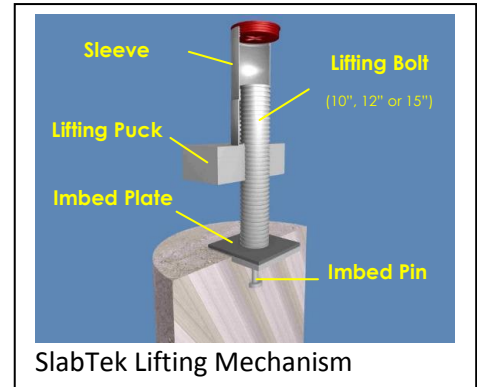


Simplified Analysis of SlabTek Lifting Mechanism Load and Resistance Factor Design (LRFD)

Section 1. Overview

This document describes the methods used for determining gravity and lateral load resistance of the SlabTek foundation system, along with some of the underlying theory and industry references.

The SlabTek foundation system elevates the slab above the local soils by means of a patented lifting mechanism sitting atop each pier in a suitably sized array of piers beneath the slab. In contrast to slab-on-grade where the lateral load is distributed along the entire surface area of the slab in contact with local grade, in the SlabTek foundation system, the lateral loads are distributed across the array of lifting mechanisms which connect the slab to the underlying piers.



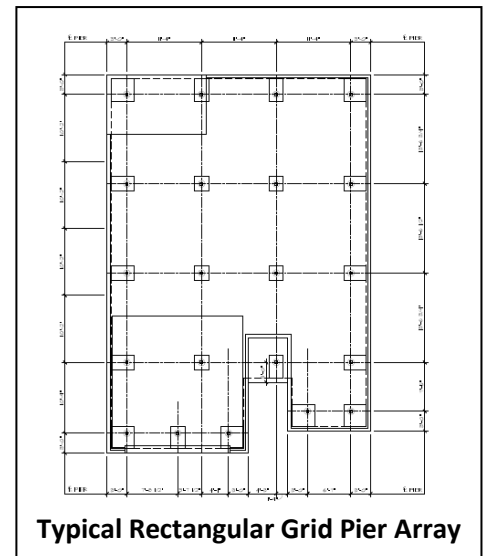
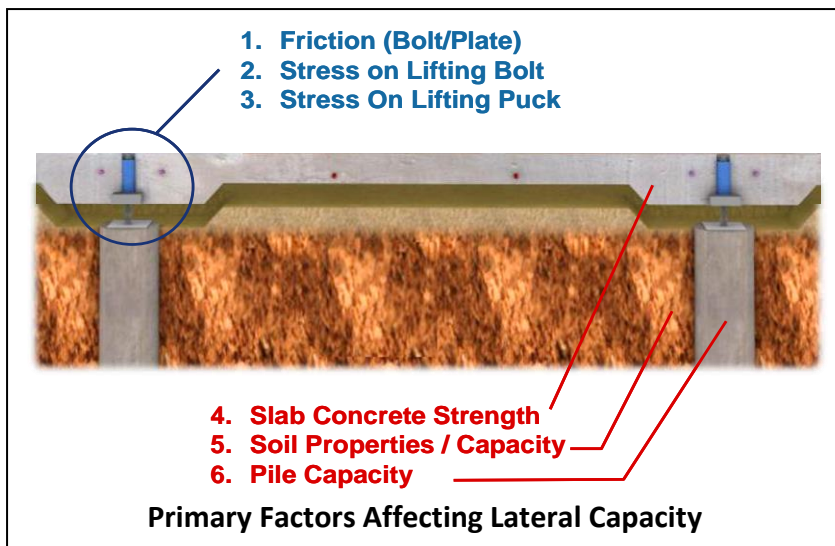
The lateral load capacity of a SlabTek foundation is determined by the lifting mechanism array

As shown above the SlabTek Lifting Mechanism consists of a load bearing plate (imbed plate) that sits atop a pile, a lifting bolt, which bears against the imbed plate, a threaded puck, cast in the bottom of the slab, which accepts the lifting bolt, a sleeve and cap which prevent concrete slurry from fouling the puck threads during slab concrete placement.

For one and two story structures, typically sufficient lateral stability is provided by the pier array required for supporting the vertical loads. For taller structures with greater wind loads, the lateral load can drive pier number and spatial density above that required for support of the gravity loads. As this is a cost concern additional lateral stability/capacity can be provided with stabilizing piers (with no mechanism). These provide significant additional lateral capacity.

As illustrated below, the primary factors affecting the lateral capacity of an installed SlabTek foundation system are

- Friction between the lifting bolt and the plate at the top of the concrete or helical pile
- Combined axial and bending stress on the lifting bolt
- Bending stresses on the lifting puck
- Compressive strength of concrete material comprising the slab
- Properties of the soil, including cohesion
- Bearing capacity of the pile



The following sections present the governing equations describing the forces and stresses listed above, and calculate the resulting load capacities given knowledge of the materials used in the SlabTek lifting mechanism, and describe any necessary assumptions used in the analysis. Each stress will be developed separately. Following this some examples are given which illustrate how the overall lateral load is calculated

In our calculations and examples that follow, we assume the perimeter beam provides zero lateral load capacity.

Section 2. Capacity Calculations

2.1 LIFTING BOLT LATERAL CAPACITY CALCULATION

We consider axial and lateral forces acting on the lifting bolt. There are two requirements for the bolt to resist these loads. The first is the bolt must not translate on the lifting plate, the second is to develop sufficient internal stress to resist load effects. If the bolt does not translate, lateral load is resisted by the bolt until it yields.

We develop the relevant generalized equations, demonstrate the friction case and then the general case.

All referenced equations from AISC 360-10 Specification for Structural Steel Buildings

AISC 360-10 Specification for Structural Steel Buildings Section H2 can be used for any shape in lieu of the provisions of Section H1. Therefore, the SlabTek lifting bolt will be evaluated using this section.

Governing equation (H2-1)
$$\left| \frac{f_{ra}}{F_{ca}} + \frac{f_{rbw}}{F_{cbw}} + \frac{f_{rbz}}{F_{cbz}} \right| \leq 1.0$$

Where

f_{ra}	required axial stress at point of consideration, ksi
F_{ca}	available axial stress at point of consideration, ksi
$f_{rbw} f_{rbz}$	required flexural stress at point of consideration, ksi
$F_{cbw} F_{cbz}$	available flexural stress at point of consideration, ksi
w	subscript relating symbol to major principal axis bending
z	subscript relating symbol to minor principal axis bending

For Load & Resistance Factored Design (LRFD) methodology, equation H2-1 will be

$$\left| \frac{\frac{P_u}{A}}{\phi_c F_{cr}} + \frac{\frac{M_u}{S_x}}{\phi_b M_n} + \frac{\frac{M_u}{S_y}}{\phi_b M_n} \right| \leq 1.0$$

Where:

ϕ_c	resistance factor for compression
ϕ_b	Resistance factor for flexure
M_u	$P_{LATERAL} \cdot h$
h	height of lift

Since the section is symmetric, and we assume lateral loading is from only one direction, we remove the term involving S_y . The critical point is where sum of the demand to capacity ratios is equal to 1. Rearranging the equation, lateral capacity is given by:

$$P_{LATERAL} = \left(1.0 - \frac{P_u}{A\phi_c F_{cr}} \right) \left(\frac{\phi_b M_n}{h} \right)$$

Calculate available lateral capacity under given gravity loads:

"Steel Design, 5th ed." by William T. Segui states that torsional buckling can only occur with doubly symmetrical cross sections with very slender cross-sectional elements, and flexural-torsional buckling can only occur with unsymmetrical cross sections including those with only one axis of symmetry.

Additionally AISC 360-10 Table E1.1 only requires the limit state of flexural buckling to be considered. Therefore, only flexural buckling will be considered in the calculation of elastic critical buckling stress.

Assume pin-fixed end conditions, $K=2.0$ for the lifting bolt and h is the height of the lift. The bolt is conservatively modeled as a solid cylinder with diameter equal to the smallest thread diameter.

Calculate elastic critical buckling stress:

$$F_e = \frac{\pi^2 E}{\left(\frac{Kh}{r}\right)^2} \quad (\text{E3-4}) \quad \text{Note: } h \text{ has been substituted for } L \text{ for clarity}$$

Calculate critical buckling stress:

$$\text{If } \frac{Kh}{r} \leq 4.71 \sqrt{\frac{E}{F_y}} \quad \text{or} \quad \frac{F_y}{F_e} \leq 2.25 \quad \text{then:} \quad F_{cr} = \left[0.658 \frac{F_y}{F_e} \right] F_y \quad (\text{E3-2})$$

$$\text{If } \frac{Kh}{r} > 4.71 \sqrt{\frac{E}{F_y}} \quad \text{or} \quad \frac{F_y}{F_e} > 2.25 \quad \text{then:} \quad F_{cr} = 0.877 F_e \quad (\text{E3-3})$$

Available axial stress is: $F_{cr} = \phi_c F_{cr}$

Calculate flexural capacity (use Section F11):

$$\begin{aligned} M_y &= SF_y \\ Z &= \frac{d^3}{6} \\ M_n = M_p &= F_y Z \leq 1.6 M_y \end{aligned} \quad (\text{F11-1})$$

F11.2(c) states that the limit state of lateral-torsional buckling need not be considered for rounds, so only flexural buckling will be considered.

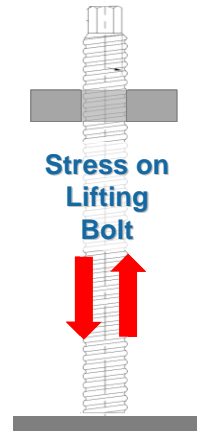
Calculate allowable lateral load from modified H2-1:

$$P_{LATERAL} = \left(1.0 - \frac{P_u}{A \phi_c F_{cr}} \right) \left(\frac{\phi_b M_n}{h} \right)$$

AISC 360-10 equations H1-1a and H1-1b can be used similarly.

2.1.1 Lifting Bolt Lateral Capacity

If the bolt does not slide in reaction to applied lateral force, it must resist it through bending. The bolt must have adequate capacity to resist combined gravity and lateral forces. Typically the lift height (h) of SlabTek foundation systems is 1.5 times the potential vertical rise (PVR) of expansive soils. In North Texas, a PVR of 6” is not uncommon, therefore the range of lift heights shown on the plots are typical.



Using the equations above and the material and section properties listed here,

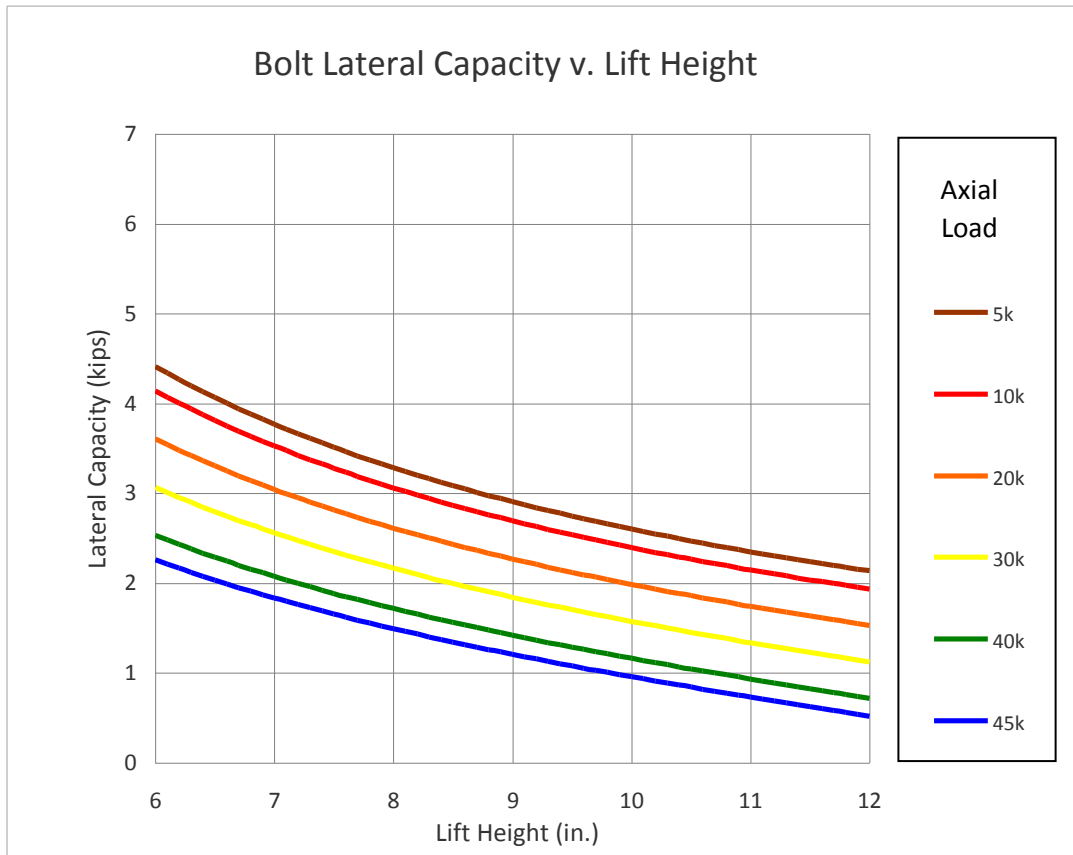
<i>LIFTING BOLT MATERIAL PROPERTIES:</i>			
E	29000	ksi	Modulus of elasticity
F _y	75	ksi	Yield strength
φ _c	0.90		Resistance factor for compression
φ _b	0.90		Resistance factor for flexure
<i>LIFTING BOLT SECTION PROPERTIES:</i>			
K	2.0		Effective length factor *
h		in	Lift height
S	0.26	in ³	Bolt elastic section modulus
A	1.48	in ²	Bolt cross-sectional area
r	0.34	in	Radius of gyration
d	1.375	in	Bolt diameter
Z	0.43	in ³	Bolt plastic section modulus

* The effective length factor is set to 2.0 reflecting fixed pin end conditions; the top of the bolt is assumed to be fixed by the concrete slab, and the bottom of the bolt is free to rotate, but not to translate

The following plot provides a family of curves plotting P_{LAT} vs h (Lateral Load vs Lifting Height) for a family of gravity loads, using physical dimensions of the SlabTek Lifting Mechanism.

As expected, lateral load capacity decreases as axial load increases.

The controlling limit state of this stress would be yielding of the bolt.

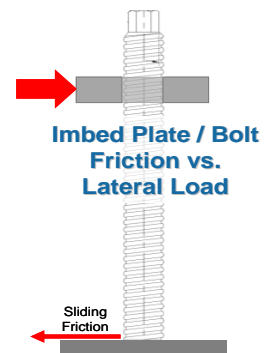


Illustrative Purposes Only – Not for Design

2.1.2 Slip Resistance of the Lifting Bolt and Lifting Plate

The slip resistance between the SlabTek lifting bolt and lifting plate is analogous to the slip-critical connections discussed in J3.8 of AISC 360-10, where available slip resistance for the limit state of slip is: $R_n = \mu D_u h_f T_b n_s$ AISC 360-10 (J3-4)

Three strength reduction factors are presented for use with equation J3-4. The lowest strength reduction factor, $\phi = 0.70$, is given for use with long-slotted holes, and is assumed to apply to this application. The mean slip coefficient, μ , depends on the classification of the surfaces, and it is taken as 0.30 to reflect the hot-dipped galvanization of the lifting plate. The factor for fillers, h_f , is taken as 1.0 because fillers are never used in this application. The multiplier D_u is specific to slip-critical connections that rely on bolt pre-tensioning, and is statistically derived to calculate nominal

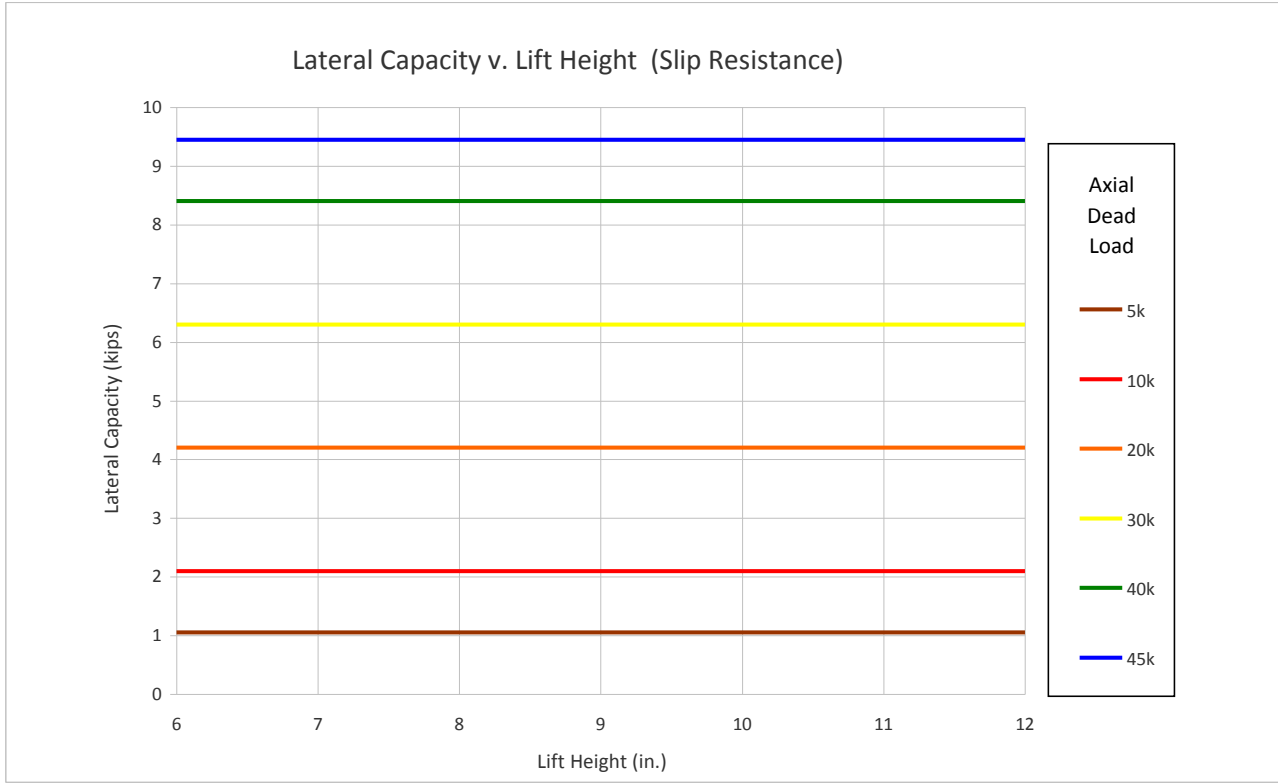


slip resistance as a function of: installation method, minimum specified pretension, and the level of slip probability selected. Because it is not relevant to this application, it will be taken as 1.0. There is one slip plane between the bolt and the lifting plate, so the number of slip planes, n_s , is 1. For high strength bolts in slip-critical connections, minimum fastener tension in kips, T_b , is taken from table J3.1. For slip resistance on the plane between the lifting bolt and the lifting plate, this force is taken as the axial load on the bolt for the load case in question. With respect to sliding, IBC 2012 equation 16-6 will generally control.

$$0.9D + 1.0W + 1.6H \quad \text{IBC 2012 (Equation 16-6)}$$

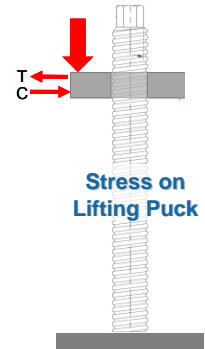
Considering the preceding discussion and assuming no lateral earth pressures are present, the available slip resistance of a lifting mechanism subjected to an axial compressive force of $\phi R_n = 0.70 \cdot (0.30 \cdot 1.0 \cdot 1.0 \cdot 28 \text{ kips} \cdot 1) = 5.88 \text{ kips}$ 28 kips (including the effects of dead load and wind) is:

The plot presented below shows the available slip resistance as a function of axial dead load. Note that the slip resistance is independent of lift height. The magnitude of the sliding resistance is very high compared to other components, thus sliding rarely will control design.



2.2 LIFTING PUCK LATERAL CAPACITY CALCULATION

We now consider bending in the lifting puck. For this analysis we assume that horizontal translation of the foundation is resisted by rotation of the lifting puck which creates bending stress. The puck is a 4.75” square piece of 1” thick steel, tapped for 1.5” threads in the center. The puck is embedded beneath the slab and lifts the slab when the bolt is rotated clockwise and bears on the lifting plate resting on the fixed pier beneath the foundation. Exceeding calculated lateral force will result in overturning of the puck.



2.2.1 Overturning Resistance

Calculate maximum lateral load with respect to overturning using IBC equation 16-6.

Governing equation: $\sigma_{DL} \geq \sigma_{LATERAL}$

Where $\sigma_{DL} = \frac{0.9 \cdot P_{DL}}{A_{PUCK}}$ and $\sigma_{LATERAL} = \frac{M}{S_z}$

The critical point is found at $\frac{0.9 \cdot P_{DL}}{A_{PUCK}} = \frac{M}{S_z}$

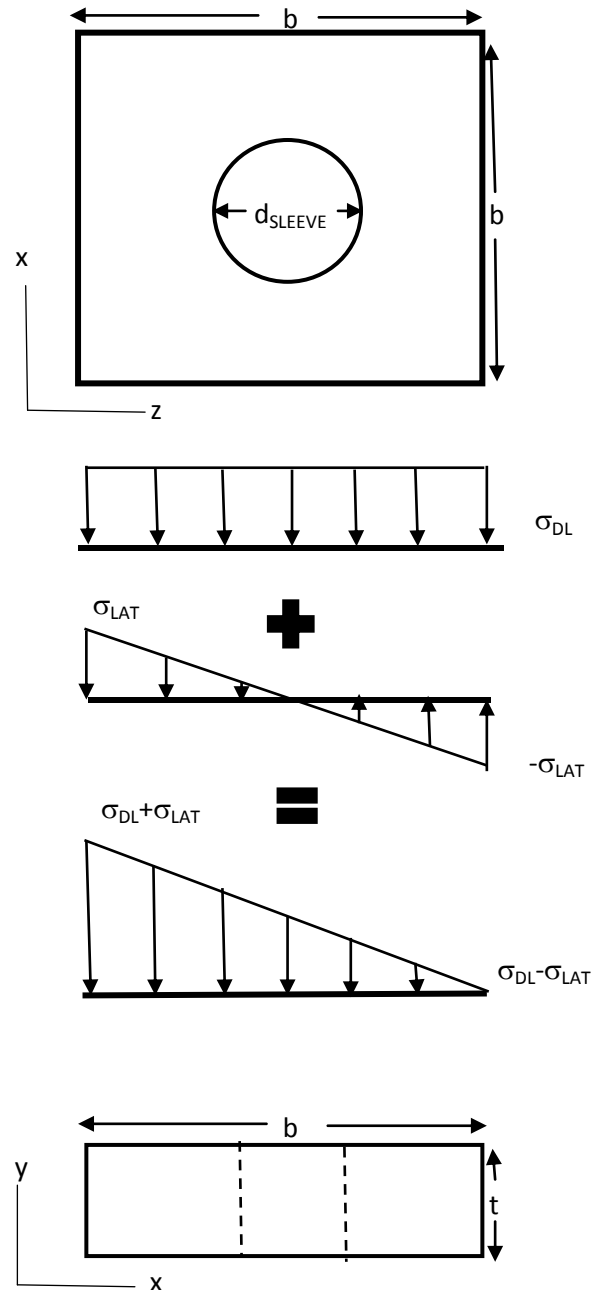
Substituting $M = P_{LAT} \cdot h$ where h=lift height

and solving for P_{LAT} yields: $P_{LAT} = \frac{0.9 \cdot P_{DL} \cdot S_z}{h \cdot A_{PUCK}}$

Substituting: $A_{PUCK} = b^2 - \frac{\pi d_{SLEEVE}^2}{4}$
 $S_z = \frac{2}{h} \cdot \left(\frac{h^4}{12} - \frac{\pi d_{SLEEVE}^4}{64} \right)$

the Lateral Force Equation becomes:

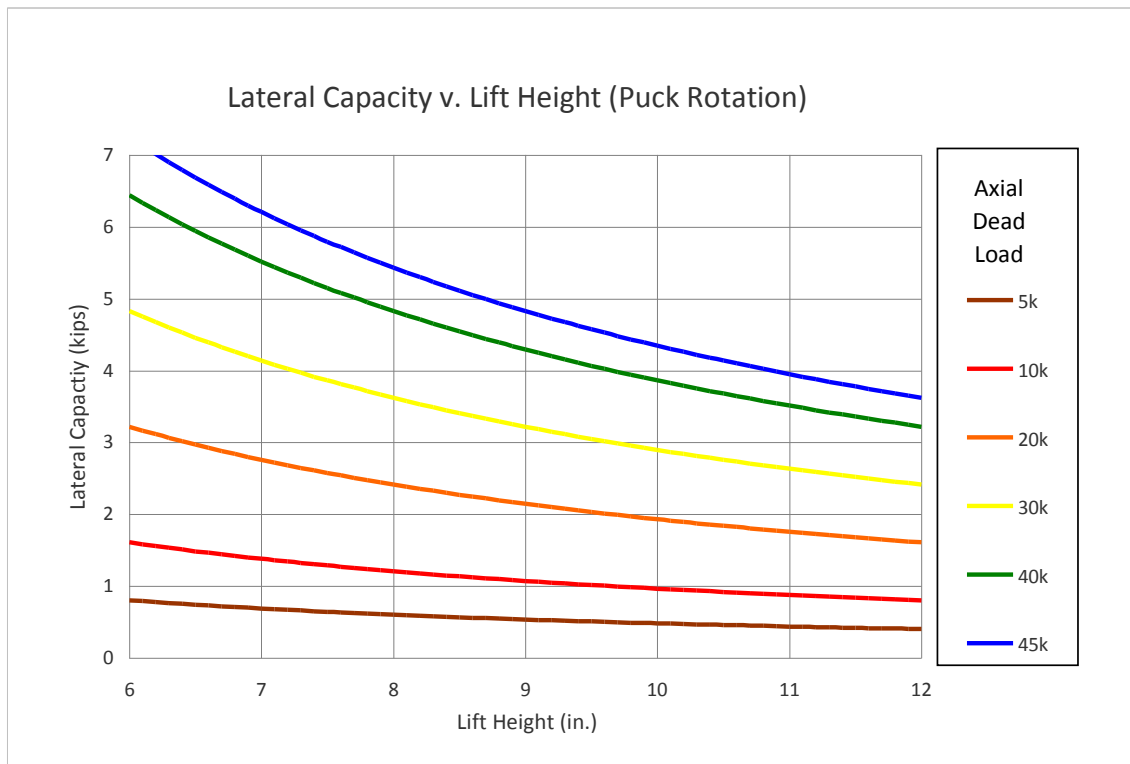
$$P_{LAT} = \frac{0.9 \cdot P_{DL} \cdot \left(\frac{h^4}{6} - \frac{\pi d_{SLEEVE}^4}{32} \right)}{h^2 \cdot \left(b^2 - \frac{\pi d_{SLEEVE}^2}{4} \right)}$$



Using this equation, and the following material and section properties,

PUCK MATERIAL PROPERTIES:			
F_y	50	ksi	Yield strength
ϕ_b	0.90		Resistance factor for flexure
PUCK SECTION PROPERTIES:			
h		in	Lift height
d	1.375	in	Bolt diameter
b	4.75	in	Puck length (square)
d_{SLEEVE}	2.75	in	Diameter of concrete void above center of puck
t	1	in	Puck thickness

The following plot shows P_{LAT} vs h (Lateral Load vs Lifting Height) for a family of dead loads, using physical dimensions of the Tella Firma Lifting Mechanism.

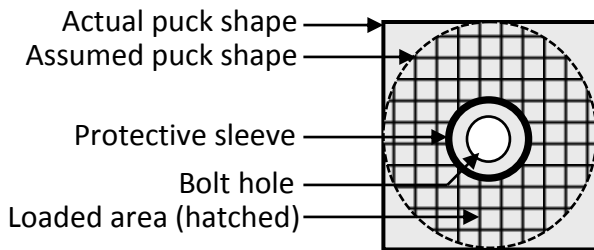
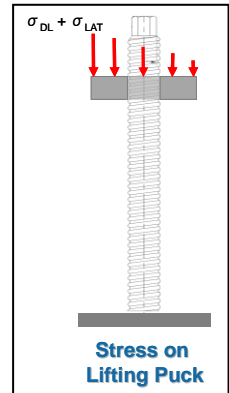


Note that the capacity of the puck to resist rotational forces induced by increasing P_{LAT} , increases with dead load. The foundation system must be robust against this stress under worst case conditions which is why no live loads are considered. The worst case condition is minimal loading, which is dead loads only.

2.2.2 Bending Stress on puck

Next we consider yielding of the puck under various load conditions. The controlling load combination will be determined in accordance with IBC Chapter 16.

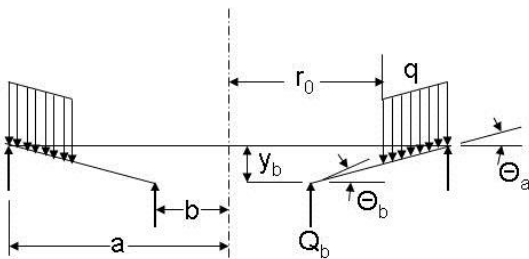
The lifting puck is analyzed using principles presented in Timoshenko’s Theory of Plates and Shells and equations put forth by Roark and Young in Formulas for Stress and Strain. The central assumption is that the lifting puck will behave in a similar manner as a circular plate with diameter equal to the width of the puck whose boundary conditions are simply supported along the inner diameter and free along the outside diameter.



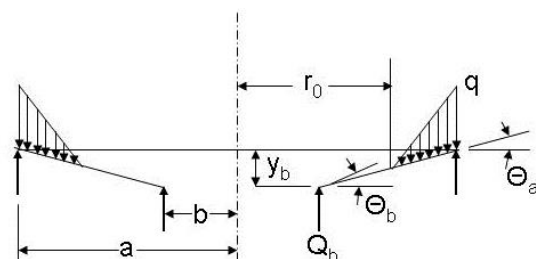
Two loading conditions are used to account for the stresses caused by lateral and axial loads. For stresses due to axial loads, a uniformly distributed load of q is applied over the puck from the outside edge of the sleeve to the puck’s outer diameter. For stresses due to lateral loads, a distributed load that increases linearly from the outer diameter of the sleeve to the outer diameter of the puck is applied, q_{lat} .

These loads are in units of psi, and calculated similarly to σ_{DL} and σ_{LAT} in the case of overturning. The difference is that the properties of the assumed shape are used to calculate q and q_{lat} . The area of the assumed round plate is 12.81 in^2 and the section modulus for determining q_{lat} is 9.7 in^3

In cases where the bending moments due to combined axial and lateral loads must be determined, the principle of superposition is used.



Case I: Uniform load from axial forces:



Case II: Increasing load from lateral forces

Close approximations of the maximum bending moments in the lifting puck due to axial and lateral loads can be found using tabulated coefficients based on the ratio of the diameter of the hole to the outside diameter of the plate given below by Rourke and Young. $M = K_m q a^2$. Negative values indicate that the bottom of the plate is in compression.

Bolt/Puck Interface Simple-Free:

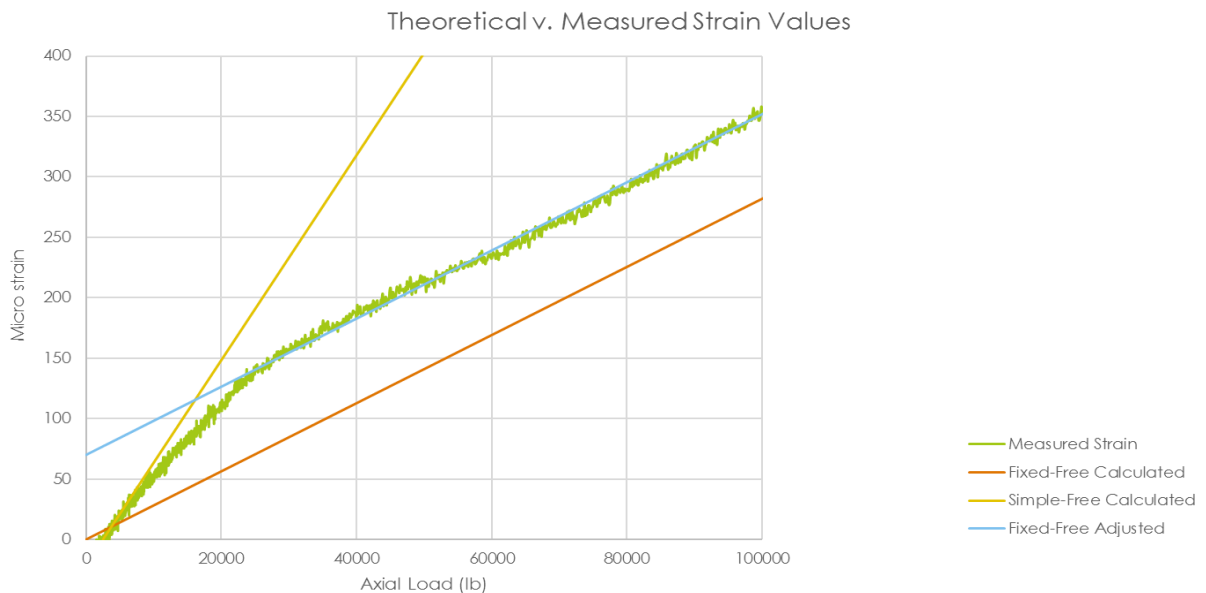
	b/a	0.1	0.3	0.5	0.7	0.9
Axial, q	$K_{m(axial)}$	-1.2734	-0.6146	-0.3414	-0.1742	-0.0521
Lateral, q_{lat}	$K_{m(lat)}$	-0.8937	-0.4286	-0.2354	-0.1186	-0.0350

Bolt/Puck Interface Fixed-Free:

	b/a	0.1	0.3	0.5	0.7	0.9
Axial, q	$K_{m(axial)}$	-0.9646	-0.4103	-0.1736	-0.0541	-0.00530
Lateral, q_{lat}	$K_{m(lat)}$	-0.5221	-0.2202	-0.0915	-0.0279	-0.00268

It should be noted that these coefficients assume that $r_0 = b$, and Poisson’s ratio is 0.30. The actual loading conditions vary because the protective sleeve prevents the concrete from reaching the inner diameter of the lifting puck. Because of this, the load transfer begins a distance, r_0 , that does not equal b . For this reason, the graphs presented are based on a rigorous analysis that accounts for this difference in addition to accounting for values of b/a that are not specifically included in the table with a method that is more accurate than interpolation.

Comparison of predicted results based on pinned and fixed boundary conditions to actual results for 6.75”x6.75”x1.5” lifting puck. Note: Yield strain for Grade 50 puck is 1750 microstrain.



These results show that the actual behavior of the lifting puck is a combination of simple-free and fixed-free conditions. Also, from a practical standpoint, lifting puck bending will not control overall design.



SLABTEK COMPANY **Lifting Mechanism Capacity Analysis**

Calculate Capacity

The vertical plastic section modulus of a 1” strip of the puck the puck is given by $Z_x = \frac{bt^2}{4}$ when L is taken as 1”.

The factored moment capacity of a 1” strip of the puck is given by AISC 360.10 Eqn F11-1 as:

$$\phi M_n = Z_x \cdot 0.90 \cdot \sigma_y \leq 1.6 \cdot M_y$$

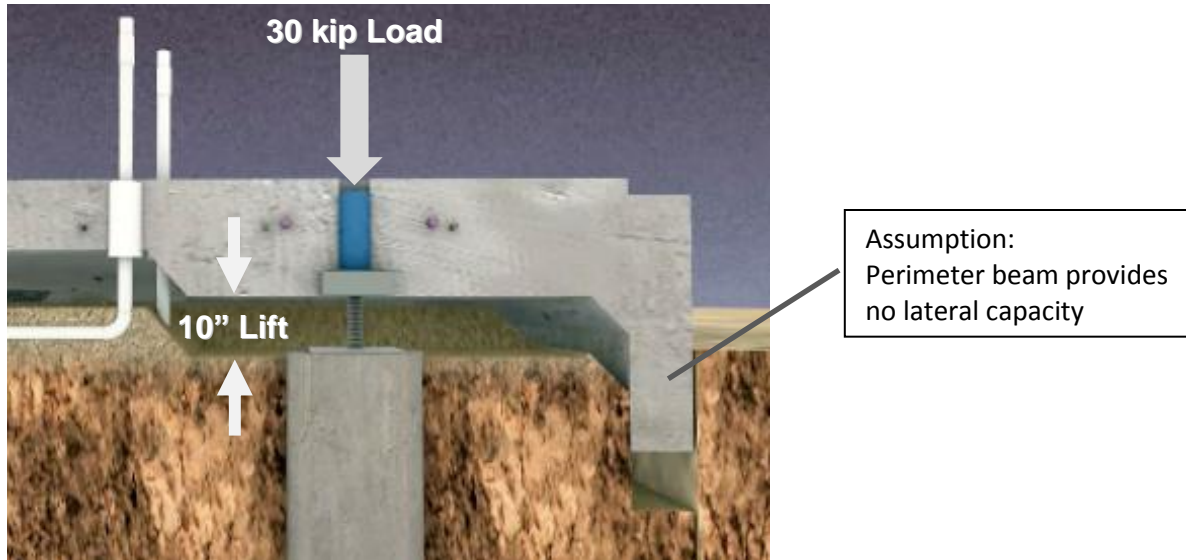
Using this equation, and the following material and section properties lifting puck capacity can be calculated.

PUCK MATERIAL PROPERTIES:			
F _y	50	ksi	Yield strength
φ _c	0.90		Resistance factor for compression
φ _b	0.90		Resistance factor for flexure
PUCK SECTION PROPERTIES:			
h		in	Lift height
d	1.5	in	Hole diameter
a	2.375	in	Assumed puck radius
d _{SLLEEVE}	2.75	in	Diameter of concrete void above center of puck
t	1	in	Puck thickness

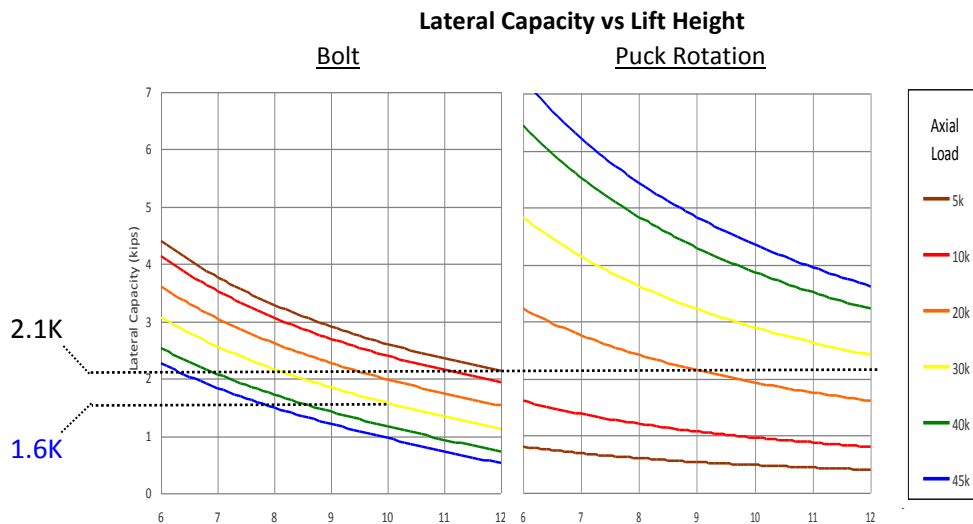
Section 3. Examples

3.1 Single Mechanism Capacity Calculation

For an example of how to use the charts above in determining the lateral capacity of a SlabTek foundation system installation, we assume a single mechanism elevated 10” with factored 30 kip axial load and 20 kip axial dead load resists puck rotation. We further assume that the perimeter beam provides no additional lateral load capacity.



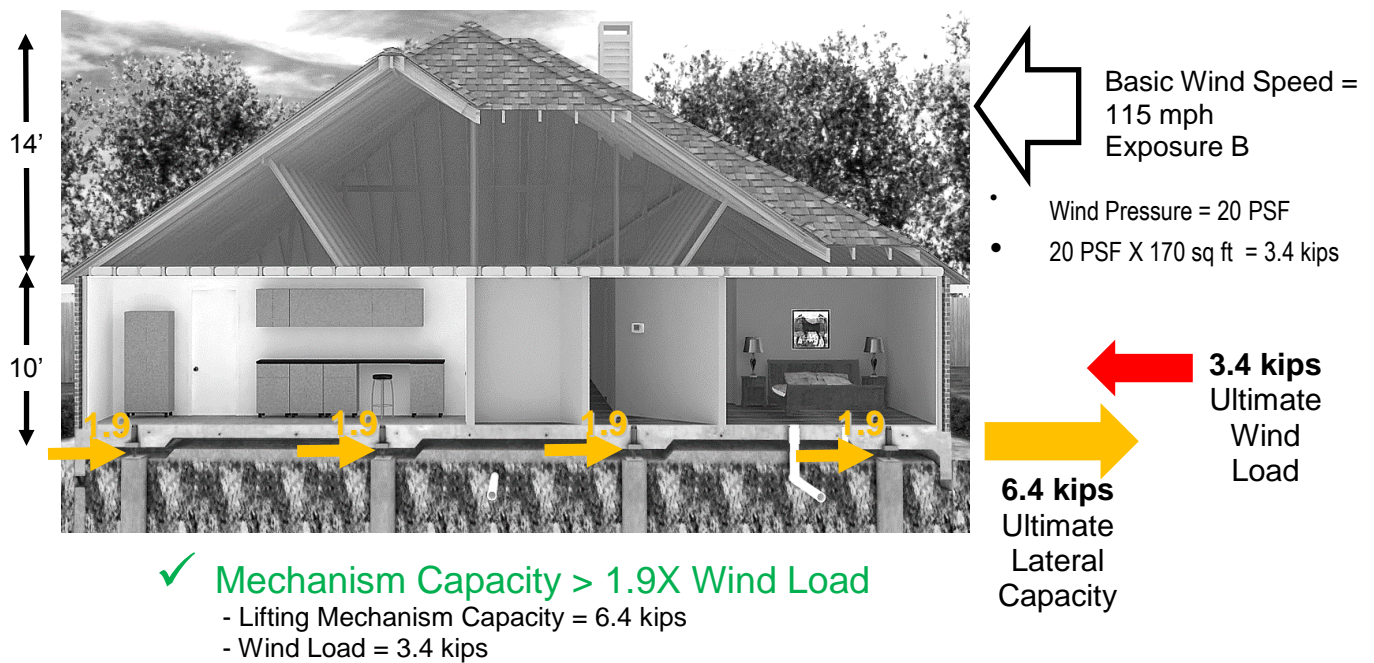
Using the charts from Section 2, we look up the intersection of 30 kip axial load curve with the 10” lift axis and read the resulting lateral capacity. The lowest lateral capacity determines the design capacity. For our example, the resulting lateral capacity is 1.6 kips as shown below.



3.1 Wind Load Capacity Calculation – Single Story Structure

SLABTEK COMPANY **Lifting Mechanism Capacity Analysis**

Next we consider the wind load on a single story structure supported by SlabTek Lifting Mechanisms in a 10' x 10' grid spacing. Along the considered axis, there are four piers. When considering the wind load, we consider the square footage for each 10' of lateral run, which corresponds to the pier spacing in the into-page dimension, rather than the total load across the entire house. In this example we assume 30 kip load per pier, 10" lift, no contribution from perimeter beam, a 115 mph wind which corresponds to approximately 20 pounds of pressure per square foot (psf). The surface slice to be considered is factored to be 17' (10' vertical wall plus half of the 14' inclined roof). Across 10' of lateral run this is 170 sq ft. Multiplying by the 20 psf wind pressure yields 3.4 kips of lateral wind load*. As developed in the preceding sections for our example, each lifting mechanism (with 30 kip axial load raised 10") provides 1.6 kip of lateral load capacity, so four mechanisms provide $4 * 1.6 = 6.4$ kip ultimate lateral capacity, which is nearly double the required load given the design assumptions. This example is depicted below.



** It is important to note that this is the load for 10' of perimeter on the windward side of the structure. Since we have defined the pier spacing to be 10' x 10', this number is also the load presented to one row of piers. If a different pier spacing is chosen, the wind loading slice must be adjusted accordingly such that the available lateral capacity and lateral load demand are properly calculated.*

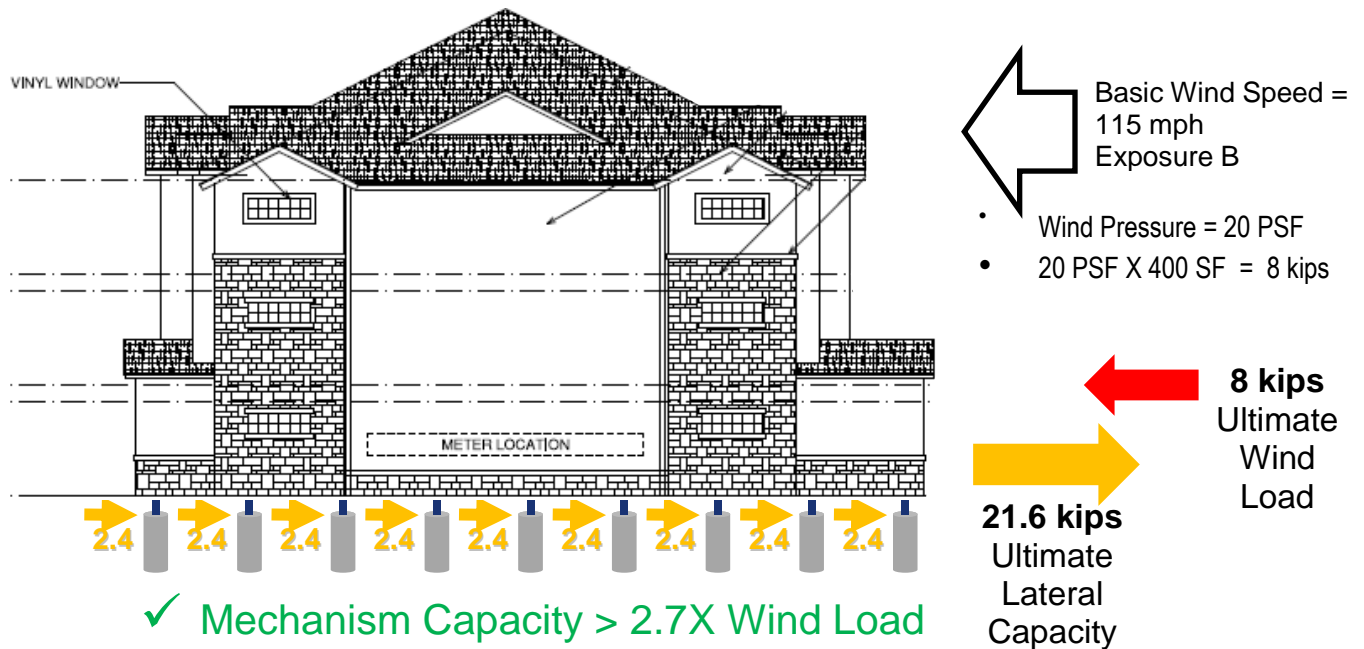
3.2 Wind Load Capacity Calculation – Three Story Structure

We next consider the wind load on a three story structure lifted 8” above grade by SlabTek Lifting Mechanisms in a 10’ x 10’ grid spacing. Along the considered axis, there are nine piers. In this example we assume the same 30 kip load per pier and 115 mph.

The surface slice to be considered is now calculated to be 400 sq ft (per 10’ pier row spacing). Multiplying by the 20 psf wind pressure yields 8 kips of lateral wind load.

Using the charts from Section 2, we determine that the lateral capacity of SlabTek Lifting Mechanisms at 8” lift height and 30 kip axial load is 2.4 kips per mechanism, so the row of 9 mechanisms provides 21.6 kips of ultimate lateral capacity.

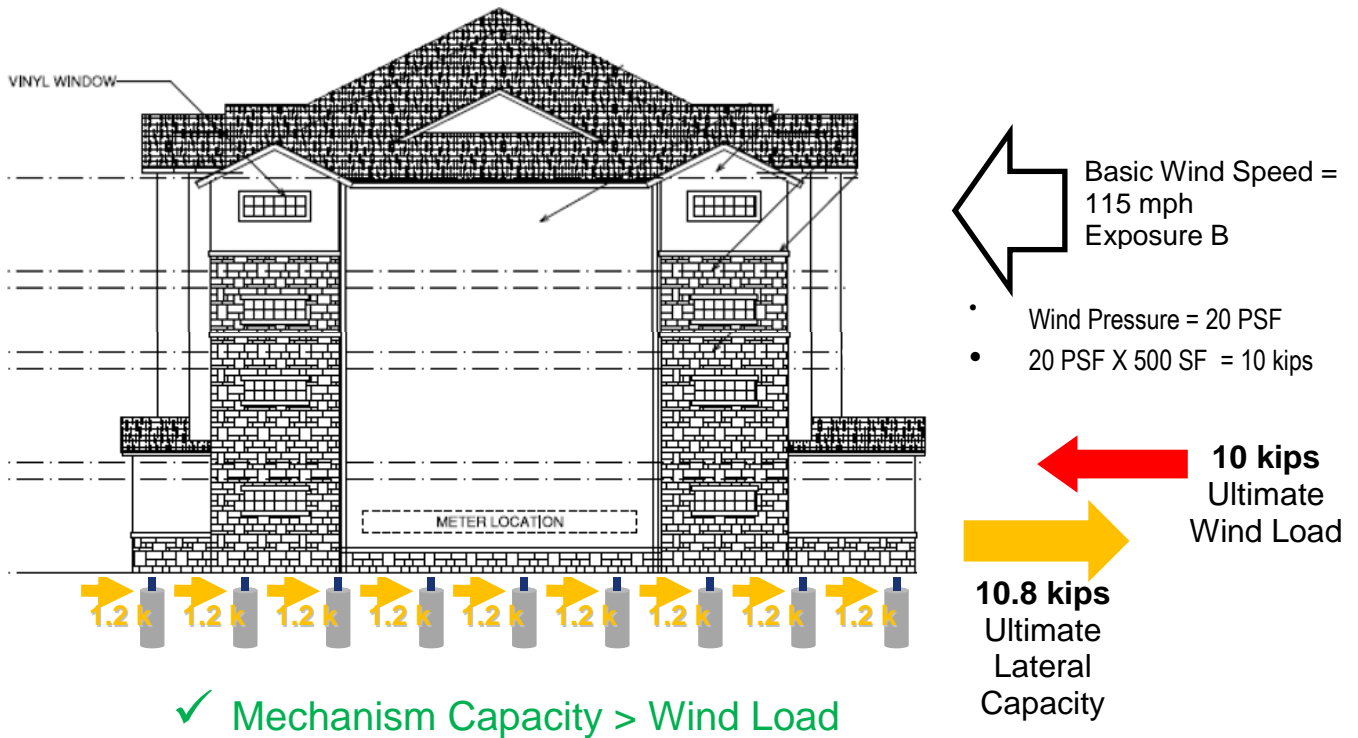
Comparing this to the 8 kip requirement again shows significant excess lateral capacity. This example is depicted below.



Parameters for Example 3.2		
30	kip	Axial load per mechanism
8	in	Lift height
10	ft	Pier column spacing
10	ft	Pier row spacing
9		Number of piers per row
115	mph	Wind speed
400	sq ft	Structure area per 10’ of perimeter on loaded side

3.3 Wind Load Capacity Calculation – Four Story Structure

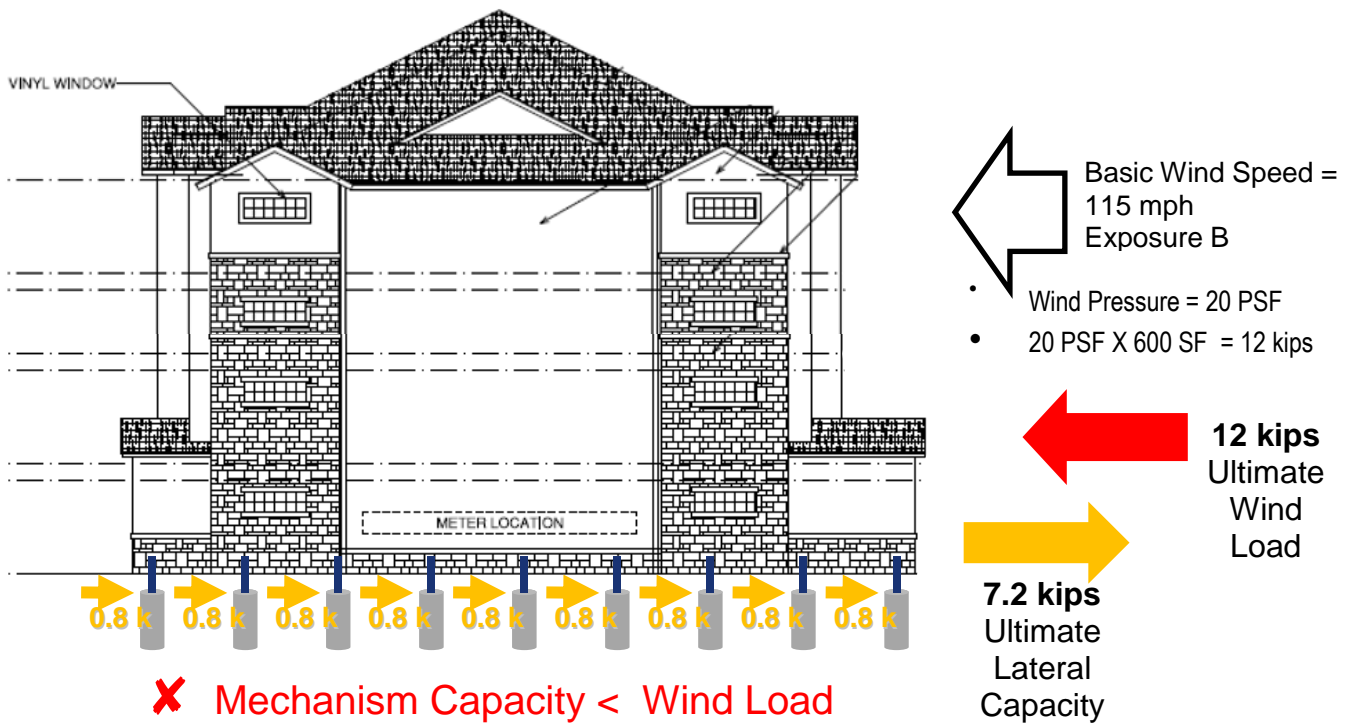
Similar to the prior two examples, the calculations for a hypothetical four story structure are shown below. In this example, we posit a 40kip load per pier, but use the same 8” lift, 10’ x 10’ pier spacing, 20 psf wind, as the prior example. We read from the charts in Section 2 that the lateral capacity of the SlabTek Lifting Mechanism under 40 kip axial load at 8” lift is 1.2 kips per pier. The row of nine piers now provides 10.8 kips of lateral capacity. The square footage judged per 10’ row of piers is now 500 sq ft, resulting in a wind load of 10 kips. As before, the required lateral capacity is available from the properly designed array of lifting mechanisms, with reduced margin as expected.



Parameters for Example 3.3		
40	kip	Axial load per mechanism
8	in	Lift height
10	ft	Pier column spacing
10	ft	Pier row spacing
9		Number of piers per row
115	mph	Wind speed
500	sq ft	Structure area per 10’ of perimeter on loaded side

3.4 Wind Load Capacity Calculation – Five Story Structure

To complete our examples, a five story building is considered. The parameters are the same as before with the exception that the axial load is now specified as 50 kip per pier, resulting in a lateral capacity per pier of 0.9 kip, and the area of the structure per 10’ row of piers is judged to be 600 sq ft. Calculations yield the ultimate lateral capacity of one row of the pier array as 7.2 kips, but the wind lateral demand for one row of the pier array is calculated to be 12 kips, therefore the configuration of piers is *insufficient* for this structure and must be adjusted.

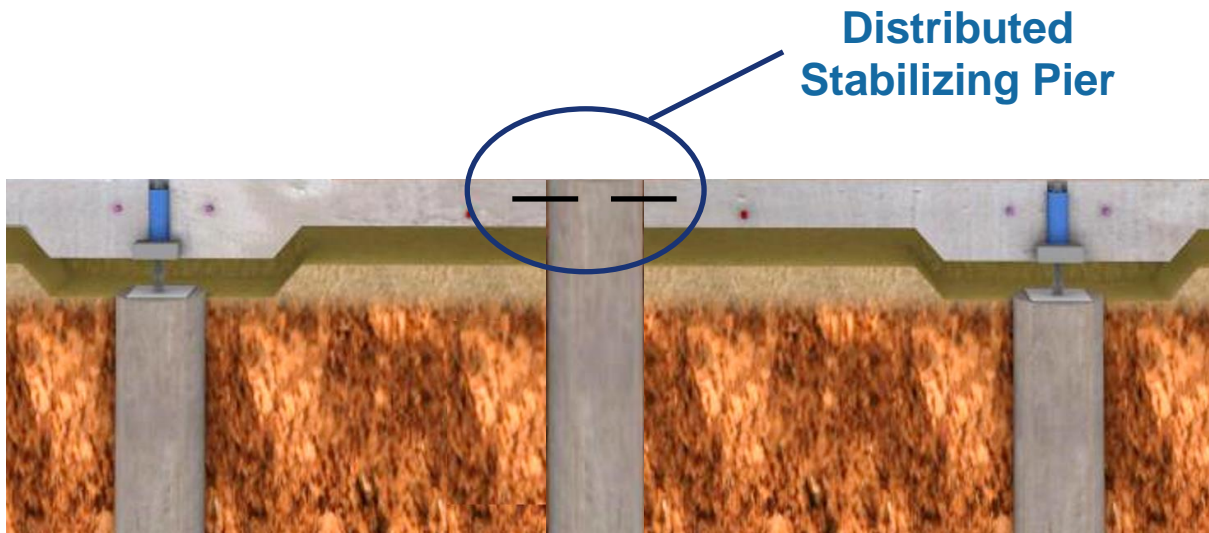


Parameters for Example 3.4		
50	kip	Axial load per mechanism
8	in	Lift height
10	ft	Pier column spacing
10	ft	Pier row spacing
9		Number of piers per row
115	mph	Wind speed
600	sq ft	Structure area per 10' of perimeter on loaded side



3.4 Methods for Increasing Lateral Capacity

When a configuration does not provide sufficient available lateral capacity for the load demand, several options are possible, among them: increasing the density of the pier array by decreasing the distance between piers, or using a heavier duty lifting mechanism. Another alternative is to use one or more dedicated ‘stabilizing’ piers to provide additional lateral capacity. Stabilizing piers, such as depicted in the diagram below, do not provide any axial load capacity, but can provide significant lateral load capacity. The calculations regarding stabilizing piers are beyond the scope of this whitepaper.



✓ **Addition of Distributed Stabilizing Piers Will Increase Lateral Capacity Above Wind Load**



SLABTEK
COMPANY

*This product and implementation of suspended slabs using this product are protected by the following United States and Canadian Patents which are owned exclusively by SlabTek
US Patents: 8458984, 8671627, 8407898, 8678712, 7823341 B2, 8069620 B2. Canadian Patent: 2628422*

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