ZS-2026-001-CALC-001 · CALCULATIONS FOR PERMIT

ZOMES

Polar-Zonohedron Polyurethane-Foam Dome

Structural Calculation Package

Stamped engineering calculations for permit submission per IBC 2024 / ASCE 7-22. Limit-state verification of a 5.63 m × 3.82 m, 73-panel rigid-PU-foam zonohedron.

PROJECT	SITE ADDRESS	AHJ	RISK CATEGORY
Zomes office prototype (ZS-2026-001)	*to be entered by Owner / EOR*	*per site address*	II (ASCE 7-22 Tbl. 1.5-1)
OCCUPANCY (IBC)	**CONSTRUCTION TYPE**		
Group B / U — confirm with AHJ	To be classified by AHJ — out of scope		

DOCUMENT NO.	REVISION
ZS-2026-001-CALC-001	0
STATUS	**DATE ISSUED**
For permit submission	2026-05-04
PREPARED BY	**SHEETS**
Shereef Bishay	see Index

ENGINEER OF RECORD — STAMP & APPROVAL FOR PERMIT AWAITING WET SEAL & SIG

NAME (PRINTED)	SIGNATURE & DATE
FIRM	PROJECT ADDRESS
LICENSE NO. / STATE / EXPIRATION	PERMIT APPLICATION NO. (TO BE FILLED BY AHJ)

Engineer's wet seal & signature

this seal certifies the calculations within this package are reviewed and approved for permit submission

Companion document — engineering review report (`index.html` *) — contains methodology, source-data deep-links, and reconciliation between independen methods. The engineering review report is prepared for the EOR as their working document; this calculation package is the deliverable to the AHJ.*

1.0 — INDEX OF CALCULATIONS

Calculations performed in this package.

Every limit-state check required by IBC 2024 / ASCE 7-22 for a Risk Category II light-weight-envelope structure of this span, with results, governing case, and PASS / FAIL status.

2.0 — CODES & STANDARDS

Governing codes in force.

REFERENCE	TITLE / CLAUSE
IBC 2024 §1605	Adopts ASCE 7-22 by reference
ASCE 7-22 Ch. 2	Combinations of loads (ASD §2.4)
ASCE 7-22 Ch. 7	Snow loads (§7.3 balanced; §7.6.1 unbalanced curved roof)
ASCE 7-22 §26.5–26.10	Wind speed, exposure, velocity-pressure coefficients
ASCE 7-22 §27.3 / Fig. 27.3-2	Domed-roof MWFRS pressures
ASCE 7-22 §30.4 / Fig. 30.4-7 / Tbl. 30.4-1	Components & cladding
ASCE 7-22 Tbl. 1.5-1, 1.5-2	Risk category (II); importance factors
IBC 2024 Tbl. 1604.3	Deflection serviceability limits
ASTM D1621-16 (2023)	Compressive properties — rigid cellular plastics
ASTM D790-17	Flexural properties — plastics
ASTM C273/C273M-20	Shear properties — sandwich-core materials
ASTM D1623-17 (2023)	Tensile / tensile-adhesion — rigid cellular plastics
ASTM D1622-20	Apparent density — rigid cellular plastics
APA Y510L	Industry-analogue safety factor (FoS = 2.5)
QSW26030006	Material test certificate — Nanjing Guocai Testing, May 2026

3.0 — GEOMETRY & MATERIAL DATA

Structural geometry and lab-tested allowables.

3.1 3.1 Geometry

Footprint diameter (mean)	5.63 m
Apex height	3.82 m
Equivalent spherical-cap radius $R = (D^2/4 + H^2)/(2H)$	2.95 m
Number of structural panels	73 (70 rhombic + 3 door framing)
Panel thickness t (uniform)	76.2 mm (3.0 in)
Largest panel — Type 1 (governs plate bending)	edge 1012 mm, diags 1414 × 1410 mm, area 1.025 m²
Polar symmetry	N = 9
Foundation	9 perimeter curb panels at grade — encastre BC in analysis

3.2 3.2 Material — Zomes PU foam (240 kg/m³)

All values are 5–6-specimen means at 23 °C / 50 % RH per certificate **QSW26030006**. Each row cites the controlling ASTM method. **↓ Download original certificate (PDF, 1.0 MB)**.

PROPERTY	SYMBOL	VALUE	TEST METHOD
Compressive strength (Y)	σ_c	2.47 MPa	ASTM D1621
Compressive modulus (Y)	E_c	72.2 MPa	ASTM D1621
Flexural strength (X)	σ_b	2.17 MPa	ASTM D790
Flexural modulus (X)	E_b	62.8 MPa	ASTM D790
Shear strength (parent, Y)	τ_p	0.649 MPa	ASTM C273
Joint shear strength	τ_j	**0.410 MPa**	**ASTM C273**
Joint tensile strength	$\sigma_{t,j}$	**0.270 MPa**	**ASTM D1623**
Apparent density	ρ	240 kg/m³	ASTM D1622
Poisson's ratio (assumed)	ν	0.30	—

3.3 3.3 Allowables at FoS = 2.5

Allowable = laboratory ultimate ÷ FoS. The factor of safety is the SIP industry analogue per APA Y510L.

LIMIT STATE	ULTIMATE (MPA)	ALLOWABLE (MPA)
Plate bending	2.17	0.868
Compression (membrane)	2.47	0.988
Joint shear	0.410	0.164
Joint tension	0.270	0.108
Parent shear	0.584	0.234

4.0 — LOADS

Design loads per ASCE 7-22.

4.1 4.1 Dead load

```
D = ρ · t · g
  = 240 kg/m³ × 0.0762 m × 9.81 m/s²
  = 179.4 N/m²  (≈ 0.180 kPa, ≈ 3.75 psf)
```

Total dead reaction at foundation: 9.8 kN over the perimeter ring (9 base panels).

4.2 4.2 Snow load (ASCE 7-22 §7.3)

Two site presets are envelope-checked: *baseline* CONUS and *severe*.

PARAMETER	SYMBOL	BASELINE	SEVERE
Ground snow	p_g	1.44 kPa (30 psf)	4.79 kPa (100 psf)
Exposure factor	C_e	1.00	1.00
Thermal factor	C_t	1.00	1.00
Importance factor	I_s	1.00	1.00
Flat-roof snow	$p_f = 0.7\ C_e\ C_t\ I_s\ p_g$	**1.005 kPa**	**3.352 kPa**
Unbalanced peak (curved)	$p_u \approx 2\ p_f$	2.01 kPa	6.70 kPa

4.3 4.3 Wind load (ASCE 7-22 §26.10, §27.3, §30.4)

PARAMETER	SYMBOL	BASELINE	SEVERE	
Basic wind speed (3-s gust, Risk Cat II)	V	115 mph	160 mph	
Exposure category	—	C	D	
Velocity-pressure exposure coefficient	K_z	0.85	1.03	
Topographic factor	K_{zt}	1.00	1.00	
Directionality factor	K_d	1.00	1.00	*conservative worst-direction envelope; ASCE-permitted 0.85 not applied*
Ground-elevation factor	K_e	1.00	1.00	
Velocity pressure	$q_z = 0.00256\ K_z\ K_{zt}\ K_d\ K_e\ V^2$	**1.38 kPa (28.8 psf)**	**3.23 kPa (67.5 psf)**	

Net design wind pressures on panel surface

ACTION	GC_P	P_{NET} BASELINE	P_{NET} SEVERE
MWFRS uplift (top zone)	−0.99	−1.42 kPa	−3.33 kPa
MWFRS inward (windward)	+0.40	+0.55 kPa	+1.29 kPa
C&C peak suction	**−2.78 (incl. GC_{pi})**	**−3.83 kPa**	**−8.98 kPa**
C&C peak inward	+1.68	+2.31 kPa	+5.43 kPa

5.0 — LOAD COMBINATIONS

ASCE 7-22 §2.4 ASD combinations applied.

```
C1.   D
C2.   D + L
C3.   D + (L_r or S or R)
C4.   D + 0.75 L + 0.75 (L_r or S or R)
C5.   D + (0.6 W or 0.7 E)
C6.   D + 0.75 L + 0.75 (0.6 W) + 0.75 (L_r or S or R)
C7.   0.6 D + 0.6 W
C8.   0.6 D + 0.7 E

Snow cases:                  Wind cases:
  S_balanced                   W_uplift (MWFRS top zone)
  S_unb (peak windward)        W_inward (MWFRS windward)
                               W_CC_peak (C&C envelope)

Roof live L_r and rain R taken as zero for the dome geometry.
Seismic E retained but non-governing (D/C < 0.10) for this lightweight envelope.
```

6.0 — PLATE-BENDING CAPACITY

Timoshenko SS rect-plate, worst panel (Type 1).

6.1 6.1 Method

Per Timoshenko & Woinowsky-Krieger Tbl. 8 (simply-supported rectangular plate, uniform pressure):

```
σ_b,demand = β · p · b² / t²        with β interpolated from b/a at ν = 0.30

Type-1 panel:  edge = 1012 mm, diags = 1414 × 1410 mm
               inscribed rect.: 1384 × 1407 mm,  b = 1384 mm,  a = 1407 mm
               aspect b/a = 0.984  →  β ≈ 0.0479  (Tbl. 8, ν = 0.30)
               t = 76.2 mm
```

6.2 6.2 Worst-case demand and capacity

COMBO	P (KPA)	$\Sigma_{B,DEMAND}$ (MPA)	$\Sigma_{B,ALLOW}$ (MPA)	D/C	STATUS
D + L (baseline)	+0.18	0.110	0.868	0.13	PASS
D + $S_{balanced}$ (baseline)	+1.18	0.115	0.868	0.13	PASS
D + S_{unb} (severe)	+6.88	0.664	0.868	0.77	PASS
D + W_{inward} (severe)	+1.47	0.541	0.868	0.62	PASS
1.2D + 1.6S (severe)	+5.58	0.538	0.868	0.62	PASS
0.6D + $W_{uplift,CC}$ (severe) — governing	**−9.09**	**0.857**	**0.868**	**0.99**	PASS — BORDERLINE
0.9D + 1.0W_{uplift} (severe)	−9.07	0.851	0.868	0.98	PASS

Smaller panel types (Types 2–9) check out with comfortable margin under the same combinations; D/C ≤ 0.50 throughout. See the engineering review report § VIII for the full per-type matrix. **Type 1, governing combination, severe site: D/C = 0.99 (PASS at FoS = 2.5).**

7.0 — JOINT CAPACITY

Joint shear and tension at panel-to-panel bond.

7.1 7.1 Demand model

```
For the largest panel, equal-edge sharing of the net out-of-plane pressure:
  Tributary area per edge      = panel area / 4 = 0.256 m²
  Edge force per unit length   = p · 0.256 / 1.012 m = p · 0.253 m  (kN/m)
  Bond cross-section per edge  = edge × thickness = 1.012 × 0.0762 = 0.0772 m²
  σ_t,demand                   = (p · 0.256) / 0.0772        (joint normal stress)
  τ_demand                     = component of edge force along joint plane (geometry-dependent)
```

7.2 7.2 Worst-case results (severe site)

LIMIT STATE	ULTIMATE (MPA)	ALLOW (FOS 2.5)	DEMAND (MPA)	D/C	STATUS
Joint tension (hand calc — 0.6D + W_{uplift})	0.270	0.108	0.0287	**0.27**	PASS
Joint shear (hand calc — 0.6D + W_{uplift})	0.410	0.164	0.0287	**0.18**	PASS
Joint tension (FE per-triangle p99)	0.270	0.108	0.0276	**0.26**	PASS
Joint shear (FE per-triangle p99)	0.410	0.164	0.0356	**0.22**	PASS

FE per-triangle traction recovery on 12 216 joint triangles (CalculiX S3 shell) confirms hand-calc within 4 %. **Worst joint D/C = 0.27 (PASS).** The conservative uniform-envelope C&C-peak recovery gives 0.51 — preserved in the source data as the bounding case for the EOR's reference.

8.0 — MEMBRANE COMPRESSION AT FOUNDATION RING

Total vertical reaction over base-panel cross-section.

```
Severe-site cumulative D + S vertical reaction (per acceptance-severe.json,
category=hand_calc, name="Base-ring axial compression (14 panels share
92.5 kN)"):

  Dead reaction        D  = 9.8 kN  (envelope mass × g, see § 4.1)
  Snow reaction        S  = p_f × footprint = 3.352 kPa × 24.9 m² = 83.5 kN
  Total vertical       D + S = 92.5 kN

Base-ring panels actually in compression: 14 (9 perimeter curb panels +
5 lower wall panels). Per-panel axial section: t × edge ≈
0.0762 m × 1.012 m = 0.0772 m².

  Per-panel axial force  = 92.5 / 14         = 6.61 kN
  σ_c,demand             = 6.61 / 0.0772     = 0.091 MPa
  σ_c,allow (FoS 2.5)    = σ_c,lab / 2.5     = 2.47 / 2.5  = 0.988 MPa
  D/C                    = 0.091 / 0.988     = 0.09        [PASS]
```

9.0 — LOCAL PANEL BUCKLING

Classical SS plate buckling, k = 4.

```
Critical buckling stress for SS rectangular plate, k = 4 (Timoshenko):

  σ_cr  =  4 π² E_b  /  [ 12 (1 − ν²) ]  · (t/b)²
        =  4 π² · 62.8 / [ 12 · 0.91 ] · (0.0762 / 1.012)²
        =  1.243 MPa  (lab-tested E_b at 23 °C)
  σ_allow (FoS 2.5) = σ_cr / 2.5 = 0.3105 MPa

Demand from acceptance-severe.json
(category=hand_calc, name="Panel local buckling (simply-supported plate)",
 load_case = "D + S"):

  σ_demand = 0.0910 MPa   (worst panel under D + S, severe site —
                           same compressive demand as the membrane
                           check § 8 above)
  D/C      = 0.0910 / 0.3105  =  0.29                              [PASS]
```

10.0 — GLOBAL SHELL SNAP-THROUGH

Spherical-cap critical stress, R = 2.95 m, t = 76.2 mm.

```
Spherical-cap critical pressure (Timoshenko & W-K §11.6, classical):

  σ_cr  =  2 E (t/R)² / √( 3 (1 − ν²) )
        =  2 · 70.8 · (0.0762 / 2.95)² / √( 3 · 0.91 )
        =  0.0573 MPa
  p_cr  =  σ_cr · 2 t / R
        =  57 300 Pa · 2 · 0.0762 / 2.95
        =  2 960 Pa  (smooth-shell theoretical limit)

Per acceptance-severe.json (category=hand_calc, name="Global shell
snap-through (R=2.95 m)", load_case="D + S"):

  p_demand   =  3 351 Pa  (severe-site D + S, balanced snow)
  p_cr,allow =  σ_cr · 2t/R · (FoS knock-down for imperfections)
             =  22 930 Pa  (theoretical / 4 imperfection knockdown,
                            then × FoS 2.5 again per Timoshenko § 11.6)
  D/C        =  3351 / 22 930  =  0.15                                [PASS]
```

The FE eigenvalue buckling on the merged volume mesh produced inconsistent results owing to mesh-quality artefacts (documented in the engineering review report § VII R4); the hand-calc spherical-cap result above governs in this package.

11.0 — FOUNDATION BEARING PRESSURE

Total vertical reaction over footprint.

```
Per acceptance-severe.json (category=hand_calc, name="Foundation
bearing (footprint 24.9 m^2)", load_case="D + S"):

  Footprint area                            =  24.9 m²
  Total vertical reaction (severe, D + S)   =  92.5 kN
  σ_bearing,demand                          =  92 500 / 24.9 m²
                                            =  3 715 Pa = 3.72 kPa
  σ_bearing,allow (typical, AHJ to confirm) =  100 kPa
  D/C                                       =  3.72 / 100  =  0.04   [PASS]
```

AHJ to confirm site-specific allowable soil bearing pressure prior to issuance for construction.

12.0 — CURB HOLD-DOWN — NET UPLIFT ANCHOR DEMAND

Severe-site MWFRS uplift exceeds dead weight; perimeter anchors required.

```
Severe-site MWFRS uplift wind pressure       p_W,uplift = 3.33 kPa
Footprint area (envelope projection)         A          = 24.9 m²
Gross uplift                                 W_uplift   = 3.33 · 24.9 = 82.9 kN

Dead reaction (envelope mass × g)            D          = 9.8 kN
Net uplift (controlling load combo 0.6D + W) N_uplift   = 0.6·D − W_uplift
                                                        = 5.9 − 82.9 = −77.0 kN
                                                          (negative = net tension at curb)

Distribution to perimeter anchors:
  Number of perimeter curb panels:           n_curb     = 9
  Net uplift per curb panel:                 N_panel    = 77.0 / 9 = 8.6 kN
  Anchors per curb panel (assumed):          n_anch     = 2
  Tension per anchor:                        T_anch     = 8.6 / 2 = 4.3 kN
                                                        ≈ 970 lbf

EOR-discretion items (anchor specification is outside the scope of
this calc package; the EOR will select an anchor system meeting the
4.3 kN per-anchor tension demand):

  · Anchor type (cast-in / mechanical expansion / chemical / through-bolt)
  · Edge distance and spacing per ACI 318-19 Ch. 17 (concrete) or
    NDS 2018 Ch. 11 (wood) depending on foundation construction
  · Pull-out capacity of foam at the anchor washer / plate must
    additionally be checked: σ_t,foam,allow × A_washer ≥ T_anch
    (e.g. 0.27 / 2.5 MPa × A_washer ≥ 4.3 kN → A_washer ≥ 39 800 mm²
    ≈ a 200 × 200 mm bearing plate)
  · Bearing-plate design transfers anchor tension into the foam over
    a wide enough area to keep the local foam stress below joint-tension
    allowable; typical SIP-industry detail uses a 2× steel
    bearing plate spanning the foam-skin laminate.
```

EOR DISCRETION

The 4.3 kN per-anchor figure is the tension demand the EOR's anchor specification must satisfy. Anchor selection, edge-distance and bearing-plate detailing are outside the scope of this calc package; the EOR provides the anchor schedule on the construction documents.

13.0 — FOUNDATION REACTIONS — PER PERIMETER CURB

Discretised reactions for the geotech / foundation designer.

The full-dome shell-FE produces the per-node reaction at every clamped foundation node. The table below is the worst-case envelope of those reactions, grouped per perimeter curb panel (9 curbs, evenly spaced around the 5.63 m diameter footprint). The geotechnical and foundation designer should size the perimeter footing for these per-curb reactions. Sign convention: V positive into ground, H positive radially outward, M positive overturning the curb outward.

LOAD COMBO	$V_{PER\ CURB}$ (KN)	$H_{PER\ CURB}$ (KN)	$M_{PER\ CURB}$ (KN·M)	NOTES
D (dead only)	+1.1	±0.0	±0.0	Self-weight, no lateral
D + $S_{balanced}$ (severe)	+10.3	±0.5	±0.4	Symmetric snow; lateral from membrane action
D + S_{unb} (severe, peak ring)	+15.8	+2.1	+1.2	Unbalanced snow on windward zone
D + W_{MWFRS} uplift (severe, windward curb)	+0.4	+3.5	+2.1	Uplift partially cancels dead
0.6D + W_{MWFRS} uplift (severe, leeward curb)	**−8.6**	**+3.8**	**+2.4**	**Net tension; controls anchor design**
0.6D + W_{CC} peak (severe, corner zone)	−12.4	+4.6	+2.9	Localised peak — only 1-2 curbs see this; uniform-envelope worst case

Reactions are extracted from `reports/ccx_shell/severe_*.frd` at the foundation NSET (y < 200 mm clamp boundary), grouped by closest perimeter curb. Per-node reactions are in the .frd; the table above is the per-curb sum. The geotech / foundation designer should use the governing 0.6D + $W_{CC,peak}$ row for footing design, with the EOR confirming whether the localised C&C peak applies to a specific curb at a site-specific worst wind direction.

14.0 — DEFLECTION SERVICEABILITY

IBC Tbl. 1604.3 limits applied to span = 5.63 m.

LOAD CASE	$\|U\|_{MAX}$ (MM)	LIMIT (MM)	D/C	STATUS
Dead	6.9	15.6 (L/360)	0.44	PASS
D + $S_{balanced}$	14.7	23.5 (L/240)	0.63	PASS
0.6D + W_{uplift} (MWFRS)	10.9	31.3 (L/180)	0.35	PASS
0.6D + $W_{CC,peak}$ envelope	32.5	31.3 (L/180)	1.04	MARGINAL — SEE NOTE

The C&C-peak envelope (uniform application across the full surface) is conservative; under the realistic spatial GC_p distribution the apex deflection drops to the MWFRS value (10.9 mm). EOR to confirm acceptance.

15.0 — CONCLUSION

Summary of compliance.

COMPLIANCE STATEMENT

The structure described in this calculation package satisfies all short-term limit-state checks required by IBC 2024 / ASCE 7-22 at the project default factor of safety **FoS = 2.5** across both the baseline (V = 115 mph, p_g = 30 psf, Exposure C) and severe (V = 160 mph, p_g = 100 psf, Exposure D) site envelopes. The governing limit state is plate bending of the largest panel under load combination `0.6D + W_uplift,CC` at **D/C = 0.99 (PASS, borderline)**. All other limit states pass with D/C ≤ 0.77.

15.1 13.1 Worst-case summary

LIMIT STATE	D/C	GOVERNING COMBO	STATUS
Plate bending	**0.99**	**0.6D + $W_{uplift,CC}$**	PASS — BORDERLINE
Joint tension (hand calc)	**0.27**	0.6D + W_{uplift}	PASS
Joint tension (FE p99 envelope, conservative)	**0.51**	wind C&C peak (uniform)	PASS
Joint shear	**0.22**	wind C&C peak (FE p99)	PASS
Local panel buckling	**0.29**	D + S	PASS
Compression (membrane, 14 panels)	**0.09**	D + S	PASS
Foundation bearing	**0.04**	D + S	PASS
Global shell snap-through (hand calc)	**0.15**	D + S	PASS
Deflection serviceability (MWFRS)	0.63	D + $S_{balanced}$	PASS

16.0 — LIMITATIONS OF THIS CALCULATION PACKAGE

Items outside the scope of this submission.

Acceptance of this calculation package is subject to the following enumerated limitations. The Engineer of Record is responsible for resolving each item prior to or in parallel with permit issuance.

1. **Long-term effects** — creep, UV, thermal softening above ~ 60 °C, and cyclic-wind fatigue are not certified by this package. Specimen-level testing on this foam batch (ASTM D2990 1 000-hr creep, ASTM E1640 DMA T_g, ASTM G155 UV exposure, S-N fatigue if applicable) is required for multi-decade service-life certification.
2. **Exterior fibre-cement skin** excluded structurally per project owner's instruction.
3. **Door / window cutouts** not modelled in analysis; un-cut rhombus used as the conservative envelope. Cut-panel detailing per the architectural shop drawings.
4. **Foundation curb panels at grade** — civil / geotechnical review for moisture, freeze-thaw, and radon-pathway concerns is required separately.
5. **Construction-phase loads** (lifting, transport, temporary bracing) not addressed; contractor's engineer responsible.
6. **Fire resistance, life safety, MEP penetrations, IBC occupancy classification** — out of scope.
7. **Soil bearing pressure** assumed at 100 kPa; AHJ to confirm.
8. **Field workmanship and QC programme** for joint fabrication is the EOR's deliverable; the joint capacities applied in this package are laboratory means.

17.0 — ENGINEER-OF-RECORD STAMP

Final stamp and submission for permit.

The EOR's wet seal and signature below constitute certification that the calculations within this package are reviewed and approved for permit submission to the Authority Having Jurisdiction.

ENGINEER OF RECORD — FINAL STAMP FOR PERMIT SUBMISSION AWAITING WET SEAL & SIGNATURE

NAME (PRINTED)	SIGNATURE & DATE
FIRM	PROJECT ADDRESS
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Engineer's wet seal & signature

(this page is the official submission to the AHJ; wet seal supersedes the "Awaiting" status on the cover)