

Two Methodologies For Vertical Shading Applications Using Architectural Terracotta

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Abstract

This paper compares the design and construction of a built application against a prototype for vertical terracotta shading fins in high-rise applications. Design of the Wasl Tower in Dubai (UAE) began in 2014 and is expected to be completed by late 2025. Its 302-meter height is clad with over 3,800 shading fins of glazed ceramic supported within an aluminum frame, earning its distinction as one of the tallest ceramic facades in the world. As part of Boston Valley Terra Cotta's 2024 Architectural Ceramic Assemblies Workshop (ACAW) in Buffalo, NY (USA), the design team was inspired to build off the work of Wasl Tower to develop a proposal that continued to evolve this approach to ceramic facades. The team worked with a terracotta manufacturer on innovating the manufacturing process to geometrically twist terracotta panels within a fin design that: (1) can adapt to various passive shading criteria; (2) increases the surface area of exposed terracotta; (3) reduces terracotta's reliance on supporting metal components; and (4), incorporates a high solar-reflectance glaze to manage heat gain.

Keywords: Terracotta, facades, vertical shading, twist, solar reflectance, urban heat island, attachment, material efficiency, optimization

1. Introduction

The UNS design approach embeds research and innovation in all facets of its design. By reflecting on and learning from past work, each new project in the studio becomes an opportunity to advance our research and refine our methods. Following a number of ceramics-clad buildings in our portfolio, the Wasl Tower in Dubai exemplifies this philosophy, showcasing a context-specific integration of terracotta into the facade. This facade design aims to create better energy efficiency and user experience by optimizing shading of the interior and improve the urban environment through terracotta's aesthetics and heat storage. Our research trajectory also draws from The Coolest White, a collaboration between UNS and Monopol for an ultra-durable, high solar reflectance paint for exterior applications, intended to combat urban heat islands.

Building on the success of these applications, we developed a terracotta shading fin prototype in the 2024 ACAW workshop environment to further develop these approaches. The primary objectives were to leverage the thermal performance of terracotta facades while reducing embodied carbon and operational energy use. This included increasing the proportion of functional terracotta while minimizing the use of high-embodied carbon materials, such as metals commonly found in attachment systems. We explored ways to balance performance with design adaptability, ensuring that the prototype's potential applications could offer diverse aesthetic possibilities, maintain visibility, and not hinder daylighting. Another key focus was amplifying the solar reflectance of the glaze, providing more insight into the role terracotta facades may play in sustainable building facades and urban heat islands.

2. Study Context & Parameters

Wasl tower serves as the basis for the building case scenario for this comparison. A super-tall building in a coastal desert climate largely lacking in shade from its surrounding context responds by maximizing passive strategies on south-facing and exposed facades to minimize solar heat gain in its interiors. The program mix, ambitions of the client and design team, as well as its prime real estate necessitated maintaining 360-degree outward views and largely transparent window-to-wall ratios on all façade orientations. The height of the building and desert storms required a strong emphasis on material and finish choices with high durability, strength, and ease of maintenance. Inspired by local, indigenous, and evolving methodologies, a major mitigation measure against solar heat gain was thus to clad the facades in thousands of composite aluminum and ceramic solar shading fins, making it one of the tallest architectural terracotta facades in the world.¹

With this as the starting point, the scope of our next iteration took form in the ACAW 2024 workshop hosted by Boston Valley Terra Cotta and was limited to a single prototype^{2,3} of a ceramic shading fin that further leverages the geometric and material potentials of the terracotta itself. The ideal outcomes we targeted were solutions that encourage the use of architectural

¹ Wasl Tower will be completed in late 2025 and requires post-occupancy evaluation to determine the effects of its ceramic fins on solar heat gain, heat island reduction, and overall building energy demands.

² Developed with similar parameters to Wasl, the applications of our ACAW design are best suited for hot, sunny environs, with applications and performance in cooler climates (including factors such as freeze-thaw cycles or winter sunlight intrusion) requiring further study.

³ The ACAW prototype was in the context of a short-term workshop environment that is yet to have a building application and an economy of scale that would warrant large-scale and iterative prototyping, testing and analysis of the physical properties and market-readiness of the final design.

terracotta in sustainability-driven, large-scale applications from a perspective that it can contribute significantly to building performance, not only from its economy and aesthetics.

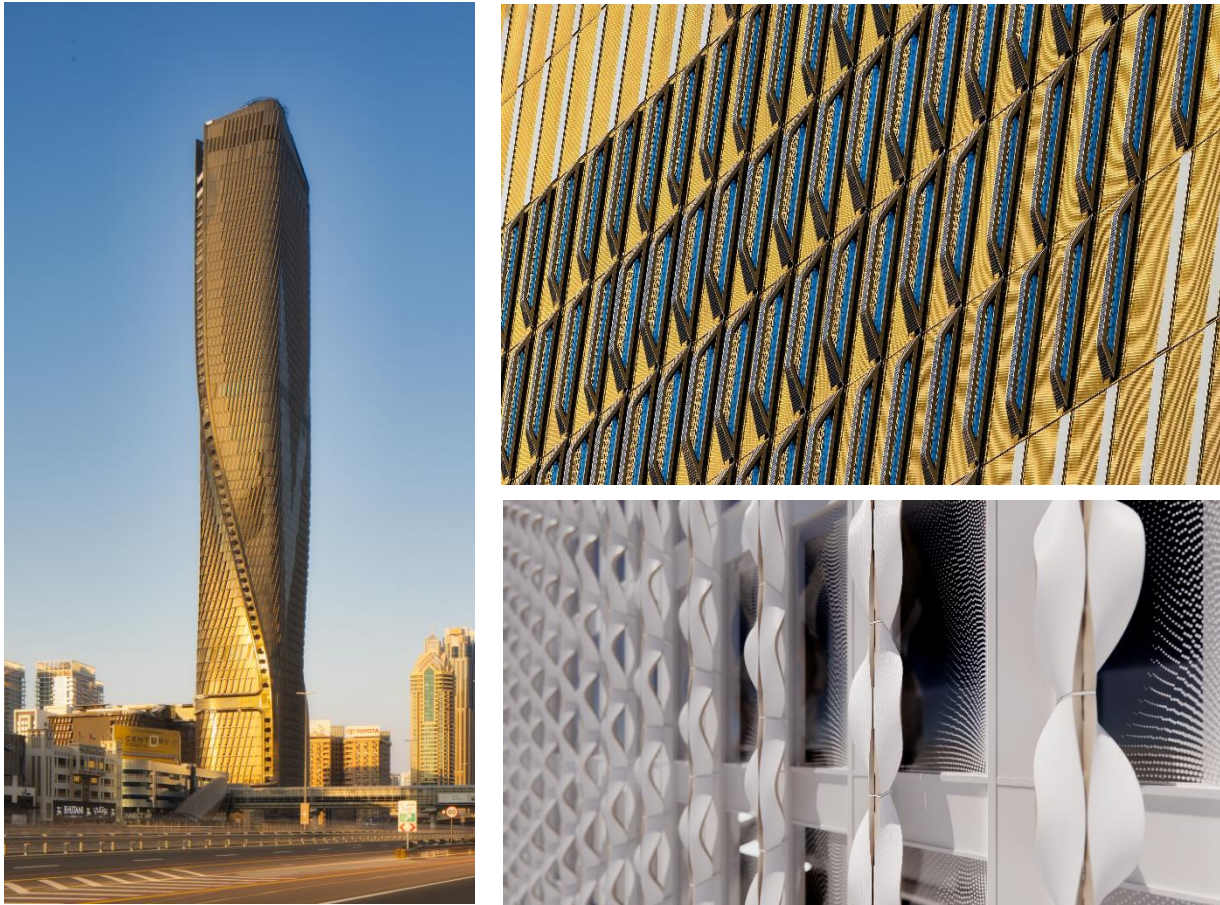


Figure 1. High-rise vertical shading fin design concepts (Left and Top-Right: Wasl Tower photographs exhibiting the tower design and terracotta facade fin system [Image credits: Johnsey Photography]; Bottom-right: conceptual rendering of application of ACAW fin design)

3. Terracotta Geometry Comparisons

Both designs take the approach of vertically stacked shading fins that are placed adjacent to high-rise curtain wall glazing to better address the lower angles and longer duration easterly and westerly sun that would otherwise penetrate deeper into the interiors. A linear array of terracotta is suspended on metal attachments outboard of the façade, with geometries that allow for a larger cavity between the ceramics and façade that permit a larger volume of lateral air

movement around and behind them.⁴ The terracotta, with its low thermal conductivity and high heat storage capacity, is able to capture and hold heat absorbed from sunlight, while radiating it back to the environment more slowly. Increasing surface area on the front and behind the terracotta that is in contact with air allows the system to dissipate heat better while not bridging or radiating the energy to the building.⁵

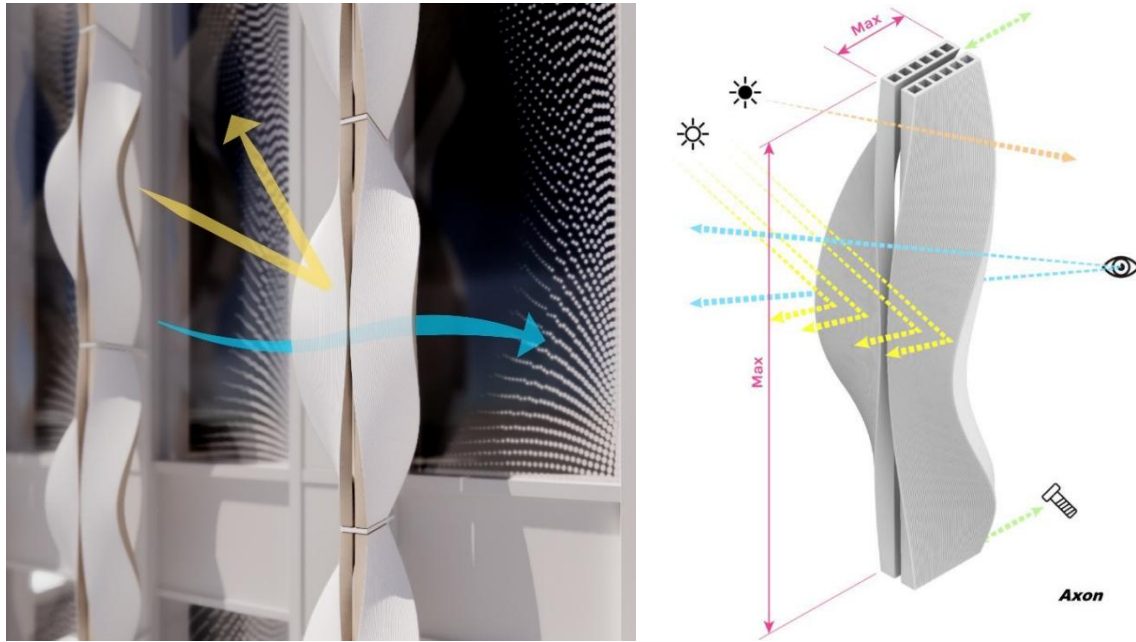


Figure 2. Concept approach to ACAW Design

3.1 Terracotta Fabrication & Composition

On large scale applications, die extrusion is typically preferred due to its higher degree of economy and efficiency over casting or pressing. To create the terracotta arch of the Wasl fin, long extruded panels are cut post-firing along their face into a series of shapes that sit in sequence to line the exterior profile of the fin. One die profile is used to create the flat surfaces while a second one is used to create the filleted returns—a shiplap detail and lateral texturing in

⁴ Each fin design can be represented by a D-shape in their side elevation, where the flat profile is the façade surface and the terracotta is arrayed along an exterior arch to suspend it away from the building with the open cavity in between. The arched forms maximize the surface area of suspended terracotta while allowing it to ‘return’ closest to façade at the top and bottom of the fins to mask their attachment hardware.

⁵ Inspiration for this functionality on Wasl Tower was driven by a radiator concept, where heat generated in the building interiors could be transferred to the ceramics as a heat sink to be dissipated by air, but was ultimately not developed for inclusion in the MEP and façade systems. Despite this, one of our major directives for improvement retains true to the radiator concept by maximizing the ratio of terracotta surface area that is exposed to potential for naturally ventilated heat transfer.

both die profiles gives the appearance of one larger terracotta surface when the pieces are placed side-by-side. Many varying pieces must be mounted individually to populate the height of the fin. By contrast, the ACAW design leverages the terracotta extruded by a single die profile, manipulated before kiln firing to achieve design intent parameters. The flat panel is then slumped onto a proprietary mold, incorporating up to a nearly 90-degree twist in the middle of the piece with its two ends retaining their original, matching orientation upon firing. This enables curvature within a single piece of terracotta, retains consistent attachment points at the ends of the panels, and eliminates the need to cut the terracotta post-firing to achieve desired forms. Stood upright, panels are duplicated and mirrored in the fin composition for easterly and westerly sun shading, requiring thereby only two terracotta pieces for each fin module.⁶



Figure 3. (Full-scale terracotta prototype in elevation and side view exhibiting the twisting geometry and minimal attachments)

3.2 Composite Attachment

Die profiles typically provide architectural terracotta with cells or grooves oriented along the extrusion length to reduce panel weight, which may be leveraged for clip or drilled fastener systems. The rear faces of the Wasl terracotta profiles are pre-drilled with bolt holes, matching up with a lock plate that is inserted into every few cell cavities. The bolts lock down a clip profile

⁶ In theory, an extruded panel that is many feet wide and whose length matches the floor-to-floor height could be produced but would be too large and heavy to manipulate in the factory and install at scale (also accounting for the size of the slump mold with which it must be fired). The maximum constraints for our prototype were a 11-inch wide by 6-feet long panel, which would necessitate stacking 2 fin modules to reach a typical floor-to-floor height in a built application.

onto the rear face which then mounts to matching holding profiles attached to the aluminum subframe running vertically behind the terracotta. The terracotta pieces are thus supported by the many shear connections created from the bolts, and transfer all lateral loads back to the aluminum subframe. Breakage and debris mitigation is addressed by dampeners that are fully bonded between the back of the terracotta pieces and aluminum subframe.

Where the Wasl Tower attachment used an aluminum extrusion subframe to support the terracotta, the ACAW prototype seeks to minimize the use of metals, with the attachments being limited to the ends of each panel. The prototype takes advantage of the extrusions' cells, utilizing a flat horizontal attachment plate with sleeve extrusions. These extrusions are inserted snugly into the cells of the terracotta with a rubber bushing to both protect the surface of the material and to ensure firm contact with the support sleeve. In this manner, the terracotta panels are simply held in place at four points each by two attachment plates and must support their own gravity as well as transfer all lateral loads along their length to the sleeve extrusions. The targeted improvement from this self-supporting approach is that there is no aluminum lining the rear face of each terracotta panel, allowing thereby both sides full air exposure to better dissipate heat. Due to the curvature of the ACAW prototype and its visibility of both the front and rear faces of the terracotta panels, any breakage solutions must also consider aesthetics. Such solutions were not explored in the limited timeframe of the ACAW workshop but could be achieved by including a wire mesh bonded to the surface of the terracotta, along with cables inserted through the nonstructural extrusion channels. The wire mesh would provide some post-breakage retention of the terracotta pieces, while the cable would provide a failsafe against the panels disengaging from the building façade after a breakage event.

3.3 Variation & Adaptability

Adaptability is a key design incentive to retain economy while responding to many orientations of the building and site conditions. Through environmental and parametric models, varying sizes of fins were developed for Wasl Tower and distributed according to floor-to-floor heights, mixed interior programs, and façade areas with more or less solar incidence (Fig. 5).

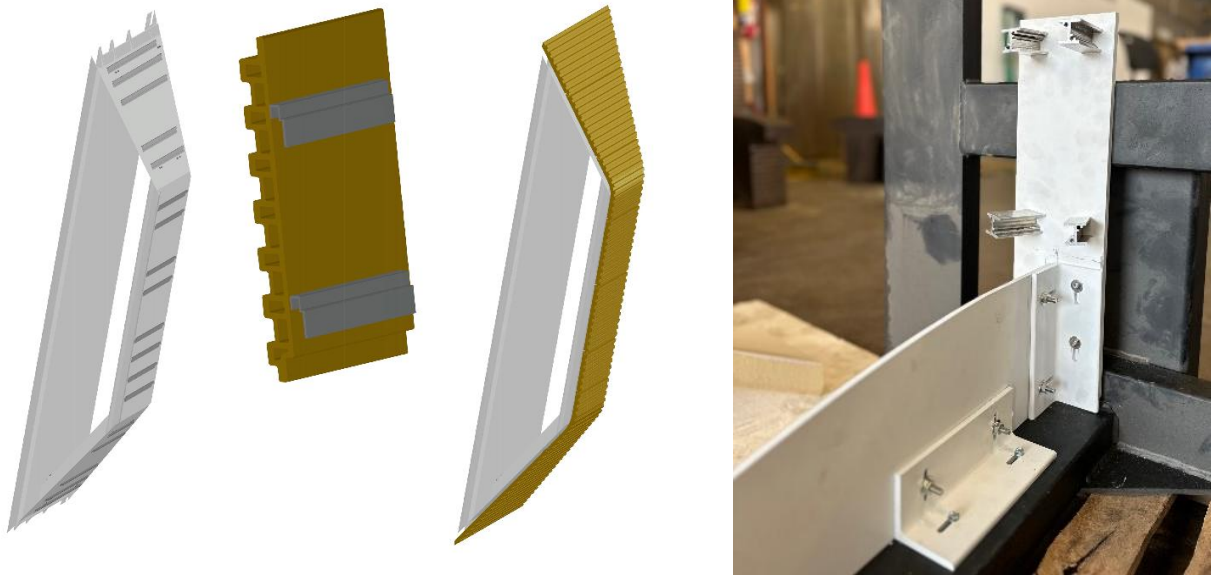


Figure 4. Terracotta attachment into fin modules (Left: Diagram of Wasl fin, drilled and bolted holders with aluminum backing, Right: ACAW prototype, sleeve extrusions attached to top and bottom plates aligned with cell profiles

Variability in height, depth, and width of the fin's aluminum armature and adding or removing terracotta panels in various cut lengths, accommodates variations in floor height and shading coverage. This ultimately proves more flexible as the dimensions of the fin are not reliant on the maximum terracotta fabrication constraints.

For the ACAW fin, the fin's dimensions are more inherent to the manufacturing process of the terracotta itself. The module's height is determined by the length of extrusion of the wet panel, the depth of the fin is determined by the panel width, and the total width of the module is twice one panel width. This ties the potential shading coverage to manufacturing and handling constraints of the terracotta.⁷ By simply twisting the flat extrusion from a single profile, the amount of terracotta used, as well as its attachment, may remain consistent between each module. Having proved a 90-degree twist is possible with our selected height and width, we can

⁷ It is important to note that a longer, thinner, and narrower panel is easier to twist to 90-degrees and back due to a lower rate of curvature and density of material along its length. A shorter, thicker, wider panel is more prone to breakage as fractures that develop during the twisting are exacerbated by shrinkage during drying, but may be accommodated by targeting a degree of twist that lower than 90. The web thickness, length, width, and rate of twist of the terracotta also has significant impact on firing and drying cycles, which already requires extensive drying times from a typical flat panel. Variable shrinkage and warping also have significant impacts on tolerances that are avoided by cutting panels after firing, as in Wasl. Further study and prototyping with the fabricator would be required to understand the limits of adaptability with these techniques.

be certain that a lesser degree of twist may be achieved, allowing variation in the width of the fin and consequent shading coverage.⁸

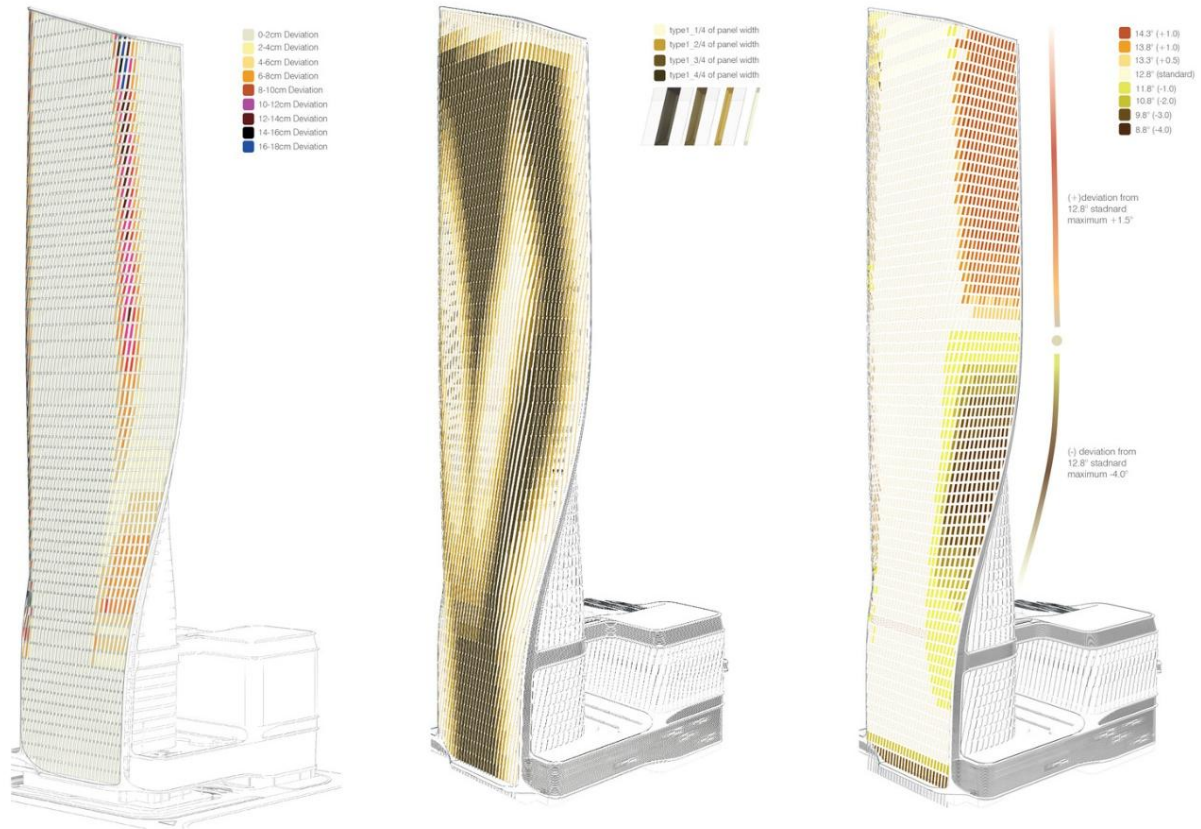


Figure 5. BIM Geometry tracking for fin types and installation on Wasl Tower. Above: (Left): Order of deviation between planarized and base double-curved surface; (Middle): Facade fin width type distribution; (Right): deviation of fin angle from typical 12.8° tilt.

3.4 Glazing Impacts, Daylighting & Visibility

As with any shading fin placed next to a window, its potential for shading coverage must be balanced with ambient daylighting into the interior and views outward for users. Due to the high-rise and landmark nature of Wasl Tower, views would be of particular importance to its inhabitants. The attachment style and width of the fins at their rear face necessitates having an opaque façade behind it, which is sized to the width of the widest fin type and affects the

⁸ Further prototyping and study could investigate twisting further than 90 degrees, which would give the fin assembly a depth that may exceed the extrusion width of the terracotta and allow better shading.

window-to-wall ratio. In plan, a chamfer is introduced to each fin to better daylight and widen the viewpoint of the window to the west; however, this reduces the amount of terracotta on the outside face of the fin while retaining the same amount of aluminum sub framing to support it. All of Wasl's fins sit immediately adjacent to the west edge of each window, meaning narrower fin types impose less on the next window over, but the view to the west will always be impeded by deepest face of each fin type.

The ACAW design provides more flexibility in orientation from its symmetrical design. The manner in which the twist resolves in the geometry and attachments along a single plane where the terracotta 'returns' to meet the façade permits a rational and compact alignment of its attachments along the mullions between curtain wall panels. Views are allowed out where the terracotta twists towards the ends of the panels. To compensate for shading coverage that may be lost from this, the middle of the twist may extend over the front elevation of windows to better protect interiors. The compact linear vertical alignment of the ACAW attachments also reduces the need for opaque panels behind the fins, meaning glazing may be placed symmetrically to either side and be shaded in the same manner whether from east or west sun. Due to having no aesthetic panels and structural framing behind the terracotta, visibility is also improved through the cavity behind the ACAW fins.

3.5. Results

Each design responds to specific constraints of their context, fabrication, installation, shading coverage, and structural integrity. They represent respective solutions that have their own merits and betterments from one another.⁹ The aluminum substructure of the Wasl fins provides more flexibility to create larger and deeper fins that cast more shade, whereas the ACAW module's size is tied to the extrusion dimensions.¹⁰ The ACAW design achieves significantly more exposed surface area of terracotta due to its double-sided nature,^{11,12} as well as slightly more

⁹ Due to the maximum fabrication constraints of the ACAW design, two of these fin modules are stacked on top of one another to be able to draw comparison to the full floor-to-floor height of one Wasl fin. As the fin depths and widths of Wasl vary, we drew comparisons against the largest typical fin.

¹⁰ Wasl's largest typical fin (700mm wide by 600mm) will cast more shade than the ACAW design (600mm wide by 300mm). As the ACAW design is symmetrical, it can partly extend over the elevation of glazing, and returns to a vertical panel at the top and bottom, it can be expected to provide similar or more shade than Wasl's other fin types (500mm by 400mm, and 300mm by 217mm).

¹¹ 63.73 square feet of exposed terracotta surface, compared to 31.35 square feet in Wasl's largest typical fin type.

¹² Raking the faces of the terracotta panels is an optimization intended to increasing their exposed surface area and is assumed to create micro-shading which supports the passive heat rejection of material. The Wasl die profile integrated rectangular cells which alternated in orientation giving the exterior surface the appearance of lateral rakes which were about 10mm deep and 25mm wide, increased the surface area of the exterior face of the terracotta by about 29%. Due to the complexities and volatility of the handling, slumping, and drying of wet, twisted clay, the die profile of the ACAW

volume of terracotta (Fig. 12). The terracotta surfaces of the ACAW design additionally face multiple orientations and mask their attachments, allowing the ceramics to account for more of the solar incidence and reflectance.

4. Glaze Comparisons¹³

Apart from its thermal properties, glazed terracotta was chosen as a key facade material for the Wasl Tower due to its aesthetics, maintainability and durability. With the occurrence of sandstorms in Dubai, the abrasion-resistance and low-permeability of the fired, glazed surface of the ceramic tiles was a desired trait to reduce the potential negative impacts of high winds and sand build-up on the facade. The pearlescent bronze glaze selected for the terracotta, as well as the raked texture introduced in the extrusion process, creates a shifting appearance based on the viewing angle and reduces the visibility of any abrasions or buildup of dirt or sand. The glaze developed for the ACAW prototype builds upon the highly performative properties of ceramic glazing, drawing inspiration from "The Coolest White," a collaboration between UNS and Monopol.

4.1 Methodology

The "Urban Heat Island" (UHI) effect occurs in a self-reinforcing feedback loop (Goward, 2021) wherein a cityscape's sources of heat and accumulated thermal storage capacity combine with thermal inertia. This may lead to daytime temperatures reaching problematic levels that exceed what can be naturally cooled overnight (Pezeshki, 2018). In other words, many contemporary urban settings follow the maxim "The hotter they get, the hotter they stay," with potentially devastating and even deadly consequences. An estimated 489,000 heat-related deaths occur globally each year (Zhao, 2021), a burden amplified significantly in densely populated areas by urban overheating (Wang, 2025). UHI also contributes indirectly to carbon emissions due to increased use of air conditioning and other cooling devices, and has even been known to affect rain patterns and worsen air pollution (Lai, 2009). One way to counter UHI is to prevent heat energy from entering an inert storage medium in the first place. Surface color correlates with its ability to absorb heat under full spectrum light (Radhi, 2014): light waves can be diverted away from a material's surface and back into the atmosphere, thereby avoiding being stored inside

prototype had to retain uniform web and panel thicknesses. This allowed only a shallower rake profile and a scalloped shape was chosen which increased the surface area of the front side of the terracotta panel by 16.0%. The stretching of the terracotta panel when slumped into its twisted form lends approximately an additional 3.8% increase compared to a flat panel.

¹³ The geometry of the ACAW fin has a more significant impact on the glazing strategy as the terracotta surface is exposed on both the front and back. Geometry explorations intended to maximize terracotta surface area in direct contact with air and sun were meant to work in conjunction with potential for photocatalytic materials in the glaze, which was ultimately not developed in the scope of the workshop.

the material as heat. The desired reflection specifically targets the electromagnetic radiation spectrum between 780 nm and 1 mm, more commonly known as the infrared (“IR”) band.¹⁴



Figure 6. Glaze comparison (Left: Wasl Tower terracotta glaze, Right: Prototype terracotta glaze)

Heat experiments were performed on various glaze formulations¹⁵ using a controlled environment and standardized ceramic samples (Fig. 7). Three chief metrics were observed:

1. Surface temperature of samples' **top/front** face after a set time of exposure to full spectrum light.
2. Surface temperature of samples' **bottom/back** face after a set time of exposure to full spectrum light.
3. Degrees of cooling of both front and back at a set time after removing light source.

Temperature was measured using both laser thermometer¹⁶ and thermocouple.¹⁷ A 2 x 100W bulb full spectrum terrarium heat lamp¹⁸ was used to heat each sample for ten minutes (t), with ten minutes to cool down (t'). Temperature readings were taken at t = 0, t = 10 and t = 20 for a total of eight different samples. A representative selection of results are demonstrated below (Fig. 7).

¹⁴ Doing precisely this was the underlying objective of UNStudio and Monopol Colors when they developed The Coolest White [TM] paint formulation. Through meticulous and documented testing, The Coolest White [TM] demonstrated its potential in solar reflection of painted metal surfaces (Monopol Colors, UNStudio, 2020). While The Coolest White's fluoropolymer (PVF) formulation is not suitable for ceramic surfaces, its pigmentation can be replicated in a ceramic glaze.

¹⁵ Shown here are the BVTC standard glaze, which we believe best approximates the Wasl Tower glaze in terms of hue and reflectivity (Fig. 6); BVTC's unglazed standard clay body; a solar-heat gain reducing paint product for masonry; and the glaze that was used for the study's mockup. Additional tests were conducted to incorporate the photocatalytic quality of compounds such as titanium dioxide and barium sulfate nanoparticles.

¹⁶ Klein Tools IR5

¹⁷ THE-373 K/J Datalogger

¹⁸ Dxophiex DLF15

4.2 Results

Three findings are observed. First, the ability to release heat varies minimally across samples.¹⁹ Second, while back side temperatures of most samples remained relatively stable during front surface heating and cooling, some continued to climb even after the light was removed. Finally, results show a clear correlation between surface color hue and peak temperature under a given thermal load, $T(t)$.

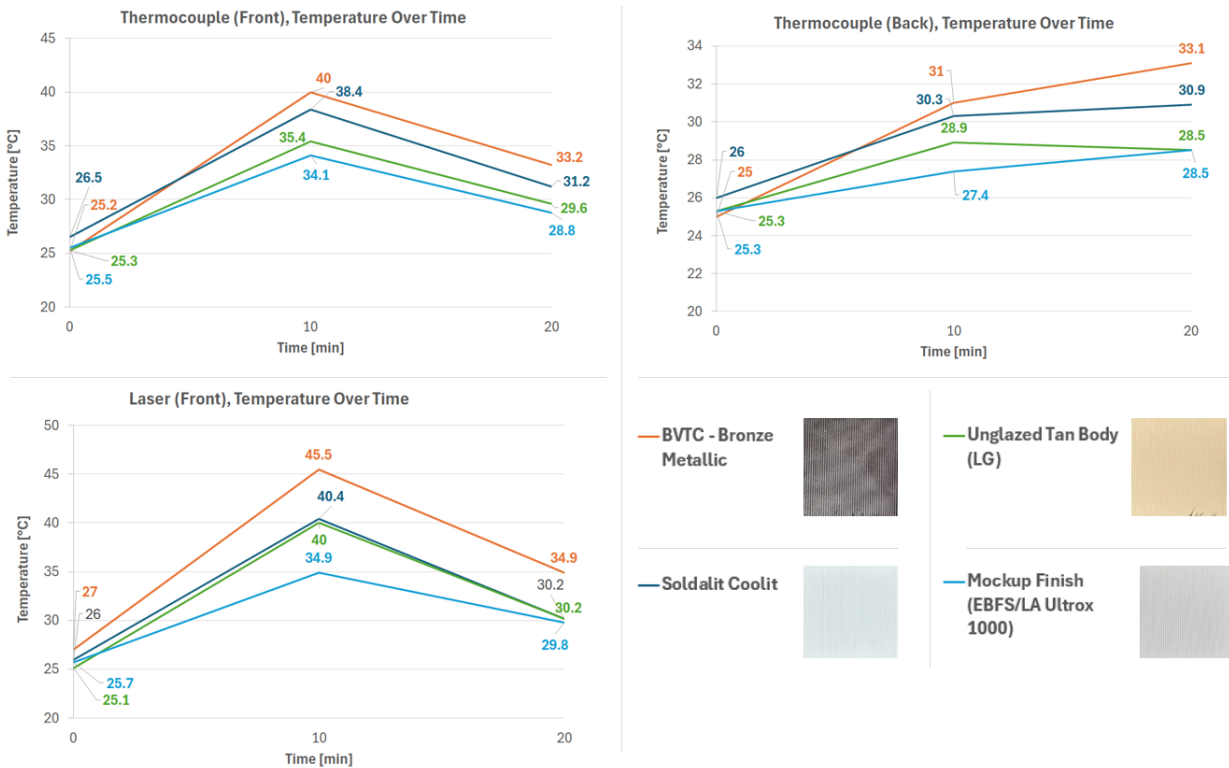


Figure 7. Glaze samples heat lamp testing results

By experimenting with the density of white pigment, our glaze shows a measurably improved solar reflectance, with the potential to both reduce heat load on buildings and limit the heat stored and released into urban environments (Radhi, 2014). While preliminary, the data suggest that the quantity of incident light diverted away from the terra cotta's surface is the most significant factor in determining how much heat the panel will absorb and retain. Further study is

¹⁹ From approximately the same surface temperature, $T(0)$, $T(t') / T(t)$ varies by 5% or less between any two samples.

needed to disaggregate the relative light-diverting capabilities of glaze color and glaze reflectivity on terracotta, as well as to quantify any interactive effects.

5. Structural Analysis

Wasl Tower's fins are preassembled separately from the unitized facade panels behind them. A clip system near the top, midpoint and bottom of the fin attaches its rear-concealed aluminum extrusions to matching clips protruding through the panel's opaque finish sheet. The fins are therefore supported by the unitized facade modules which, in turn, are supported by the building floor slabs in a conventional unitized facade assembly.

The ACAW prototype, similarly to the Wasl Tower attachment, is designed to be installed in a modular fashion within a unitized curtainwall system without compromising system performance. To limit the loading imposed onto the otherwise typical framing, a vertical steel tube is pre-installed inside of one portion of the unitized curtainwall (Fig. 8). This steel tube has discrete outrigger plates that extend through the vertical curtainwall joint to support the attachment plates which hold the terracotta panels. Finally, the steel attachment plate is bolted to the vertical outrigger by steel angles to accommodate field tolerances and provide a quick method of installation.

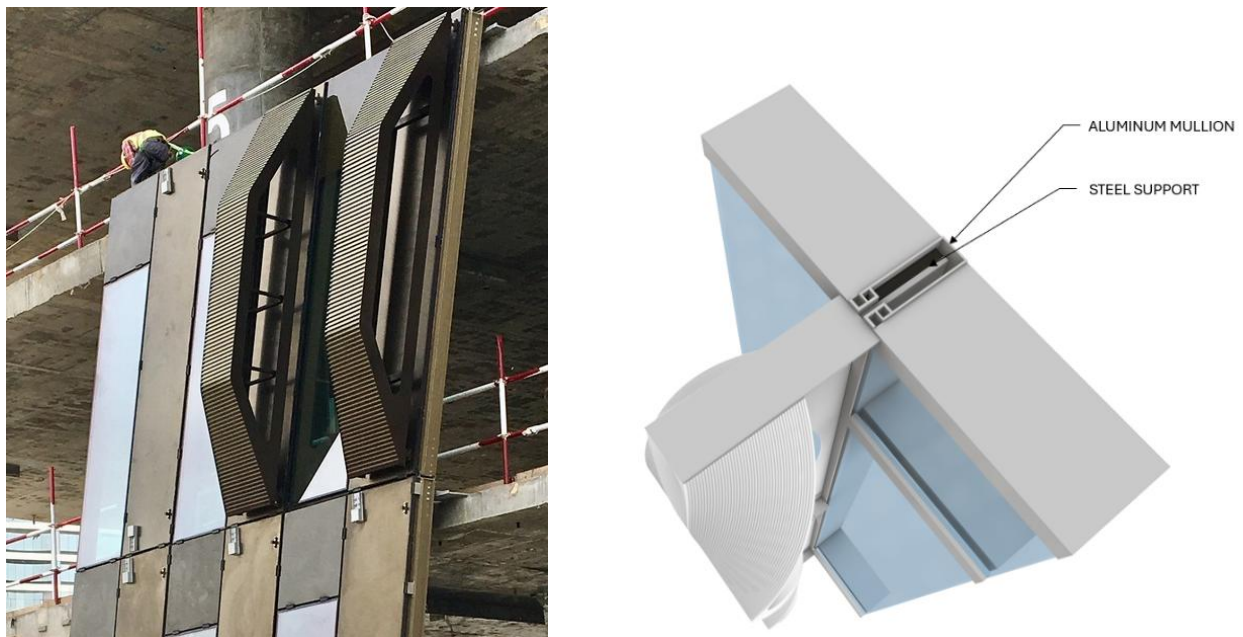


Figure 8. Attachment concepts to curtain wall (Left: Wasl Tower, outboard clips; Right: ACAW design concept, mullion-integrated steel support)

5.1 Methodology

The Wasl Tower façade was designed for a components and cladding wind pressure of 3.5kN/m^2 , or 73 psf. Due to its projection from the building's face, the system receives load from three directions: positive pressure towards the façade, negative pressure away from the façade, and parallel pressures along the face of the façade (Fig. 9). The terracotta panels span the aluminum framing elements, distributing the pressures as line loads to the framing, which then transfers them to the anchor points. To provide a comprehensive comparison between the Wasl Tower application and the ACAW prototype, the same loading assumptions and magnitudes are used for the curved terracotta panels.²⁰ However, the impact of the conservative assumptions noted below are amplified as the panel geometry accommodates more flow of wind behind the panel surface. Moreover, due to the geometry of the terracotta fin, an additional unbalanced load condition that is not present in the Wasl system is considered which assumes 150% of the design load on one face of the system and 50% on the other (Fig. 9).²¹ This twisted geometry was also compared against a single flat fin profile of similar cross section, oriented perpendicular to the facade to study how the unique twisted and curved geometry compares to a more typical traditional shading system. A detailed summary of the results of the flat fin study is not included within the scope of this paper however, the controlling results and behavior are briefly discussed as a comparative baseline in this section and within the conclusion section of the paper. The ACAW system was modeled in FEA software to accurately study the impacts of these loading conditions on the complex terracotta geometry. The FEAM accounts for both curving surface elements and the internal cellular structure of the terracotta extrusion to stiffen the system. The mesh size was limited to a maximum dimension of 0.25" to minimize impacts of edge discontinuities creating unrealistic peak stresses. The limiting strength values represent the tensile failure stress of the material at the 5% percentile value (Equation 1), which will always control over any compressive or buckling modes of failure.²²

$$R_{nominal} = R_{mean} - K \cdot S_{dev} = 2415 \text{ psi}$$

Equation 1: Nominal Modulus of Rupture calculated as the 5% percentile: mean minus K times standard deviation.

²⁰ Assumptions: 1) that the system is fully exposed to the development of internal pressures. Since this system is outboard of the building envelope, it is unlikely that the internal pressure will reach the same magnitude as what would be used for the analysis and design of the curtainwall system; 2) that full design pressures will be applied across the faces of the system under the parallel wind condition. Wind speeds along the façade's boundary surface will likely not develop sufficiently to affect the fins in this manner.

²¹ This pressure amounts to an increase in design wind speed of approximately 123%. All load conditions have been analyzed in both the positive and negative orientations.

²² The terracotta capacity is determined through ASTM C67 Modulus of Rupture tests provided by the fabricator (Alfred University, Inamori School of Engineering, 2024). The average Modulus of Rupture is modified to determine the 5% fractile value to provide a high degree of statistical confidence in the limiting strength values used in the study (The Aluminum Association, 2020).

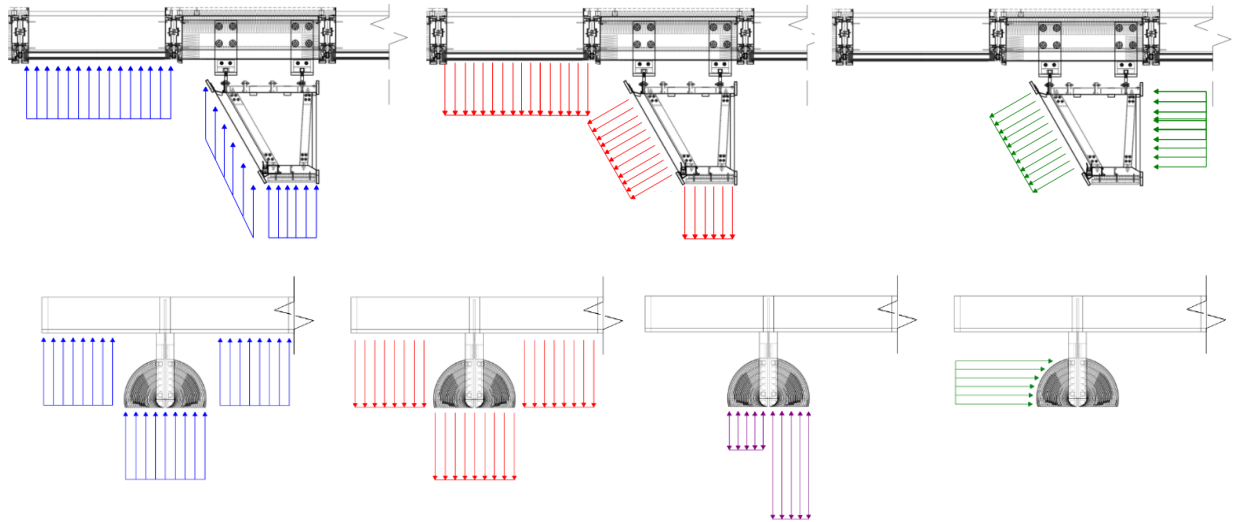


Figure 9. Wind load cases comparison (Top: Wasl wind load cases for positive pressure, negative pressure and parallel pressure; Bottom: ACAW design wind load cases for positive pressure, negative pressure, unbalanced load condition and parallel pressure)

5.2 Results

Under the envelope of Uniform Load Conditions, the maximum principal tensile stress in the terracotta panel is approximately 328 psi, for a factor of safety of 7.4. The maximum principal tensile stress under the Unbalanced Load Conditions is approximately 473 psi, for a factor of safety of 5.1 (Fig. 10). By comparison, the flat fin profile experiences approximately 376 psi for a factor of safety of 6.4. Additionally, both the attachments to the internal steel framing as well as the framing itself were modeled for a full floor span in order to study the effects of system flexibility and understand panel movement in a high wind environment. As the steel is embedded inside a unitized curtainwall with a glass unit attached via silicone bond, the system utilizes the in-plane stiffness of the glass to brace the unit. This is accommodated via a continuous linear spring at the outboard face of the steel frame, which models the silicone joint into the glass unit (Fig. 11). The stresses and deflections of this joint were analyzed to ensure that the silicone joint is not overstressed and could accommodate the loads imposed by this diaphragm behavior.²³ When comparing the results of the curved panel to the flat fin baseline profile, the lateral deflection and the silicone stress results of the flat fin are nearly double that of

²³ The maximum deflection of the outboard face of the panel is limited to approximately 0.473 in under the worst-case loading, with the internal steel member deflecting a maximum of 0.195 in within the curtainwall frame. The silicone stress to develop diaphragm behavior is limited to a maximum of 4 psi, well below recommended design limitations of 20 psi. The steel strength utilization is limited to approximately 15% of its capacity, allowing it to additionally brace the curtainwall members. These results, along with the Factor of Safety demonstrated in the terracotta material, indicate that the design is structurally feasible with a reasonable degree of safety and confidence.

the curved panel, due to a larger surface area receiving wind pressures in the weak direction of the system.

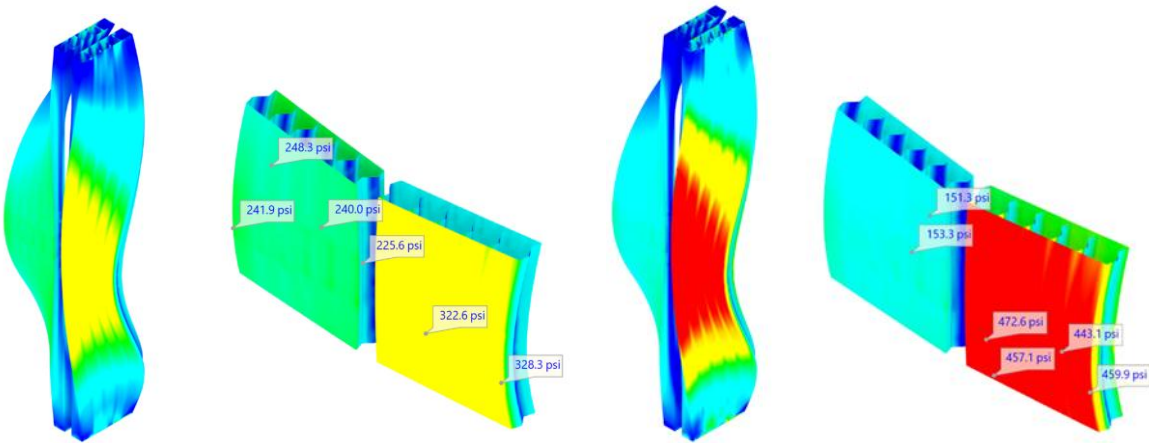


Figure 10. Maximum principal tensile stress.

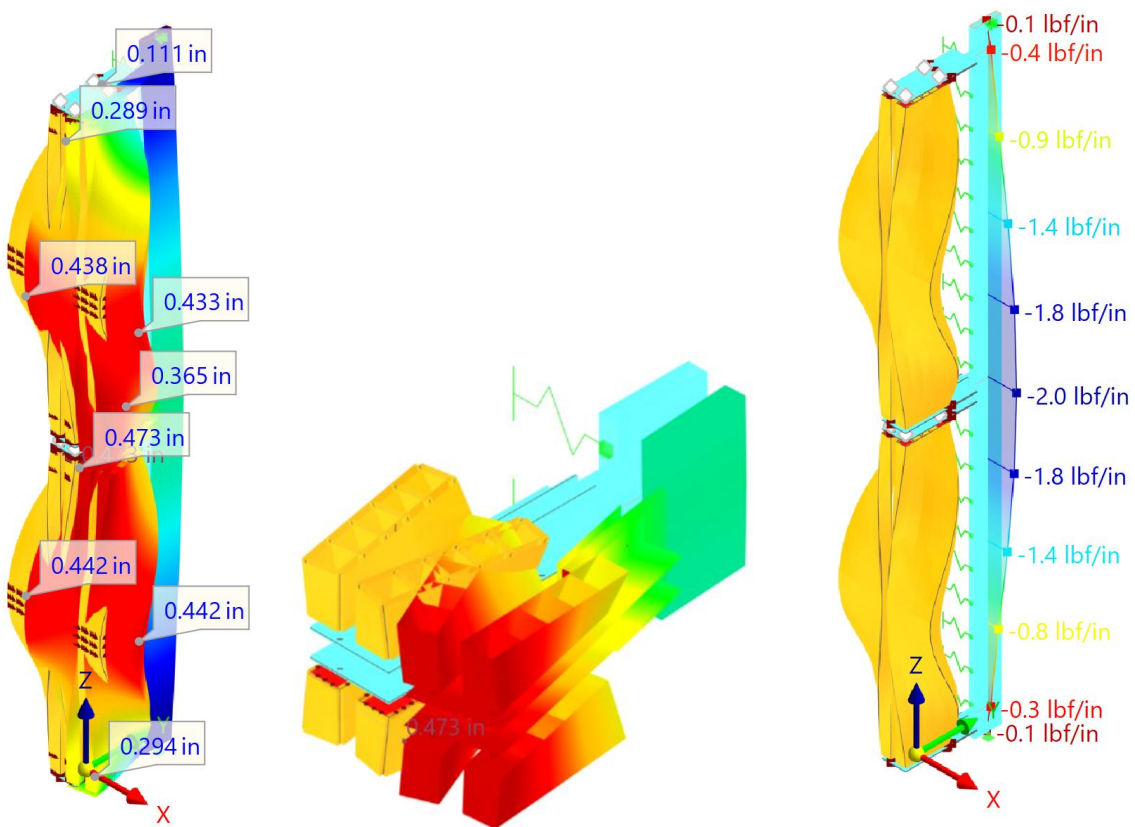


Figure 11. Composite action via silicone bond.

6. Embodied Carbon Assessment

The embodied carbon assessment compared a prototypical Wasl Tower fin to the ACAW fin prototype. The global warming potential (GWP) was estimated for both designs for lifecycle stages A1-A3. The assessment assumed North American manufacturing and used embodied carbon data from industry-average environmental product declarations (EPDs) for all materials except terracotta, which used the same product-specific EPD for both designs.²⁴

6.1 Methodology

The scope of the assessment included the respective models' curtainwall framing and fins.^{25,26} Since the object of comparison is the fin assembly, the curtainwall for the ACAW model is assumed to be identical to that of the Wasl model.²⁷ The curtainwall framing, glass, spandrel panels, and insulation were included for the purpose of contextualizing the fin within the exterior wall assembly.²⁸ The systems are assumed to be approximately functionally equivalent, however, detailed analysis of the effects of the façade design on building energy use was outside the scope of the ACAW design exercise.

²⁴ Embodied carbon data for materials other than terra cotta is based on industry average EPDs consistent with the 2025 Carbon Leadership Forum Material Baselines (Waldman, 2025). For terracotta embodied carbon data, see Boston Valley's Terra Cotta Cladding EPD Results Excluding Aluminum Framing published February 2023 (Boston Valley Company, 2023) and Environmental Product Declaration: Terra Cotta Cladding (Boston Valley Company, 2023). The declared unit of the EPD is 1m² of cladding products, however, the mass provided in the EPD was used to estimate the embodied carbon per kilogram of terra cotta, and used to estimate the embodied carbon of the unique panel shapes used in both the Wasl and ACAW designs. Through discussion with the manufacturer, the team learned that the energy input of the kiln is not a fixed amount per kiln cycle, but is also dependent on the mass of material in the kiln. Thus the impact per unit of mass for these custom panels was assumed to be similar to that of the products represented in the EPD.

²⁵ Curtainwall framing consists of aluminum extrusion, glass, metal spandrel panels, spandrel insulation, and reinforcing. The fin consists of terracotta and aluminum panels, fin support materials, and connections of the fin to the curtainwall unit.

²⁶ The CLF material baseline report does not provide embodied carbon data for fasteners, gaskets, sealants, or the laminated glass interlayer. As these components are assumed to make up less than 5% of the total mass of the assembly, they were excluded from the scope of the assessment.

²⁷ Namely, the same window-to-wall ratios, glass make-ups, spandrel assemblies, insulation, and framing system.

²⁸ The bill of materials for the Wasl curtainwall and fin design is based on shop drawings and a Rhino model of the system. The bill of materials for the ACAW fin is based on the ACAW design and analysis models, and the bill of materials for the ACAW curtainwall is assumed to be identical to that of the Wasl curtainwall.

6.2 Results

The ACAW design shows a significant optimization in GWP compared to the Wasl design. While similar in mass the ACAW design is significantly lower in GWP. This further development is primarily due to the reduction in the quantity of aluminum used (Fig. 12).

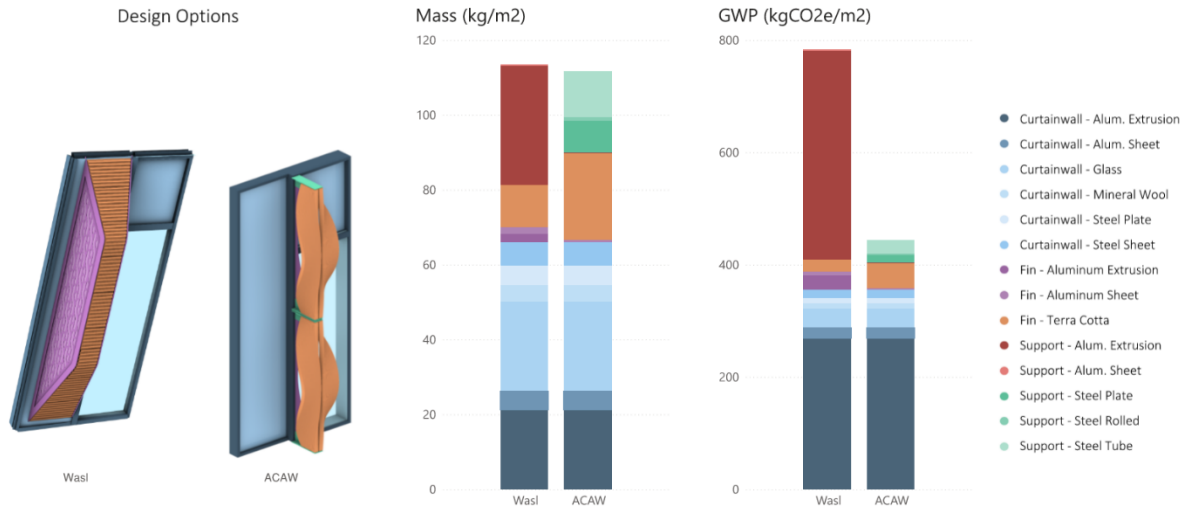


Figure 12. Mass and GWP by assembly, per square meter of exterior wall

7. Conclusion

Over time since the industrial revolution, the proportion of total construction costs from material versus labor have inverted (ENR Construction Economics Dept, 2025), leading to a shift in focus away from material efficiency in favor of speed of assembly. Grossly simplified, where sparing use and material economy were once necessity, construction can now “afford to throw material” at any problem. This is of course only true inside a system that measures material costs solely in economic terms, while ignoring, or at least downplaying, environmental aspects. We draw inspiration from history as the intuitive basis for the experimental system described in this paper. The genesis was a desire to move away from a relatively heavy dependency on metal sub-framing, instead relying on the terracotta itself to “do the work” of transferring self-weight and environmental loads as its own primary load path.

Manipulating geometry as a means to achieve structural efficiency is an ancient principle, present in the vaults, arches and domes of millennia of building tradition. These historical precedents share a relatively high stiffness-weight ratio, using relatively little material to achieve high load-bearing capacity. For our ACAW prototype, the increase in stiffness added through its curvature and resulting reduced connection points, minimizes the need for attachment hardware

and sub framing. A main goal achieved in this study, thereby, is a reduction in embodied carbon over a comparable, metal framed system (Fig. 12). While there is uncertainty inherent to estimating embodied carbon, we believe that the ACAW design represents a significant improvement over the Wasl application in this domain. Further, the ACAW design represents a way in which a geometric gesture may integrate multiple layers of functionality. Beyond the improved structural efficiency, the twist provides depth to the façade surface in order to self-shade and reduce solar heat gain, while still promoting visibility from, and daylight to, the interior. Additionally, it maximizes the dimensional fabrication constraints of a single extruded terracotta component.

The authors believe that these preliminary results suggest a high degree of integration between geometry and load transfer that is worthy of further exploration. There is potential to render our use of material more efficiently, thereby lowering the embodied carbon content of certain construction assemblies. Similarly, while the glazing experiment was done in a fairly rudimentary fashion, it nevertheless shows promise in lowering operational carbon emissions and combating the Urban Heat Island effect. We see a wealth of possibility to explore in several domains related to this study, and we intend to produce additional publications building on extant and future experimental data.

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