# Between Rain
# Integrated Water-Catchment Canopy

Common Ground · Reports 01–03

1. Structure: Karamba3D frame check

2. Water: does the skin drain?

3. Skin: glass or ETFE?

Sharon Robinson · October 2026

# Structure: Karamba3D frame check

*Between Rain · Integrated Water-Catchment Canopy · Assignment 4 report, section 1 of 3*

**PROVISIONAL.** A design-development check by the designer, not engineering certification. Loads, load factors and deflection limits are assumed (AS/NZS 1170 to be confirmed) and every result is to be verified by a structural engineer.

**Approved changes stated on this report** (my decisions, 9 Oct 2026):

- rib pattern from the Test 19 tile (route a)
- hooks removed at V-joints (option c)
- level short ends
- Canopy_Lift +300 mm: throat 2.05 m, branch node 3.11 m, crowns 5.57 m, level ends 4.89 m
- slim collar ring CHS 48.3 × 3.2 kept
- short-end overhang 3.1 m (outline 51.2 × 38.0 m, was 54.0 × 38.0 m) with end ribs CHS 76.1 (adopted frame v11g)
- glass skin load revised to 0.65 kPa for the glass comparison

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## 0. Frame development

The canopy's form was settled on 7 October by **Test 19**, a form study in Rhino. Trunk, branches and roof became one continuous system: 20 vertical members per funnel rise past the throat and split into the crossed ribs of the canopy, so it reads as a grove rather than a roof on columns. It was a study of form only. Every member was the same thickness, the bracing was assumed to come from the glass and the skin, and the sheet itself recorded "Structure NOT checked".

On 8 October the canopy was rebuilt in Grasshopper so that it could be analysed. The Test 19 rib pattern was kept, as a tile repeated on the structural grid; each tree became 26 trunk members with the branch node at 2.81 m (3.11 m after the +300 mm lift). The steel was then added in stages: hoops, a ring base plate and a footing for each tree, then a hierarchy of member sizes. Two problems raised in the Test 19 critiques, "everything is the same thickness" and "the trunk base reads as bars", are the ones this hierarchy and the hoops and base plate later answered.

Karamba3D then checked the rebuilt frame. That is where the results below begin.

*Figure 0a.* Test 19, long view along the rows (form study, 7 Oct 2026; structure not checked; opaque placeholder skin).
`Model/Test19_Trunks_Verticals_Only_views_v01/A4_T19_1_Test19_6_long_view_along_rows_28mm.png`

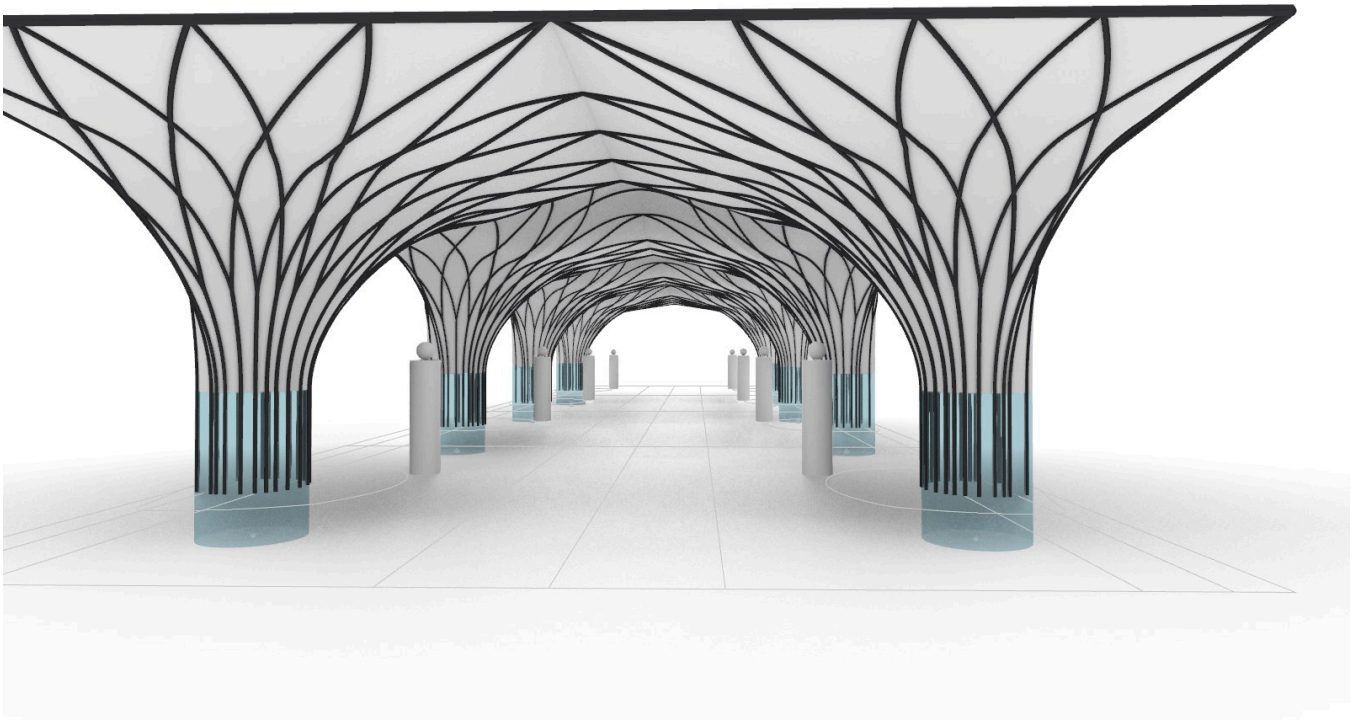
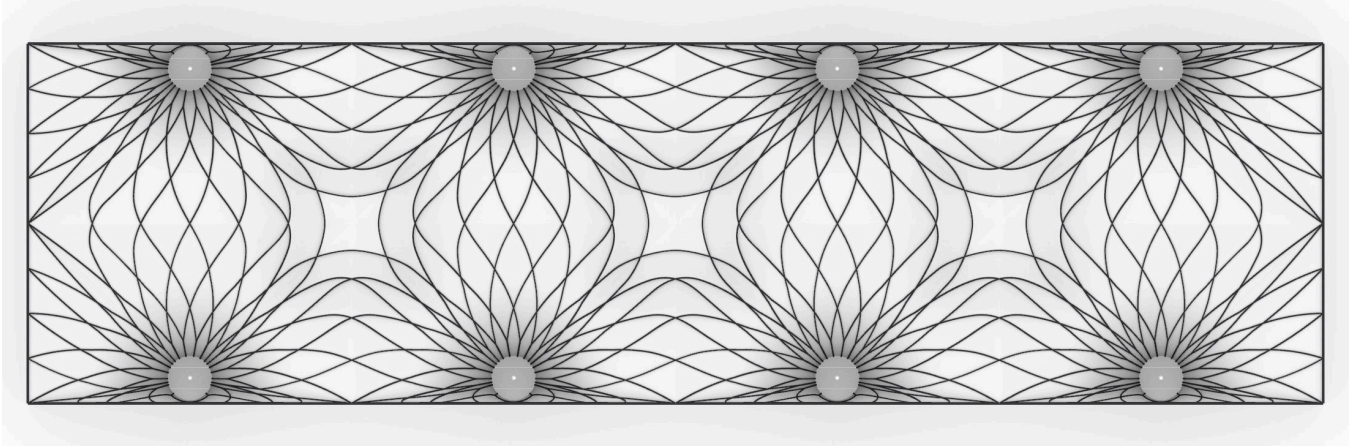


*Figure 0b.* Test 19, roof plan of four bays by two rows: the rib pattern carried into the adopted frame (compare Figure 5).
`Model/Test19_Trunks_Verticals_Only_views_v01/A4_T19_1_Test19_1_roof_plan.png`



## 1. Why the check was run

The canopy is a field of 24 steel “trees”: each trunk of 26 tubes opens into a funnel and a web of ribs that carries the skin and channels rain to the downpipe at the trunk’s core. Two questions had to be answered before the skin could be chosen and the frame drawn:

1. Is the frame strong and stiff enough, and where does it work hardest?
2. How much does the skin choice (heavy glass or light ETFE) change the answer?

## 2. What was tested

**Model.** The full steel frame, built in Grasshopper and analysed in Karamba3D (EDU licence) through the Karamba scripting API from Rhino:

- 24 trees, 26 trunk members each; 3 hoops per tree; smooth rib network; edge beam
- 18,206 to 19,454 beam elements (19,216 in the adopted frame); bases fixed; no loose rib ends (checked)
- steel S355, E 210 GPa
- solver check: a 1 m CHS 60.3 cantilever gave 0.120 mm in Karamba against 0.119 mm by hand

**Assumed loads** (AS/NZS 1170, to confirm):

| Load | Value |
|---|---|
| Glass skin, including fixings | 0.50 kPa (revised to 0.65 kPa for the glass comparison) |
| ETFE skin, including fixings | 0.12 kPa |
| Roof live load | 0.25 kPa |
| Wind uplift | 0.50 kPa |
| Uniform temperature change | ±25 °C |

**Load cases**

| Case | Combination |
|---|---|
| Strength (ULS) | 1.2 G + 1.2 skin + 1.5 Q |
| Uplift | 0.9 G + 0.9 skin + Wu |
| Sag (SLS) | G + skin + 0.7 Q |
| Temperature | ±25 °C uniform; thermal-only cases TH± reported separately |

**Sag guide** (to confirm): span/250 in the bays and overhang/125 at the edges, about 36 mm. Glass needs it; ETFE tolerates more movement.

**Simplification.** The skin load is spread evenly over all canopy steel, not panel by panel; to be refined once the panels are final.

## 3. Results

### 3.1 Four options for the collar ring and end ribs (Canopy_Lift +300, 4.5 m short-end overhang)

| | A No ring | B Slim ring CHS 48.3 | C Ring + end ribs CHS 76.1 | D Ring + end ribs CHS 88.9 |
|---|---|---|---|---|
| Sag, short ends, glass (4.5 m overhang) | 136 mm | 89 mm | 74 mm | 66 mm |
| Sag, short ends, ETFE | 80 mm | 53 mm | 45 mm | 41 mm |
| Sag, long edges, glass (3.1 m overhang) | 43 mm | 20 mm | 20 mm | 20 mm |
| Sag, interior bays, glass | 30 mm | 24 mm | 24 mm | 25 mm |

| | A No ring | B Slim ring CHS 48.3 | C Ring + end ribs CHS 76.1 | D Ring + end ribs CHS 88.9 |
|---|---|---|---|---|
| Sag, funnels, glass | 13 mm | 7 mm | 7 mm | 7 mm |
| Highest utilisation (1.0 = capacity) | **1.17 hoops (fail)** | 0.94 | 0.82 | 0.84 |
| Trunk member max compression | 25 kN | 16 kN | 16 kN | 16 kN |
| Temperature only ±25 °C, max movement | 9 mm | 8 mm | 8 mm | 8 mm |
| Steel in the model | 85.0 t | 86.4 t | 87.3 t | 88.5 t |

*Figure 1.* Utilisation plans A–D (`Model/v11d_S4_Karamba_views_v01/S4_util_plans_A-D_v11e.png`).

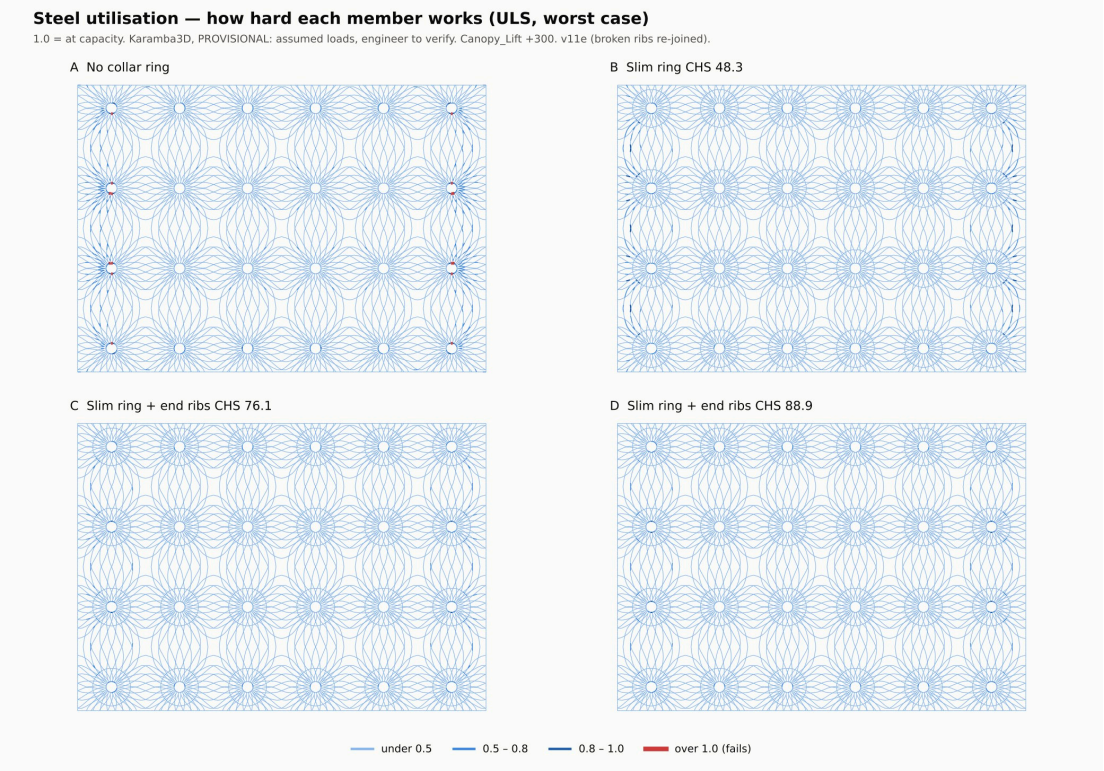



*Figure 2.* Glass sag plans A–D (`S4_defl_plans_A-D_v11e.png`).

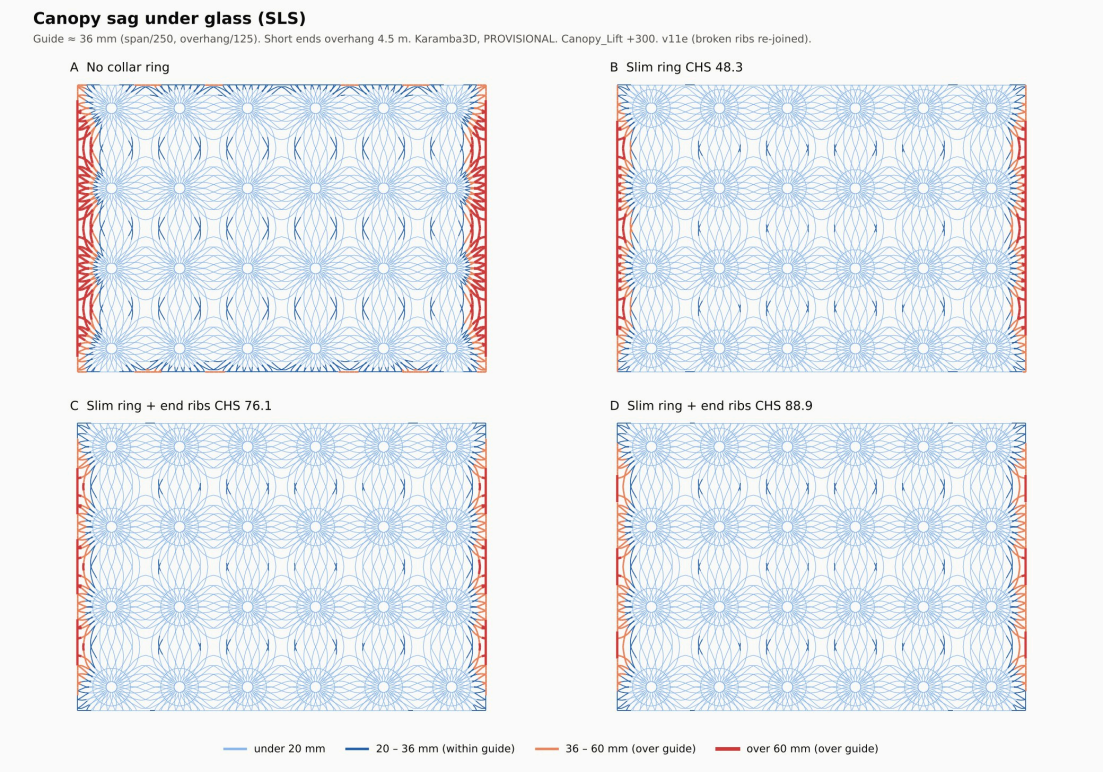
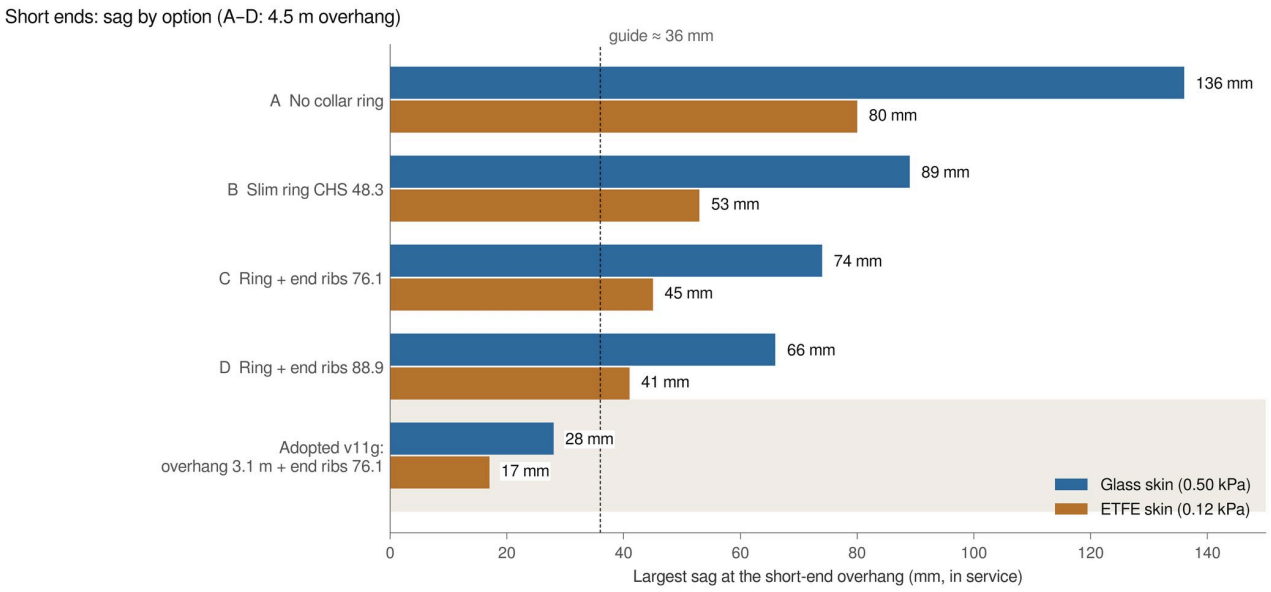


*Figure 3.* Short-end sag by option, including the adopted frame (`Production/Sheets/sim_v03/B1_support_short_end_sag_v03.png`).




### 3.2 Follow-up: deeper short-end edge beam (b) and stiffer outer trees (e), all with the slim ring

| Run | End ribs | Short-end edge beam | Outer trees (e) | Short-end sag glass | ETFE | Bays glass | Highest util. | Steel |
|---|---|---|---|---|---|---|---|---|
| C (reference) | 76.1 | 114.3 | — | 74 mm | 45 mm | 24 mm | 0.82 | 87.3 t |
| E1 | 76.1 | 168.3 | — | 70 mm | 45 mm | 25 mm | 0.85 | 88.4 t |
| E2 | 76.1 | 219.1 | — | 69 mm | 47 mm | 25 mm | 0.88 | 89.8 t |
| E3 | 76.1 | 114.3 | yes | 52 mm | 32 mm | 24 mm | 0.67 | 93.2 t |
| E4 | 76.1 | 168.3 | yes | 48 mm | 31 mm | 24 mm | 0.70 | 94.4 t |
| E5 | 76.1 | 219.1 | yes | 47 mm | 32 mm | 24 mm | 0.76 | 95.8 t |
| E6 | 88.9 | 219.1 | yes | 43 mm | 30 mm | 24 mm | 0.78 | 97.0 t |

Option (e) as tested gave the 8 outer-row trees primary ribs CHS 114.3 (from 88.9) and a collar ring CHS 76.1. **This breaks the approved member hierarchy** (the primary ribs would equal the trunk diameter). It was raised as an OMISSION ALERT and **was not adopted**.

### 3.3 Option (c): short-end overhang 4.5 → 3.1 m (tested with my approval)

Slider `Canopy_EdgeX` 4500 → 3100, so the short ends match the long edges. Outline 54.0 × 38.0 → 51.2 × 38.0 m; skin 2,280 → 2,177 m². 1,256 ribs, 56 V-joints (8 short-end V-joints fall away), 0 broken ribs, 0 tight bends, no loose ends. Skin ponding check: no hollows. (A comparison with 101.6 outer primaries was not approved, so it was not run.)

| | Short-end sag glass | ETFE | Long edges | Bays | Funnels | Highest util. | Steel |
|---|---|---|---|---|---|---|---|
| (c) + standard ribs (60.3 at the ends) | 37 mm | 21 mm | 19 mm | 23 mm | 5 mm | 0.61 | 85.2 t |
| (c) + end ribs CHS 76.1 | **28 mm** | **17 mm** | 19 mm | 23 mm | 5 mm | 0.61 | 85.7 t |
| for comparison: 4.5 m + end ribs 76.1 (C) | 74 mm | 45 mm | 20 mm | 24 mm | 7 mm | 0.82 | 87.3 t |

Trunk member max compression 16 kN; temperature-only movement 7 mm. With standard 60.3 end ribs the glass result is 1 mm over the guide; with 76.1 end ribs it passes clearly, within the approved hierarchy (76.1 < 88.9 < 114.3) and with less steel than option C.

### 3.4 Adopted frame v11g (my decision, 9 Oct: option (c) with the 76.1 end ribs)

| Zone | Sag, glass (SLS, 0.50 kPa) | Sag, ETFE (SLS) |
|---|---|---|
| Short ends | 28 mm | 17 mm |
| Long edges | 19 mm | 11 mm |
| Interior bays | 23 mm | 13 mm |

| Zone | Sag, glass (SLS, 0.50 kPa) | Sag, ETFE (SLS) |
|---|---|---|
| Funnels | 5 mm | 3 mm |

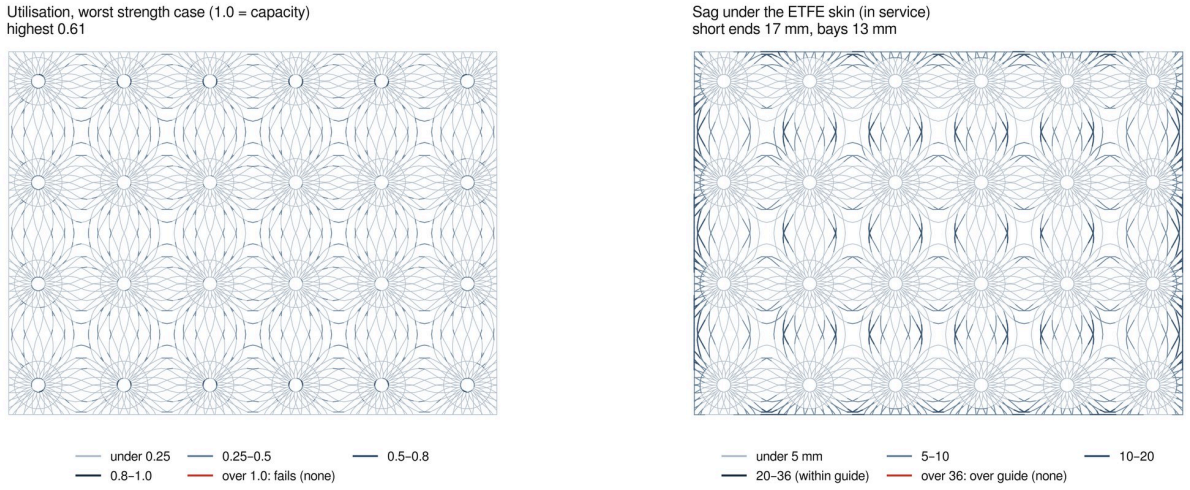
- Highest utilisation 0.61 (hoops, ULS glass); trunk member max compression 16 kN; temperature-only movement 7 mm.
- **Every zone is within the ≈ 36 mm guide for both skins.**

Highest utilisation by member type in the adopted frame (from the Karamba report; worst of each case, "95 %" = 95 % of pieces below):

| Member | ULS glass | ULS ETFE | Uplift (glass / ETFE) | Temperature T+ / T− | Pieces |
|---|---|---|---|---|---|
| Hoop | 0.61 (95 % < 0.46) | 0.38 | 0.07 / 0.10 | 0.45 / 0.30 | 1,872 |
| Field rib | 0.50 (95 % < 0.31) | 0.30 | 0.05 / 0.08 | 0.28 / 0.28 | 4,976 |
| End rib | 0.38 (95 % < 0.29) | 0.24 | 0.06 / 0.05 | 0.23 / 0.28 | 640 |
| Collar ring | 0.33 (95 % < 0.24) | 0.21 | 0.05 / 0.05 | 0.20 / 0.22 | 1,248 |
| Trunk | 0.25 (95 % < 0.19) | 0.16 | 0.04 / 0.04 | 0.19 / 0.13 | 3,120 |
| Primary rib | 0.24 (95 % < 0.19) | 0.16 | 0.04 / 0.04 | 0.18 / 0.13 | 6,868 |
| Edge beam | 0.15 (95 % < 0.13) | 0.10 | 0.02 / 0.02 | 0.09 / 0.11 | 492 |

No piece is over 1.0 in any case. Max displacements: ULS glass 39 mm, ULS ETFE 25 mm; uplift 6 mm (both skins); T+ 23 mm, T− 25 mm (combined cases); TH± 7 mm (temperature only).

*Figure 4.* Adopted frame: utilisation and sag under ETFE (`Production/Sheets/sim_v03/B1_main_adopted_frame_v03.png`).




### 3.5 Glass load revised to 0.65 kPa (approved by me, 9 Oct)

A realistic glass build-up from research R1 (outer 8 mm heat-strengthened, coated and fritted / cavity / 6 + 6 heat-strengthened laminated with a frosted interlayer, plus pressure-plate fixings for about 2,390 triangles) replaced the 0.50 kPa placeholder for the glass comparison.

| Adopted frame v11g at 0.65 kPa | Result |
|---|---|
| Glass sag: short ends / long edges / bays / funnels | 33 / 22 / 27 / 6 mm |
| Highest utilisation | 0.70 |
| Trunk member max compression | 18 kN |
| Against the ≈ 36 mm guide | passes; at 0.75 kPa: 36 mm (limit) |

The ETFE results (0.12 kPa) are unchanged.

## 4. Member schedule, adopted frame v11g (members only, PROVISIONAL)

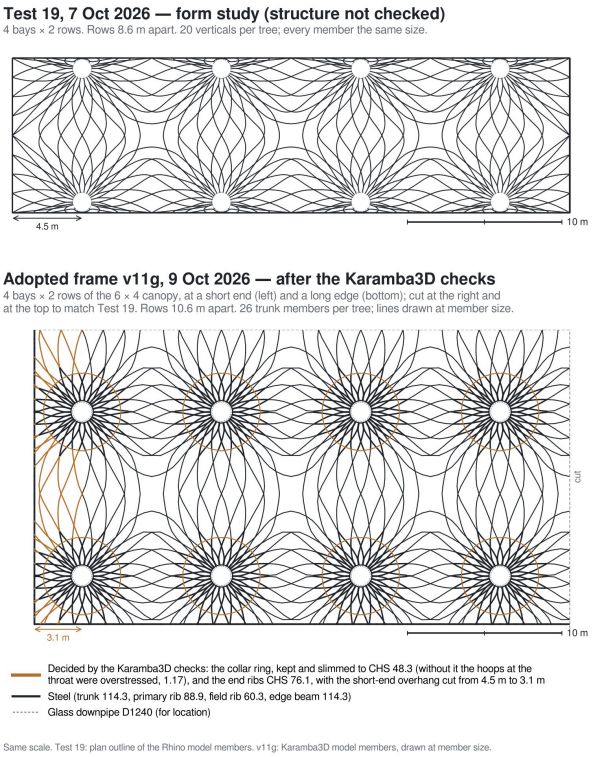
| Member | Section | Length | Mass |
|---|---|---|---|
| Trunk | CHS 114.3 × 6.0 | 1,971 m | 31.6 t |
| Primary rib | CHS 88.9 × 5.0 | 2,966 m | 30.7 t |
| Field rib | CHS 60.3 × 4.5 | 2,444 m | 15.1 t |
| End rib | CHS 76.1 × 4.5 | 319 m | 2.5 t |
| Collar ring | CHS 48.3 × 3.2 | 378 m | 1.3 t |
| Edge beam | CHS 114.3 × 6.0 | 180 m | 2.9 t |

| Member | Section | Length | Mass |
|---|---|---|---|
| **Total** | | | **84.2 t** |

Karamba's model total is 85.7 t (it includes the hoops and its own segment lengths). Hierarchy (approved): trunk 114.3 > primary rib 88.9 > end rib 76.1 > field rib 60.3; ring 48.3; edge 114.3. Fabrication: 13,144 smooth arcs, none tighter than 5 × D; hooks removed at 56 V-joints; 24 tree modules + 816 field pieces.

## 5. What the check showed, and what changed

*Figure 5.* From Test 19 to the adopted frame, at the same scale. Test 19 (7 Oct) was a form study with every member the same size. In the adopted frame v11g (9 Oct), the members in timber ochre were decided by the Karamba3D checks: the collar ring, kept and slimmed to CHS 48.3, and the end ribs CHS 76.1, with the short-end overhang cut from 4.5 m to 3.1 m. Other differences (member sizes, edge beam, row spacing 8.6 → 10.6 m, 26 trunk members, the row rib) came from other steps. `Production/Comparison/T19_vs_v11g_plan_comparison_v02.png`




1. **The frame is strong enough.** With the slim ring every member works well below capacity. The trunks carry only about 16 kN each, because the load is shared by 26 members per tree.
2. **The collar ring earns its place, and it can be slim.** Without it the hoops at the throat are overstressed (1.17) and the canopy sags far more. A 48.3 mm ring fixes both, against the 88.9 mm placeholder.
3. **Sag, not strength, governs, and only at the two short ends.** The interior bays, funnels and long edges are within the guide; the 4.5 m short-end overhangs were not.
4. **The outer trees are the lever, but the fix had to respect the hierarchy.** Stiffening the outer trees cut the short-end sag far more than heavier end ribs or a deeper edge beam, but only by breaking the hierarchy. Shortening the overhang to 3.1 m solved the short ends for both skins within the hierarchy and with less steel.
5. **Thermal movement is small** (7 mm, temperature only), so no movement joint is indicated at this stage.
6. **The skin choice is not decided by the frame.** The adopted frame carries glass at 0.65 kPa within the guide. The choice of ETFE was decided by water and form (see report section 3).

## 6. Limits of this check

- Loads, combinations and the sag guide are assumed; AS/NZS 1170 values, wind and the deflection criteria are to be confirmed by the engineer.
- The skin load is spread evenly over the canopy steel, not applied panel by panel.
- Not yet checked: local stresses at the funnel/collar, the connections and cast nodes, whether the utilisation figures include member buckling (to confirm), and the ETFE fixings, air main and saddle drains added after S4 (not in the S4 load).
- The member sizes are the designer's proposal for design development, subject to the structural engineer's review and sign-off.

## 7. How AI was used

- **Claude:** wrote and ran the Karamba scripts (`Grasshopper/scripts_v11_steel/08_`, `08b_`, `08c_karamba_S4_v11.py`); checked the solver against a hand calculation; located where the sag occurs; traced and fixed a modelling defect; produced the plots and tables.

- **Me:** I spotted missing rib pieces in the first results. The cause was a modelling defect: 9 ribs were broken in two and one half dropped (5 at the crowns on the y = +10.6 m row, 4 near the short edges). They were re-joined in v11e (each rib end extended by at most 28 mm, no joint moved), and all results above come from the repaired frame. The main change was the interior-bay sag: 39 mm in the first run came from a loose rib end; the true value is 24–25 mm.
- **I decided:** canopy height +300; keeping the slim ring; testing (b) + (e); not adopting (e) because it breaks the hierarchy; testing and then adopting (c) with 76.1 end ribs; the 0.65 kPa glass load.

## Files

- Results record: `Production/A4_S4_Karamba_results_for_presentation_2026-10-09_v05.md`
- Data: `Model/v11d_S4_Karamba_views_v01/S4_results_data_v11e_rib_gap_fix.json`, `S4_results_data_v11g_ADOPTED.json`
- Plots (working): `Model/v11d_S4_Karamba_views_v01/`; (sheet A4-02): `Production/Sheets/sim_v03/`
- Adopted Grasshopper file: `Grasshopper/A4_Umbrella_GH_2026-10-09_v11g_ADOPTED_short_end_3100.gh`

# Water: does the skin drain?

*Between Rain · Integrated Water-Catchment Canopy · Assignment 4 report, section 2 of 3*

> **Geometry checks on the model, not a rain simulation.** They test the shape of the skin. Rainfall intensity, flow rates, the rise of the inflated cushions and the weight of standing water are not modelled. Drainage sizes are assumptions for the ETFE and drainage contractors to confirm.

**Approved changes stated on this report** (my decisions, 9–10 Oct 2026):

- ETFE cushions are the skin (glass tested and rejected, report section 3)
- drained saddle node: an outlet at each joint low point with a drain along the steel to the nearest collar
- smooth 2,000 mm transition at the level short ends kept (End_Blend option a)

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## 1. Why water decides this element

The canopy is a rain catchment. Every square metre of the 2,177 m² skin should send water to one of the 24 funnels, down the glass downpipe in each trunk and into storage. Water that stands on the roof is a leak risk, a load and a maintenance problem; water that runs the wrong way bypasses the catchment. As the designer, I set the standard for this work from the start: watertightness had to be demonstrated, either by a simulation of the model or by published research, before any skin could go forward, and only options that would be feasible on a real project were considered.

**The intended water path**

| Step | Element |
|---|---|
| 1 | ETFE cushion surface, frosted and fritted |
| 2 | Keder joints between cushions (aluminium double-keder extrusion, 80 × 55 mm, capped) |
| 3 | Funnel collar (six moulded segments per tree) with a gutter extrusion where it meets the ETFE |
| 4 | Stainless throat clamp, then the glass downpipe D1240 inside the 26 trunk members |
| 5 | First-flush diverter at each downpipe (24), then storage (final project) |
| Edges | Perimeter edge extrusion; 150 × 100 box gutter along the two level short ends (76 m) |

## 2. Test 1: does any part of the skin hold water?

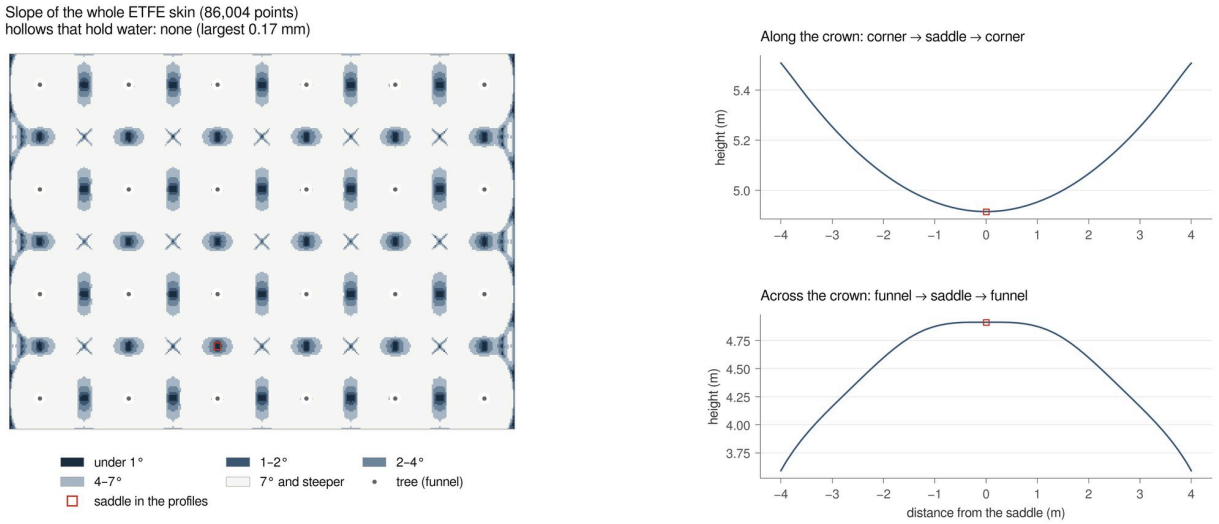
**Method.** A priority-flood over all 86,004 points of the smooth skin surface (adopted shape v11j): water may leave only at the edge or into a funnel; any point that cannot drain marks a hollow, and its depth is measured.

**Result.** No hollow deeper than 0.17 mm anywhere, which is the resolution of the grid, not a real pond.

What looks like a dip from below is a **saddle**: midway between trees the skin dips along the crown but falls away across it, down to the two funnels on either side. Water leaves sideways, but slowly, because the centre of each saddle is almost flat (about 0.5° along the crown; about 0° across it at the very top).

*Figure 1.* Slope of the whole skin, flattest areas darkest, with the profiles along and across one saddle.

`Production/Sheets/sim_v03/B2_main_pond_check_v03.png`




## 3. Test 2: does the frame's sag create ponds?

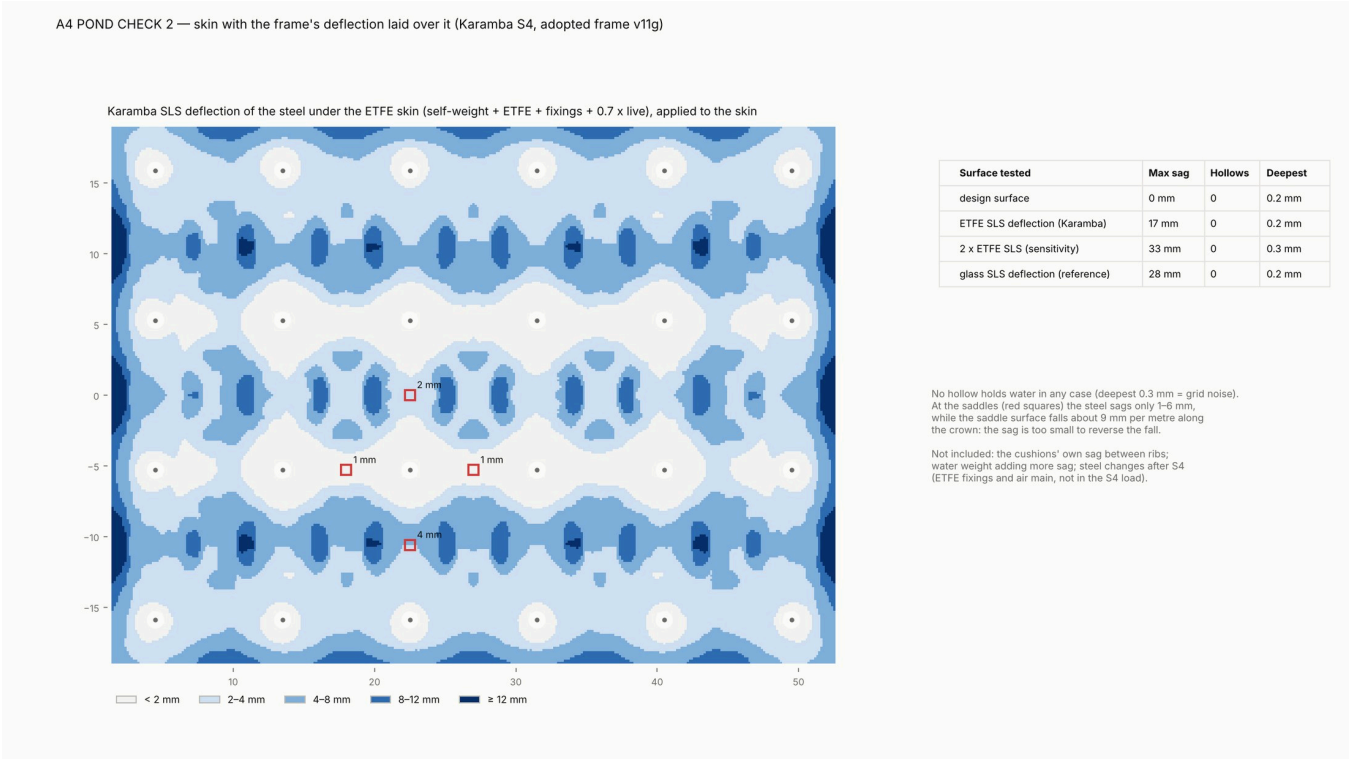
A flat saddle could turn into a shallow pond if the steel beneath it sags. The Karamba sag of the adopted frame (report section 1) was laid over the skin and the priority-flood run again.

| Surface tested | Max sag | Hollows | Deepest |
|---|---|---|---|
| Design surface | 0 mm | 0 | 0.2 mm |
| ETFE in service (Karamba SLS) | 17 mm | 0 | 0.2 mm |
| 2 × ETFE (sensitivity) | 33 mm | 0 | 0.3 mm |
| Glass in service (reference) | 28 mm | 0 | 0.2 mm |

No hollow holds water in any case. At the saddles the steel sags only 1–6 mm, while the saddle surface falls about 9 mm per metre along the crown, so the sag is too small to reverse the fall.

Not included: the cushions' own sag between ribs, the extra sag caused by the weight of water, and steel added after the frame check (ETFE fixings, air main).

*Figure 2.* Pond check 2: sag of the steel laid over the skin. `Model/v11j_S5b2_glass_gate_views_v01/skin_pond_check_v2_deflected.png`




## 4. Test 3: where do the cushion joints hold water?

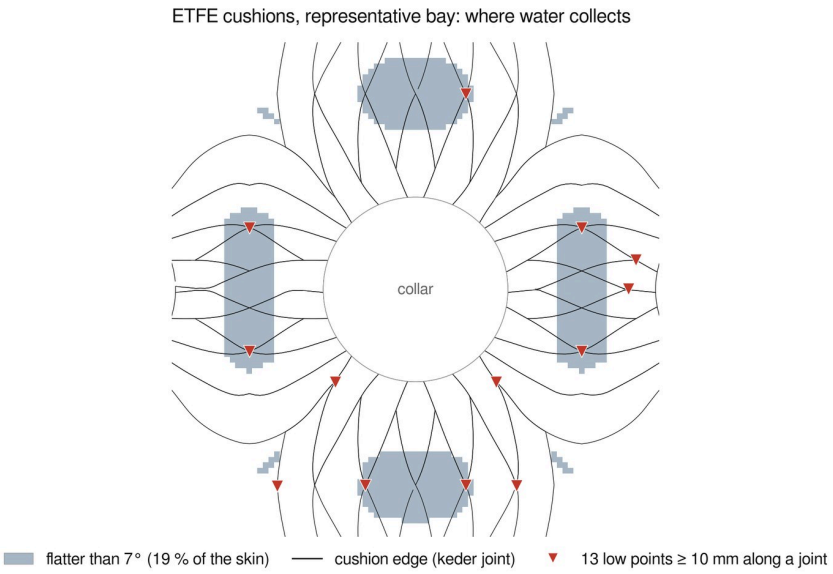
A smooth surface can drain while the joints in it do not. Each keder joint between two cushions is a shallow valley, so water runs along it, and where a joint dips it collects.

**Method.** The representative bay (around one tree, 51 cushion panels) was checked joint by joint, with the same rules used for the glass version (report section 3): surface flatter than 7° (the published minimum for glass roofs, used for comparison) and low points along each joint.

| ETFE, representative bay | Result |
|---|---|
| Skin flatter than 7° (collar funnel excluded) | 19 % (22.0 of 118.9 m²) |
| Keder joints | 43 |
| Low points along a joint, 10 mm deep or more | **13** (18 found in total) |

The cushion rise is not modelled, so depth is measured along the joint line. All the low points sit on the near-flat saddles midway between trees, the same places Test 1 identified.

*Figure 3.* ETFE cushions in the representative bay: flat areas and the 13 joint low points. `Production/Sheets/sim_v03/B2_support_etfe_bay_v03.png`




## 5. What changed: the drained saddle node

Three options were set out (R4): (a) change the shape so the saddles fall to the funnels, (b) drain the low points, or (c) leave it as an open item for the contractor.

- **(a) was withdrawn.** Lifting the saddles enough to make them fall would need a rise of more than about 660 mm, changing the canopy's form.
- **(b) was approved** (my decision, 10 Oct): a drained saddle node.

**The node.** A stainless outlet box (200 × 120 × 40 mm) under the keder extrusion at each joint low point, holding 32 mm of standing water before it overflows; a side elbow; and a 50 mm drain pipe run along the side of the steel to the collar of the nearest tree, at a steady fall of at least 1:100.

**Checked at one instance first (REPEAT GATE).** The first outlet, at (21.14, −10.60), drains to the collar of tree 8: 3.3 m of pipe, 0.75 m of fall, clearance at least 5 mm to the steel and over 300 mm to the air main. Two faults were found and fixed before it was shown: rises in the pipe (v1), and the pipe passing inside the steel at nodes and at the outlet (v1b).

**Repeated after I approved it:**

| Saddle drains | Representative bay | Whole roof |
|---|---|---|
| Outlets | 13 | 211 (counted) |
| 50 mm drain | 35.7 m, 0 rises | not yet totalled |
| Clearances | ≥ 4 mm to steel, ≥ 26 mm to the air main, ≥ 575 mm between drains | |

*Figure 4.* The first outlet from below. `Model/v11j_S5b1_saddle_drain_gate_views_v01/S5b1_GATE_saddle_01_outlet_from_below_close.png`

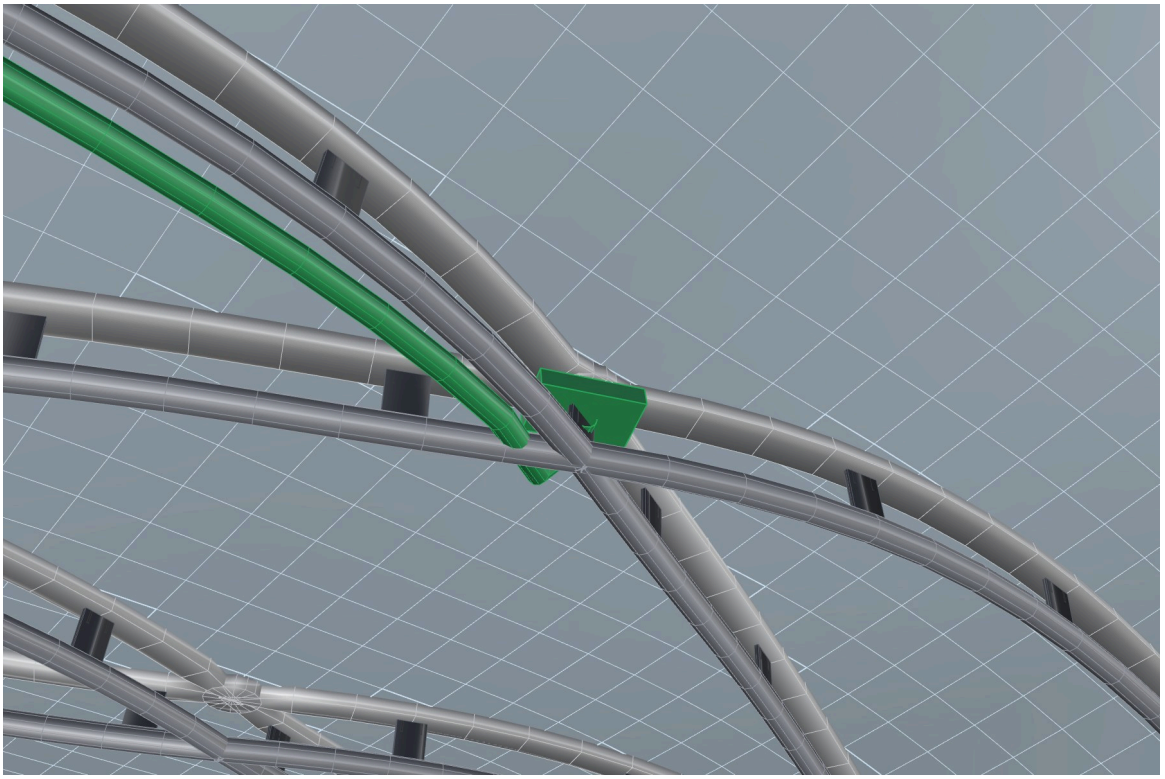
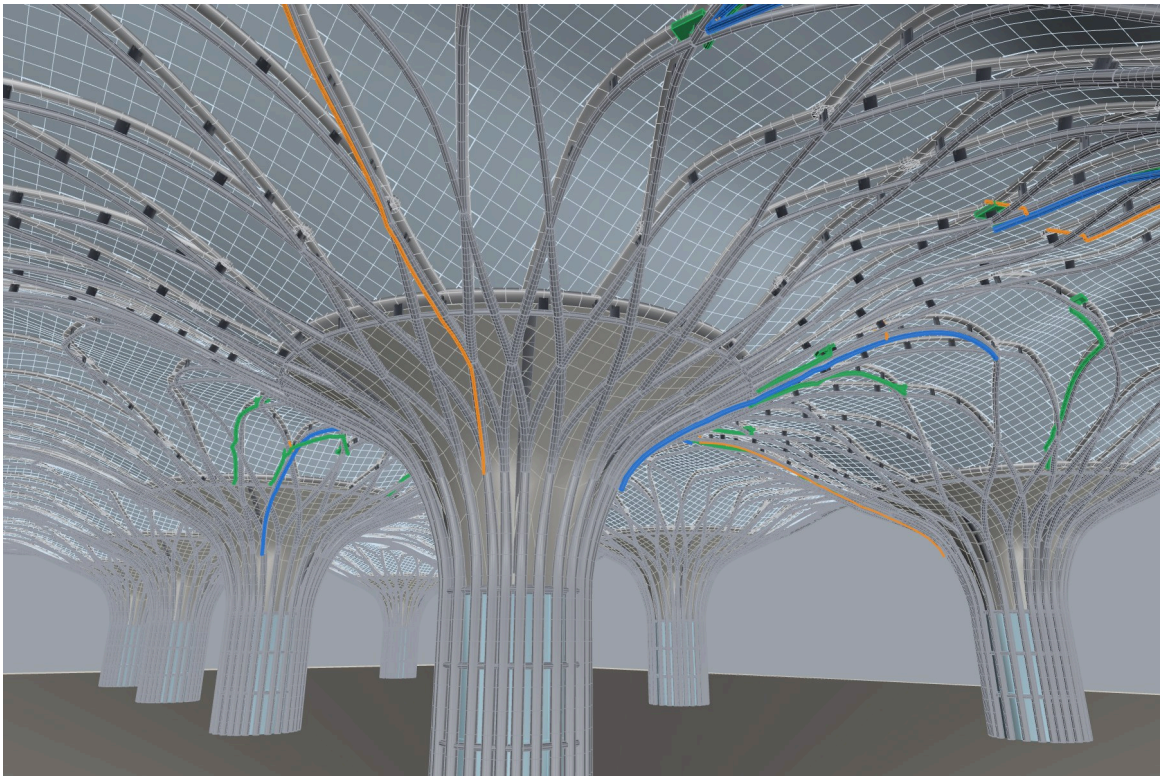


*Figure 5.* Saddle drains in the representative bay, from below.
`Model/v11j_S5b1_saddle_drain_gate_views_v01/S5b1_saddle_drains_v2c_02_rep_bay_from_below.png`



## 6. What the checks showed

1. **The canopy shape drains.** No hollow anywhere, with or without the sag of the steel.
2. **The weak points are the saddles.** They are almost flat, so water leaves them slowly, and the cushion joints across them hold small amounts of water.
3. **The fix is a detail, not a new form.** 211 small outlets drain the joint low points to the funnels, so the water still reaches the catchment and the canopy keeps its shape.
4. **The cushions must stay inflated.** Deflated cushions would hold water; a back-up fan and emergency power are required (R4).

## 7. Limits and open items

- Geometry checks only: no rainfall intensity, flow rate, overflow or blockage case; the cushion rise and the weight of water are not modelled.
- The 7° threshold is the glass-roof minimum, used for comparison; no published minimum slope for ETFE cushion roofs was found (R4).
- Open: the drain component is not yet in the Grasshopper definition; the collar discharge spout is to be detailed; pipe size to be confirmed by the contractor; all wetted parts to AS/NZS 4020 or tested (R3).
- Saddle drains and air supply are modelled in the representative bay only and counted for the whole roof.

## 8. How AI was used

- **Claude:** wrote and ran the pond checks (priority-flood over the skin, then with the Karamba sag), the joint-by-joint water test (`Grasshopper/scripts_v11_steel/12_water_test_S5b2_v1.py`, `13_water_test_plot.py`) and the saddle-drain script (`07d_saddle_drain_GATE_v1c.py`, then `07d_saddle_drains_S5b1_v2c.py`); found and fixed the pipe faults before showing them; produced the plots and counts.
- **Me:** I asked, from what I could see in the model, whether the curves would pond, which led to the whole-skin pond check; I set the standard that watertightness must be backed by simulation or research; I chose the drained saddle node and approved it at the REPEAT GATE before it was repeated.

## Files

- Plots (sheet A4-02): `Production/Sheets/sim_v03/`
- Working plots and data: `Model/v11j_S5b2_glass_gate_views_v01/` (skin_pond_check_v1.png, skin_pond_check_v2_deflected.png, S5b2_water_test_v1.png, water_test_v1_data.json, skin_v11j_vertices.json)
- Saddle drain views: `Model/v11j_S5b1_saddle_drain_gate_views_v01/`
- Model: `Model/A4_v11k_S5b1_saddle_drains_REVIEW_2026-10-10.3dm`
- Research: `Research/A4_R4_watertightness_glass_ETFE_v01.md`

# Skin: glass or ETFE?

*Between Rain · Integrated Water-Catchment Canopy · Assignment 4 report, section 3 of 3*

**Desk research and model checks**, not yet confirmed by a glazing or ETFE contractor, an engineer or a water-quality specialist. Items marked **(verify)** could not be confirmed from an accessible source.

**Approved changes stated on this report** (my decisions, 9–10 Oct 2026):

- hybrid skin: one moulded funnel collar per tree (six segments), with panels between the ribs beyond it; cells below a minimum size merged (R2)
- minimum panel size set by the manufacturer's minimum; where none is published, 400 mm wide / 0.25 m² ("subject to the manufacturer's minimum")
- glass modelled as a realistic comparison only, at 0.65 kPa
- the smooth 2,000 mm transition at the level short ends kept, so the 16 inner collars share one mould and the 8 outer collars need their own (an approved change to R2 condition 3, "one mould")
- flat faceted glass tested and rejected; hot-bent glass researched and rejected; ETFE cushions selected
- ETFE on a rain catchment accepted on three conditions (R3)
- rain experienced as shadows and sound: frosted and fritted skin, no clear zones, no rain-noise mesh

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## 1. The question

The canopy skin does three jobs at once: it is the roof of a public interior in subtropical Brisbane, it is a doubly curved surface stretched over the rib network, and it is the catchment that sends rain to the funnels. A skin that suits one job can fail another. Two families were considered, laminated glass and ETFE cushions, and judged on the same seven points:

| Criterion | Why it matters here |
|---|---|
| Solar heat gain | A nearly continuous translucent roof over a public interior in a subtropical climate must not become a greenhouse. |
| Fit to the curved form | Every panel between the ribs is doubly curved, and almost every panel is different. |
| Weight | The skin load drives the steel (report section 1). |
| Watertightness | The roof is the catchment; joints that hold water leak. |
| Experience of rain | The concept is *Between Rain*: how rain is seen and heard under the canopy. |
| Quality of the harvested water | The skin is the first surface the stored water touches. |
| Upkeep | Cleaning, replacement and services over the life of the canopy. |

As the designer, I set one condition over all of these: only options that would be feasible on a real project go forward, and watertightness had to be demonstrated by a simulation of the model or by published research.

## 2. Glass and ETFE compared (research R1)

**Glass.**

- **Overhead safety:** sloped and overhead glazing is normally laminated, with the lowest layer laminated where safety governs (CWCT TU4, TU10). In Australia this falls under AS 1288; the exact rules could not be accessed **(verify)**.
- **Solar heat gain:** plain glass has g ≈ 0.88. Coated and fritted double glazing reaches about 0.27, as on the freeform roof of Jewel Changi in tropical Singapore (SHGC 0.27, visible light 64 %).
- **Curvature is the big constraint.** Hot-bent doubly curved glass needs moulds or specialised machines and is "laborious and expensive" (Gavriil et al., 2020). Cold bending is cheaper but limited by stress.
- **Weight:** about 25–30 kg/m² for 2 × 6 mm laminated glass; an insulated unit roughly doubles it.

**ETFE cushions.**

- **Weight:** 2–3.5 kg/m², about a tenth of laminated glass.
- **Light and solar control:** single layer 85–95 % light transmission; printed frit gives g ≈ 0.48 (two layers) to ≈ 0.35 (three layers).
- **Form:** follows curved geometry cushion by cushion.
- **Life and upkeep:** over 30 years (Architen) to over 50 years (Domerama); external cleaning every 2–3 years; inflation units serviced yearly; cushions hold pressure for about 3–6 hours if the power fails.
- **Rain:** cushions can drum in rain; an acoustic mesh cuts this by up to 10 dB but also halves the light.
- **Risks:** bird pecking (small, patchable punctures) and reliance on the air supply. Hail behaviour in Brisbane **(verify)**.
- **Australian precedent:** Macquarie University Arts Precinct, Sydney (2020, about 2,000 m² of ETFE).

**Energy code.** A nearly fully glazed roof will almost certainly fall outside the NCC Section J deemed-to-satisfy roof-light provisions **(verify the J4 limits; the page could not be fetched)**, so a performance solution with whole-building energy modelling would be expected for either skin.

| | Laminated glass (frosted, fritted) | ETFE cushions (fritted) |
|---|---|---|
| Weight | ~25–60 kg/m² | 2–3.5 kg/m² |
| SHGC achievable | ~0.27 (coated + frit, insulated) | ~0.35–0.48 (fritted, 2–3 layers) |
| Doubly curved funnels | flat facets or limited cold bending; hot-bent very costly | follows the curvature cushion by cushion |
| Frosted look | acid etch, translucent interlayer or frit | frit gives a translucent look |
| Sense of rain | rain visible, quiet | rain heard; less visible through frit |
| Durability and upkeep | very durable, heavy, cleaning | 30–50+ years, cleaning, air plant maintenance, puncture risk |
| Structure | heavier ribs and trunks | lighter ribs and trunks |

## 3. Dividing the skin between the ribs (research R2 and panel layout S5a)

**Hybrid approach.** Close to each trunk, where 26 ribs converge, the cells between them are slivers too thin to panel, so that zone becomes one moulded **funnel collar**. Beyond it, the skin is divided into panels between the ribs, and cells below a minimum size merge with a neighbour (the rib still runs underneath). R2 found this realistic on four conditions: a minimum panel size, ETFE preferred for the irregular cells, the collar as one repeated moulded element, and manufacturer and engineer confirmation stated as outstanding.

**Panel layout of the adopted frame (S5a).**

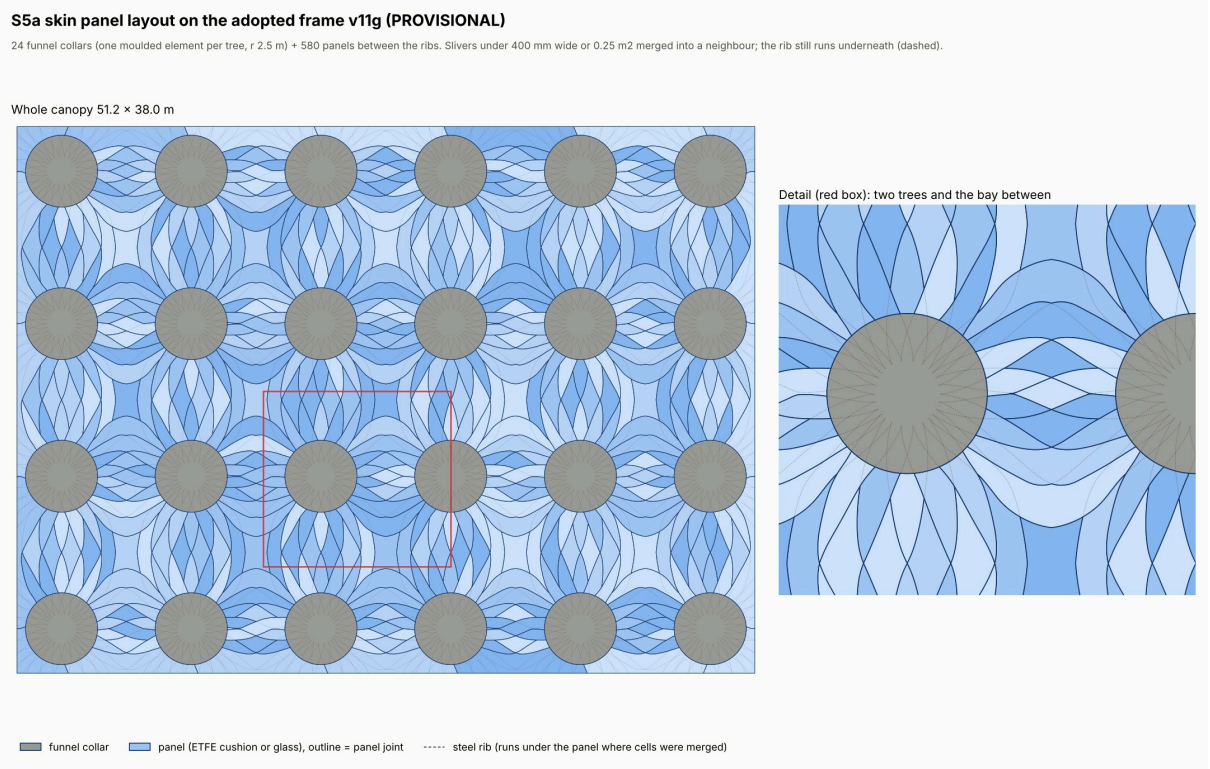
| Step | Result |
|---|---|
| Closed cells between members (plan) | 2,860 |
| Cells inside the collar ring (r 2.5 m) | become 24 funnel collars, about 5 m across, each split into 6 identical segments for transport |
| Merges below 400 mm wide or 0.25 m² | 1,008, giving **580 panels** |
| Panel area | min 1.04, median 2.08, max 11.10 m² |
| Panel short span | min 0.76, median 1.04, max 2.77 m |

- **ETFE:** every panel is within the cushion span without cables (about 3.5–4.0 m wide, length effectively unlimited; Architen, Domerama).
- **Glass:** every panel is strongly curved (out of plane: median 191 mm, max 515 mm). None meets the cold-bend assumption, so all 580 would be flat glass triangles, about 2,390 of them, and any triangle edge not on a rib needs an extra glazing bar.
- No published ETFE minimum panel size was found. Viridian (an Australian maker) publishes an insulated-glass-unit minimum of 350 × 350 mm and maximum of 3,500 × 2,000 mm; the 400 mm minimum clears it.

**Precedents.**

| Project | What it shows |
|---|---|
| Jewel Changi Airport, Singapore (Safdie Architects; Buro Happold) | freeform glass gridshell of more than 9,300 unique triangular panels; an oculus feeding the 40 m Rain Vortex |
| Kogod Courtyard, Smithsonian, Washington DC (Foster + Partners; Gartner) | glazed canopy with the roof drainage integrated into the columns |
| Beijing National Aquatics Centre, “Water Cube” (PTW / Arup) | ETFE cushions in an irregular “soap bubble” geometry |
| Westfield London (Knippers Helbig; seele) | 18,000 m² free-formed glass roof |
| Stuttgart 21 light eyes (Ingenhoven; Werner Sobek; seele) | steel-and-glass light eyes on chalice supports |
| Macquarie University Arts Precinct, Sydney (MakMax) | Australian ETFE roof, about 2,000 m² |

*Figure 1.* Panel layout of the adopted frame: 24 collars and 580 panels. `Model/v11g_S5a_panel_views_v01/S5a_panel_layout_plan.png`




## 4. Making glass a fair comparison

I did not think glass was a good candidate, but I wanted it tested, and tested as a realistic option: a thickness suitable for overhead use and solar control that meets the research. If no suitable glass existed, it would be left out and the reason recorded.

**A suitable glass exists.** Jewel Changi is the deciding precedent: a tropical climate and a freeform roof of flat triangular double-glazed panels, the same geometry this canopy would need. The comparison build-up follows it:

- outer 8 mm heat-strengthened, triple-silver low-e coating and ceramic frit
- 12–16 mm cavity
- inner 6 + 6 mm heat-strengthened laminated, 1.52 mm frosted interlayer (laminated innermost layer for overhead safety)
- SHGC target 0.27 or lower; thickness to be confirmed under AS 1288 **(verify)**; within Viridian's limits (13.52 mm laminate maximum, 3.5 × 2.0 m maximum unit)

**Weight.** About 20 mm of glass ≈ 0.50 kPa, plus a pressure-plate system for about 2,390 triangles ≈ 0.10–0.15 kPa: **≈ 0.65 kPa**, higher than the 0.50 kPa placeholder in the frame check. The frame still carries it (report section 1):

| Glass load | Short ends | Long edges | Bays | Funnels | Highest utilisation | Trunk member compression |
|---|---|---|---|---|---|---|
| 0.50 kPa (placeholder) | 28 mm | 19 mm | 23 mm | 5 mm | 0.61 | 16 kN |
| **0.65 kPa (adopted for glass)** | **33 mm** | 22 mm | 27 mm | 6 mm | 0.70 | 18 kN |
| 0.75 kPa (heavier check) | 36 mm | 24 mm | 30 mm | 7 mm | 0.76 | 20 kN |

**Glass panels modelled at two instances (REPEAT GATE).** The first attempt failed and was not shown: one panel split into 19 triangles with slivers (shortest edge 144 mm, smallest angle 2°). The second limited edge splitting (Min_Edge 350 mm) and maximised the smallest angles:

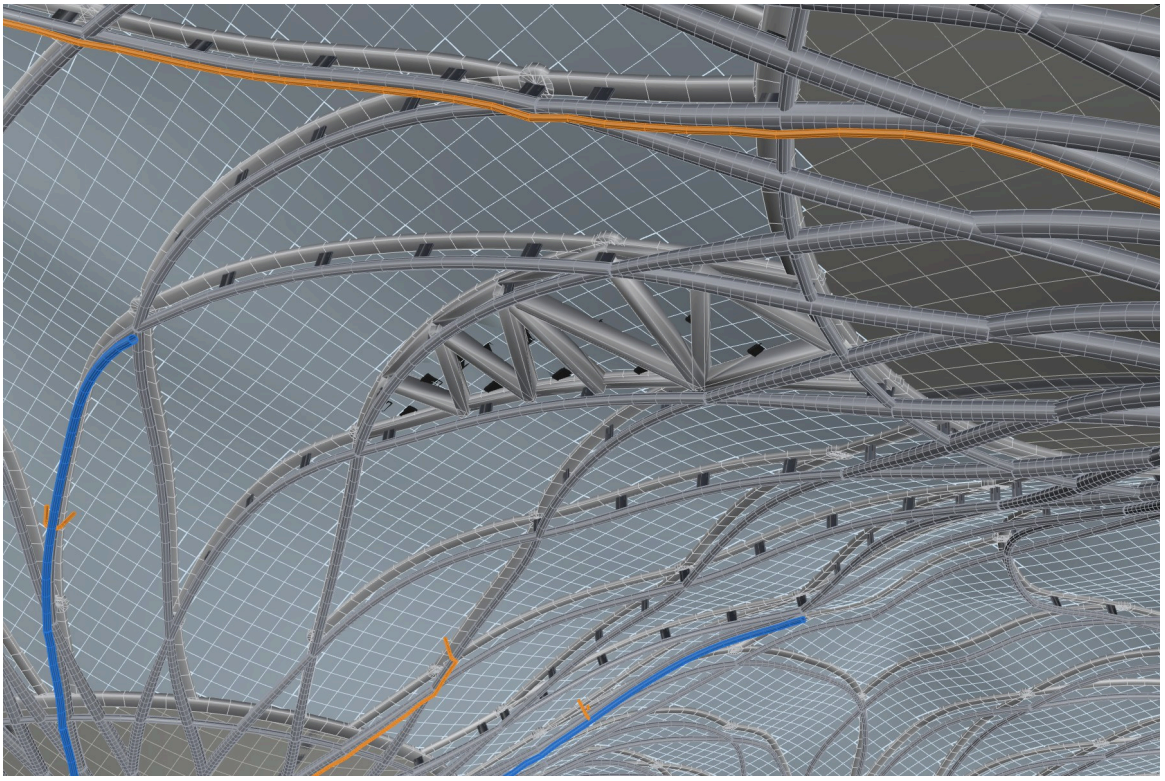
| | Instance 1 (narrow strip) | Instance 2 (compact) |
|---|---|---|
| Panel area | 2.09 m² | 2.08 m² |
| Triangles | 13 | 11 |
| Shortest edge / smallest angle | 357 mm / 24° | 392 mm / 24° |
| Diagonal glazing bars | 12 | 10 |
| Flat edge off the curved rib | up to 28 mm | up to 18 mm |

Insulated units 37.5 mm (8 HS low-e + frit / 16 / 6 + 6 HS laminated, 1.52 mm frosted interlayer); diagonal glazing bars 60 × 110 mm aluminium; rib carriers with pressure plates, caps, EPDM gaskets and setting blocks.

**What one panel shows.** Where ETFE needs one cushion, glass needs about 11–13 units and 10–12 diagonal bars, roughly 6,000–7,500 units over the roof (an estimate, not counted). The 18–28 mm gap between a flat glass edge and the curved rib needs a tapered or adjustable carrier, and from

below the diagonal bars read as a dense zigzag.

*Figure 2.* Glass gate panel 2 from below, in context. `Model/v11j_S5b2_glass_gate_views_v01/S5b2_GATE_05_compact_panel_from_below_in_context.png`



## 5. Watertightness (research R4 and the water test)

**Research findings.**

- **Flat faceted glass roofs exist.** The British Museum Great Court has 3,312 unique triangular double-glazed units, with no leaks reported in the source; but there the triangulated steel grid *is* the structure and carries the glass directly, unlike this canopy.
- **Minimum slope:** for wide-span glass roofs, the inclination "should not fall below 7 degrees" (Siebert); simple lean-to rooflights quote 2.5–5°.
- **Sealing:** two levels, an outer seal and an inner drainage level; crossing points must be tight. A roof of triangles and hexagons needed three cascaded drainage levels at its star-shaped junctions. Common causes of damage include low slope, transoms that bend and stop drainage, screws through the lower seal, faulty seal bonding and water standing in the drainage channel (Siebert).
- **Hot-bent glass:** approved soft low-e coatings currently work on the concave surface only, curved insulated units can build extreme internal pressures, and bent sizes are limited by radius and furnace. Here all 580 panels are doubly curved and all different: one mould or set-up per panel.
- **ETFE:** each cushion is a sealed welded envelope; the keder edge slots into an aluminium profile capped "to form a watertight frame". A primary fan keeps at least 250 Pa, with a back-up fan and an emergency power option; deflated cushions carry water only temporarily (Temme Obermeier). No published minimum slope for ETFE roofs was found.

**Water test, same bay, same rules** (geometry check, not a rain simulation; 7° threshold applied to both for comparison):

| | Flat faceted glass | ETFE cushions |
|---|---|---|
| Area flatter than 7° | 17 % (121 of 664 facets) | 19 % of the skin (collar excluded) |
| Joints | 613: **527 across the flow** (a raised cap dams water), 25 valleys (13 flatter than 7°), 61 ridges | 43 keder joints, each a valley between cushions |
| Where water collects | **21 star-junction nodes** | **13 points along joints, 10 mm deep or more** |

Both sets of low points sit on the near-flat saddles midway between the trees: the canopy shape itself causes them (report section 2).

*Figure 3.* Flat faceted glass in the representative bay: flat areas, joints across the flow, flat valleys and low star-junctions.
`Production/Sheets/sim_v03/B3_support_glass_bay_v03.png`

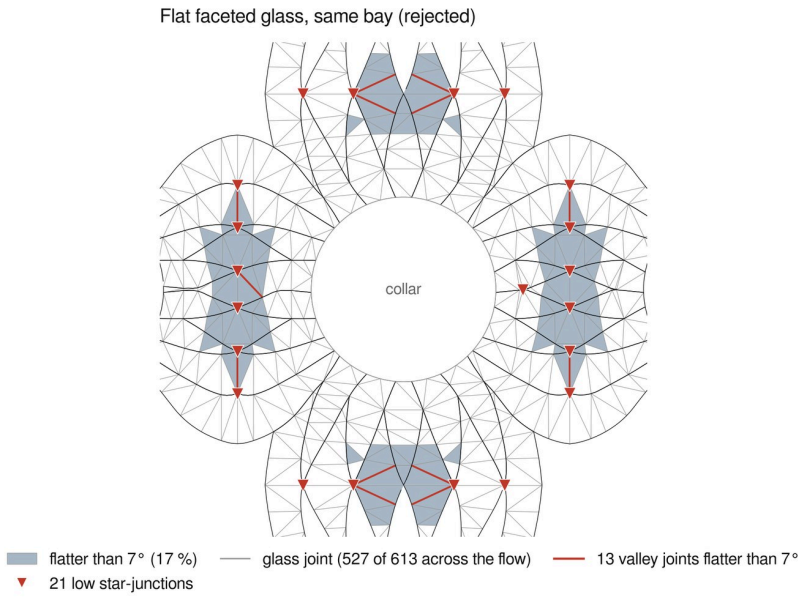
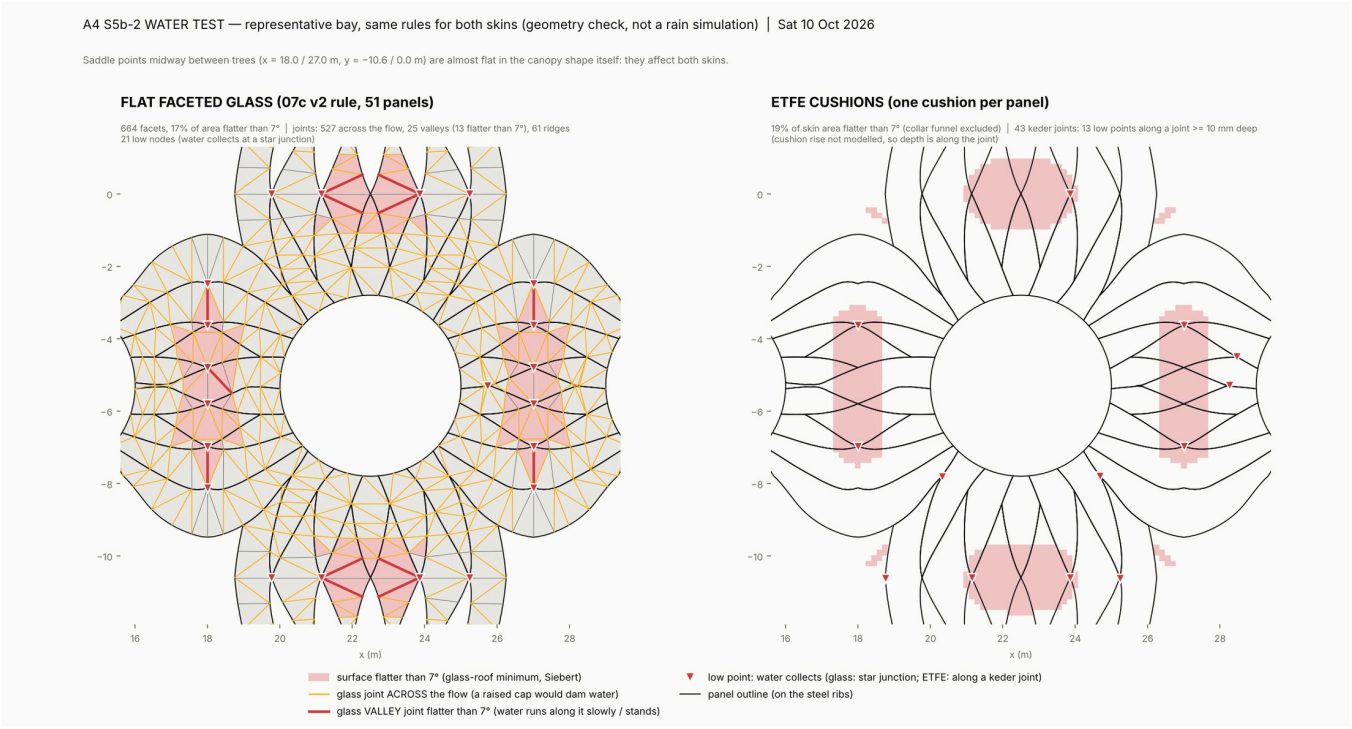



*Figure 4.* Both skins under the same water test (working plot). `Model/v11j_S5b2_glass_gate_views_v01/S5b2_water_test_v1.png`




**Reading.** Flat faceted glass is not shown to be feasible: a sixth of its area is below the glass minimum, most of its joints would need flush detailing everywhere, 21 junctions would need cascaded drainage levels, and no precedent was found for glazing bars spanning between curved ribs like this. Hot-bent glass is not a candidate. ETFE remains, with its saddle drainage resolved by the drained saddle node (report section 2).

## 6. Water quality on a catchment (research R3)

I asked whether ETFE could contaminate the stored water, since the research up to that point had not covered it.

- ETFE is a fluoropolymer; one of its manufacturers (AGC) describes it as “polymeric PFAS”, and fluoropolymers fall within the broad regulatory definitions of PFAS. They are proposed for inclusion, with exemptions, in the EU’s universal PFAS restriction **(verify the status at the time of design)**.
- The documented concern centres on manufacture, end of life and small amounts of non-polymeric PFAS that can remain in the material.
- **No published study was found that measures PFAS in rainwater harvested from an ETFE roof.** The risk is unquantified: shown neither safe nor unsafe.
- Australian rainwater guidance (enHealth, 2010) lists common roof materials as suitable, does not mention polymer roofs or PFAS, and asks for tanks and pipes in prolonged contact with the water to comply with AS/NZS 4020.

- Rain already carries trace PFAS: the first Australian study of PFAS in rain (RMIT with EPA Victoria, Melbourne) detected 8 of 30 compounds at ng/L levels, with PFOS and PFOA below the drinking-water guideline values (NHMRC 2025: PFOS 8 ng/L, PFOA 200 ng/L, PFHxS 30 ng/L, PFBS 1,000 ng/L).

**How it applies.** The ETFE only guides the water to the collar and downpipe; it does not store it, so contact time is short. The end use of the stored water (irrigation of the Smart Farm's crops, other non-potable uses or drinking) sets the level of risk and is a final-project decision. The other wetted parts (frit inks, keder extrusions, gaskets and sealants, the collar, the downpipe) matter as much as the foil.

**Decision.** ETFE stays the preferred skin on three required conditions, not optional ones:

1. a **first-flush diverter** at each downpipe (24), so the first, dirtiest runoff is diverted from storage
2. **manufacturer leaching data or AS/NZS 4020 compliance** for the ETFE foil and every wetted component
3. **testing the stored water** before use, matched to the end use decided in the final project

## 7. The experience of rain

Under frosted, fritted glass, rain would be seen only as soft moving shadows; under ETFE, it depends on the foils (clear foil shows drops and running water, printed foil shows shadows). I chose shadows and sound: the skin stays frosted and fritted with no clear zones, partly so it keeps diffusing the solar heat gain, and the drumming of rain on the cushions is embraced rather than suppressed, so there is no acoustic mesh. The space under the canopy is for sitting and listening to the rain; the café sits on the other side of the structure, not under it.

## 8. Decision

| | Laminated glass (frosted, fritted) | ETFE cushions (fritted) |
|---|---|---|
| Weight (incl. fixings) | 25 to 60 kg/m²; 0.65 kPa in the frame check | 2 to 3.5 kg/m²; 0.12 kPa in the frame check |
| Frame check (adopted v11g) | short-end sag 33 mm (guide 36); highest utilisation 0.70 | short-end sag 17 mm; highest utilisation 0.38 |
| Solar heat gain (SHGC) | about 0.27 (coated, fritted double glazing) | about 0.35 to 0.48 (fritted 2 to 3 layer cushions) |
| Doubly curved form | flat facets or cold-bent panels; hot-bent needs one mould per panel (580) | follows the curvature cushion by cushion |
| Watertightness (bay test) | 17 % below the 7° minimum; 527 joints across the flow; 21 low star-junctions: not shown to be feasible | sealed cushions in a capped keder frame; 13 low points along joints at the saddles: drained outlets |
| Rain experience | rain seen; quiet | rain heard; seen as soft shadows through the frit |
| Harvested water | not assessed (R3 covered ETFE) | fluoropolymer (PFAS family); runoff risk unquantified: three conditions |
| Upkeep | very durable; cleaning | 30 to 50+ years; cleaning every 2 to 3 years; fans serviced; back-up power |
| **Outcome** | **REJECTED** (flat faceted: tested; hot-bent: researched) | **SELECTED** |

**ETFE cushions are the skin**, frosted and fritted for solar control. Glass was not rejected for weight (the frame carries it) or for solar control (a suitable glass exists), but for water and form: on this canopy's shape it cannot be shown to be watertight, and curving it to the form would need a mould for almost every panel. The glass work is kept as evidence of the comparison; no glass was modelled beyond the two gate panels.

**Conditions carried with ETFE:** a back-up fan and emergency power; drained saddle outlets at the joint low points (211); the three water-quality conditions; manufacturer and engineer confirmation of panel sizes, extrusions and fixings; separate moulds for the 8 outer collars.

## 9. Limits and items to verify

- AS 1288 glass rules and NCC 2022 Part J4 roof-light limits could not be accessed or fetched.
- Hail behaviour of ETFE in Brisbane; the EU PFAS restriction status at the time of design.
- No published minimum slope for ETFE cushion roofs, and no published ETFE minimum panel size, were found.
- The water test is a geometry check (cushion rise not modelled); the glass unit count (6,000–7,500) is an estimate.
- ETFE print or frit pattern and cushion layers are not yet specified (contractor to confirm for solar control).

## 10. How AI was used

- **Claude:** carried out the desk research R1–R4 and recorded sources and unverified items; wrote the panel-layout script (S5a, `Grasshopper/scripts_v11_steel/07_skin_panels_S5a_v11g.py`), the glass gate-panel script (`07c_glass_panel_S5b2_GATE_v2.py`) and the water test (`12_water_test_S5b2_v1.py`, `13_water_test_plot.py`); checked the glass build-up against R1 and re-ran Karamba at 0.65 kPa; recommended rejecting flat faceted and hot-bent glass.
- **Me:** I asked the questions that started R2 (could manufacturers realistically produce the hybrid approach), R3 (could ETFE contaminate stored water) and R4 (watertightness backed by simulation or research); I required glass to be tested as a realistic option or left out with the reason recorded; I set the 0.65 kPa glass load, the minimum panel size rule and the six-segment collar; I chose shadows and sound, no acoustic mesh, and the ETFE decision with its three water-quality conditions; I asked for the tests and research to be presented as findings, as evidence of how thoroughly the options were tested.

## Sources


**R1 Glass vs ETFE**

- Architen — ETFE: an economical alternative to glass: https://www.architen.com/articles/etfe-foil/
- Architen — ETFE guide: controlling solar gain: https://www.architen.com/2012/09/etfe-guide-controlling-solar-gain/
- Architen — ETFE cushion with acoustic rain suppression layer: https://www.architen.com/products/architen-acoustic/
- Domerama — Design guide for ETFE foil: https://domerama.com/coverings/etfe/design-guide-for-etfe-foil
- MakMax Australia — Macquarie University Arts Precinct ETFE roof: https://makmax.com.au/project/macquarie-university-arts-precinct-etfe-roof
- Vitro — Jewel Changi Singapore Airport: https://projects.vitroglazings.com/jewel-changi-singapore-airport/
- Gavriil et al. (2020), Computational Design of Cold Bent Glass Façades: https://arxiv.org/pdf/2009.03667
- CWCT Technical Update 10, Use of glass overhead (2003): https://cdn.shopify.com/s/files/1/0192/5660/6786/files/tu10.pdf
- CWCT Technical Update 4 (2000): https://cdn.shopify.com/s/files/1/0192/5660/6786/files/tu04.pdf
- Master Builders — Technical bulletin on AS 1288-2021 changes: https://armida-4898.c16.cw.ironstar.io/library/technical-bulletin-1018-changes-to-as-1288-*as-1288-2021*
- CCC Engineering — NCC 2022 Section J overview: https://cccengineering.com.au/design-memos/ncc-2022-section-j-overview/
- NCC 2022 Part J4 Building fabric (could not be fetched): https://ncc.abcb.gov.au/editions/ncc-2022/adopted/volume-one/j-energy-efficiency/part-j4-building-fabric

**R2 Skin panelling (hybrid approach)**

- Domerama — Building with foil cushions: https://domerama.com/coverings/etfe/building-with-foil-cushions
- Architen — Architectural ETFE foil cushions: https://architen.com/?p=4423
- University at Buffalo Reporter — Water Cube: https://www.buffalo.edu/reporter/vol39/vol39n45/articles/WaterCube.html
- Birdair — Design details (ETFE extrusions): https://www.birdair.com/resources/design-details/
- Buitink Technology — Detailing ETFE air cushions: https://www.buitink-technology.com/architecture/etfe-cushion-roofs/detailing-etfe-air-cushions
- Buro Happold — Jewel Changi Airport: https://www.burohappold.com/projects/jewel-changi-airport/
- YKK AP — YSK 750 Sloped Glazing installation manual: https://www.ykkap.com/commercial/productguide/instman/04-4018-09.pdf
- Josef Gartner — Robert & Arlene Kogod Courtyard (catalogue): https://pdf.archiexpo.com/pdf/josef-gartner/robert-arlene-kogod-courtyard-washington-dc-usa/58213-149695.html
- Knippers Helbig — Westfield roof construction: https://www.knippershelbig.com/en/projects/dachkonstruktion-westfield/
- Werner Sobek — S21 gridshells & light eyes: https://www.wernersobek.com/projects/s21-gridshells/
- seele — First look at the Stuttgart 21 light eyes: https://seele.com/article/first-look-at-the-stuttgart-21-light-eyes
- Steel Tube Institute — Bending of hollow structural sections: https://steeltubeinstitute.org/resources/hss-bending-hollow-structural-sections/
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### Files

- Research: `Research/A4_R1_glass_vs_ETFE_v01.md`, `A4_R2_skin_panelling_hybrid_v01.md`, `A4_R3_ETFE_water_quality_v01.md`, `A4_R4_watertightness_glass_ETFE_v01.md`
- Panel layout: `Model/v11g_S5a_panel_views_v01/`; review model `Model/A4_v11h_S5a_panels_REVIEW_2026-10-09.3dm`
- Glass gate panels: `Model/v11j_S5b2_glass_gate_views_v01/S5b2_GATE_01…05`; model `Model/A4_v11j_S5b2_glass_GATE_REVIEW_2026-10-10.3dm`
- Water test: `Model/v11j_S5b2_glass_gate_views_v01/S5b2_water_test_v1.png`, `water_test_v1_data.json`
- Sheet A4-02 plots: `Production/Sheets/sim_v03/`