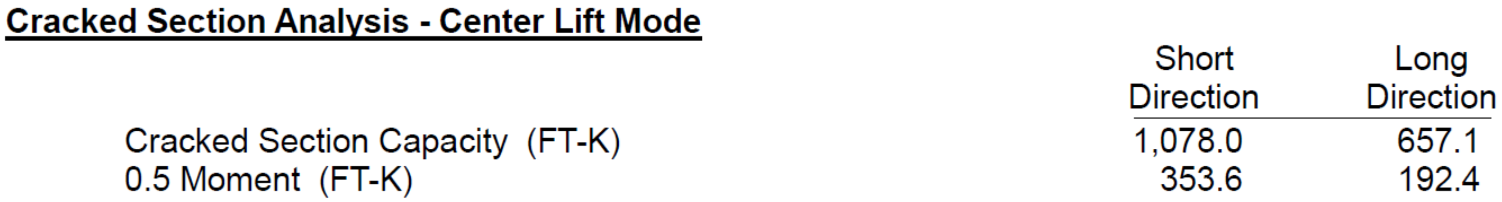


Design Sections, Actions, Shear (Kip)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 178.41
Min: -193.12

| Allowable shear stress: | |
|---|---|
| • Short direction | 181 psi |
| • Long direction | 182 psi |
| **Max shear capacity:** | |
| • Short direction | 331 K |
| • Long direction | 214 K |
| **Shear @ Beta** | |
| • Short direction | 46.3 K OK |
| • Long direction | 37.6 K OK |
| **Max shear demand** | |
| • Short direction | 114.37 K OK |
| • Long direction | 193.12 K OK |

# Cracked Section Analysis – Center Lift Mode

PTISlab

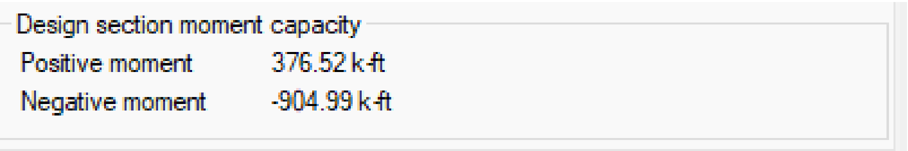


**Cracked Section Analysis - Center Lift Mode**

|  | Short Direction | Long Direction |
|---|---|---|
| Cracked Section Capacity (FT-K) | 1,078.0 | 657.1 |
| 0.5 Moment (FT-K) | 353.6 | 192.4 |

FEM

Short direction:

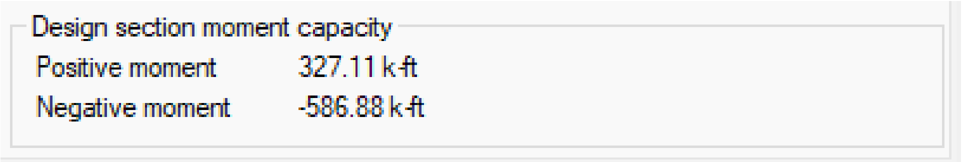


Design section moment capacity

| | |
|---|---|
| Positive moment | 376.52 k-ft |
| Negative moment | -904.99 k-ft |

| | |
|---|---|
| 0.5 M @ Beta | 298 K-FT **OK** |
| 0.5 M Max | 311 K-FT **OK** |

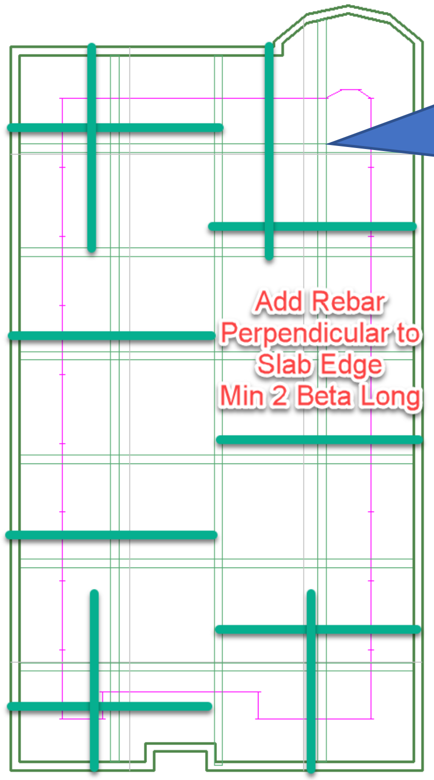
Long direction:



Design section moment capacity

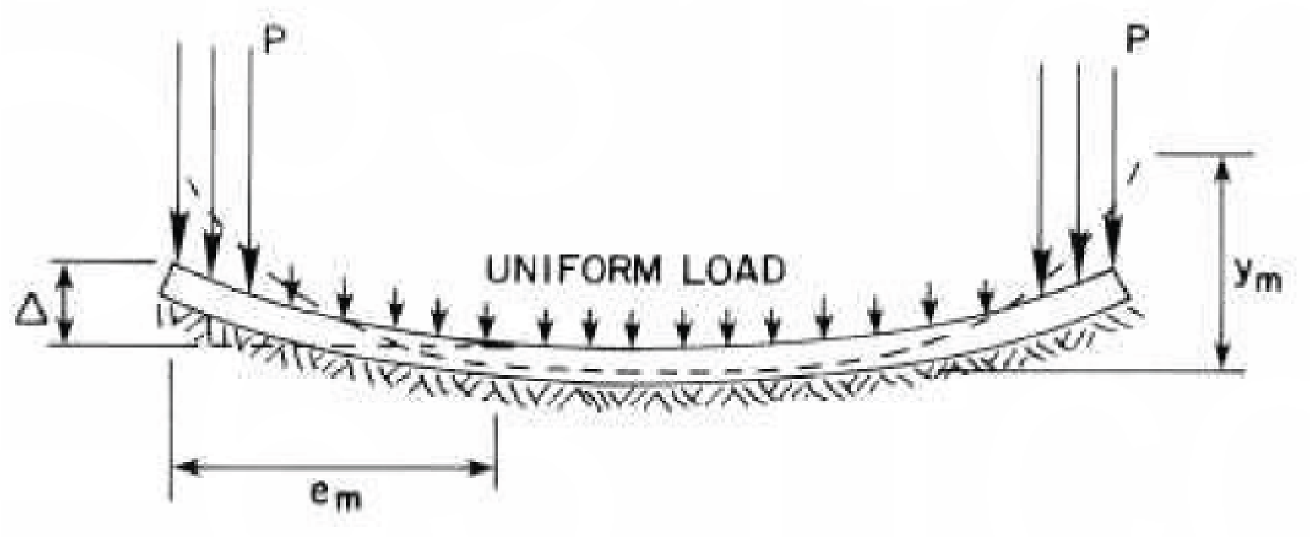
| | |
|---|---|
| Positive moment | 327.11 k-ft |
| Negative moment | -586.88 k-ft |

| | |
|---|---|
| 0.5 M @ Beta | 377 K-FT **NG** |
| 0.5 M Max | 423 K-FT **NG** |



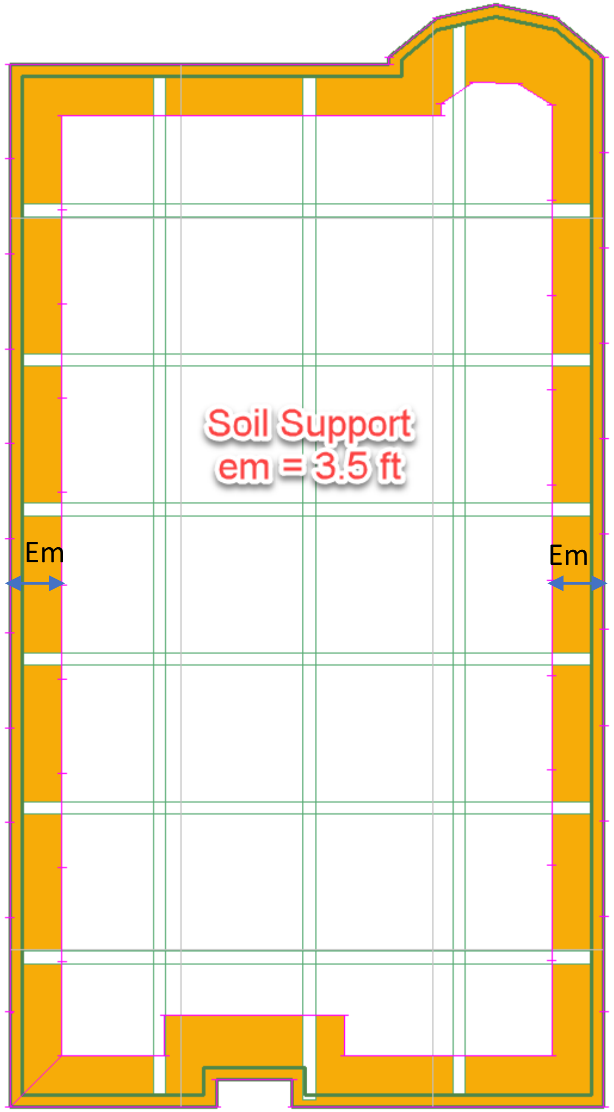
To meet PTI 6.9, add rebar or increase PT

# Edge Lift Mode



PTI Figure 3.5

| Select Soil Parameters: | Edge Lift | Center Lift |
|---|---|---|
| Edge Moisture Distance, ft (em) | 3.5 | 6.7 |
| Differential Soil Movement, inches (ym) | 2.1 | 1.5 |



To simulate Edge Lift Mode, heaving soil support is limited to outer distance em (3.5 ft) from perimeter of slab.

# Edge Lift Moment Analysis

**PTISlab**

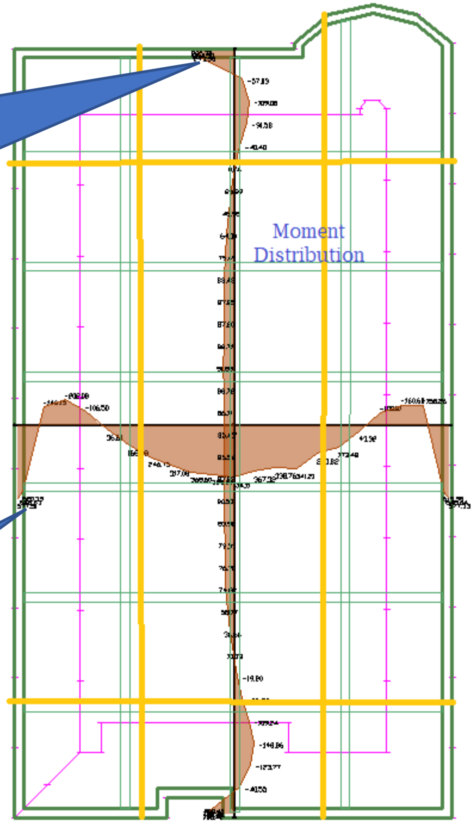
**Moment Analysis - Edge Lift Mode**

| | |
|---|---|
| Maximum Moment, Short Direction | 8.44 FT-K/FT |
| Maximum Moment, Long Direction | 7.01 FT-K/FT |

**FEM**

Maximum moments and shears don't coincide with Beta distance.

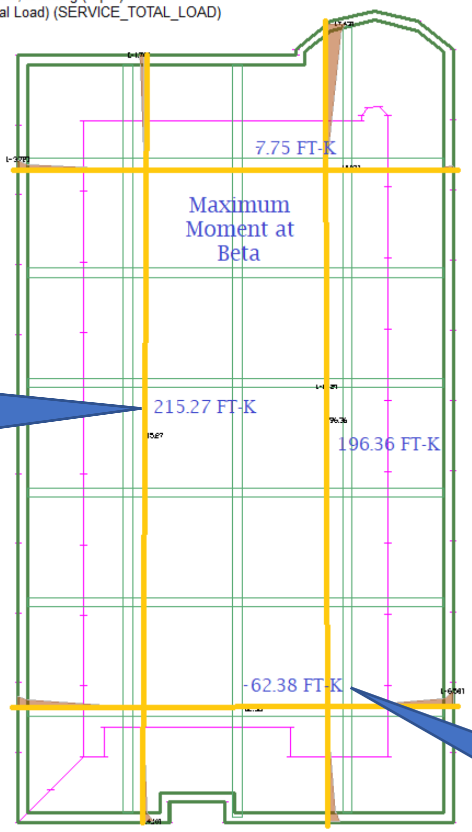
Design Sections, Actions, Bending (Kip-ft)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 577.51
Min: -202.08



FEM Max value is 295.7 PTI value is 280.4

FEM Max value is 577.5 PTI value is 590.8

Manual Design Sections, Actions, Bending (Kip-ft)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 215.27
Min: -62.38



PTI value is 280.4

PTI value is 590.8

Stresses @ beta distance pass.

# Edge Lift Moment Stress Analysis

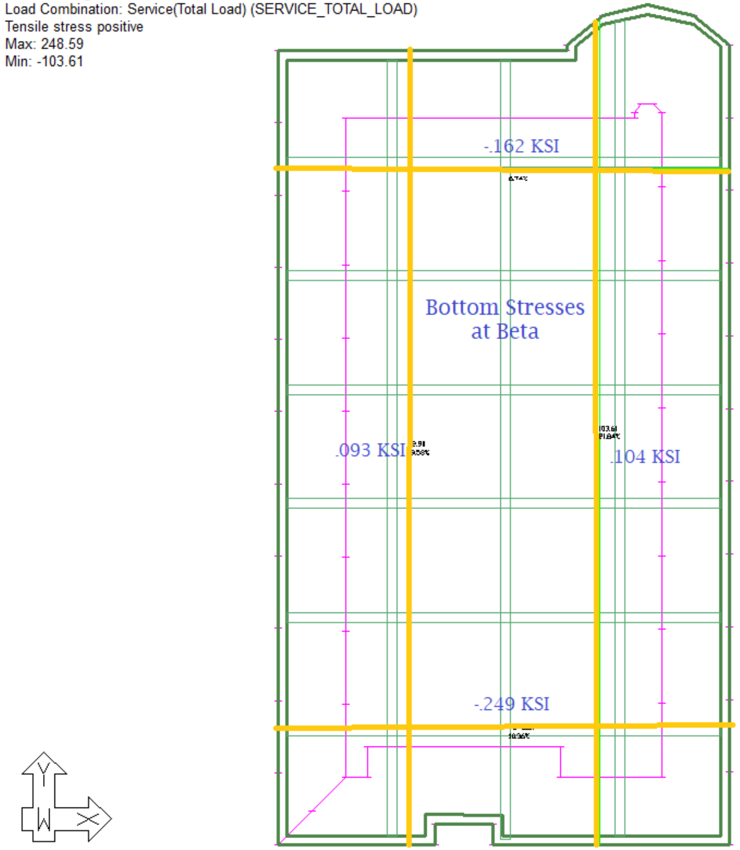
**PTISlab**

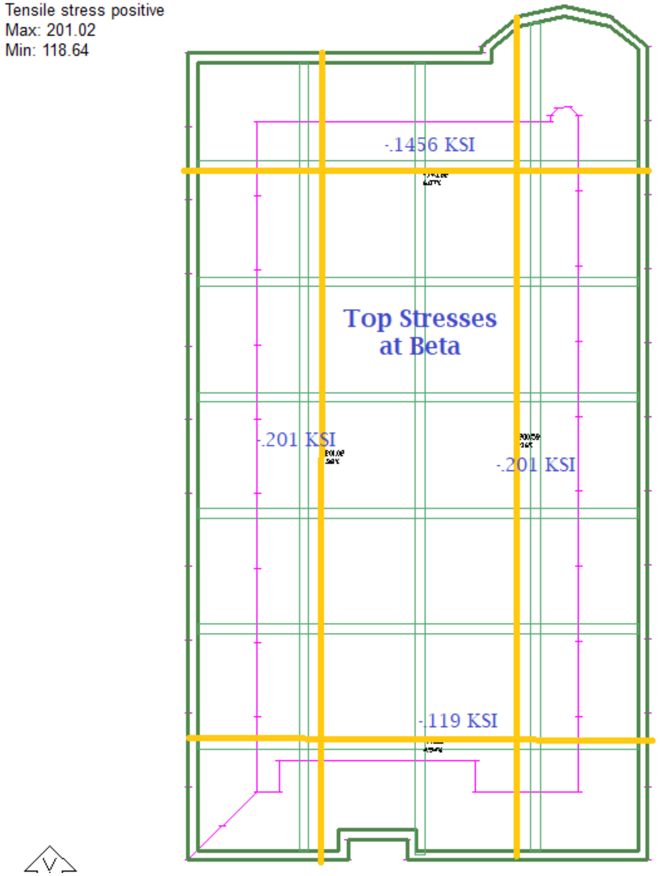
**Moment Analysis - Edge Lift Mode**

| | | |
|---|---|---|
| Maximum Moment, Short Direction | 8.44 | FT-K/FT |
| Maximum Moment, Long Direction | 7.01 | FT-K/FT |

| | Tension in Bottom Fiber (KSI) | | | Compression in Top Fiber (KSI) | |
|---|---|---|---|---|---|
| | Short Direction | Long Direction | | Short Direction | Long Direction |
| Allowable Stress | -0.379 | -0.379 | Allowable Stress | 1.800 | 1.800 |
| Actual Stress | -0.319 | -0.176 | Actual Stress | 0.299 | 0.262 |

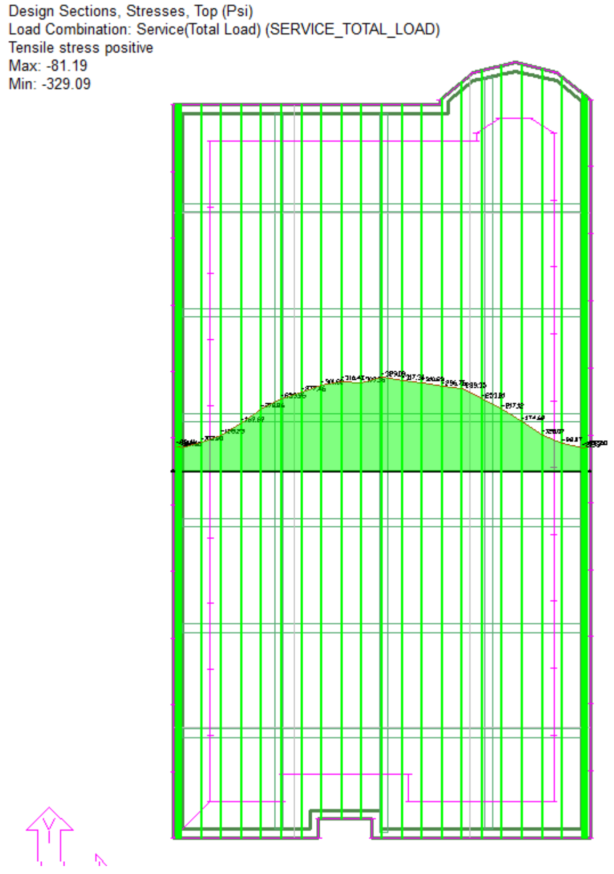
**FEM**


Manual Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 248.59
Min: -103.61

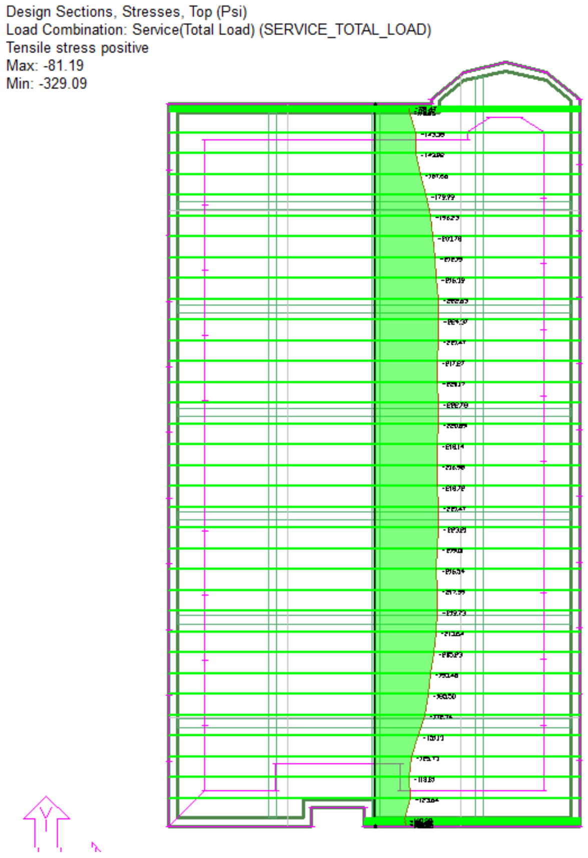

Manual Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 201.02
Min: 118.64

# FEM – Moment Analysis @ All Sections – Edge Lift Mode

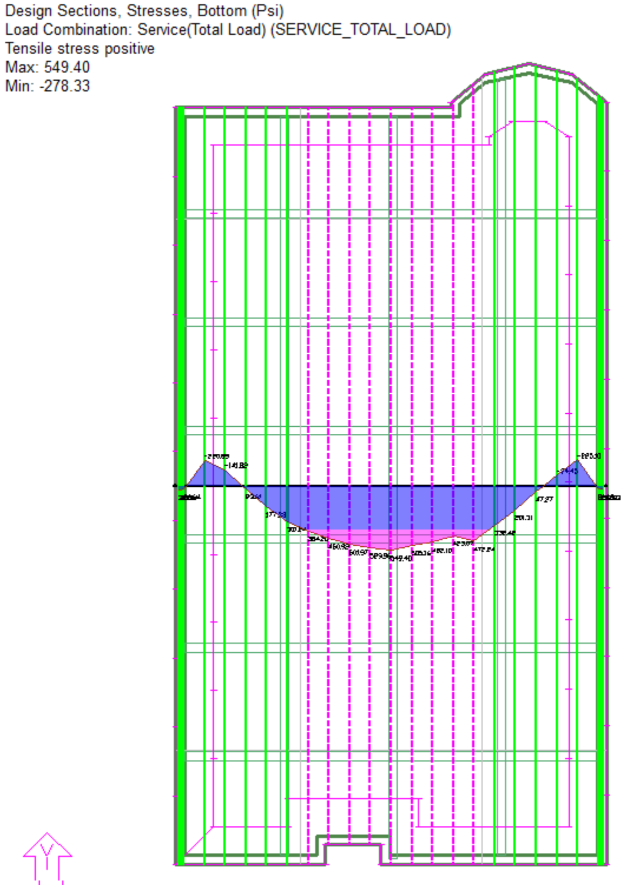
When checking stress distribution in slab, short direction bottom stresses in beams exceed cracking stress.



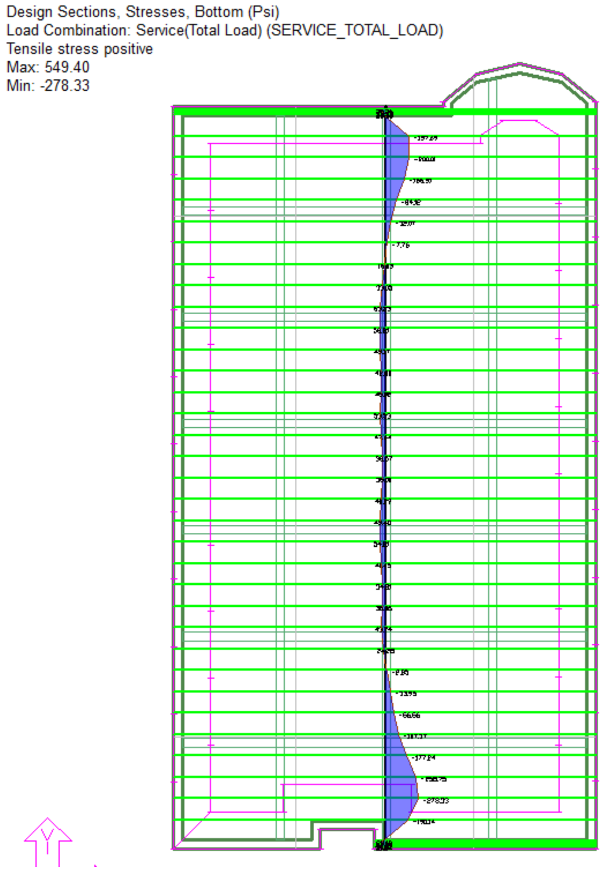
Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: -81.19
Min: -329.09



Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: -81.19
Min: -329.09



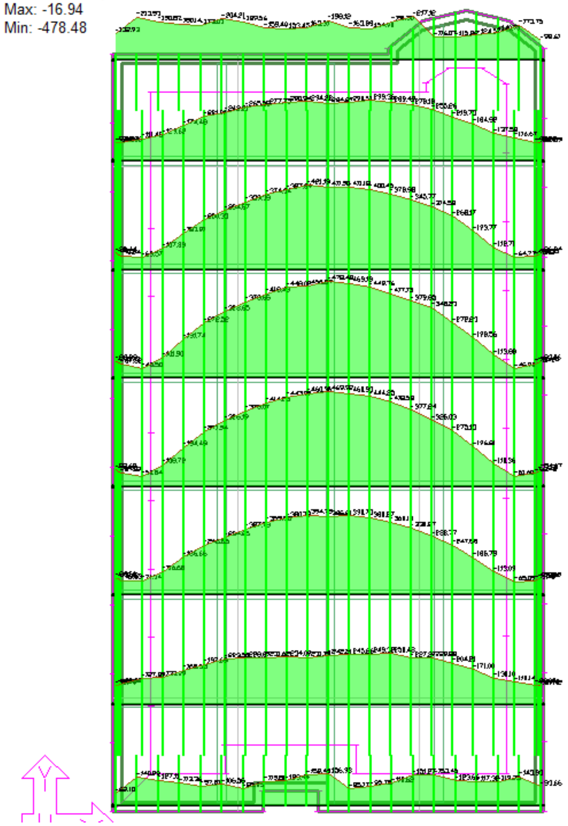
Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 549.40
Min: -278.33



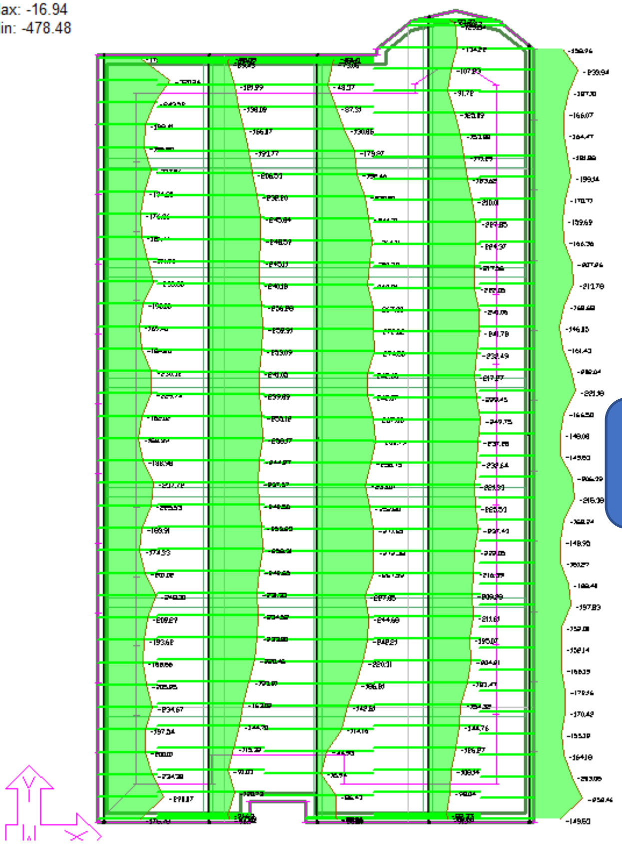
Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 549.40
Min: -278.33

# FEM – Moment Analysis @ Detailed – Edge Lift Mode

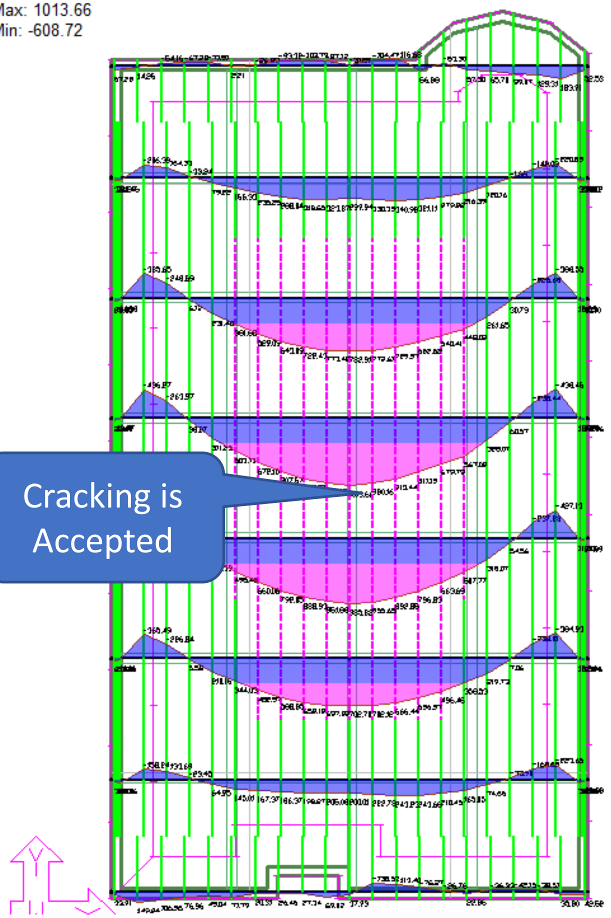
FEM can provide more detailed and localized stress distribution, a useful guide for added rebar placement.



Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: -16.94
Min: -478.48

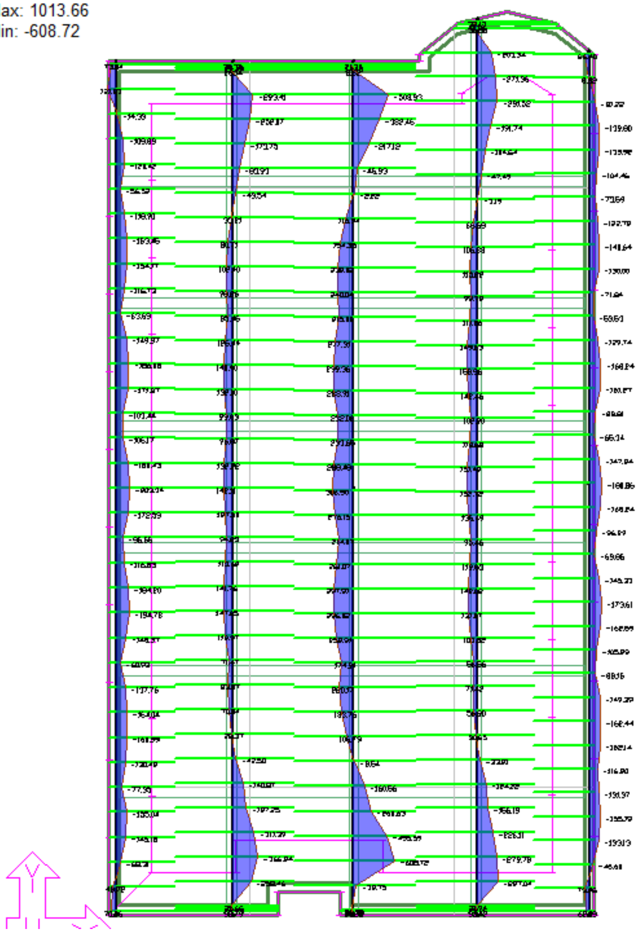


Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: -16.94
Min: -478.48



Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 1013.66
Min: -608.72

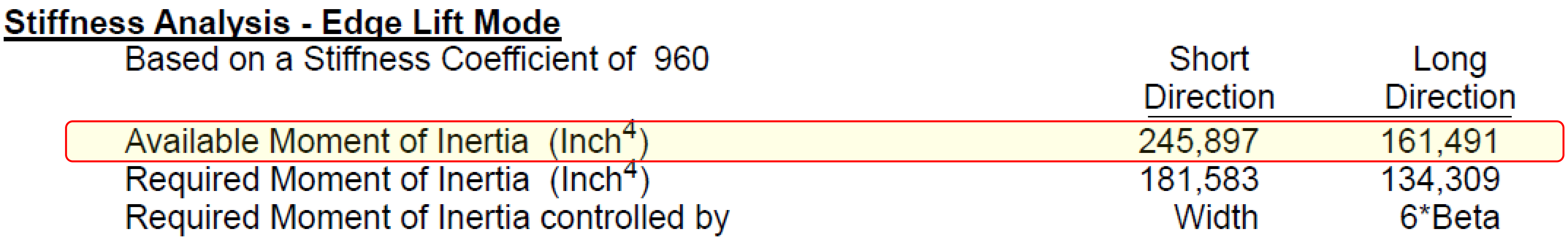
Cracking is Accepted



Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 1013.66
Min: -608.72

# Stiffness Analysis – Edge Lift Mode

**PTISlab**

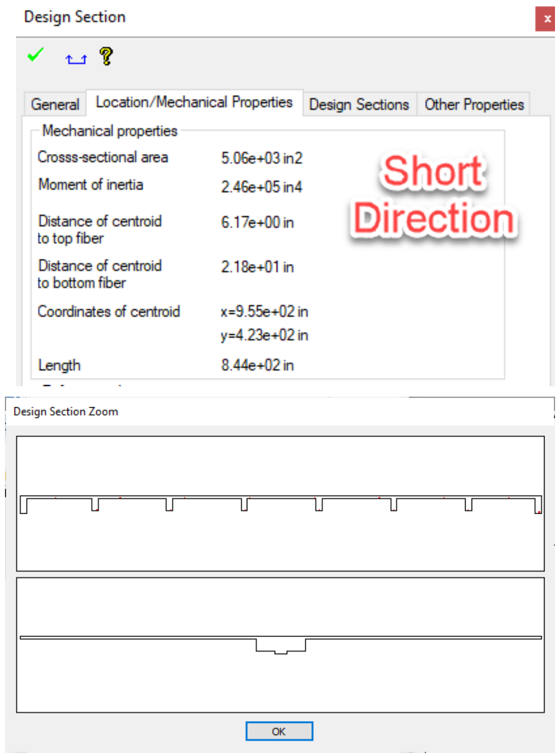


**Stiffness Analysis - Edge Lift Mode**

Based on a Stiffness Coefficient of 960

| | Short Direction | Long Direction |
|---|---|---|
| Available Moment of Inertia (Inch$^4$) | 245,897 | 161,491 |
| Required Moment of Inertia (Inch$^4$) | 181,583 | 134,309 |
| Required Moment of Inertia controlled by | Width | 6*Beta |

**FEM**



Mechanical properties

| | |
|---|---|
| Crosss-sectional area | 5.06e+03 in2 |
| Moment of inertia | 2.46e+05 in4 |
| Distance of centroid to top fiber | 6.17e+00 in |
| Distance of centroid to bottom fiber | 2.18e+01 in |
| Coordinates of centroid | x=9.55e+02 in<br>y=4.23e+02 in |
| Length | 8.44e+02 in |

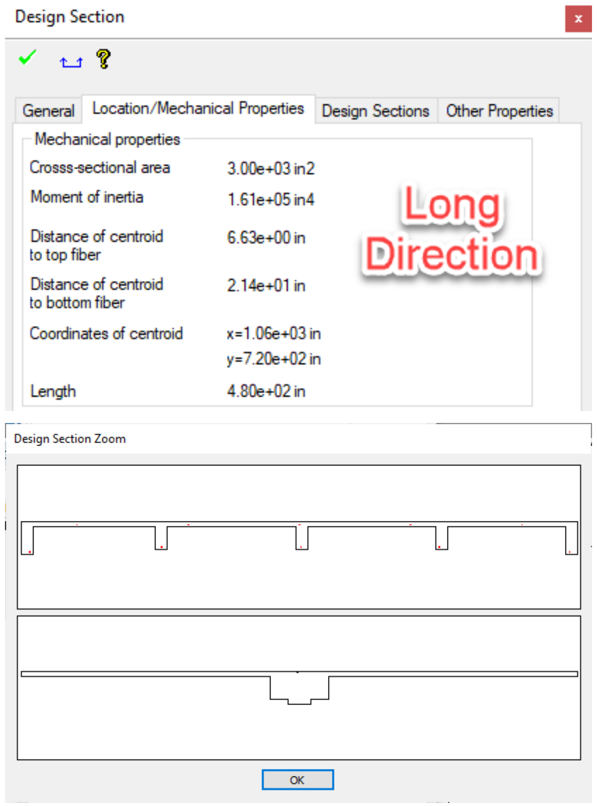
Short Direction

Short direction:

- Required 181,583 (in4)
- Available 246,000 (in4)
- **OK**

Long direction:

- Required 134,309 (in4)
- Available 161,000 (in4)
- **OK**

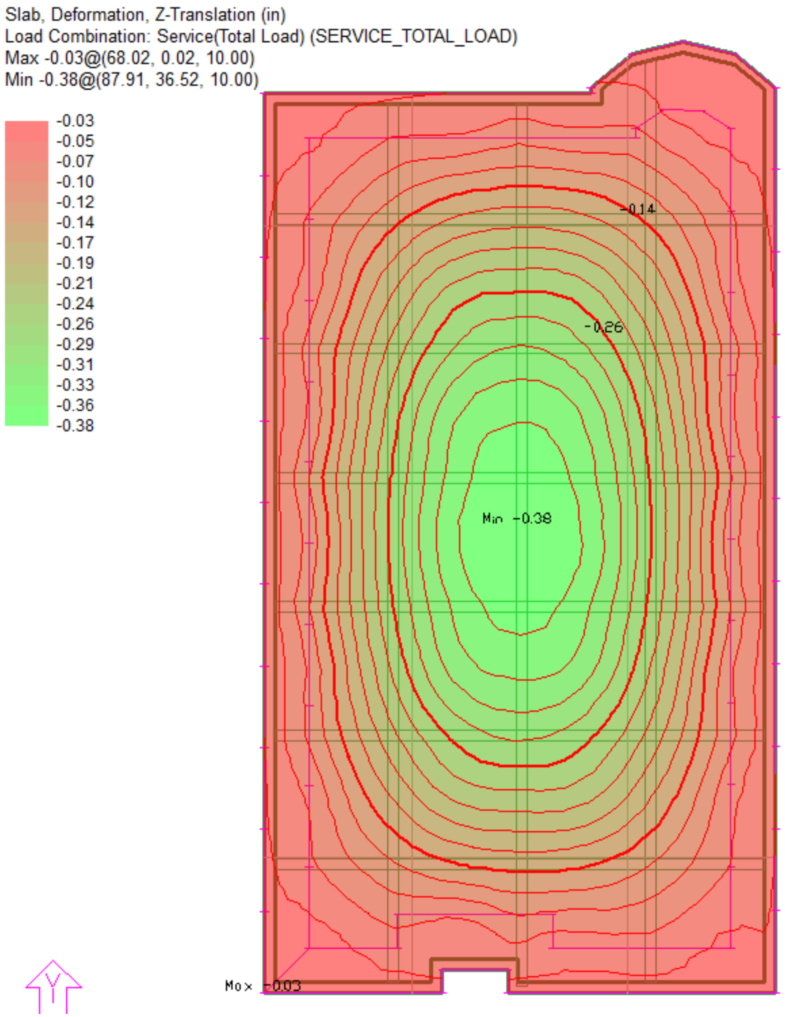


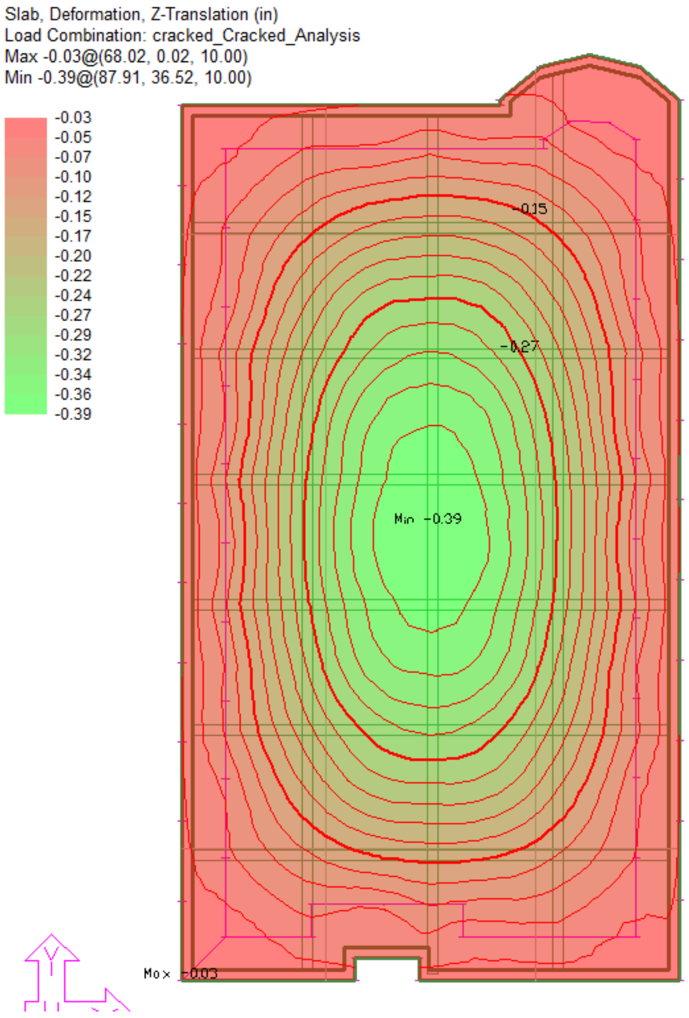
Mechanical properties

| | |
|---|---|
| Crosss-sectional area | 3.00e+03 in2 |
| Moment of inertia | 1.61e+05 in4 |
| Distance of centroid to top fiber | 6.63e+00 in |
| Distance of centroid to bottom fiber | 2.14e+01 in |
| Coordinates of centroid | x=1.06e+03 in<br>y=7.20e+02 in |
| Length | 4.80e+02 in |

Long Direction

# Stiffness Analysis – Edge Lift Mode - Using Required I


Slab, Deformation, Z-Translation (in)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max -0.03@(68.02, 0.02, 10.00)
Min -0.38@(87.91, 36.52, 10.00)


Slab, Deformation, Z-Translation (in)
Load Combination: cracked_Cracked_Analysis
Max -0.03@(68.02, 0.02, 10.00)
Min -0.39@(87.91, 36.52, 10.00)

Use actual deflection to check deflection criteria.

| | |
|---|---|
| Stiffness coefficient | 480 |
| Max allowable deflection | 1.0 in |
| Max deflection (uncracked) | 0.38 in **OK** |
| Max deflection (cracked) | 0.39 in **OK** |

# Shear Analysis – Edge Lift Mode

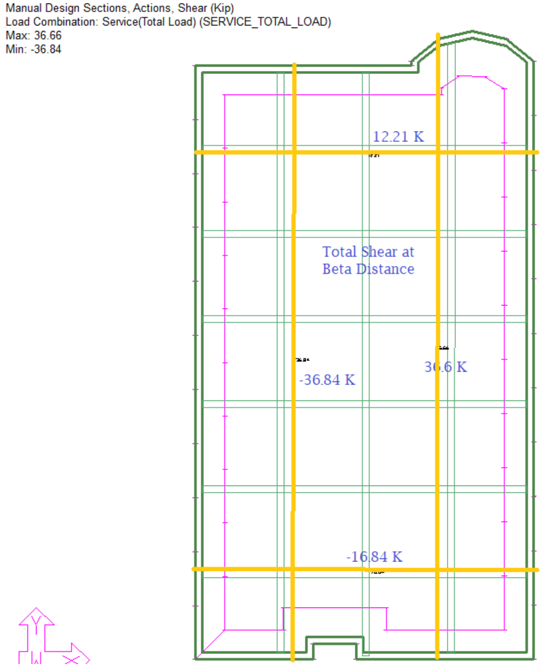
PTISlab

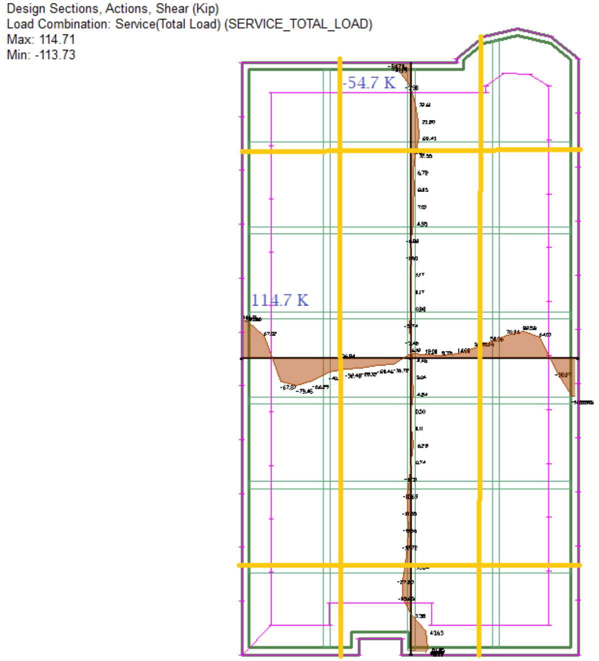
**Shear Analysis - Edge Lift Mode**

Maximum Shear, Short Direction 3.76 K/FT
Maximum Shear, Long Direction 3.95 K/FT

| | Short Direction | Long Direction |
|---|---|---|
| Allowable Shear Stress (PSI) | 181 | 182 |
| Actual Shear Stress (PSI) | 131 | 123 |

FEM


Manual Design Sections, Actions, Shear (Kip)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 36.66
Min: -36.84


Design Sections, Actions, Shear (Kip)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 114.71
Min: -113.73

Allowable shear stress:

- Short direction 181 psi
- Long direction 182 psi

Max shear capacity:

- Short direction 331 K
- Long direction 214 K

Shear @ Beta

- Short direction 37 K OK
- Long direction 17 K OK

Max shear demand

- Short direction 55 K OK
- Long direction 115 K OK

# Cracked Section Analysis – Edge Lift Mode

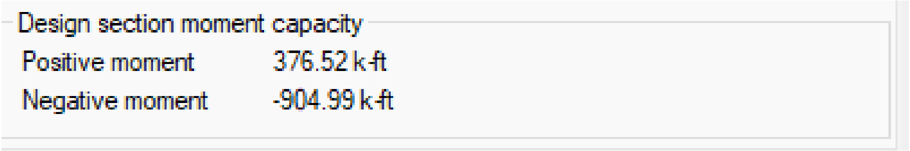
**Cracked Section Analysis - Edge Lift Mode**

PTISlab

|  | Short Direction | Long Direction |
|---|---|---|
| Cracked Section Capacity (FT-K) | 410.4 | 263.6 |
| 0.5 Moment (FT-K) | 295.5 | 140.2 |

FEM

Short direction:

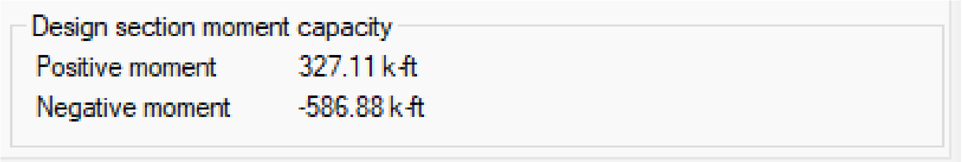


Design section moment capacity

| | |
|---|---|
| Positive moment | 376.52 k-ft |
| Negative moment | -904.99 k-ft |

| | |
|---|---|
| 0.5 M @ Beta | 108 K-FT OK |
| 0.5 M Max | 148 K-FT OK |

Long direction:



Design section moment capacity

| | |
|---|---|
| Positive moment | 327.11 k-ft |
| Negative moment | -586.88 k-ft |

| | |
|---|---|
| 0.5 M @ Beta | 31.2 K-FT OK |
| 0.5 M Max | 289 K-FT OK |

# Summary Table Comparing Design Values

| General Design Criteria | PTISlab 3.5 | FEM CL Em Limited to 5ft | FEM CL Em 6.7ft |
|---|---|---|---|
| Soil Bearing (uniform) PSF | 163 | 1011 | Same |
| Effective Prestress PSI | 138 / 125 | 142 / 122 | Same |
| | | | |
| **Center Lift Mode Design Criteria** | | | |
| Max Moment @ Beta Short FT-K | 707 | 754 | 509 |
| Max Moment @ Beta Long FT-K | 384.8 | 596 | 580.7 |
| Max Total Moment Short FT-K | 707 | 846 | 1129.8 |
| Max Total Moment Long FT-K | 384.8 | 622 | 865.7 |
| Stiffness Check Approach | Rq'd Moment of Inertia | 0.55 in Deflection | 0.97 in Deflection |
| Max Shear @ Beta Short K | 165.9 | 46.3 | 109.12 |
| Max Shear @ Beta Long K | 88.8 | 37.6 | 100.7 |
| Max Total Shear Short K | 166 | 114.4 | 119.7 |
| Max Total Shear Long K | 89 | 193 | 193 |
| | | | |
| **Edge Lift Mode Design Criteria** | | | |
| Max Moment @ Beta Short FT-K | 590.8 | 215.3 | n.a. |
| Max Moment @ Beta Long FT-K | 280.4 | 62.4 | n.a. |
| Max Total Moment Short FT-K | 591 | 295.7 | n.a. |
| Max Total Moment Long FT-K | 280 | 577.5 | n.a. |
| Stiffness Check Approach | Req'd Moment of Inertia | 0.38 in Deflection | n.a. |
| Max Shear @ Beta Short K | 263 | 37 | n.a. |
| Max Shear @ Beta Long K | 158 | 17 | n.a. |
| Max Total Shear Short K | 263 | 55 | n.a. |
| Max Total Shear Long K | 158 | 115 | n.a. |

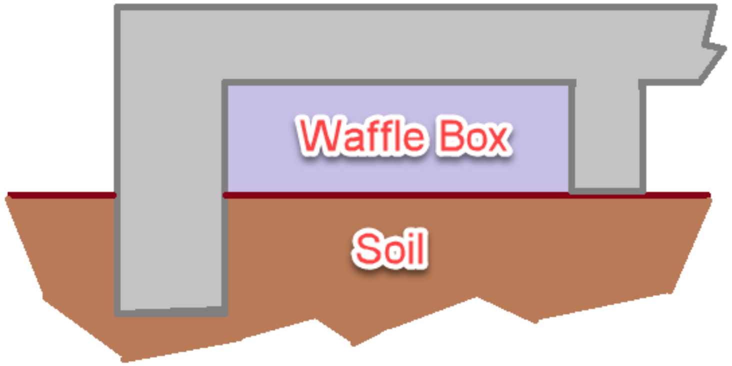
- FEM values higher for soil bearing
- FEM higher for Center Lift
  (not limited to $e_m$ = 5ft)
- PTISlab higher for Edge Lift
  (Soil / Slab interaction less understood)

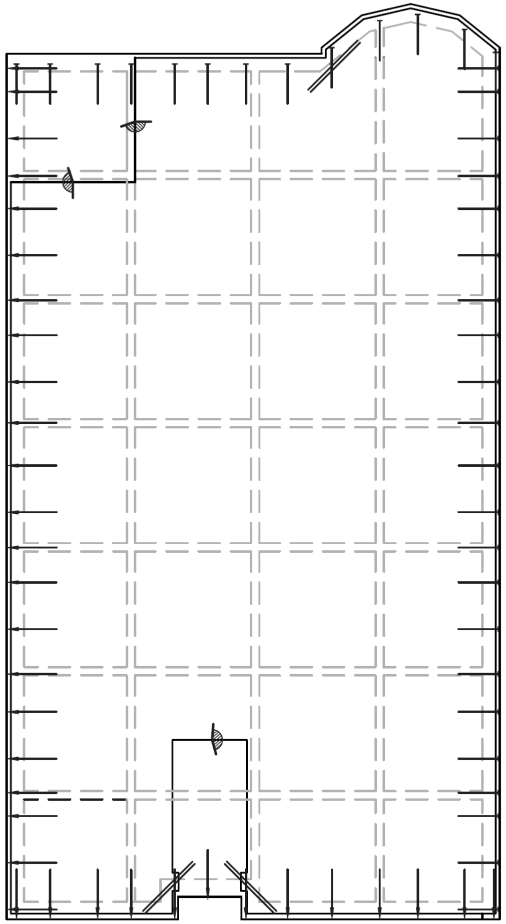
# Best Practice for Using FEM to Design Slab-on-Ground Foundations

- Create base model with geometry, loading and tendons
- Reduce effective PT force to account for losses
- Check soil bearing pressure
- Check min 50 psi effective prestress requirement
- Model design strips to allow checking of slab at multiple sections
- Create Center Lift model by removing soil em from perimeter
  - Check moment stresses
  - Check stiffness
  - Check shear
  - Check cracking moment
- Create Edge Lift model by applying soil em from perimeter or by applying edge displacement
  - Calculated deflection limited to ym
  - Run through all design checks

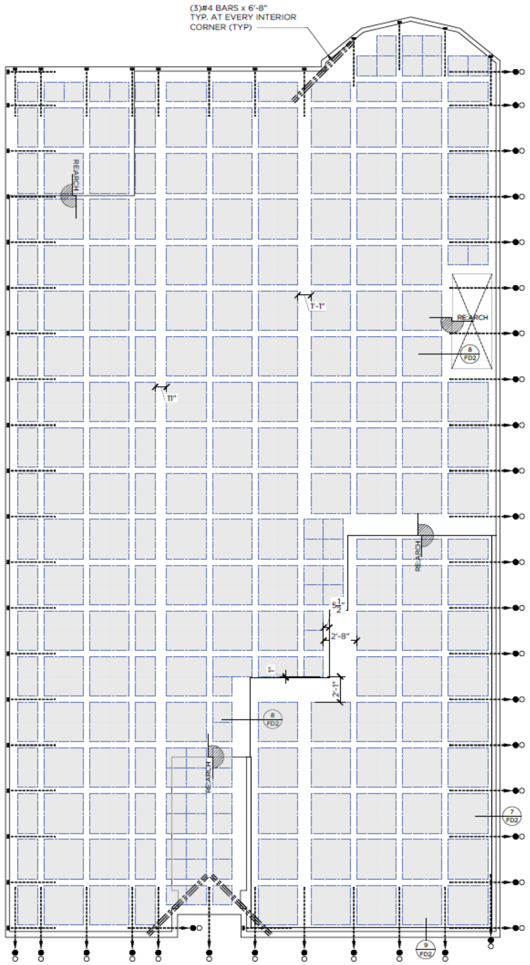
# Wafflemat Foundation Design using FEM

- 32 in perimeter beams
- 4 in slab
- 8.5 in boxes
- 12.5 in interior beams

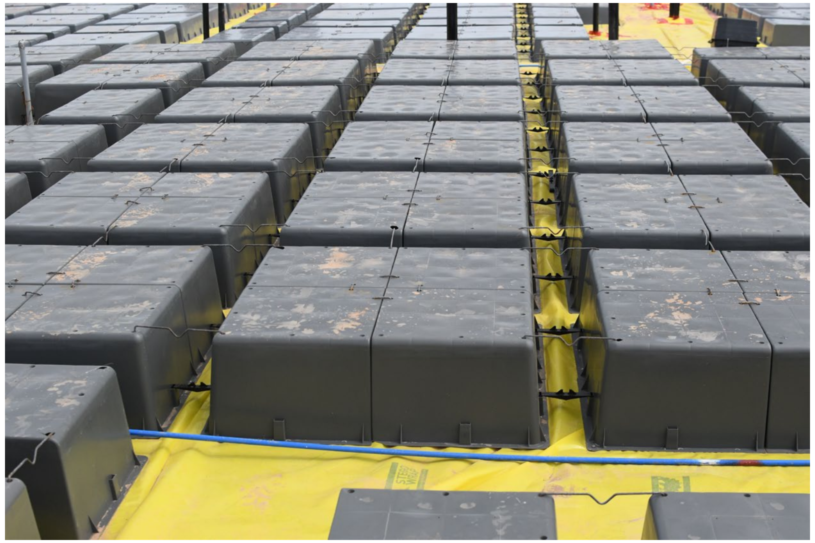




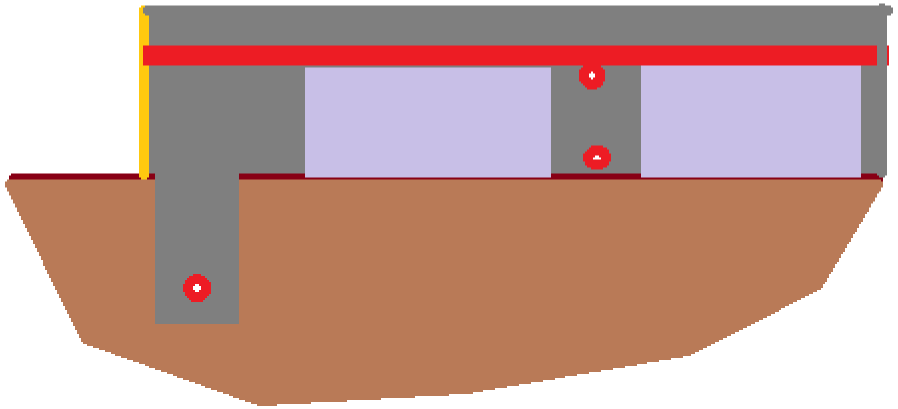
Traditional Ribbed Layout



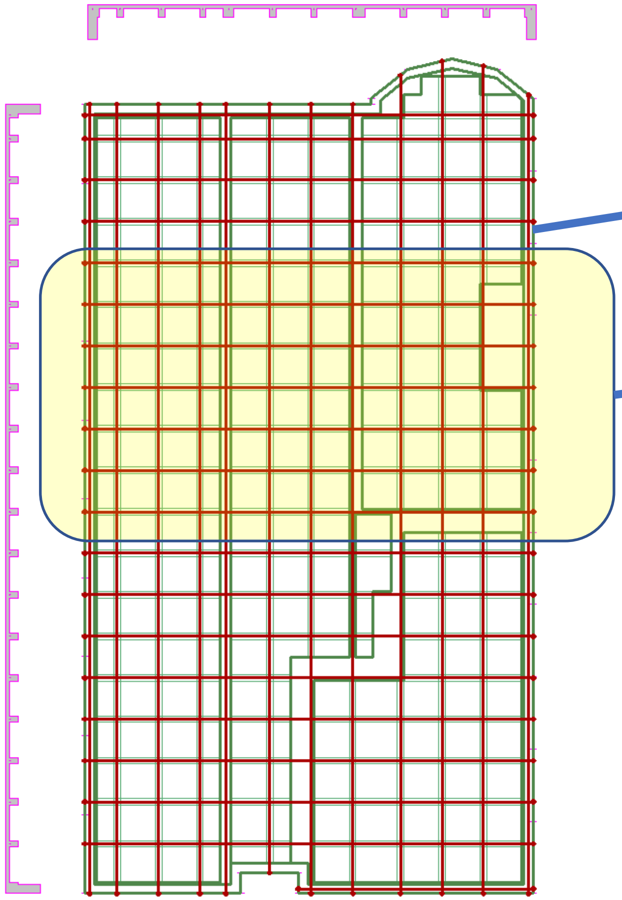
Wafflemat Layout

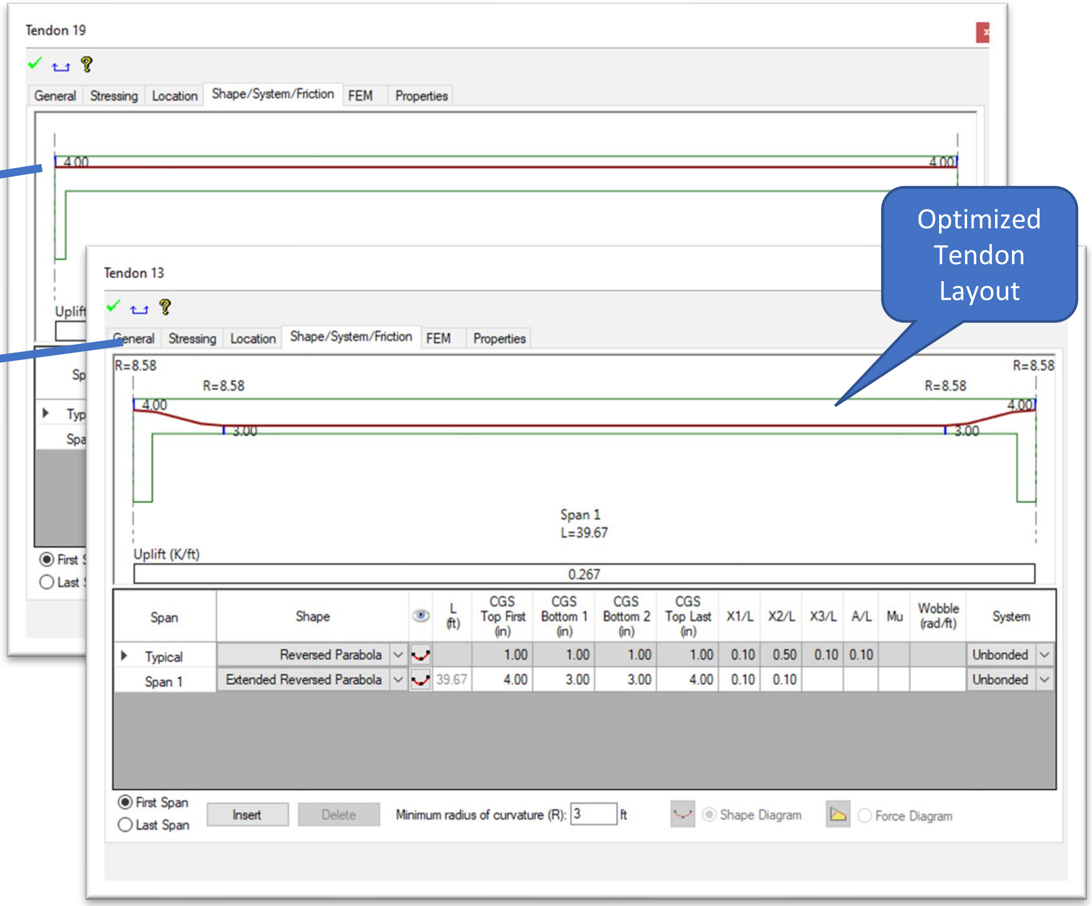


# Wafflemat Construction Sequence



# FEM Wafflemat Foundation Analysis Model





Tendon 19

Tendon 13

Uplift (K/ft): 0.267

| Span | Shape | L (ft) | CGS Top First (in) | CGS Bottom 1 (in) | CGS Bottom 2 (in) | CGS Top Last (in) | X1/L | X2/L | X3/L | A/L | Mu | Wobble (rad/ft) | System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Typical | Reversed Parabola | | 1.00 | 1.00 | 1.00 | 1.00 | 0.10 | 0.50 | 0.10 | 0.10 | | | Unbonded |
| Span 1 | Extended Reversed Parabola | 39.67 | 4.00 | 3.00 | 3.00 | 4.00 | 0.10 | 0.10 | | | | | Unbonded |

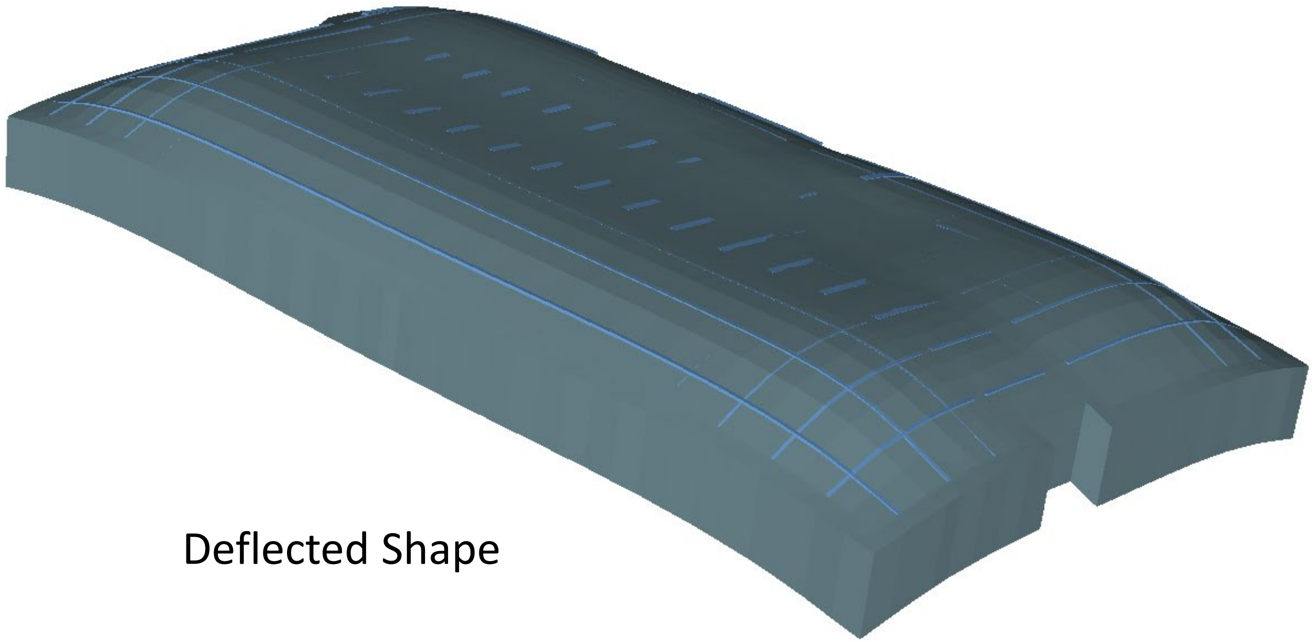
● First Span
○ Last Span

Minimum radius of curvature (R): 3 ft

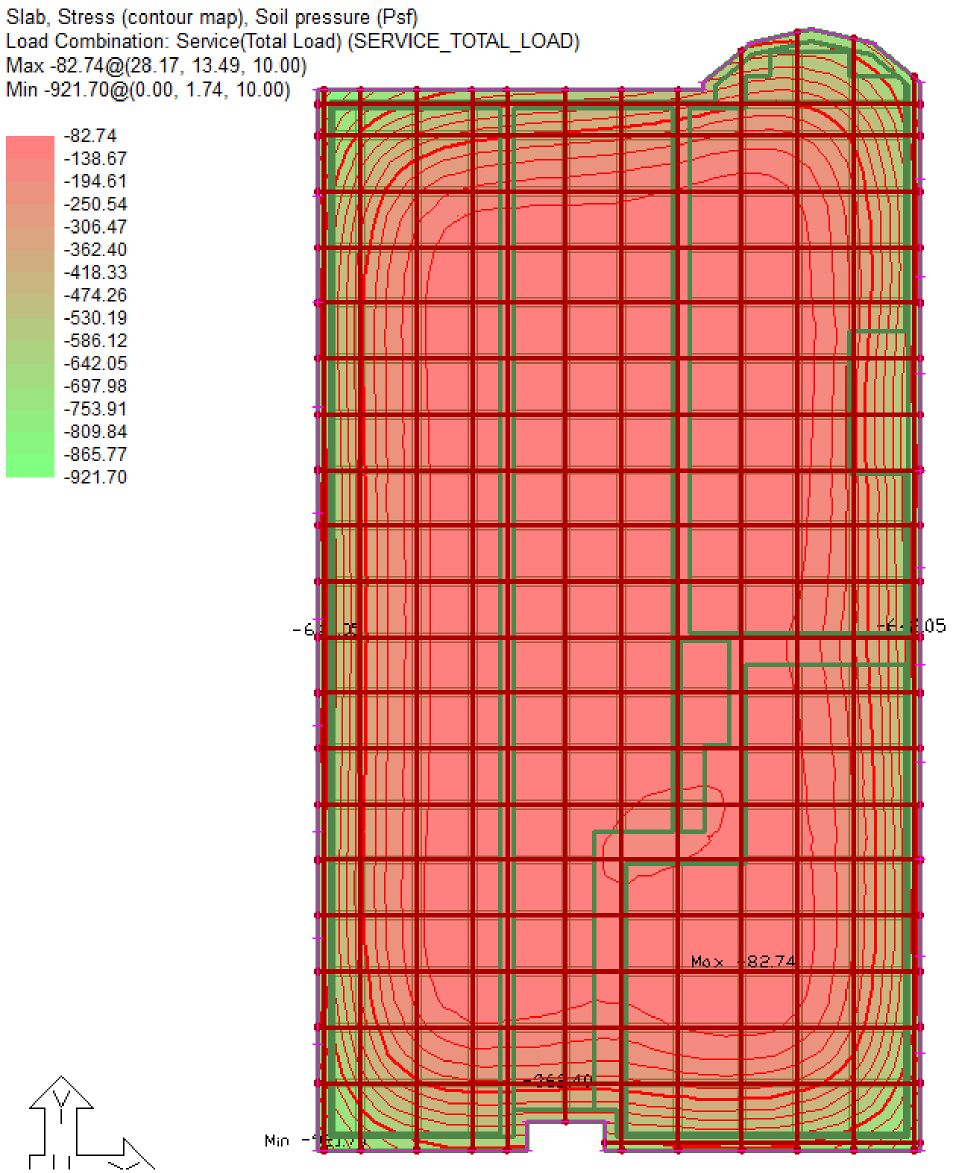
Optimized Tendon Layout

# FEM - Soil Bearing Analysis

- Assumes uniform soil support
- Max pressure on soil 921.7 PSF < allowable 1,500 PSF **OK**



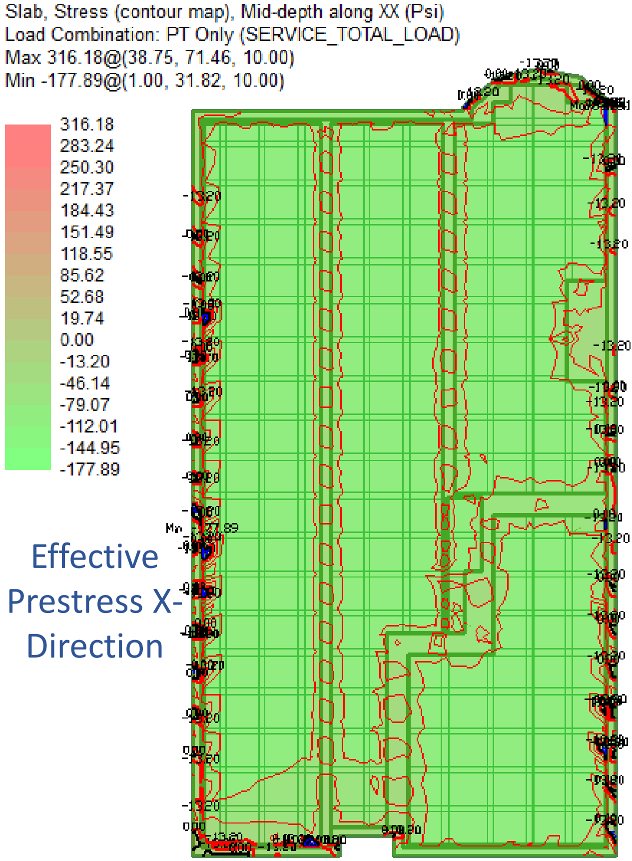
Deflected Shape



Slab, Stress (contour map), Soil pressure (Psf)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max -82.74@(28.17, 13.49, 10.00)
Min -921.70@(0.00, 1.74, 10.00)

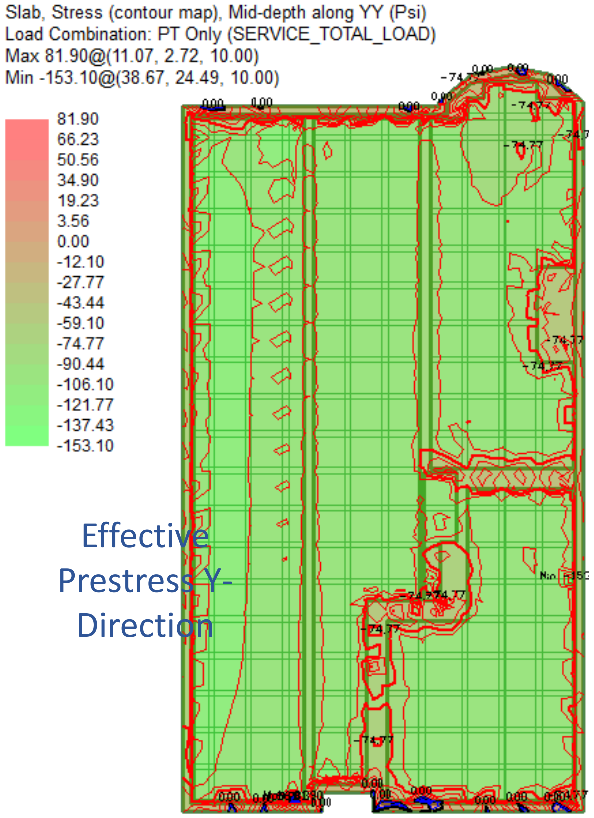
# FEM – Effective Prestress Calculations

Reduced PT force applied to model.



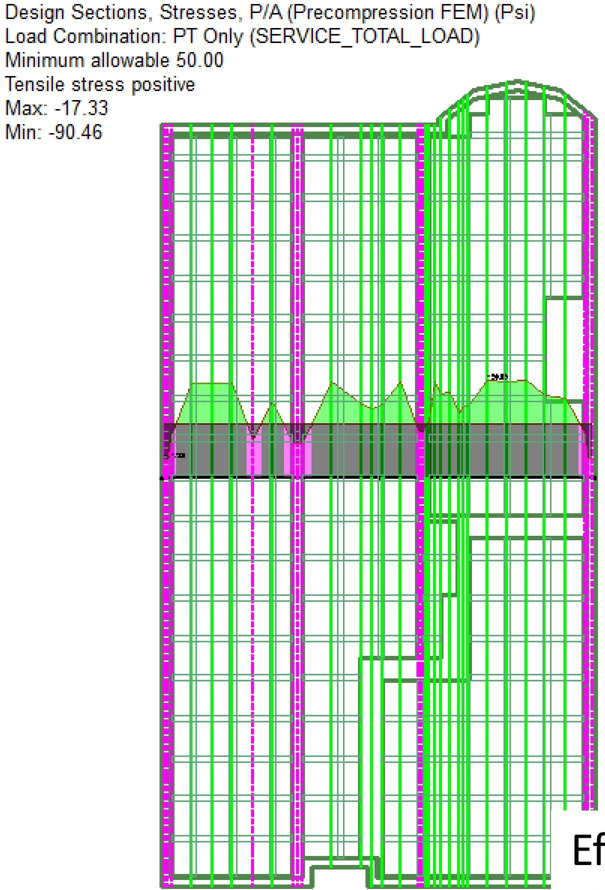
Slab, Stress (contour map), Mid-depth along XX (Psi)
Load Combination: PT Only (SERVICE_TOTAL_LOAD)
Max 316.18@(38.75, 71.46, 10.00)
Min -177.89@(1.00, 31.82, 10.00)

Effective Prestress X-Direction

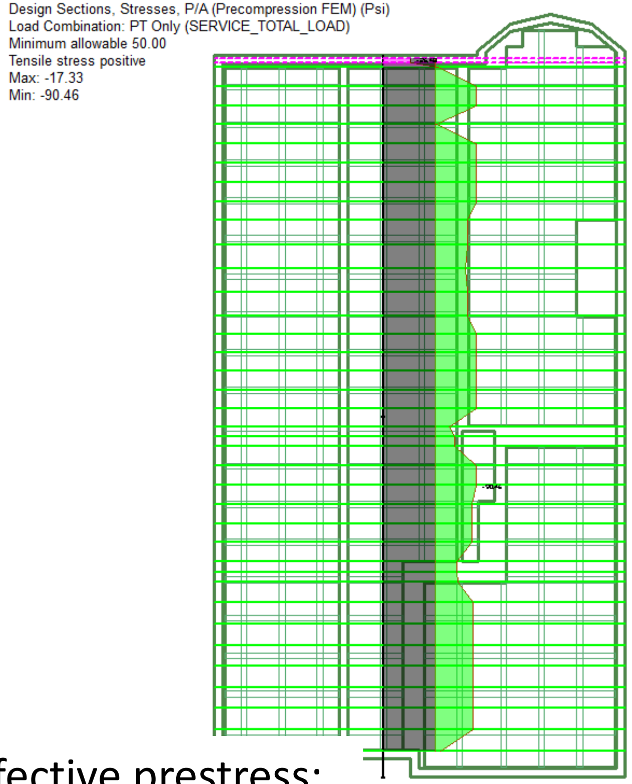


Slab, Stress (contour map), Mid-depth along YY (Psi)
Load Combination: PT Only (SERVICE_TOTAL_LOAD)
Max 81.90@(11.07, 2.72, 10.00)
Min -153.10@(38.67, 24.49, 10.00)

Effective Prestress Y-Direction



Design Sections, Stresses, P/A (Precompression FEM) (Psi)
Load Combination: PT Only (SERVICE_TOTAL_LOAD)
Minimum allowable 50.00
Tensile stress positive
Max: -17.33
Min: -90.46

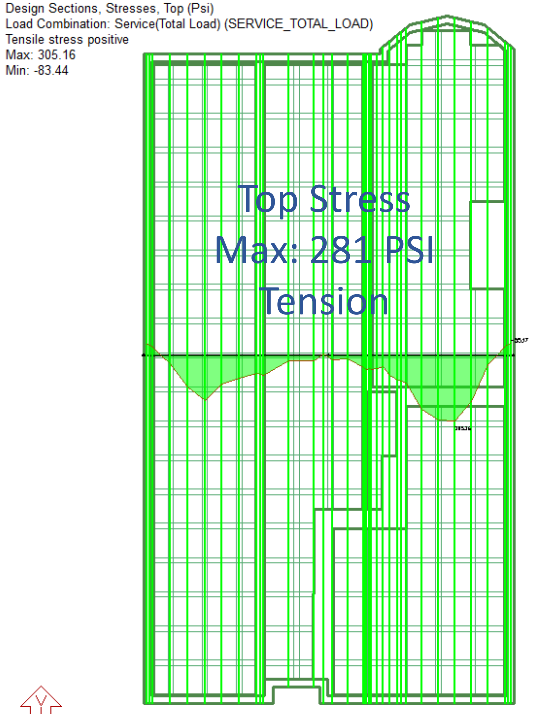


Design Sections, Stresses, P/A (Precompression FEM) (Psi)
Load Combination: PT Only (SERVICE_TOTAL_LOAD)
Minimum allowable 50.00
Tensile stress positive
Max: -17.33
Min: -90.46

Effective prestress:
Short = 90 psi
Long = 90.46 psi **OK**

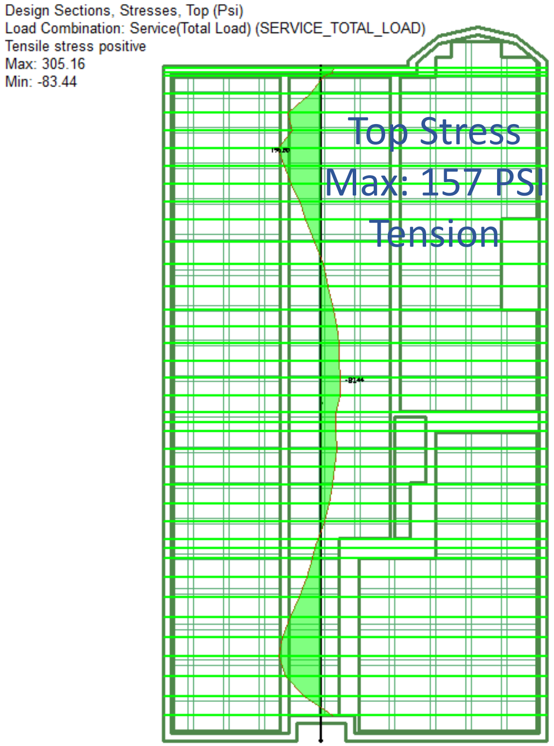
# FEM – Moment Stress Analysis – Edge Drop/Center Lift Mode

All stresses are within limits – **OK**.



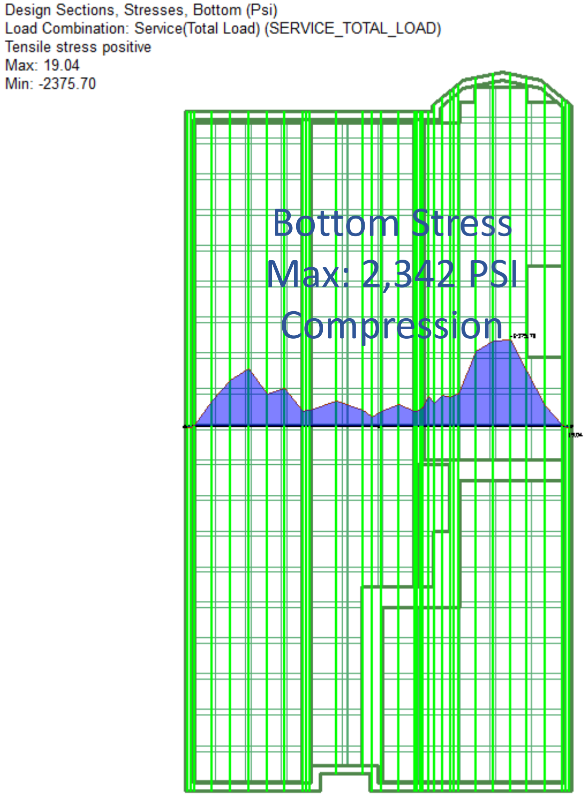
Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 305.16
Min: -83.44

Top Stress
Max: 281 PSI
Tension



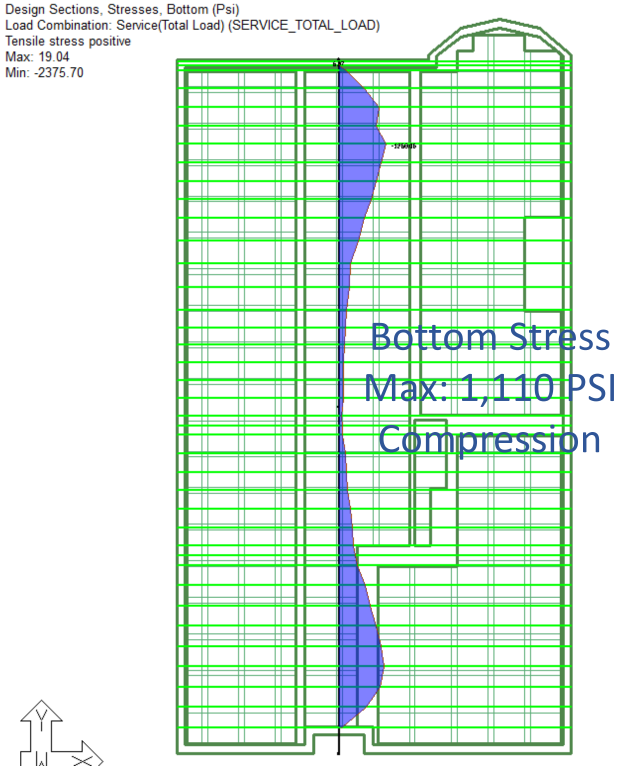
Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 305.16
Min: -83.44

Top Stress
Max: 157 PSI
Tension



Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 19.04
Min: -2375.70

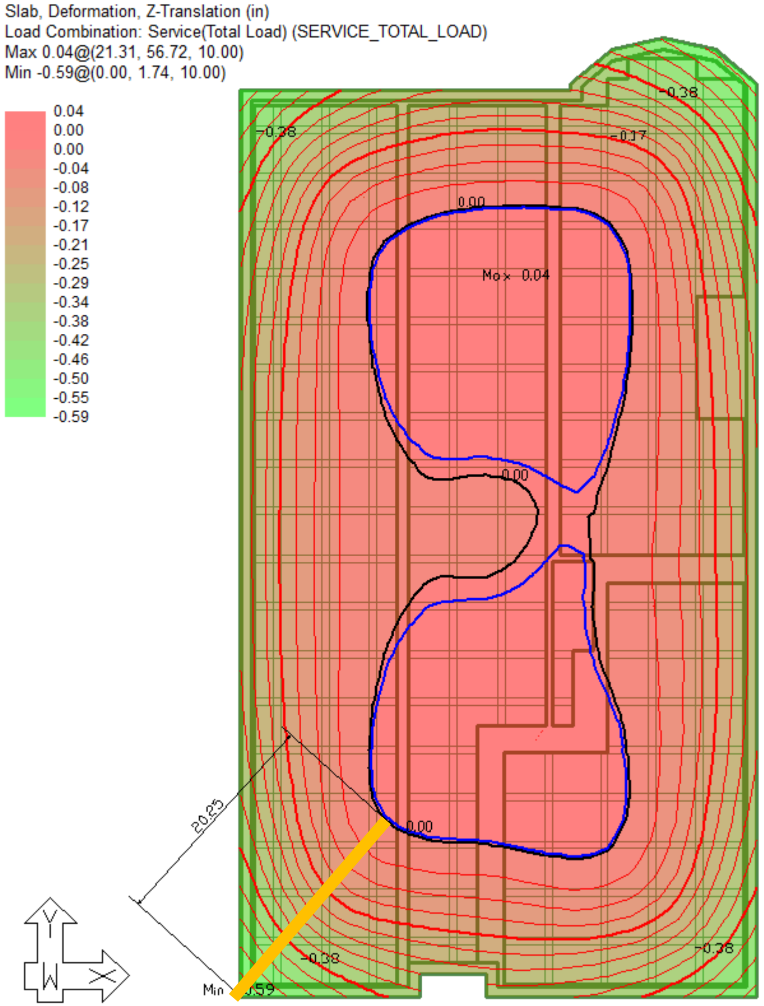
Bottom Stress
Max: 2,342 PSI
Compression



Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 19.04
Min: -2375.70

Bottom Stress
Max: 1,110 PSI
Compression

# FEM – Stiffness Analysis – Edge Drop/Center Lift Mode


Slab, Deformation, Z-Translation (in)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max 0.04@(21.31, 56.72, 10.00)
Min -0.59@(0.00, 1.74, 10.00)

Deflection check:

- Cantilever length at max deflection = 20.25 ft
- Max allowable deflection based on L / 480 = 1.0 in
- Max calculated deflection 0.59 in < 1.0 in **OK**

Stiffness comparison (moments of inertia Inch$^4$):

- Short direction
  - Traditional ribbed slab 245,897
  - Wafflemat 248,000
- Long direction
  - Traditional ribbed slab 161,491
  - Wafflemat 183,000

Wafflemat has 1% greater Moment of Inertia

Wafflemat has 13% greater Moment of Inertia

Wafflemat is stiffer in both directions compared to conforming ribbed slab **OK**

# FEM – Shear Analysis – Center Lift Mode

- Allowable shear stress:

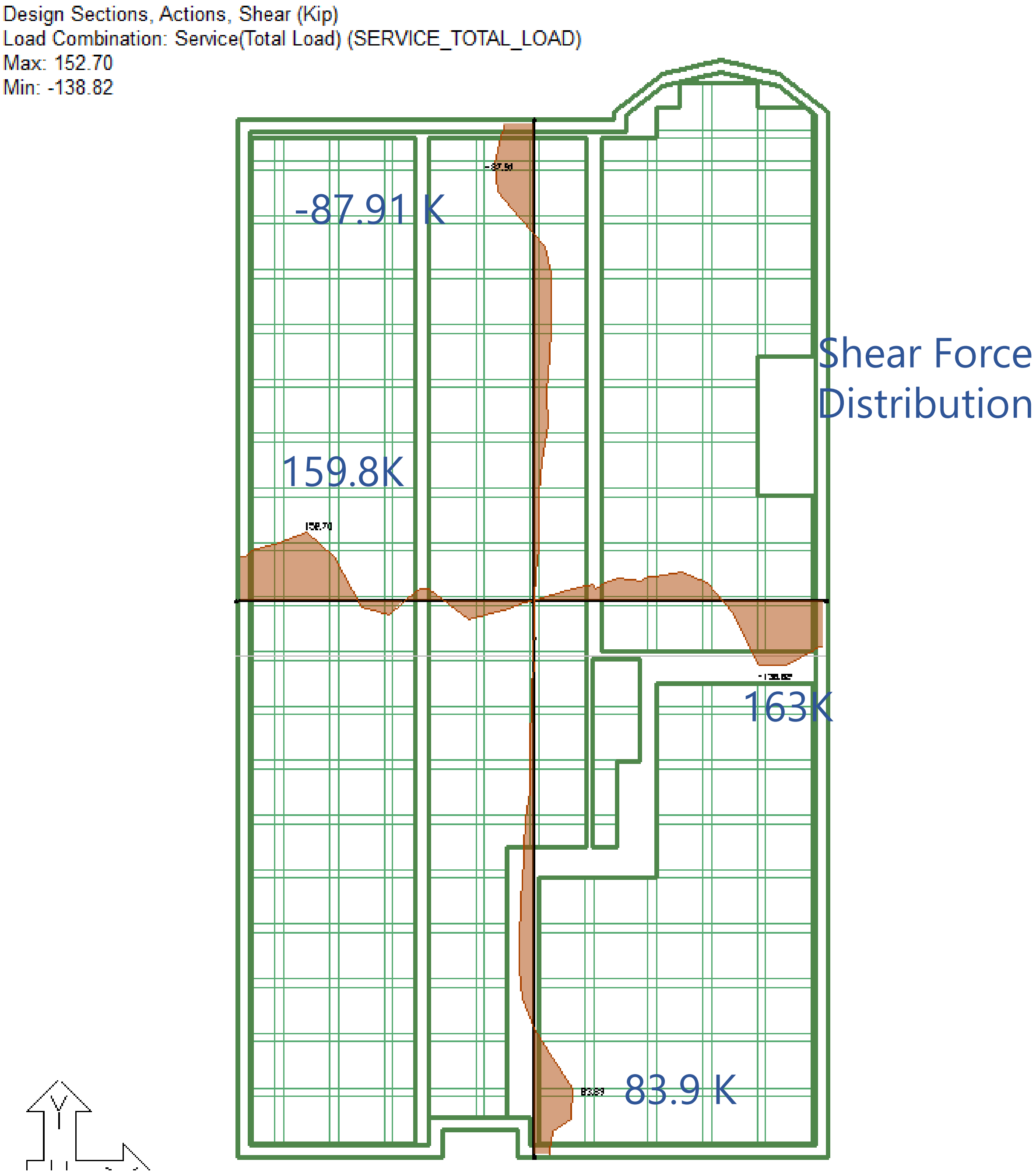
| | |
|---|---|
| Short direction | 169 psi |
| Long direction | 169 psi |

- Max shear capacity:

| | |
|---|---|
| Short direction | 391 K |
| Long direction | 335 K |

- Max shear demand

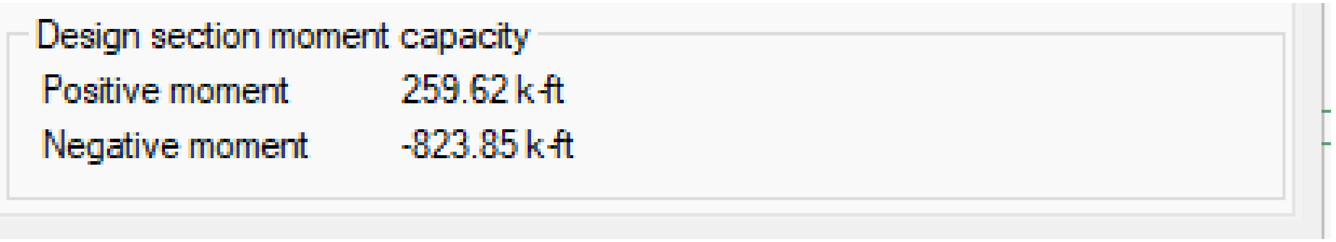
| | |
|---|---|
| Short direction | 88 K **OK** |
| Long direction | 163 K **OK** |



Design Sections, Actions, Shear (Kip)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 152.70
Min: -138.82

# FEM – Cracked Section Analysis – Center Lift Mode

Short direction:

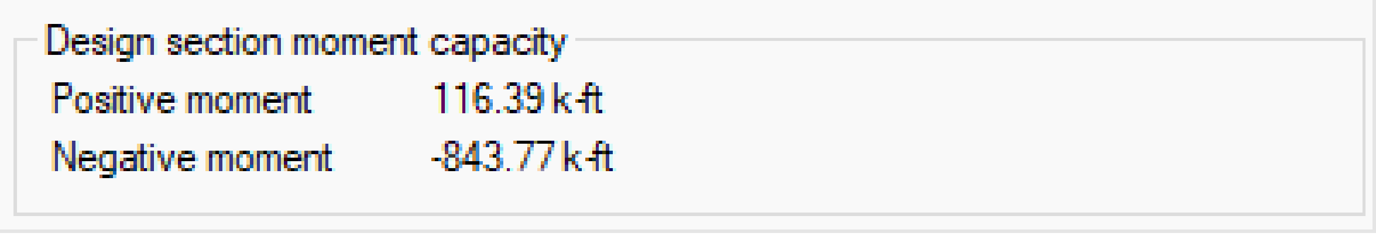


Design section moment capacity

| | |
|---|---|
| Positive moment | 259.62 k-ft |
| Negative moment | -823.85 k-ft |

0.5 M Max -253.8 K-FT **OK**

Long direction:



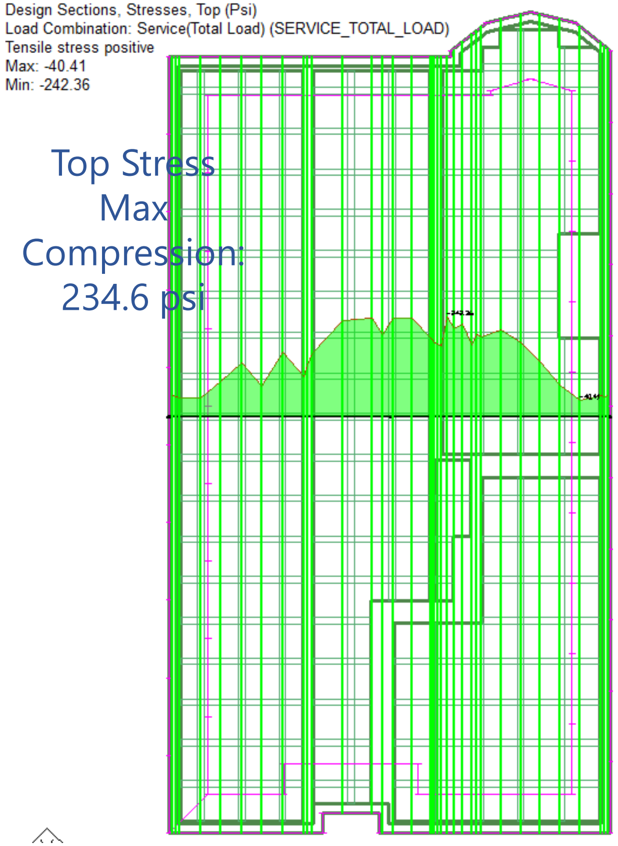
Design section moment capacity

| | |
|---|---|
| Positive moment | 116.39 k-ft |
| Negative moment | -843.77 k-ft |

0.5 M Max -385.14 K-FT **OK**

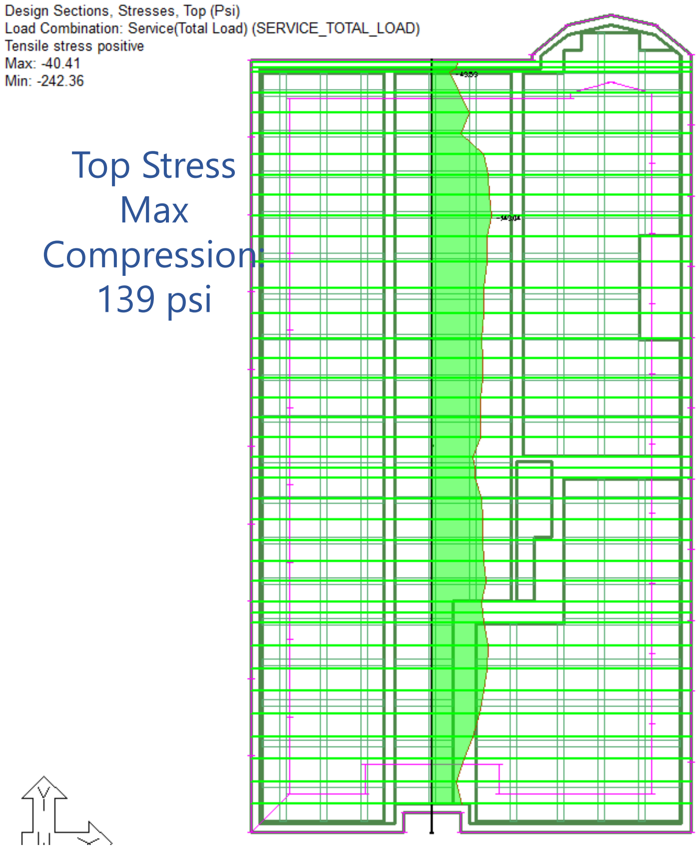
# FEM – Moment Analysis – Edge Lift Mode

Bottom tension stresses in Short direction exceed allowable – same as traditional ribbed slab – check cracked deflection.



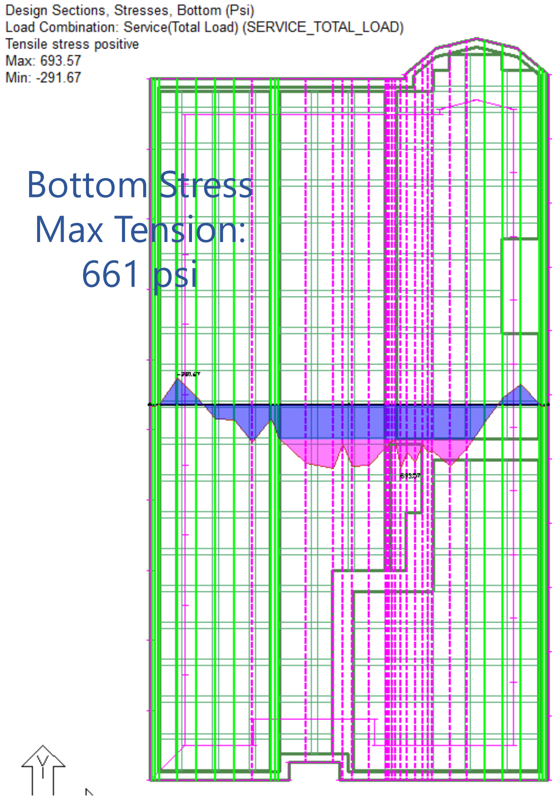
Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: -40.41
Min: -242.36

Top Stress
Max
Compression:
234.6 psi



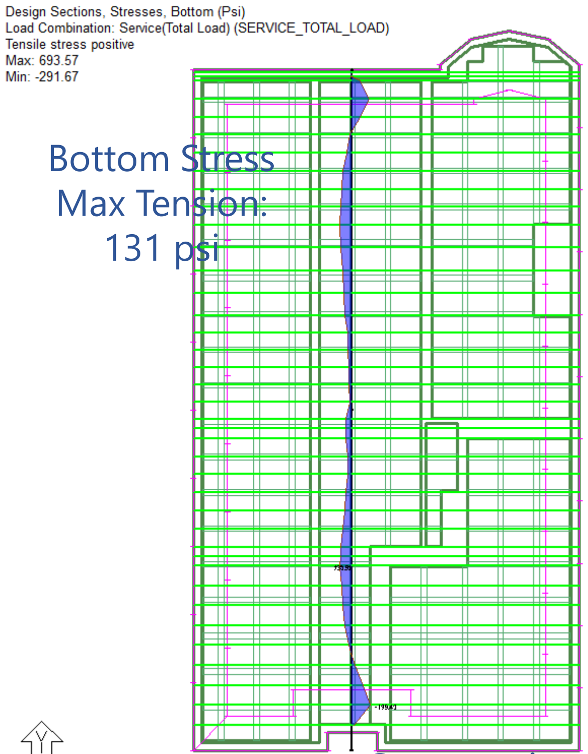
Design Sections, Stresses, Top (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: -40.41
Min: -242.36

Top Stress
Max
Compression:
139 psi



Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 693.57
Min: -291.67

Bottom Stress
Max Tension:
661 psi



Design Sections, Stresses, Bottom (Psi)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Tensile stress positive
Max: 693.57
Min: -291.67

Bottom Stress
Max Tension:
131 psi

Compression:
198.4 psi

# FEM – Stiffness Analysis – Edge Lift Mode

Deflection check:

- Span = 40 ft
- Max allowable deflection based on L / 480 = 1.0 in
- Max calculated deflection 0.69 in < 1.0 in **OK**

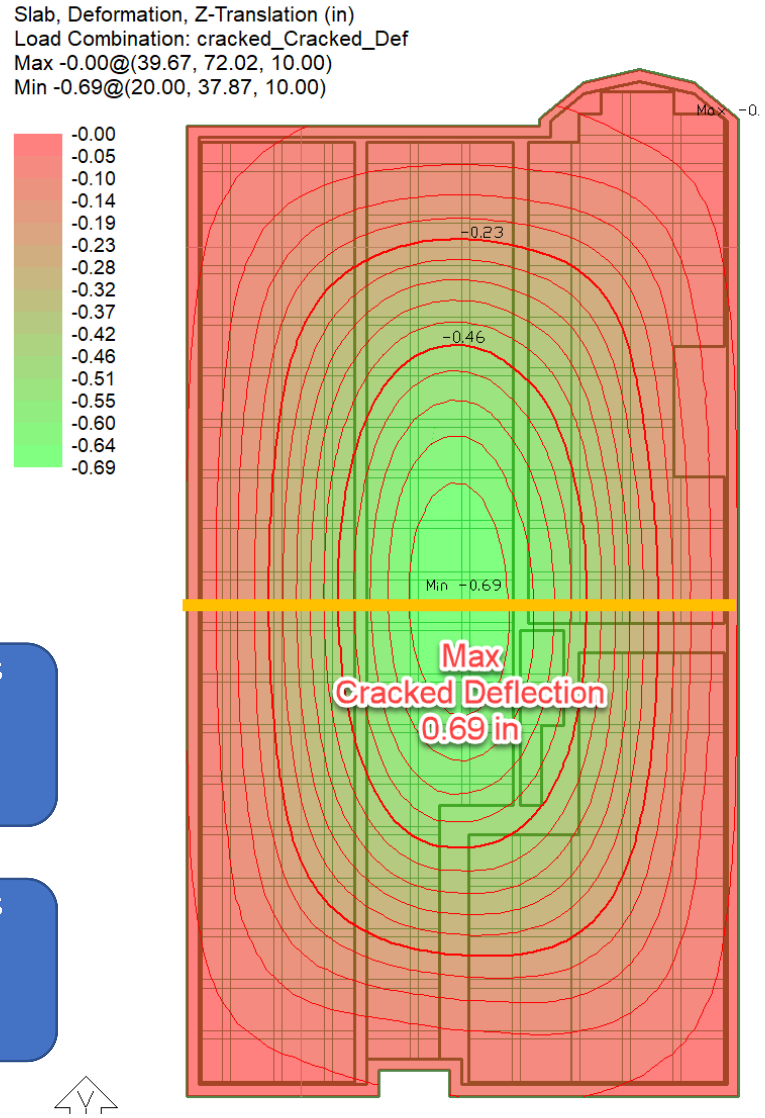
Stiffness comparison (moments of inertia Inch$^4$):

| | |
|---|---|
| Short direction | |
| Traditional ribbed slab | 245,897 |
| Wafflemat | 248,000 **OK** |
| Long direction | |
| Traditional ribbed slab | 161,491 |
| Wafflemat | 183,000 **OK** |

Wafflemat has 1% greater Moment of Inertia

Wafflemat has 13% greater Moment of Inertia

Wafflemat is stiffer in both directions compared to conforming ribbed slab



Slab, Deformation, Z-Translation (in)
Load Combination: cracked_Cracked_Def
Max -0.00@(39.67, 72.02, 10.00)
Min -0.69@(20.00, 37.87, 10.00)

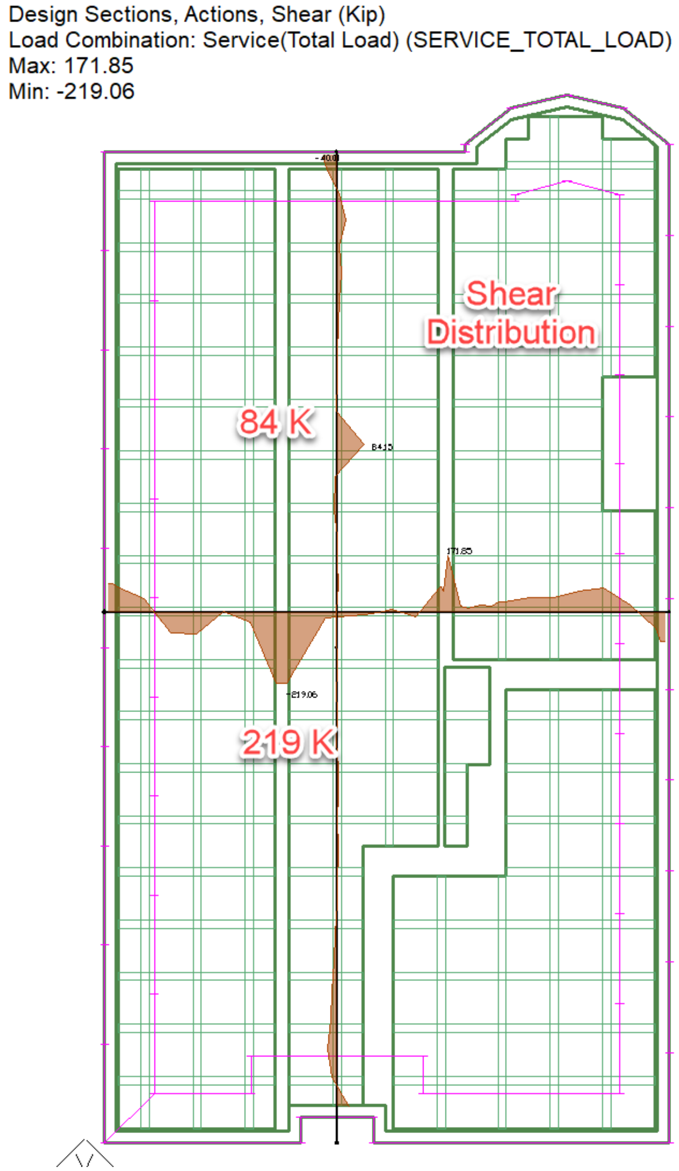
Max Cracked Deflection 0.69 in

# FEM – Shear Analysis – Edge Lift Mode

- Allowable shear stress:
    - Short direction 169 psi
    - Long direction 169 psi

- Max shear capacity:
    - Short direction 391 K
    - Long direction 335 K

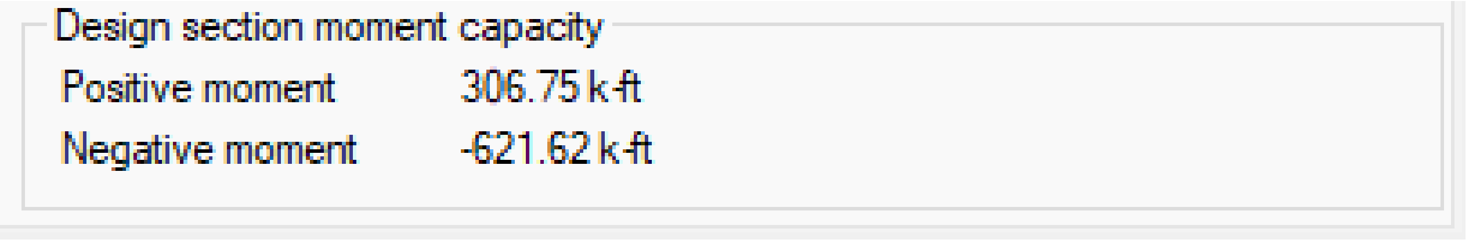
- Max shear demand
    - Short direction 219 K **OK**
    - Long direction 84 K **OK**



Design Sections, Actions, Shear (Kip)
Load Combination: Service(Total Load) (SERVICE_TOTAL_LOAD)
Max: 171.85
Min: -219.06

# FEM – Cracked Section Analysis – Edge Lift Mode

Short direction:

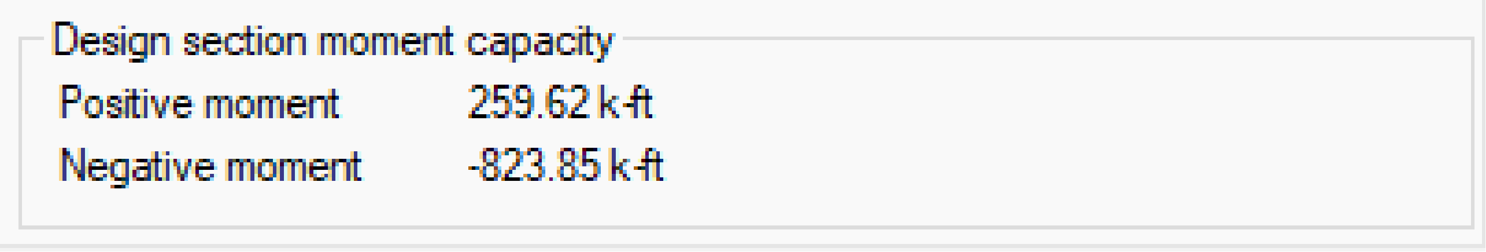


Design section moment capacity

| | |
|---|---|
| Positive moment | 306.75 k-ft |
| Negative moment | -621.62 k-ft |

0.5 M Max 260 K-FT **OK**

Long direction:



Design section moment capacity

| | |
|---|---|
| Positive moment | 259.62 k-ft |
| Negative moment | -823.85 k-ft |

0.5 M Max 101 K-FT **OK**

# Concluding Remarks

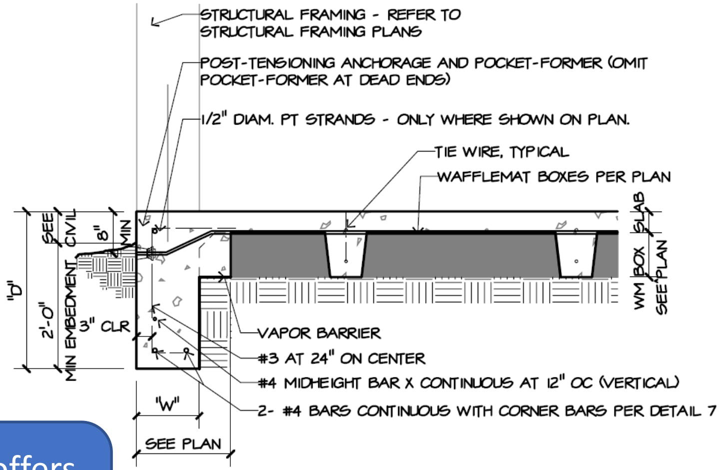
- The FEM method of analysis and design is a valid option for slab-on-ground designs
- We benchmarked the PTISlab method against the FEM method for a 40x70 ribbed slab
- A best practices design methodology based on FEM was presented
- Using the FEM method, we successfully analyzed and validated a wafflemat design

Material Savings:

| Concrete | PT Tendons (Lf) |
|---|---|
| WM: 75 cy (with waste factor) | WM: 1,621 lf (64 Live ends) |
| Traditional: 95 cy (with waste factor) | Traditional: 2,410 lf (94 Live Ends) |

Wafflemat offers 21% reduction in concrete

Wafflemat offers 33% reduction in lf of tendons



PERIMETER EDGE

# This concludes the Educational Content of this activity

# Thank you !

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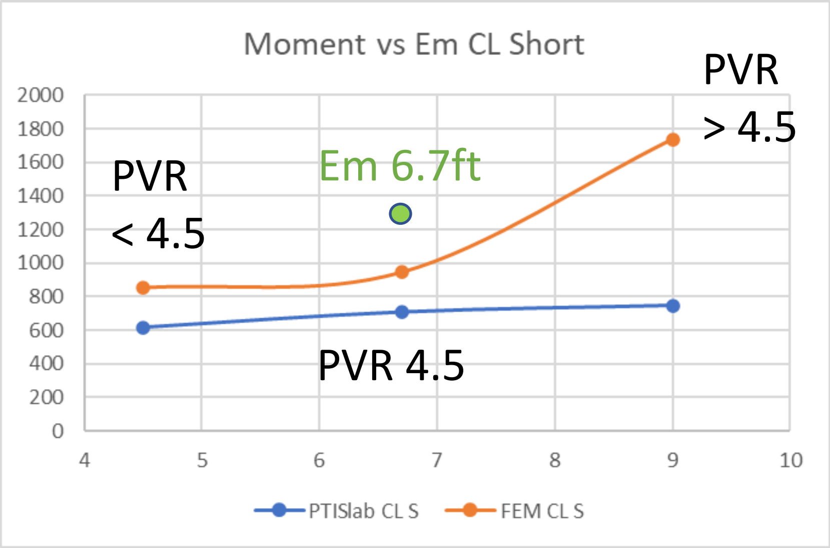
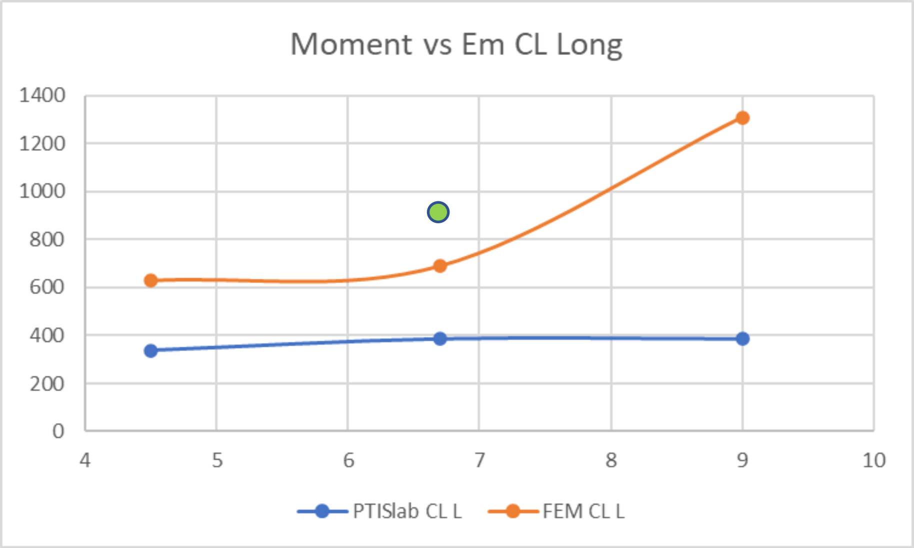
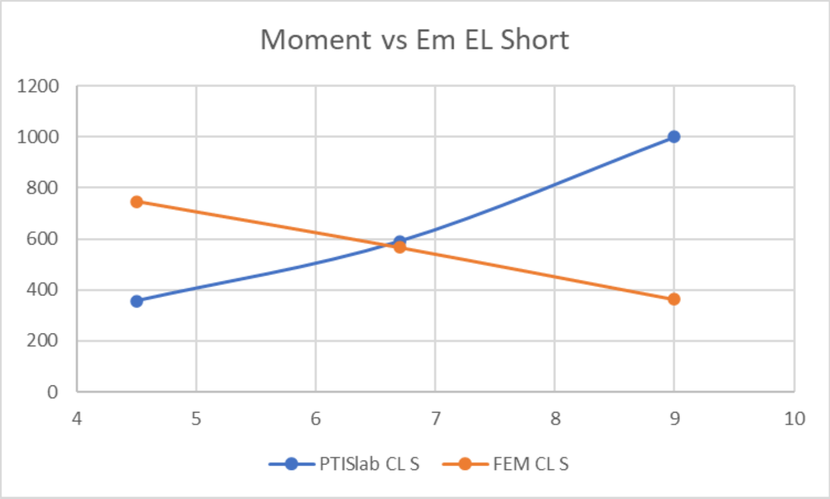
Anna@Wafflemat.com

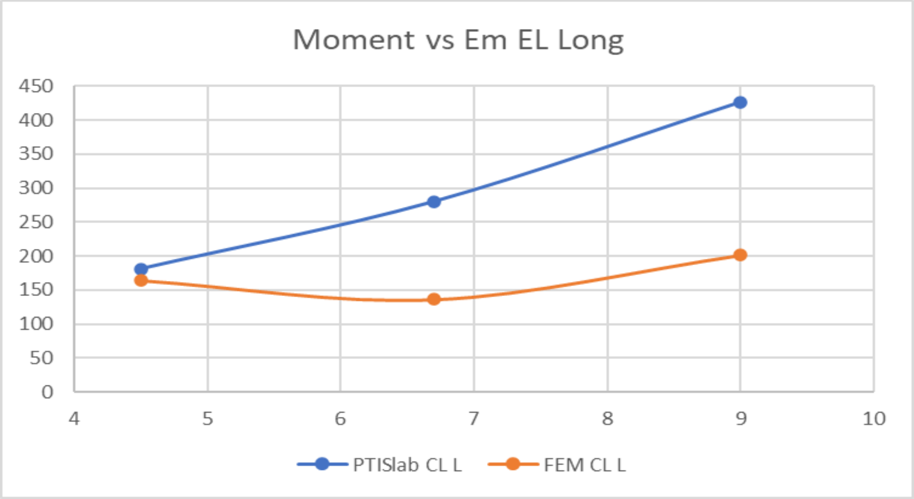
WAFFLEMAT™
A SMARTSENSE STRUCTURAL SYSTEM

# Parametric Study for Different $E_m$ Soil Conditions - Moment

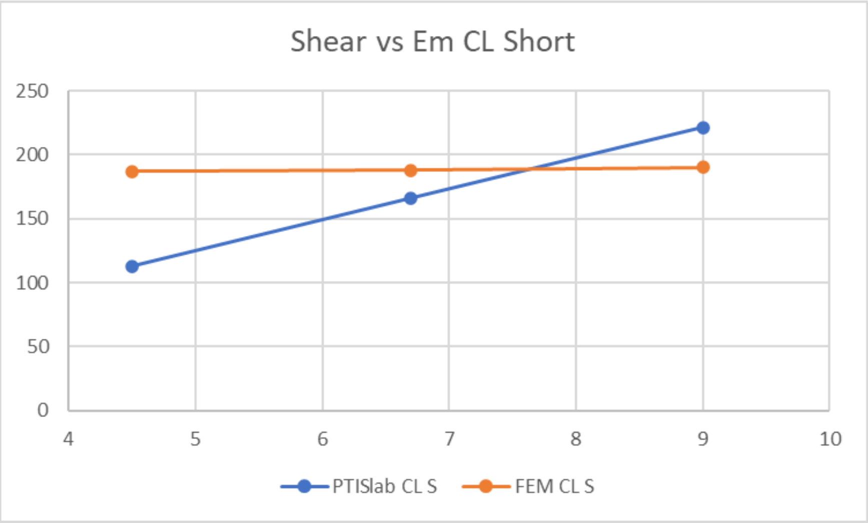


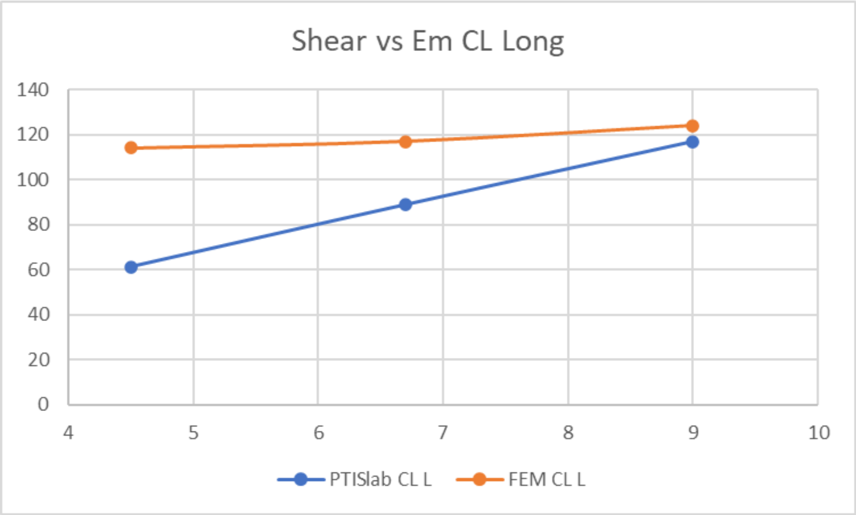


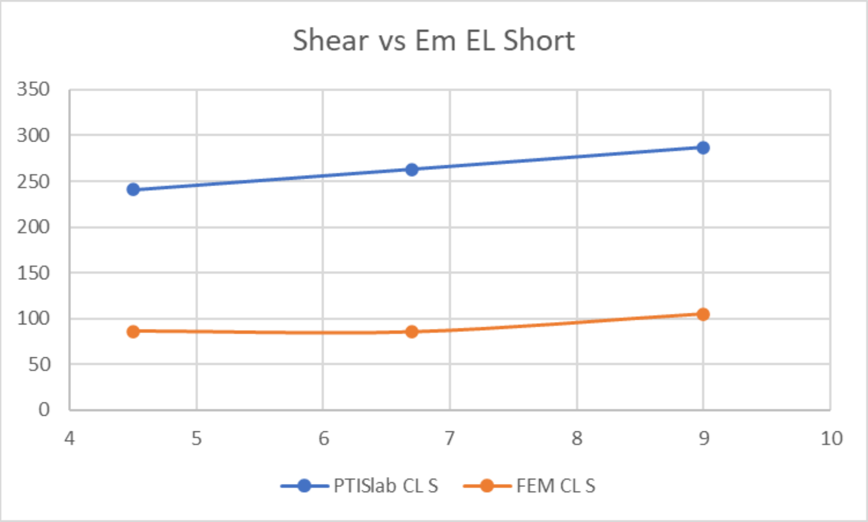


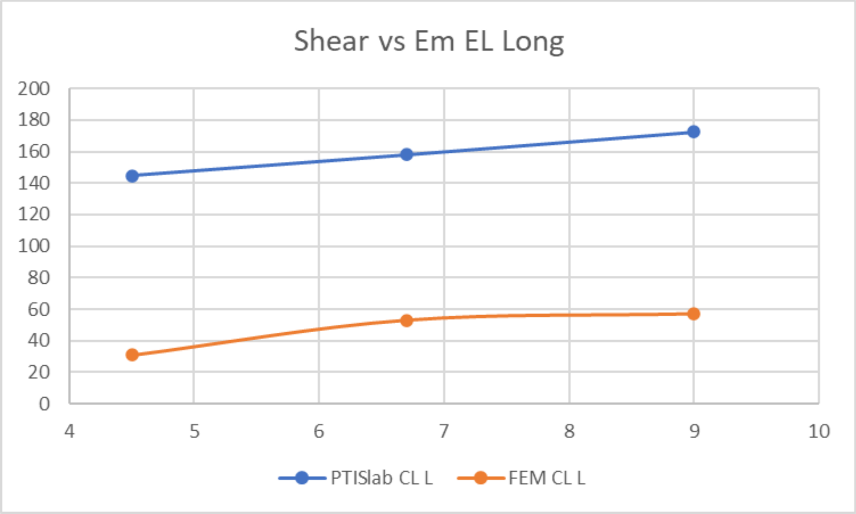


# Parametric Study for Different $E_m$ Soil Conditions - Shear

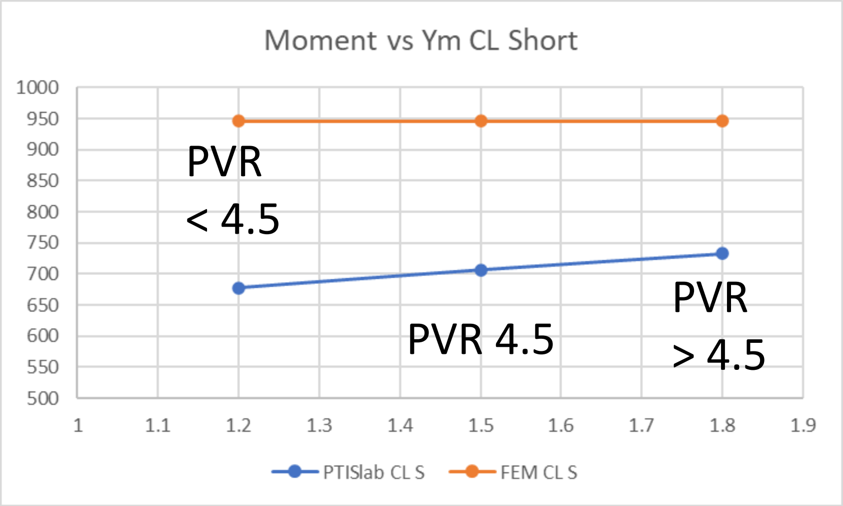

Shear vs Em CL Short


Shear vs Em CL Long

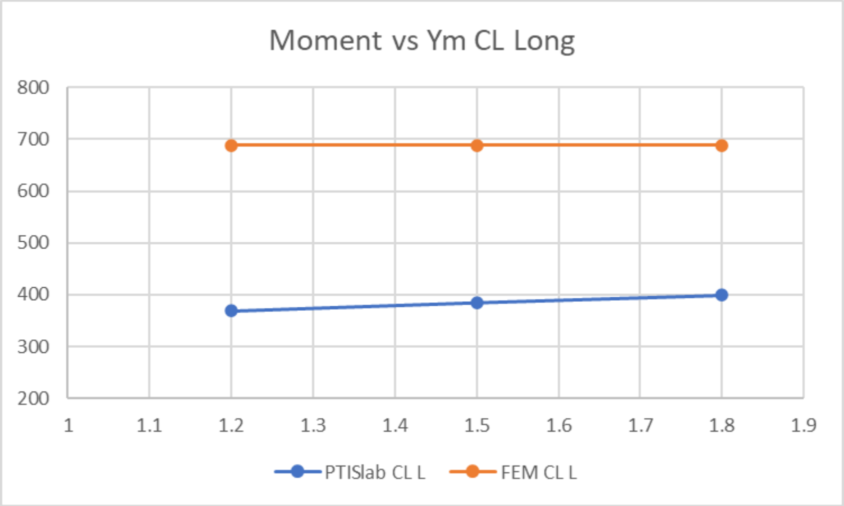

Shear vs Em EL Short


Shear vs Em EL Long

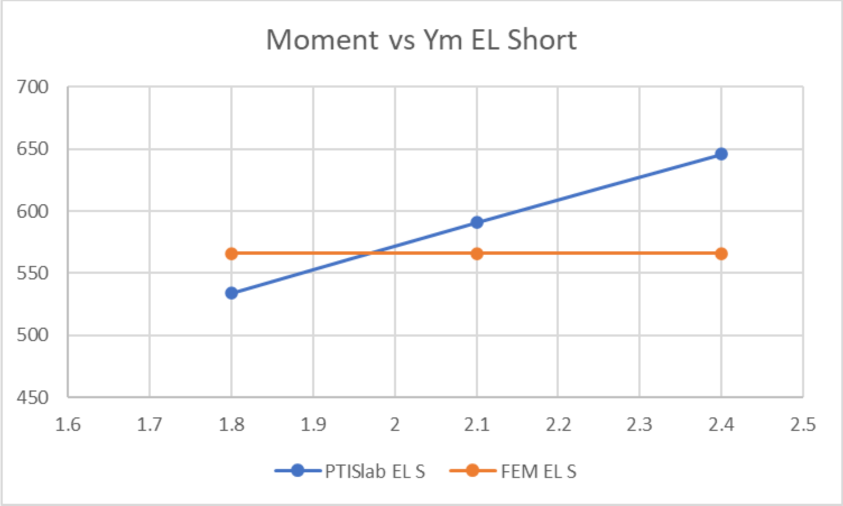
# Parametric Study for Different $Y_m$ Soil Conditions - Moment



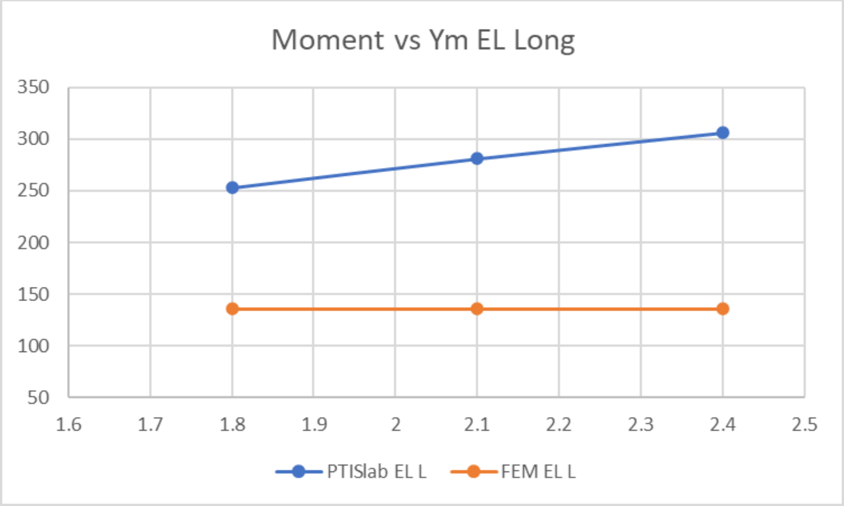
Moment vs Ym CL Short



Moment vs Ym CL Long

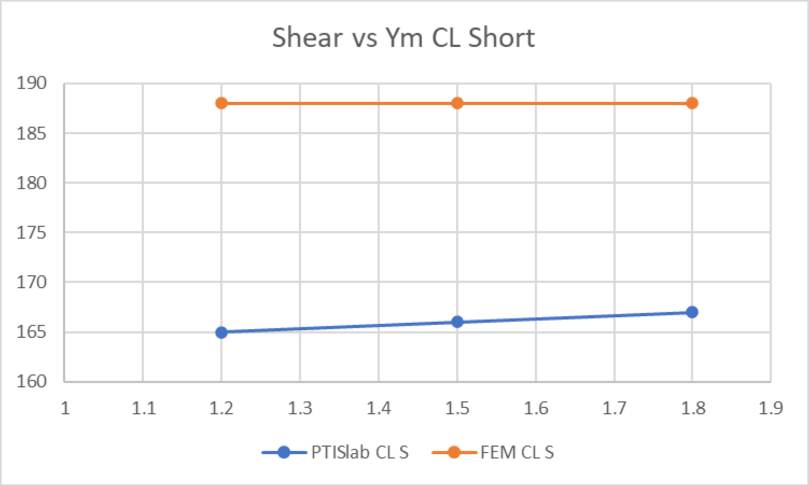


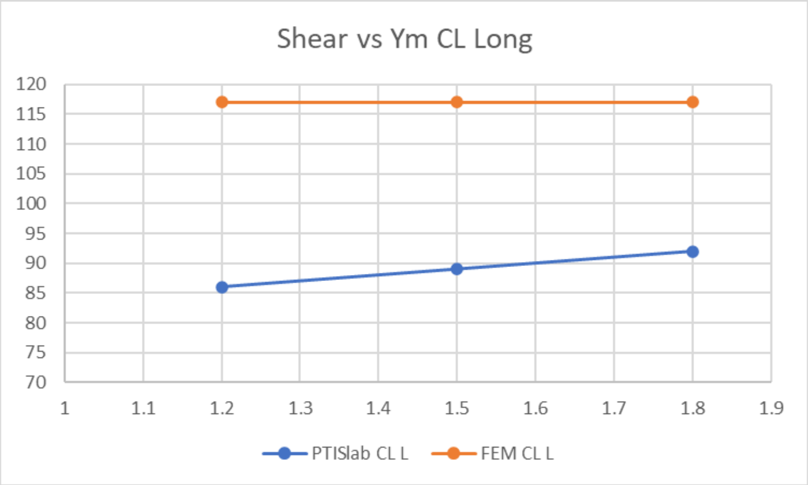
Moment vs Ym EL Short

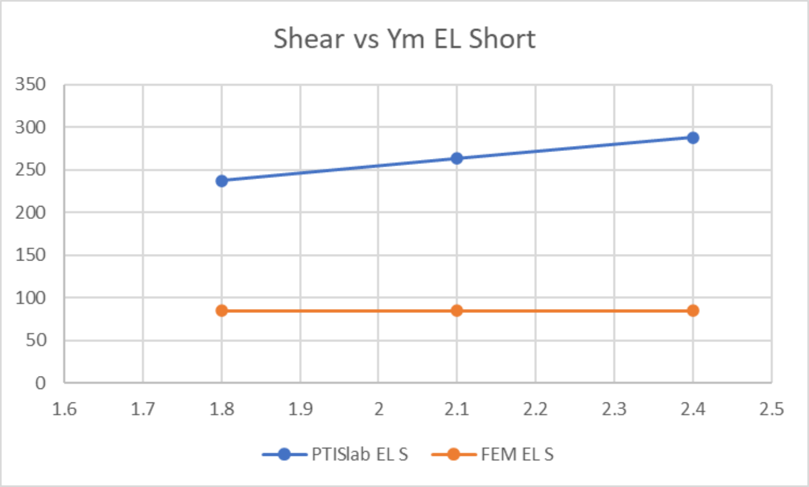


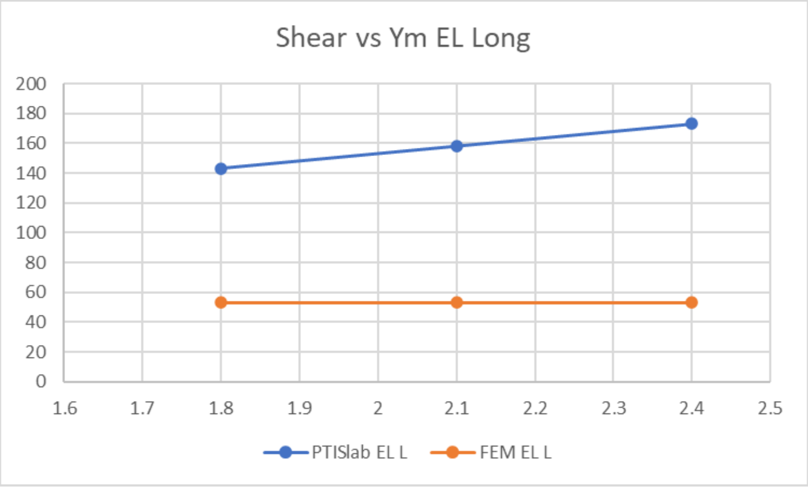
Moment vs Ym EL Long

# Parametric Study for Different $Y_m$ Soil Conditions - Shear


Shear vs Ym CL Short


Shear vs Ym CL Long


Shear vs Ym EL Short


Shear vs Ym EL Long