Designing Rooftop Paving Slabs for Wind Effects

PAV-MAN-007

MASONRY & HARDSCAPES

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INTRODUCTION

This manual focuses on the selection, design, and specification of pavement systems for rooftop applications. In particular, this section will focus on "segmental concrete paving slabs," for rooftop applications.

DESIGN PROCEDURE CHECKLIST

The objective of this section is to provide the contractor or designer of record (DOR) with a procedural checklist for selecting, designing, and specifying a segmental concrete paving slab system for a rooftop application. It is imperative to note that many of the following checklist items simply do not apply for paving systems at grade.

1. **Consult a professional structural engineer.**
   This is extremely important because there are some aspects of designing rooftop paving systems that are just too complex for the lay person—or even non-engineering design professionals. To correctly design and install a rooftop paving system requires familiarity with structural engineering codes and publications for the determination of the environmental forces to which the paving system will be subjected. In addition, a structural engineer will be key in helping to ensure that there is a complete "load path," (see below), perhaps the most important aspect of the design of the concrete paving slabs.

2. **Collect the necessary design information for the structural engineer.**
   There are several given parameters that the engineer will require to determine the forces on the paving system. These parameters include the following information:

   a. The proposed site location of the building;
      This is required to determine which building code(s) will be applicable. For instance, in the United States, the International Building Code (IBC) is modified by the individual state codes (e.g.—the California Building Code and the Florida Building Code). Similarly, in Canada, the National Building Code of Canada (NBCC) is modified by the individual provincial codes (e.g.—the Ontario Building Code and the British Columbia Building Code).

      Additionally, the location of the building would determine which design codes (per structural materials; such as steel, concrete, timber, and steel) would be applicable. For example, consider steel design. In the United States, the American Institute of Steel Construction (AISC 360) would be the governing basic steel specification. In Canada, the governing steel design specification would be the Standards Council of Canada (CAN/CSA S16).

      Key environmental loads (such as the wind velocity to be considered, environmental exposure, seismic parameters, snow loads, etc.) also vary greatly per the proposed location. In particular, the wind load is influenced greatly by the exposure condition surrounding the proposed location. Additionally, in areas of high seismicity, the decision on which type of rooftop paving system (or, the feasibility of whether to use a rooftop paving system at all) may need to be considered.

      All of these various environmental loads, along with the structural dead load, are combined, per the above-mentioned building codes, to arrive at the controlling load combinations for the design.

   b. The proposed use and/or occupancy of the building;
      This information is used to determine the risk category of the building; that is, the importance factors that will be used for determining the individual, discrete loads for the design of the paving system.

   c. The proposed overall geometry of the building (e.g.—design drawings); The geometry (i.e.—the major architectural aspects of the building) are extremely influential in the determination of the loads to which the building roof (and the overall building) is subjected. Some of the geometric aspects include:

      i. The maximum height of the roof;
      ii. The dimensions and shape of the roof;
      iii. The location and number of major openings (e.g.—to determine if the building is "open", "enclosed"/"partially-open", or "partially-enclosed").
      iv. The slope of the roof (given that the discussion is on rooftop paving systems, we'll assume that the roof is a low-slope roof);
      v. Major appurtenances or mechanical equipment that will be on the roof;
      vi. A general scheme for how the roof will drain (e.g.—plumbed drains, scuppers, etc.); and,
      vii. The edge condition of the roof (e.g.—will there be parapets at the perimeter of the roof?).

   d. The proposed roofing system, the roof framing structural system and framing layout for the building;

      i. Is the roof framing steel? (e.g.—steel wide-flange beams and/or open- web steel joists)

   ii. If the roof framing is steel, what is the infill? (e.g.—steel decking and/or concrete slab)
   iii. Is the roof framing concrete with a slab?
   iv. Is the roof framing wood (sawn timbers or dimensional lumber) with plywood/OSB infill?

e. If applicable, the age of the existing building;
   i. Is the building new construction or remodel/retrofit of an existing building?
   ii. What was the original use/occupancy of the building?
   iii. What were the original design loads considered for the building; in particular, for the building roof?

3. **Select some preliminary systems (manufacturers/makes/models) that you prefer to be used for the design.**
   If you have a good idea of the system that you'd like to use for the design, provide this information to the structural engineer. Each manufacturer's proprietary systems have their own set of idiosyncrasies that will need to be considered in the design. In fact, some manufacturer's systems will simply not be appropriate for some design applications. This is why it's important to communicate which specifc product you may have in mind; and, also to have an alternate, just in case your first choice of system does not lend itself to the application.

4. **Maintain communication with your structural engineer.**
   Communication is key to a successful design. Make sure to share any information that you think may be important. Some examples of extra information that would be important to the design include:

   a. Making the engineer aware if some design parameters are still undecided;
   b. Making the engineer aware if some design parameters are "set in stone";
   c. If you're an architect, consider giving your engineer access to speak to the contractor to ask questions or gather additional information; or,
   d. If you're a contractor, consider giving your engineer access to speak to the architect to ask questions or gather additional information.

WHAT IS THE "LOAD PATH"?

In order to help understand the concept of "load path", consider this question: What is the role of a structural engineer? The answer is: To ensure that all loads applied to a structure are safely transmitted to the ground. The way that the loads are transmitted through the structure, and ultimately to the ground, is the "load path". Another way to think of the "load path" is like a "chain" that runs through the components/elements of a structure. You don't want a weak leak in the "chain"; and, you definitely don't want a break in the chain (i.e.—a missing link), or there will be a failure of the structural system. That is, the loads will not be safely transmitted all the way to the ground.

Though this seems like "common sense, the necessity for the provision of a "load path" is even recognized in the building code. For instance, in the United States, the International Building Code (IBC) emphasizes the concept of a "load path" in Section 1616 ("Structural Integrity").

Here's a "real world" example of load path to help illustrate the concept. Refer to **Figures 1 and 2** (below). You can see that one can very simply follow the load path from the beginning (i.e.—the application of the load) to the end (i.e.—the safe transmittal of the load to the ground).

Load Origin illustrated in **Figure 1**:

1. As wind flow moves across the rooftop of a building (particularly, a low-slope roof), the wind induces an uplift pressure to the entire roof and all of the rooftop components.
2. The rooftop paving slabs have a weight (like all objects on earth that have mass).
3. If the rooftop paving slabs are not heavy enough to cancel out the uplift pressure due to the wind flow, we have a design issue (i.e.—an additional consideration); that is, we have a net uplift force (the uplift pressure applied to the surface of the paving slabs). Therefore, we must ensure that the paving slabs are held **down** to the roof.

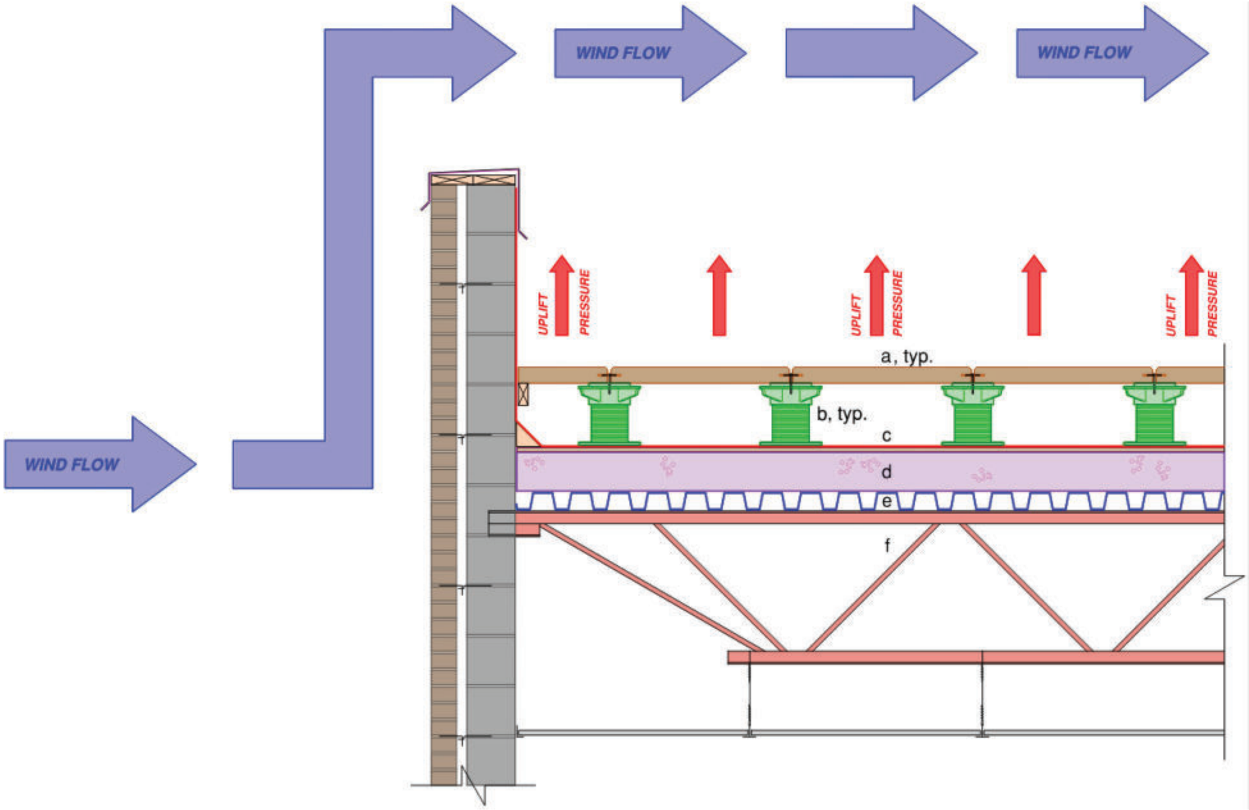

Figure 1: Uplift pressure created by wind flow over a near-flat, low-slope rooftop with segmental concrete paving slabs; Note: for identification of individual system components, refer to **Figure 3** (below).

Time Out:
Stop and think about this! It may be intuitive that a structural system must be able to hold **up** a building. But, far less intuitive, is that a structural system, many times, also must be able to hold **down** a building. Here's another reason to bring in an experienced structural engineer. The engineer will be familiar with these concepts (like having to hold down a building just as much as having to hold it up).

Still not a believer? Do a quick online search for videos of the destruction of homes in high winds (e.g.—tropical storms, hurricanes, or tornados). (Check this out: search "IBHS edge-metal failure demonstration" on YouTube.) Almost always, the first thing that happens (if the building wasn't properly built to resist the uplift with appropriate hold- downs and straps) is that the roof covering lifts off the building, followed by structural failure (1). Then, the walls blow away. Hasta la vista! Again, this is a good example that illustrates how people sometimes forget that a structural system has to work both ways effectively—that is, the structural system has to: (1) be able to hold a building up; and (2) be able to hold a building down.

Deep Dive:
Detailed information on engineering physics is far beyond the scope of this document. But, those interested in the physics of how wind affects our structures should research the following topics: "fluid dynamics" (yes; air behaves like a fluid), "conservation of energy", and the "Bernoulli Effect". In a nutshell, as the wind flows over a building at the windward face, the air has to speed up (refer to **Figure 2**). The conservation of energy states that if the velocity increases, the air pressure must decrease. This is why some areas on a building (like the roof, sides and leeward face) develop this negative pressure (or suction). This is known as the "Bernoulli Effect". Here's another interesting fact: This is how airplanes fly! Look it up!

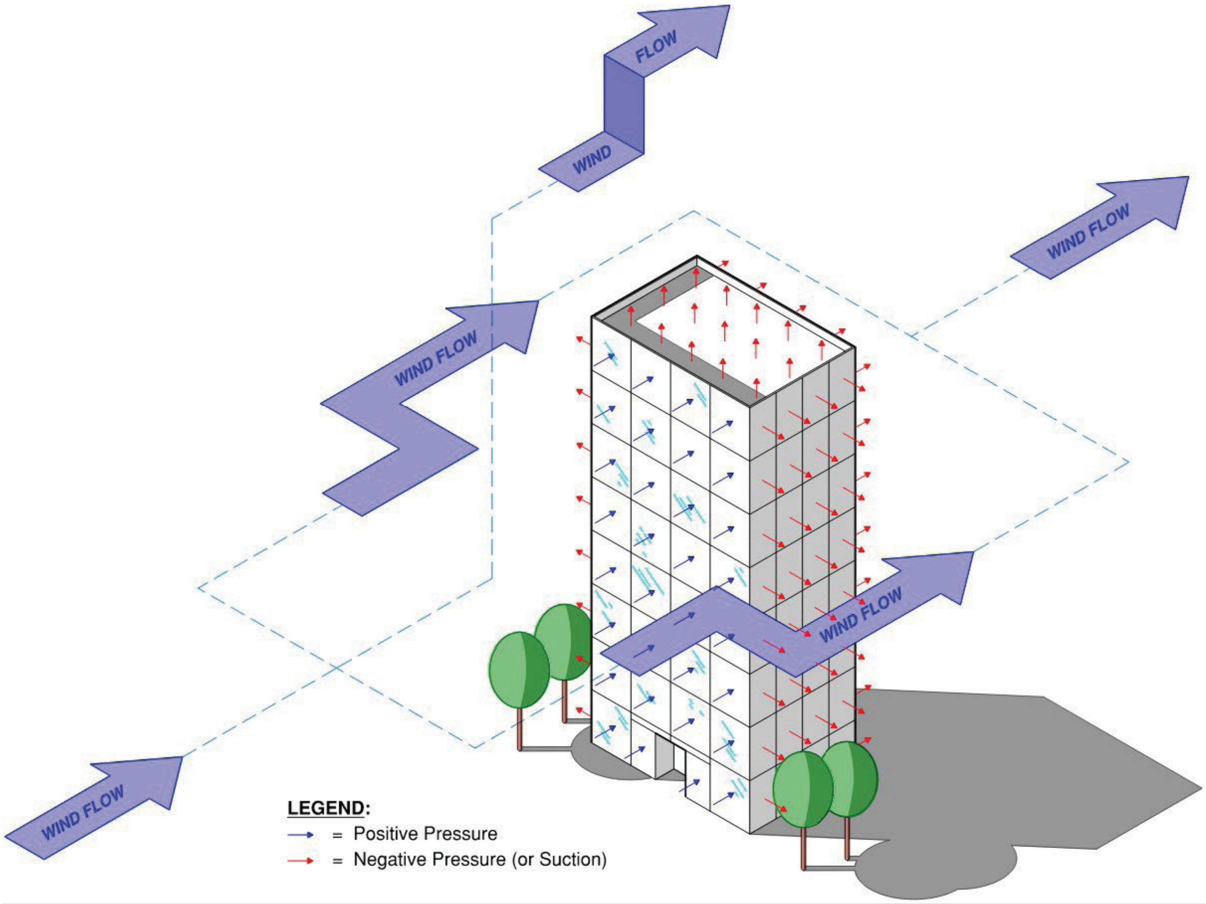

Figure 2: Uplift pressures created by wind flow over a typical building; Note that the arrows on the building surfaces indicate the direction of the pressures resulting from the wind flow. In particular, note the negative pressure, or uplift pressure on the roof of the building.

Let's take a look at a complete structural load path for a rooftop concrete paving system. Refer to **Figure 3**, below.

Load Path illustrated in **Figure 3:**

1. The segmental concrete paving slabs are held down to the pedestals.
   There are several ways proprietary systems hold down the paving slabs. For example, some use hold-downs at the corners of the paving slabs; and some are even hidden on the side of the paving slabs.
2. The pedestals are held down to the single-ply, Thermoplastic Polyolefin (TPO) roof membrane. This is usually done by an appropriate adhesive. The adhesive must be compatible with the TPO single-ply roof membrane.
3. The single-ply TPO roof membrane is held down to the polyisocyanurate insulation (ISO) by an appropriate adhesive.
4. The polyisocyanurate insulation (ISO) is held down to the structural infill of the roof (in this case, steel roof decking). This is accomplished using steel screws through the oriented strand board (OSB) nailer on the ISO (in this case, part of the ISO insulation product that is glued to the insulation) into the steel decking.
5. The steel roof decking is held down to the open-web steel joists with welds and/or steel deck screws (i.e.—self-drilling/self-tapping TEK screws).
6. The open-web steel joists are held down at their connections to the masonry walls or primary steel framing (steel wide-flange girders).
7. In the case of the masonry walls, the walls (not shown) carry the loads from the steel open-web joists down to the ground (i.e.—strip footings; not shown).
8. In the case of the primary steel framing, the girders (not shown) carry the loads back to the columns (not shown). The columns then carry the loads down to the ground (i.e.—isolated footings; not shown).

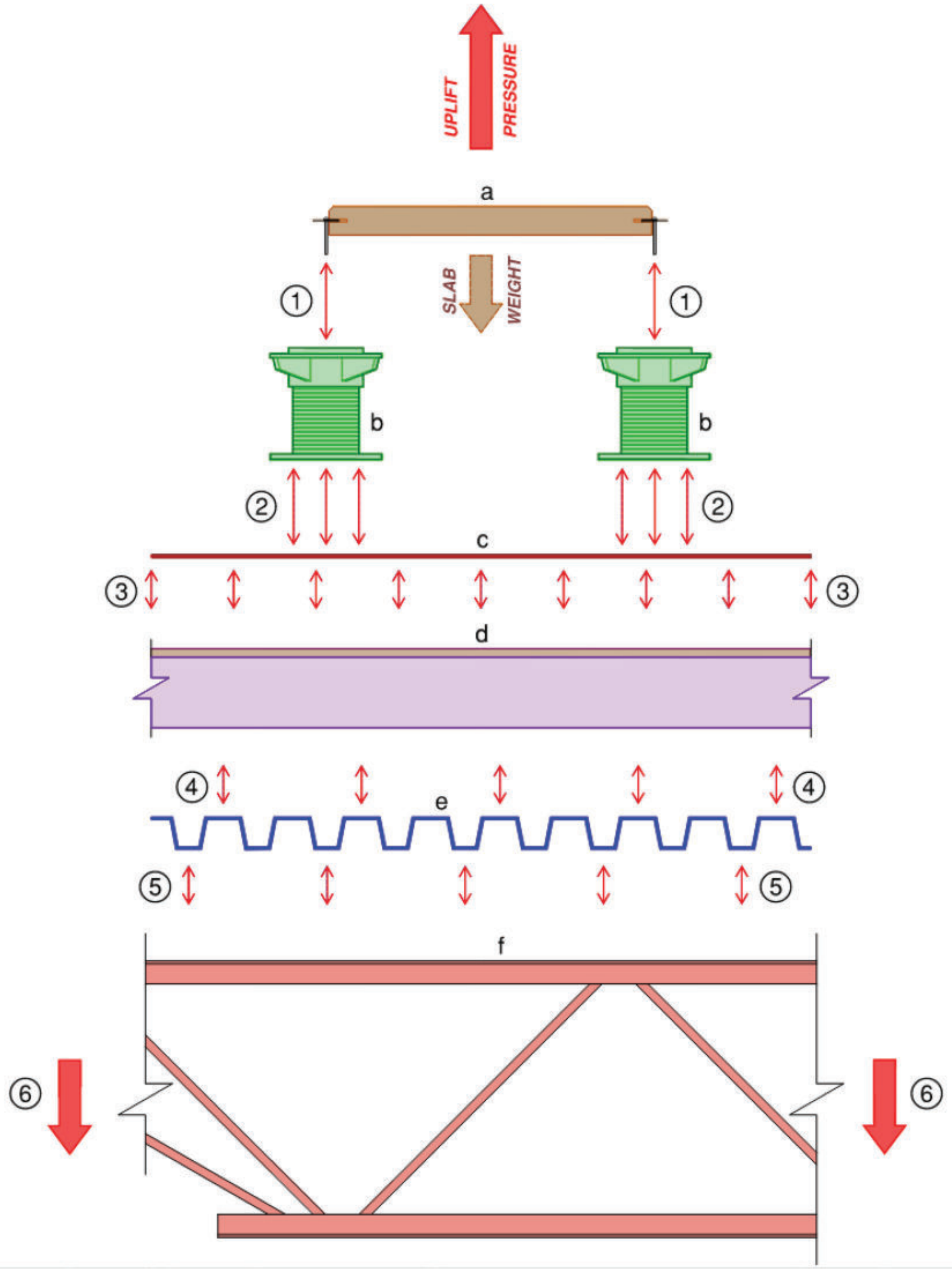

Figure 3: Load path for a segmental concrete paving system installed on a rooftop of a building; Note that numbers denote load path (refer to the body of the text); and, lower-case letters denote the system components: (a) concrete paving slab; (b) adjustable pedestal supports; (c) single-ply roof membrane; (d) polyisocyanurate (ISO) insulation with bonded wood layer (OSB) for screw connections; (e) steel roof deck; (f) open-web steel joist.

Note that is an example to illustrate the concept of load path. Obviously, this represents just one possible configuration of: segmental concrete paving system, built-up roofing system, and structural system. The possible combinations between these components are seemingly endless [e.g.—all types of commercially-available paving products, with all different types of roofing systems, and all different types of structural systems (concrete walls, concrete framing, steel framing, masonry walls, timber framing, etc.)]. The overall point is that it is essential that a continuous load path is provided—however, the load path needs to be modified for your system configuration; that is, your proprietary system of concrete paving slabs (and components), roofing system, and structural system. Again, the bottom line is that the resistance to wind uplift relies heavily upon the attachment between the various roof assembly layers and components; all of which should be reviewed by a structural engineer.

Example calculations for the analysis of wind uplift on roofs is done using ***ASCE 7: Minimum Design Loads and Associated Criteria for Buildings and Other Structures*** (2) in the U.S. or in Canada the ***NBCC: National Building Code of Canada*** (3).

REFERENCES:

1. "A Recommendation for an ENHANCED FUJITA SCALE", Texas Tech University Lubbock, Texas, 2006 https://www.depts.ttu.edu/nwi/Pubs/EnhancedFujitaScale/EnhancedFujitaScale.php
2. ASCE 7 Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers, Reston, VA.
3. National Building Code of Canada, National Research Council Canada, Ottawa, Ontario. 2020.

APPENDIX A

Example calculation using ASCE 7: Minimum Design Loads and Associated Criteria for Buildings and Other Structures

CLIENT Interlocking Concrete Pavement Institute JOB NO. 100054390 SHEET 01 OF 12
SUBJECT Segmental Rooftop Paving System BY JKL DATE 05/08/2022
Structural Design for Support of Paving Slabs CKD. RJD REV. 0

Problem Statement:

1. Using the information provided by the contractor/architect, design the segmental concrete paving slab system shown in Figure 1 (below).

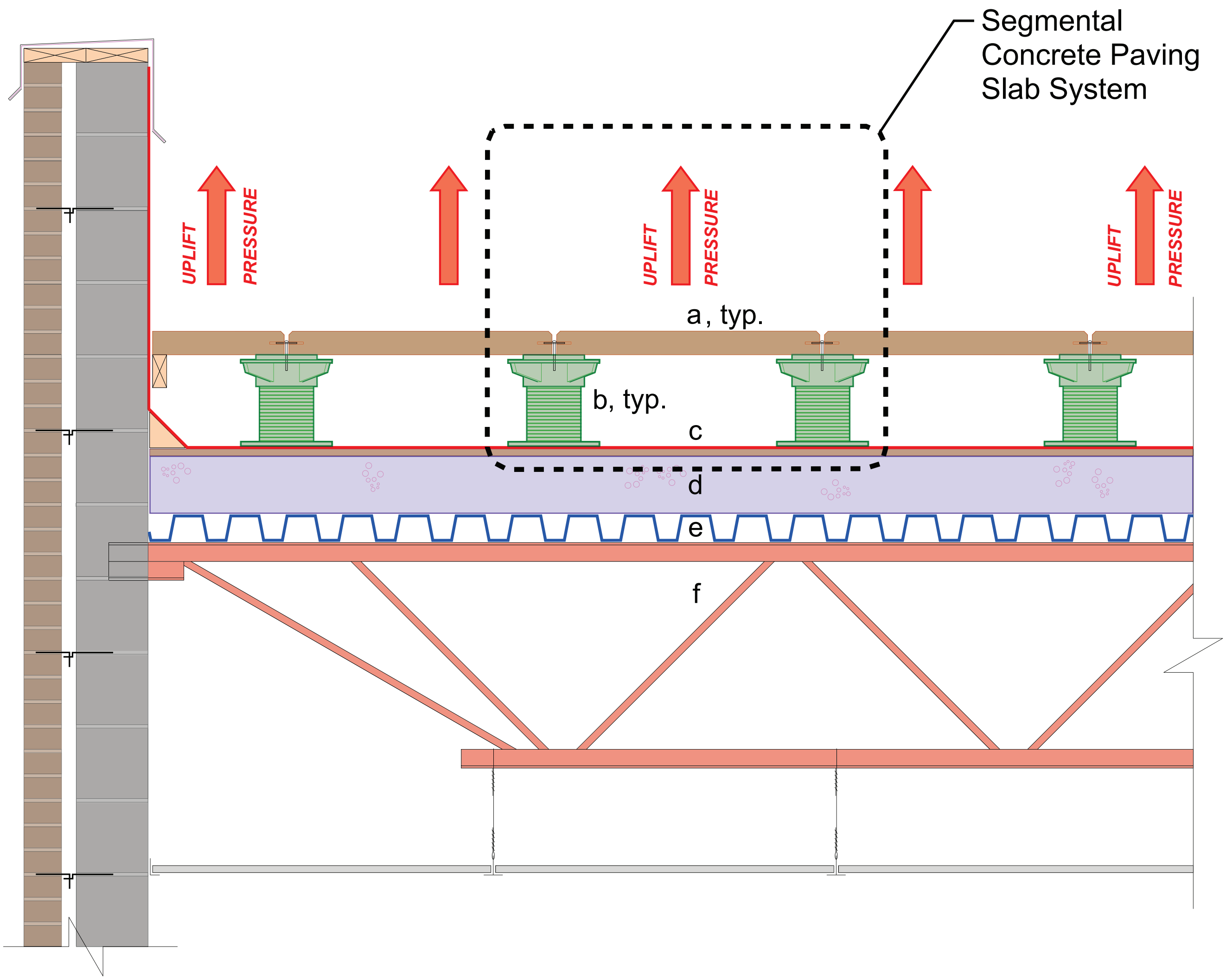

Figure 1: Segmental Concrete Paving Slab System
(a) concrete paving slab; (b) adjustable pedestal supports; (c) single-ply roof membrane; (d) polyisocyanurate (ISO) insulation with bonded wood layer (OSB) for screw connections; (e) steel roof deck; and, (f) open-web steel joist.

Problem Statement: (continued)

2. Given design information (provided by the contractor/architect):

a. Building site location: Lake Buena Vista, Florida
Address: 12151 S. Apopka Vineland Road, Lake Buena Vista (Orlando), FL 32836

b. Proposed use/occupancy of the building: High-rise apartments (Occupancy less than 200)

c. Overall geometry of the building:

i. Max. roof height: 6-story; Ave. Story Ht. = 14'

ii. Dimensions/Roof shape: Rectangular; 45' x 85'

iii. Roof slope: Near flat (min. roof slope for drainage).

iv. Major roof appurtenances: HVAC mechanical units.

v. Roof drain scheme: (4) Internal plumbed drains toward centerline of building.

vi. Roof edge condition: 2.5' parapet at the roof perimeter.

d. Proposed roof framing system: Steel-framed roof, supported by masonry bearing walls
i. Primary steel: Wide-flange members
ii. Secondary steel: Open-web steel joists

3. Preliminary, preferred proprietary system selected by contractor:

PaveTECH® Roof Paving Systems, Inc. (fictitious vendor for sample calculations.)

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Problem Statement: (continued)

4. Engineering reponses to given design information (provided by the contractor/architect):

a. Building site location: Lake Buena Vista, Florida
Address: 12151 S. Apopka Vineland Road, Lake Buena Vista (Orlando), FL 32836

[Note: All engineering responses in black text.]

$V = 135$ mph [ATC Hazards by Location, Online]
Exposure C [Google Earth, Online]
$S_{DS} = S_{D1} = 0.111g$ Note: Seismic loads are negligible; Wind will govern design.
$p_g = 20$ psf [ATC Hazards by Location, Online]
Governing Codes: Florida Building Code, 7th edition (2020)
IBC 2018 , ASCE 7-16

b. Proposed use/occupancy of the building: High-rise apartments (Occupancy less than 200)
Risk Category II [ASCE 7-16, Table 1.5-1]

c. Overall geometry of the building:

i. Max. roof height: 6-story; Ave. Story Ht. = 14' $h = 84$ ft

ii. Dimensions/Roof shape: Rectangular; 45' x 85'

iii. Roof slope: Near flat (min. roof slope for drainage). $\theta = 0.0°$

iv. Major roof appurtenances: HVAC mechanical units. Given location, neglect contribution from snow drifts.

v. Roof drain scheme: (4) Internal plumbed drains toward centerline of building.
Slope accounted for in ISO.

vi. Roof edge condition: 3' parapet at the roof perimeter.
Research method the proprietary system works along parapets.

d. Proposed roof framing system:
Steel-framed roof, supported by masonry bearing walls
i. Primary steel: Wide-flange members
ii. Secondary steel: Open-web steel joists

Preliminary, preferred proprietary system selected by contractor:
PaveTECH® Roof Paving Systems, Inc. (fictitious vendor for sample calculations.)

Obtain all pertinent cut-sheets for technical data on components of preliminary selected system.

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Load Calculations: Dead Load

5. Calculate the dead load of the segmental concrete paving slab system.
From the cutsheet information provided by the vendor:

a. Thickness of concrete paving slabs: 2.25"
b. Slab dimensions: 30" x 30", Typ.
c. Density of concrete slab material: 140 lb/ft^3

The dead load (DL) of the concrete paving slabs is:

DL = (140 lb/ft^3)(2.25"/12)
= **26.3 psf**

Note that the weight (or dead load) of a single concrete paving slab is:

(DL)slab = (140 lb/ft^3)(2.25"/12)(30" x 30")/144
= **164 lb/slab**

DL = 26.3 psf
(DL)slab = 164 lb/slab

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Load Calculations: Wind Load

6. Calculate the wind load to which the segmental concrete paving slab system will be subjected.

Calculate the velocity pressure (qz or qh):

qz = (0.00256)(~~Kz~~)(Kzt)(Kd)(Ke)(V^2) [ASCE 7-16, Eqn. 26.10-1]
qh = (0.00256)(Kh)(Kzt)(Kd)(Ke)(V^2)

a. Basic wind speed (V): V = 135 mph

b. Exposure coefficient (Kh): Kh = 1.22 [ASCE 7-16, Table 26.10-1] [h = 84'; Exposure C]

c. Topographical factor (Kzt): Kzt = 1.0 [Assumed]

d. Directionality factor (Kd): Kd = 0.85 [ASCE 7-16, Table 26.6-1]

e. Ground elev. factor (Ke): Ke = 1.0 [ASCE 7-16, Table 26.9-1]

qh = (0.00256)(1.22)(1.0)(0.85)(1.0)(135 mph^2)
= **48.4 psf**

Calculate the design wind pressure (p):

p = q(GCp) - qi(GCpi) [ASCE 7-16, Eqn. 30.5-1]
p = qh(GCpr) - qh(GCpi)
= qh{ (GCpr) +/- (GCpi) }

a. External pressure coefficients for the roof (GCpr): [ASCE 7-16, Figure 30.5-1] [See next sheet.]

Zone	(GCp)
1	-1.4
2	-2.3
3	-3.2

b. Internal pressure coefficients (GCpi): [ASCE 7-16, Table 26.13-1]
(GCpi) = +/- 0.18 [Refer to "Appendix A".]

p = qh{ (GCpr) +/- (GCpi) }

Zone	qh	(GCp)	(GCpi)	p
1	48.4 psf	-1.4	-0.18	**-76.5 psf**
2	48.4 psf	-2.3	-0.18	**-120.0 psf**
3	48.4 psf	-3.2	-0.18	**-163.6 psf**

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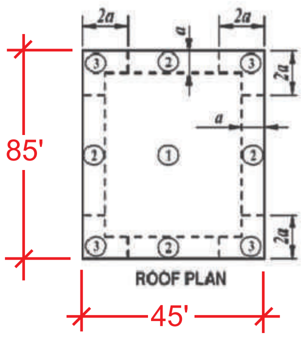
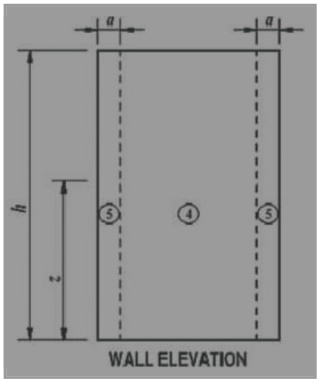
Load Calculations: Wind Load (continued)

Diagrams

a = (0.1)(45')
= 4.50'
> 3.00' ✓

Note: Use a = 5.0' for (2) slab widths.



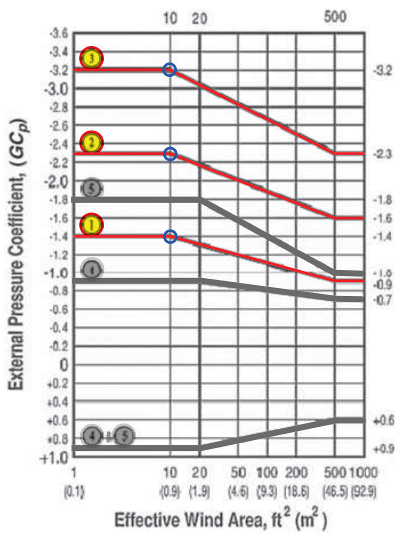


Notation

a = 10% of least horizontal dimension, but not less than 3 ft (0.9 m).
h = Mean roof height, in ft (m), except that eave height shall be used for $\theta \leq 10°$.
z = Height above ground, in ft (m).
θ = Angle of plane of roof from horizontal, in degrees.

External Pressure Coefficients

Zone	(GCp)
1	-1.4 Min(-)
2	-2.3
3	-3.2 Max(-)



Notes

1. Vertical scale denotes (GCp) to be used with appropriate q_z or q_h.
2. Horizontal scale denotes effective wind area A, in ft² (m²)
3. Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.
4. Use q_z with positive values of (GCp) and q_h with negative values of (GCp).
5. Each component shall be designed for maximum positive and negative pressures.
6. Coefficients are for roofs with angle $\theta \leq 7°$. For other roof angles and geometry, use (GCp) values from Fig. 30.3-2A–2I and Fig. 30.3-5A,5B and attendant q_h based on exposure defined in Section 26.7.
7. If a parapet equal to or higher than 3 ft (0.9 m) is provided around the perimeter of the roof with $\theta \leq 10°$, Zone 3 shall be treated as Zone 2.

FIGURE 30.5-1 Components and Cladding, Part 3 [$h > 60$ ft ($h > 18.3$ m)]: External Pressure Coefficients, (GC_p), for Enclosed, Partially Enclosed Buildings—Walls and Roofs

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Load Combinations:

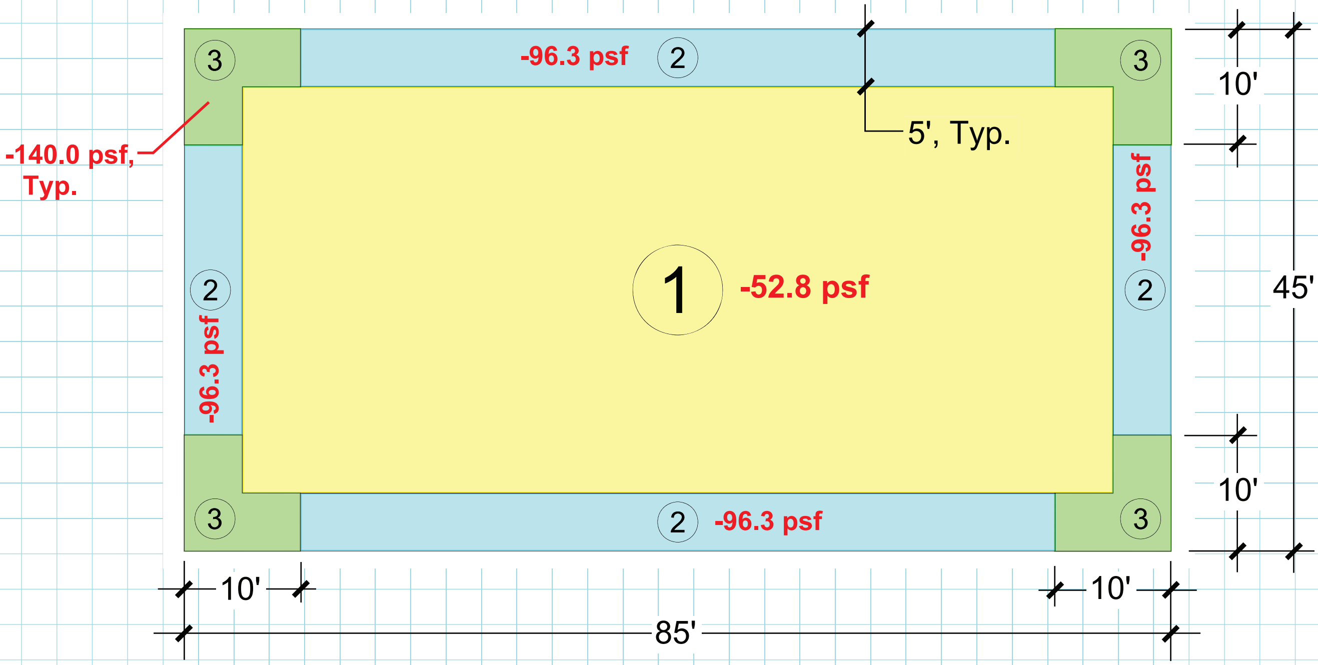
7. Use the ASCE-7 load combinations to determine the net uplift pressures on the segmental concrete paving slab system.

   Use the ASCE-7 load combinations for strength design (i.e.--LRFD methodology)

1. $1.4D$
2. $1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$
4. $1.2D + 1.0W + L + 0.5(L_r \text{ or } S \text{ or } R)$
5. $0.9D + 1.0W$ ← Use this load combination to determine the net uplift pressures.

Zone	D	W	wu = (0.9)(D) + (W)
1	26.3 psf	-76.5 psf	**-52.8 psf**
2	26.3 psf	-120.0 psf	**-96.3 psf**
3	26.3 psf	-163.6 psf	**-140.0 psf**

Summary of Uplift Pressures:



ROOF PLAN

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Hold-Down Design:

8. Design the hold-down components for the segmental concrete paving slab system. Consider the worst-case scenario, Zone 3:

Uplift on a single slab: Tu = (1/144)(30")(30")(140 psf) = 875 lb/slab

Uplift on a single pedestal: Tu = (4 slabs/pedestal)(0.25 x 875 lb/slab) = 875 lb/pedestal

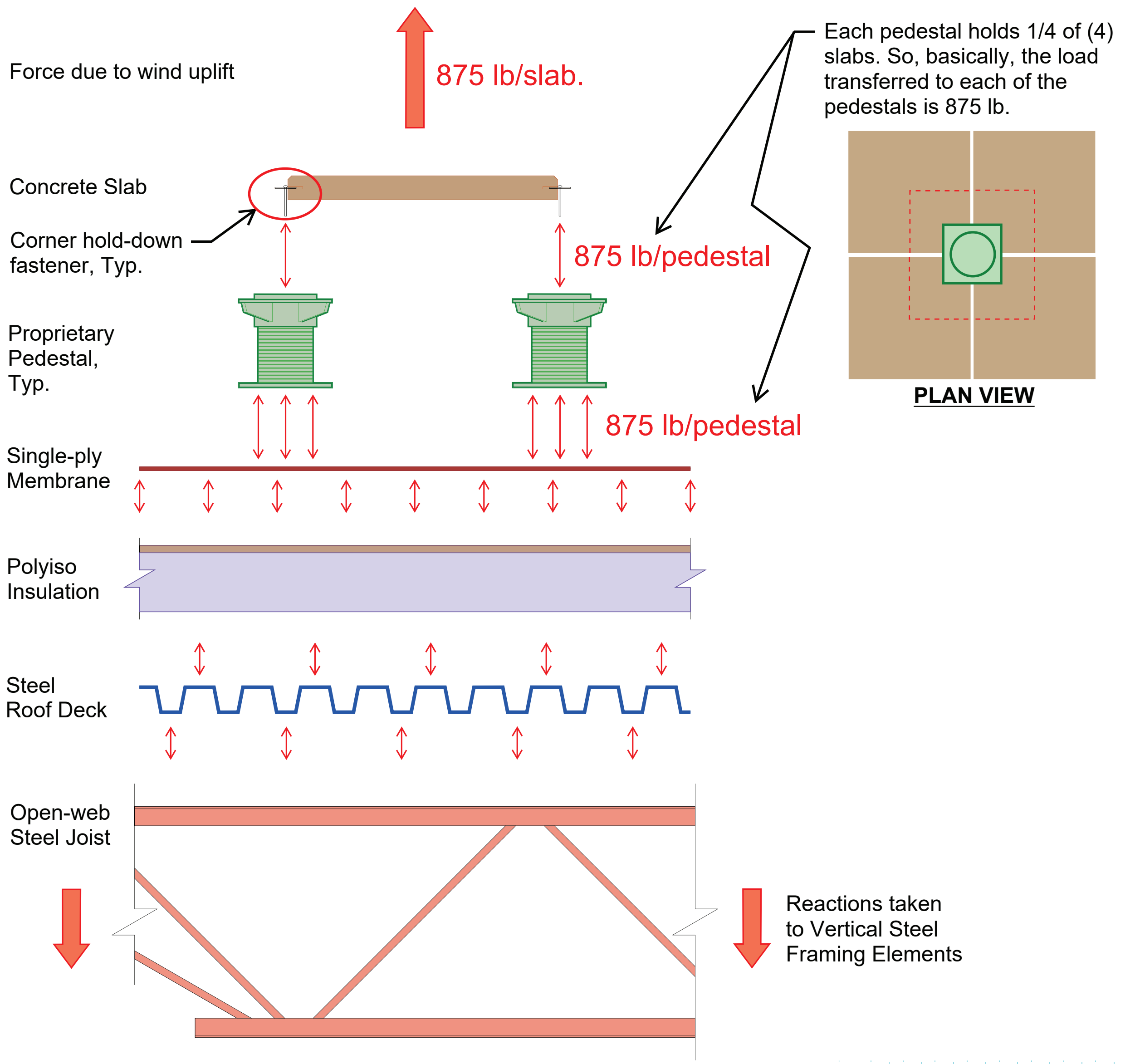

Figure 2: Free-body Diagram of Segmental Concrete Paving Slab System, Roofing System, and Roof Framing

Hold-Down Design: (continued)

8. Design the hold-down components for the segmental concrete paving slab system. (continued)

   a. Design the corner hold-down fastener for the concrete slabs:
      T_u = 875 lb/hold-down fastener
      Per the vendor's cutsheets (not shown), the following fastener is used with the pedestal:
      1/4"-28, 316 Stainless Steel Button Head Hex Drive Screw, Fu = 70 ksi.

      Minor Diameter = 0.211" (for 1/4"-28) [Online Lookup]

      $$\phi T_n = \frac{(0.75)(70\text{ ksi})(\pi)(0.211")^2}{(4)}$$

      = 1835 lb/screw (fracture on net section)

      > {Tu = 875 lb/fastener}; **O.K.**

      Therefore, the screw provided by the pedestal manufacturer is adequate.

   b. Design the pedestal to restrain the concrete slabs against uplift:
      T_u = 875 lb/pedestal

      Per the vendor's cutsheets (not shown), the pedestal has been experimentally tested to provide the following ultimate strengths:

      ϕP_n = 11,000 lb (compression)

      ϕT_n = 3000 lb (tension)
      > {Tu = 875 lb/pedestal}; **O.K.**

      Therefore, the pedestal provided by the manufacturer is adequate.

   c. Design the connection of the pedestal to the single-ply membrane for the roofing system:

      Per the vendor's cutsheets (not shown), the recommended method for connecting the pedestal to the single-ply roofing system is by using a polyurethane construction adhesive. (Note: The product must be checked for chemical compatibility with the single-ply membrane.)

Hold-Down Design: (continued)

c. Design the connection of the pedestal to the single-ply membrane for the roofing system: (continued)

The cutsheet for the recommended adhesive (not shown), provided the following technical data:

Ultimate Tensile Strength of Adhesive: 3000 psi

Additional information:
i. The round pedestal base is 5.75" in diameter (from vendor cutsheets; not shown);
ii. Assume 25% coverage in the application of the polyurethane adhesive.

$$\phi Tn = \frac{(0.75)(0.25)(3000\text{ psi})(\pi)(5.75")^2}{(4)}$$

= 14,600 lb/pedestal (tensile failure of adhesive)

> {Tu = 875 lb/pedestal}; **O.K.**

Therefore, the polyurethane adhesive recommended by the pedestal manufacturer is adequate.

The structural calculations should continue to check the entire load path for the transfer of the uplift pressures induced by the wind. Additionally, the load path should be checked for the maximum governing downward force effects.

At this point, the structural calculations will cease. Since, the scope of this document is the demonstration of the load path structural checks for the components of the segmental concrete paving system.

End of Calculations.

Wind Load Calculations: Discussion on Internal Pressure Coefficients (GCpi)

Here, we will focus on the "Internal Pressure Coefficients" (GCpi) used in the example calculation. The space beneath the pedestal-supported paving system is given an "enclosure classification" for the purpose of determining an internal pressure coefficient. This internal pressure coefficient shall be used in the calculation of the net wind pressure on the concrete paving slabs. Recall, from step 6 in the example calculation:

6. Calculate the wind load to which the segmental concrete paving slab system will be subjected.

Calculate the design wind pressure (p):

p = q(GCp) - qi (GCpi) [ASCE 7-16, Eqn. 30.5-1]
p = qh(GCpr) - qh (GCpi)
= qh{ (GCpr) +/- (GCpi) }

Internal Pressure Coefficients

a. External pressure coefficients for the roof (GCpr): [ASCE 7-16, Figure 30.5-1] [See next sheet.]

Zone	(GCp)
1	-1.4
2	-2.3
3	-3.2

Internal Pressure Coefficients

b. Internal pressure coefficients (GCpi): [ASCE 7-16, Table 26.13-1]
(GCpi) = +/- 0.18 [See next page of Appendix.]

p = qh{ (GCpr) +/- (GCpi) }

Zone	qh	(GCp)	(GCpi)	p
1	48.4 psf	-1.4	-0.18	**-76.5 psf**
2	48.4 psf	-2.3	-0.18	**-120.0 psf**
3	48.4 psf	-3.2	-0.18	**-163.6 psf**

Internal Pressure Coefficients

In step 6.b. (above), we have made an assumption regarding the classification of the space beneath the pedestal-supported paving system. Referring to the table of internal pressure coefficients in ASCE 7-16 [Table 26.13-1], one can see that we have assumed the space to be "enclosed" (or "partially open"); with a "moderate" level internal pressure coefficient of +/- 0.18. Then, the value is "conservatively added" to the value of GCp [i.e.--the product of the gust-effect factor (G) and the exterior pressure coefficient (Cp)]. That is, the value of GCpi is combined with GCp for the maximum absolute value. In this case, since the value of GCp is negative, we add a negative value of GCpi. This creates the worst-case (conservative) wind load effect on the paving slab system.

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Wind Load Calculations: Discussion on Internal Pressure Coefficients (GCpi) (continued)

Not Considered

Taken from ASCE 7-16

Enclosure Classification	Criteria for Enclosure Classification	Internal Pressure	Internal Pressure Coefficient, (GC_{pi})
Enclosed buildings	~~A_o is less than the smaller of $0.01A_g$ or 4 sq ft (0.37 m) and $A_{oi}/A_{gi} \le 0.2$~~	Moderate	+0.18 −0.18
Partially enclosed buildings	~~$A_o > 1.1A_{oi}$ and $A_o >$ the lesser of $0.01A_g$ or 4 sq ft (0.37 m) and $A_{oi}/A_{gi} \le 0.2$~~	High	+0.55 −0.55
Partially open buildings	A building that does not comply with Enclosed, Partially Enclosed, or Open classifications	Moderate	+0.18 −0.18
Open buildings	Each wall is at least 80% open	Negligible	0.00

Notes
1. Plus and minus signs signify pressures acting toward and away from the internal surfaces, respectively.
2. Values of (GC_{pi}) shall be used with q_z or q_h as specified.
3. Two cases shall be considered to determine the critical load requirements for the appropriate condition:
   a. A positive value of (GC_{pi}) applied to all internal surfaces, or
   b. A negative value of (GC_{pi}) applied to all internal surfaces.

Table 26.13-1 Main Wind Force Resisting System and Components and Cladding (All Heights): Internal Pressure Coefficient, (GC_{pi}), for Enclosed, Partially Enclosed, Partially Open, and Open Buildings (Walls and Roof)

End of "Appendix A".

APPENDIX B

Example Calculations using NBCC: National Building Code of Canada 2015

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Subject	Segmental Rooftop Paving System	By	JD	Date	2022-06-24
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Problem Statement

1. Design check the segmental paving slab system previously described according to the National Building Code of Canada 2015 and applicable provincial codes.
   The building characteristics, dimensions, and structural system will remain the same as in the American calculations, except the location will be changed to City 'X', Province 'Y' in Canada.

2. Given design information (provided by contractor/architect):

   a. Building Location: City 'X', Province 'Y', Canada

   b. Proposed occupancy: Residential, high-rise apartments

   c. Overall geometry of the building: Rectangular

      6-Storey building, average story height = 14 ft = 4.267m

      i. Max. roof height: 25.603 m = 84.00 ft

      ii. Roof dimensions:
         Width (Shorter dimension) W: 13.716 m = 45.00 ft
         Length (Longer dimension) D: 25.908 m = 85.00 ft

      iii. Roof slope: Near flat (min. roof slope for drainage).

      iv. Major roof appurtenances: HVAC mechanical units.

      v. Roof drain scheme: (4) Internal plumbed drains toward centerline of building.

      vi. Roof edge condition: 2.5 ft = 0.762 m parapet at the roof perimeter.

   d. Proposed roof framing system: Steel-framed roof, supported by masonry bearing walls
      i. Primary steel: Wide-flange members
      ii. Secondary steel: Open-web steel joists

3. Preliminary, preferred proprietary system selected by contractor:

   PaveTECH Roof Paving Systems, Inc. (fictitious vendor for sample calculations.)

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Problem Statement: (continued)

4. Engineering reponses to given design information (provided by the contractor/architect):

a. Building site location: City 'X', Province 'Y', Canada

[Note: All engineering responses in black text.]

Governing Codes: National Building Code of Canada 2015

Building Importance: Normal
Exposure: Open terrain

Hourly wind pressure q 1/50: 0.58 kPa =12.11 psf (NBCC 2015 Appendix C, Climatic and Seismic Information)

b. Proposed use/occupancy of the building: High-rise apartments (Occupancy less than 200) Importance: Normal

c. Overall geometry of the building:

i. Max. roof height: 6-story; Ave. Story Ht. = 14' h = 25.603 m = 84 ft

ii. Dimensions/Roof shape: Rectangular; 45' x 85'

iii. Roof slope: Near flat (min. roof slope for drainage). $\theta = 0.0°$

iv. Major roof appurtenances: HVAC mechanical units. Given location, neglect contribution from snow drifts.

v. Roof drain scheme: (4) Internal plumbed drains toward centerline of building.
Slope accounted for in ISO.

vi. Roof edge condition: 3' parapet at the roof perimeter.
Research method the proprietary system works along parapets.

d. Proposed roof framing system:

Steel-framed roof, supported by masonry bearing walls
i. Primary steel: Wide-flange members
ii. Secondary steel: Open-web steel joists

Preliminary, preferred proprietary system selected by contractor:
PaveTECH® Roof Paving Systems, Inc. (fictitious vendor for sample calculations.)
Obtain all pertinent cut-sheets for technical data on components of preliminary selected system.

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5. Assumptions:

- The resistance design/check of the paver slabs and the pedestals to downward gravity loads (snow, roof live load, and dead load) are not part of these calculations.
- The structural resistance of the building framing is outside the scope of these calculations.
- This design example is limited to the effects of wind uplift on the paver slabs only.
- Seismic loads and their effects are not part of these calculations.

Load Calculations: Dead Load

6. Paver slab properties:

a. Thickness: 57.2 mm = 2.25"
b. Width: 762 mm = 30.0"
c. Length: 762 mm = 30.0"
d. Density of concrete: 22.0 kN/m^3 = 140.0 lb/ft^3
e. Weight per slab: (0.762m x 0.762m x .0572m)x22.0 kN/m^3 = 0.73 kN = 164.1 lb

The dead load DL of the concrete paving slabs is:

DL = 22.0 kN/m^3 x 0.0572m = 1.26 kN/m^2 = 26.26 psf

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Load Calculations: Wind loads

7. Design method and parameters:

Building dynamically sensitive: NO. Use Static Procedure.
Importance factor Iw: 1.00 for Normal importance. Table 4.1.7.3
Terrain: Open
Reference Height: 25.603 m = 84.0 ft

8. External Pressure:

External exposure factor Ce = (h/10)^0.2 = (25.603m/10)^0.2
Ce = 1.207 Cl. 4.1.7.3.(5) and Fig. A-4.1.7.5.(2) and (3)
External pressure gust factor:
Cge = 2.50 Cl. 4.1.7.3.(8).(b)
Topographic factor:
Ct = 1.00 Cl. 4.1.7.4.(1)
External Pressure coefficient Cp:
High building: Calculate Cp as per Cl. 4.1.7.5
Low Building: Calcualte Cp as per Cl. 4.1.7.6

Check if it is a low building per Cl. 4.1.7.6
H/20 m = 25.603 m / 20.0 m = 1.280 > 1.0 and
H <= smaller plan dimension: 25.603 m > 13.716 m, False
Then: The building is not considered a low structure, use Cl. 4.1.7.5

Calculate Cp per 4.1.7.5.(4).(c) and A-4.1.7.5.(2), (3), and (4).
H/D (lengthwise) = 25.603 m / 25.908 m = 0.988
H/D (widthwise) = 25.603 m / 13.716 m = 1.867 Controls.

Corner areas Cp = -2.30 Fig. A-4.1.7.5.(4)

Corner area width (0.2 x max(W or D) = 5.182 m = 17.00 ft

Corner area CpCg(c) = 2.50 x (-2.30) = -5.75

Perimeter areas Cp = -1.50 Fig. A-4.1.7.5.(4)

Perimeter area CpCg(s) = 2.50 x (-1.50) = -3.75

Perimeter area width (0.1 x max(W or D) = 2.591 m = 8.50 ft

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Inner roof areas Cp = -1.00 Fig. A-4.1.7.5.(4)
Inner roof areas CpCg(r) = 2.50 x (-1.00) = -2.50

Note: a negative Cp factor indicates pressure away from the paver surface, that is, suction.

A-4.1.7.5.(2) and (3) Pressure Coefficients for Main Structural System on Rectangular Buildings.

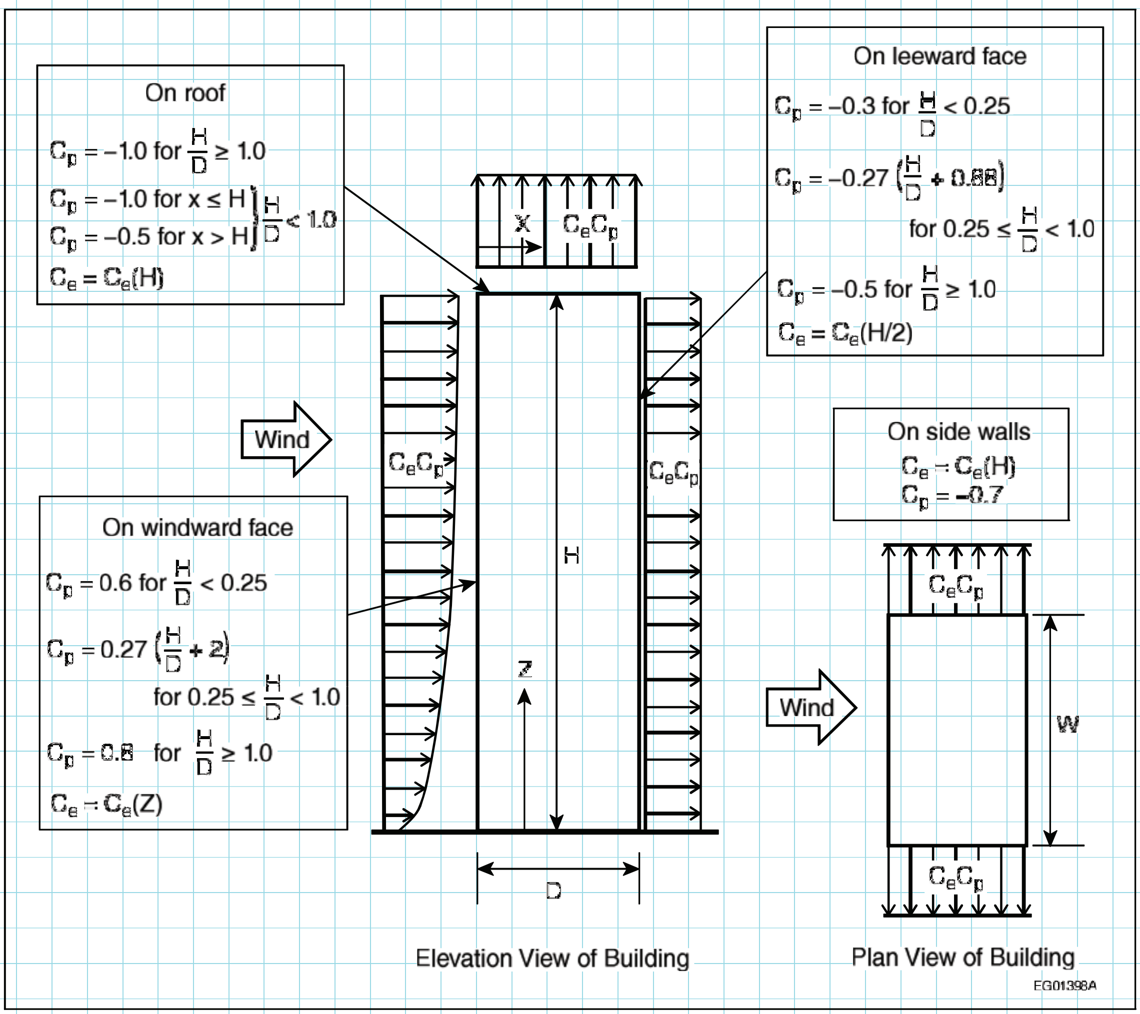

Figure A-4.1.7.5.(2) and (3)
Values of C_p for main structural system on rectangular buildings

Taken from NBCC 2015 Vol. 1

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A-4.1.7.5.(4) Pressure coefficients for roof and wall claddings and secondary structural supports of cladding on rectangular buildings.

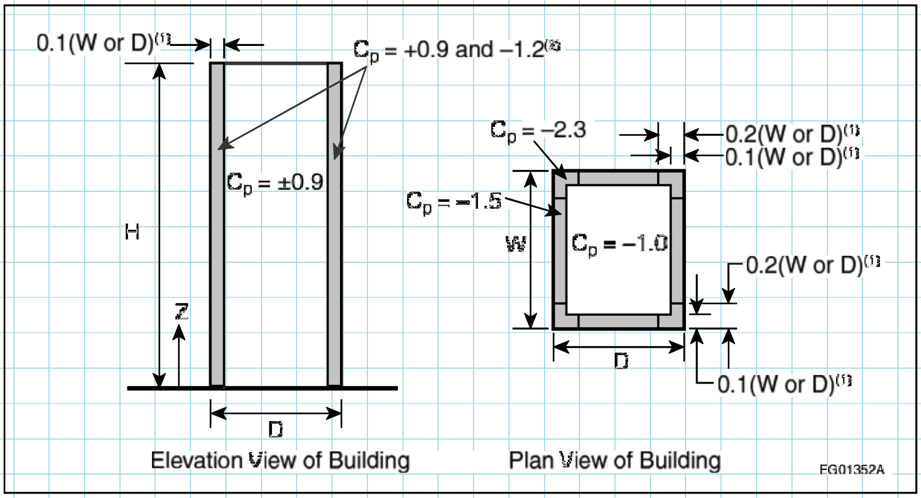

Figure A-4.1.7.5.(4)
Values of C_p for roof and wall claddings and secondary structural supports of cladding on rectangular buildings

Notes to Figure A-4.1.7.5.(4):
(1) The larger of W or D is to be used.
(2) Where vertical ribs deeper than 1 m are present on the walls, the dimensions 0.1D and 0.1W must be changed to 0.2D and 0.2W and the negative value of C_p must be changed from –1.2 to –1.4.

Taken from NBCC 2015 Vol. 1

Controlling External CpCg = -5.75

Design External Pressures

Corner Pext(c) = Iw.q1/50.Ce.Ct.CpCg(c) = 1.0 x 0.59 x 1.207 x 1.0 (-5.75)

= -4.02 kPa = -84.06 psf

Perimeter Pext(s) = Iw.q1/50.Ce.Ct.CpCg(c) = 1.0 x 0.59 x 1.207 x 1.0 (-3.75)

= -2.62 kPa = -54.72 psf

Inner roof Pext(r) = Iw.q1/50.Ce.Ct.CpCg(c) = 1.0 x 0.59 x 1.207 x 1.0 (-2.50)

= -1.75 kPa = -36.55 psf

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9. Internal Pressure:

- Internal pressure occurs between the roof surface and the bottom surface of the pavers when they are supported on pedestals. This condition could be associated to category 2 in the NBCC 2015 Structural Commentary I, article 26, summarized in Table 4.1.7.7 below.

- When the pavers rest directly on the roofing material, the internal pressure is zero and the air leak is less than 0.1%. This condition could be associated to category 1 in the NBCC 2015 Structural Commentary I, article 26, summarized in Table 4.1.7.7 below.

- A positive pressure coefficient indicates pressure against the bottom surface of the paver.

Table 4.1.7.7.
Internal Pressure Coefficients
Forming Part of Sentence 4.1.7.7.(1)

Building Openings	Values for C_{pi}	
Uniformly distributed small openings amounting to less than 0.1% of the total surface area of the *building*	–0.15 to 0.0	Category 1
Non-uniformly distributed openings of which none is significant or significant openings that are wind-resistant and closed during storms	–0.45 to +0.30	Category 2
Large openings likely to remain open during storms	–0.70 to +0.70	Category 3

Taken from NBCC 2015

Internal Exposure Factor Cei: Same as the external exposure factor per Cl. 4.1.7.3.(7).(a) and A-4.1.7.5.(2) and (3)

Cei = 1.207

Internal Gust Factor Cgi

Cgi = 2.07 Cl. 4.1.7.3.10

Internal Pressure Coefficient Cpi:
1- Assume the pavers will rest directly on the roof. Categoty 1 applies.
Cpi = 0.0 (no internal pressure).

Pint = 0.0 kPa

Then, net factored uplift Pf= 0.9 DL + 1.4 WL, where
DL denotes Dead Load
WL denotes Wind Load = (Pext + Pint)

Pf= 0.9 x 1.26 + 1.40 x (-4.02 + 0.0) = -4.49 kPa < 0 Uplift

The pavers require a positive connection to the roof by means of pedestals.

Recalculate Cpi for Category 2

Cpi = +0.3

Internal Pressure Pint = Iw.q1/50.Ct.Cpi.Cgi = 1.0 x 0.59 x1.0 x 0.3 x 2.0

= 0.42 kPa = 8.77 psf

Note: The internal pressure is considered uniform for the whole roof area.

10. Specified wind pressure:

In general the net specified pressure is the algebraic difference between the external and internal pressure:

P = Pext - Pint

Corner P(c) = Pext(c) - Pint = -4.02 - 0.42 = -4.44 kPa = -92.83 psf

Perimeter P(s) = Pext(s) - Pint = -2.62 - 0.42 = -3.04 kPa = -63.59 psf

Interior roof P(r) = Pext(r) - Pint = -1.75 - 0.42 = -2.17 kPa = -45.32 psf

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Load Calculations: Factored loads

11. Factored Uplift pressure

Factored uplift loads for the design of pedestals and connections will be calculated based on the load combinations shown in NBCC 2015 Table 4.1.3.2-A.

The following load combination will be used for the calculation of the uplift pressures acting on the paver slabs:

Factored pressure Pf = 0.9 DL + 1.4 WL

Thus,

For the corner areas Pf(c) = 0.9 x 1.26 + 1.4 x (-4.44) = -5.09 kPa = -106.33 psf

For the Perimeter areas Pf(s) = 0.9 x 1.26 + 1.4 x (-3.04) = -3.13 kPa = -65.40 psf

For the inner roof areas Pf(r) = 0.9 x 1.26 + 1.4 x (-2.17) = -1.91 kPa = -39.81 psf

The corner area factored uplift pressure controls the design of the hold-down system.

In the case of this fictitious example, negative values for the factored pressures indicate a net uplift condition which requires a positive connection to the roof by means of a pedestal system complete with fasteners and adhesive.

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Hold-down Design

12. Factored Uplift loads:

The design is controlled by the roof corner factored pressure.

Design factored load Tf = Pf(c) x slab width x slab length

Thus, Tf = -5.09 kPa x 0.762 m x 0.762 m = -2.96 kN = -664.6 lb

13. Design check of pedestal system components:

It is assumed in this example that the pedestal supplier will provide the Factored resistances of the pedestal system components.

a. Corner hold-down anchors:

1/4"-28 316 Stainless Steel Button head, hex drive screws. 1 anchor per pedestal.

Factored Tension resistance Tr:

Tr = 7.22 kN / screw = 1623.1 lb / screw (provided by pedestal supplier)

Therefore, Tf/Tr = abs(2.96) / 7.22 = 0.41 < 1.0, the fastener is adequate.

b. 4" Hybrid adjustable pedestal:

Factored Tension resistance Tr:

Tr = 13.00 kN / pedestal = 2923.0 lb / pedestal (provided by pedestal supplier)

Therefore, Tf/Tr = abs(2.96) / 13.0 = 0.23 < 1.0, the pedestal is adequate.

c. Adhesive to connect pedestal to roof membrane:

Factored Tension resistance Tr:

Tr = 16.25 kN / pedestal = 3653.0 lb / pedestal (provided by pedestal supplier)

Therefore, Tf/Tr = abs(2.96) / 16.25 = 0.18 < 1.0, the adhesive is adequate.

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14. General notes:

a. The structural capacity and verification of the roof system and the building structural framing is outside the scope of these calculations.

b. Complete structural calculations that include the effects of gravity loads such as dead loads, snow, ice, and rain loads, and roof live loads, combined with wind and seismic loads must be performed by a professional engineer for all structural and non-structural building components as required by the National Building Code of Canada 2015 and applicable provincial codes .