



Crystal Cladding: Detailing Faceted Glazed Geometries

TJ DeGanyar
Jeff Vaglio
Mark Dannettel*
Mic Patterson

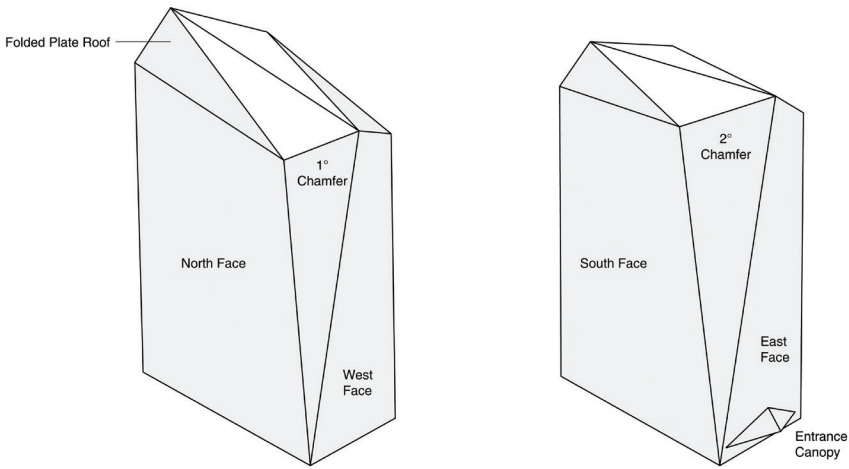
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A recent trend in glazed envelope systems has been the use of complex faceted geometries. These enclosures create a gem-like aesthetic while implementing many standard practices better refined in typical curtain wall construction. However, these faceted skin systems magnify numerous fabrication and installation concerns such as tolerances, anchorage, weatherproofing, alignment, warping and movement. This paper reviews four recent faceted facades of different scale and system type, and identifies the relative advantages and disadvantages of each system. Each project is evaluated for its efficiency of implementation, as well as its performance as an enclosure with respect to detailing, fabrication, installation and 3D geometry management.

* Thornton Tomasetti
Los Angeles, California, USA

Figure 1. Faceted tower geometry (this page) and photo (opposite page left).

Figure 2 (opposite right). AESS glazed lobby canopy feature.



1 INTRODUCTION

In recent decades applications of complex geometrical forms in architecture have challenged engineers to continuously advance the versatility of facade enclosures and redefine fabrication and installation methods. The new geometric and technological possibilities are in part the result of the significant freedom and parametric control of current CAD systems enabling designers to produce radically new forms [1]. The increasing presence of free-form geometry in architectural design has given rise to some beautiful glazed forms, such as Frank Gehry’s DG Bank (Berlin, 2000), while simultaneously challenging the gap between original design form and what can feasibly be constructed [2]. Forms which require many unique glass panel geometries, such as the 12,000+ unique glass sizes of Capital Gate tower in Abu Dhabi [3], lack the repetition required to justify application of doubly-curved glass panels formed using molding techniques previously developed by the automotive industry [4]. To achieve economic viability many digital free-form incarnations are rationalized through the application of faceted glazed structures.

The complexity associated with free-form and faceted glazed systems is ideally approached through a design/assist process, involving the builder at an early stage of concept development to assure an aesthetically pleasing, structurally efficient and economical solution [5]. It is important for architects to engage with facade consultants during the design process of complex building skins to properly design

the system details, conduct preliminary engineering to ascertain system feasibility, and to ensure that superimposed loads are coordinated with the building’s structure. Moving forward with advanced computing, modeling and information control, lessons learned from existing faceted forms should be considered as a means to optimize and implement appropriate facade solutions incorporating complex crystalline forms.

2 DESIGN GEOMETRY

2.1 Faceted Aesthetic

Facade geometries that advance beyond the rectilinear form by introducing angled and sloped planes can achieve a gem-like aesthetic. These systems are characterized by angular folds and sharp points of convergence.

2.2 Faceted Solutions of Curved Aesthetic

A common method of panelizing a complex transparent free-form shape of double curvature is with a faceted skin. Approximating a smooth surface with triangular elements is the oldest and still most common means of panelization [2]. Triangulated surfaces can be utilized to represent any free-form shape [6], but are economically less advantageous and structurally less efficient than equivalent surface structures comprised of two-way spanning quadrilateral facets. Triangulated panelization is wasteful because it requires the entire material of a rectangle lite, of which the excess material cannot be recycled unless it is truly cullet without coatings. The efficiency of a quadrangular mesh over a

triangular mesh can be attributed to the reduction of diagonal cuts, mullions and excess material, but is only economically effective if the glass facets remain planar [7]. Known principles of translation surfaces can be implemented during surface rationalization to ensure planarity of quadrangular facets.

When a planar glass facet is asked to achieve curvature through the introduction of deformed shape, the stiffness resulting from the curvature can lead to improved structural performance. Recent technological refinement in cold-bent glass now represents to achieve a smooth double-curved glass envelope [8].

3 EVALUATION METHODOLOGY

3.1 Considerations

The implementation of complex faceted glazed structures presents a series of amplified design considerations. Especially with faceted planes representing a curved surface, the design solution requires analysis of geometric characteristics and installation strategies to realize a safe faceted glass application [3]. The complex faceted facades are evaluated in consideration of the final form’s 1) ability to sustain the original design intent, 2) complexity of form, 3) variation of components, 4) structural transparency, 5) fabrication requirements, 6) installation requirements, and 7) three-dimensional geometry coordination.

3.2 Quantitative Analysis

Several metrics are developed to analyze



glazed faceted structures. Further research will adopt Loeb’s valency definitions for 3D structures [9] to analyze patterns of interactions between crystalline forms.

3.2.1 Maximum Nodal Coordination

The maximum number of planes converging to a single vertex of glazing attachment on a project is described as $C_{node,max}$. This is comparable to the maximum valency of a vertex toward planes.

3.2.2 Average Panel Density Index

Equation 1 describes the average number of glazed panels per architectural facet:

$$[1] \quad \rho_{panels} = n_{P,total} / n_F$$

where,
 $n_{P,total}$ = total number of panels
 n_F = total number of facets

3.2.3 Paneling Efficiency

The efficiency of paneling can be summarized by using Equation 2:

$$[2] \quad \eta_{panels} = (n_{P,total} - n_{P,unique} + 1) / n_{P,total}$$

where,
 $n_{P,unique}$ = number of panel geometries

3.2.4 Structural Transparency

Equation 3 describes how structural transparency is considered in this evaluation:

$$[3] \quad \tau_{structure} = A_{vision,int} / A_F$$

A_F = area of facet glazed plan
 $A_{vision,int}$ = area of view from interior out normal to glazed facet

3.3 Qualitative Analysis

Several qualitative considerations are included within the evaluation of each faceted facade; however, an objective metric is not applied herein. Qualitative considerations include issues of fabrication, installation and 3D geometry coordination.

4 CASE STUDIES

4.1 Circa Center, Philadelphia (2005)

This faceted geometry designed by architect César Pelli is applied to a 437 ft high rise. The 29 story tower employs a glazed aluminum unitized curtain wall system, while an architecturally exposed structural steel (AESS) system creates a dramatic protruding lobby canopy feature.

4.1.1 Tower and Skylight Curtain Wall

The numerous facets and sloped surfaces of the geometrically complex curtain wall create an elegant variation on conventional high-rise building form. The facade design includes a 45° cut at the southeast corner of the building, and slopes inward 5° up the height of the tower (Fig. 1). The northwest corner transitions to a 63° cut with a 4° inward slope scaling the elevation, creating a custom glass skin unique to each of the projects 29 floors.

Unitized curtain wall envelops 275,000 sf across 10 unique facets of the tower and skylight. The system includes a total of 7,852 lites derived from 791 unique glass panel geometries. The maximum nodal coordination, $C_{node,max} = 5$, occurs at a junction of 2 elevation and 3 skylight planes.

Vertical mullions of 3.75-in wide by 7-in deep support the insulated glass units (IGU) at typical conditions. Reinforced mullions occur near corner folds of the tower massing due to increased wind loads. An advantage of a unitized system is that it facilitates the overall quality of the product and can significantly shorten installation duration.

Additionally, unitized systems enable the curtain wall to withstand building and thermal movement while providing an effective means of water drainage. Vision and spandrel units alternate up the building height, significantly reducing the systems effective transparency.

4.1.2 Lobby Canopy

Along the east street level a 4 story glazed lobby system seamlessly transitions from the unitized tower above to an AESS-supported faceted protrusion to create a dramatic canopy entrance (Fig. 2). The AESS framing is comprised of HSS 3x6 members, slightly more slender than the unitized vertical mullions, to achieve a greater structural transparency. The faceted lobby skirt and canopy encloses 11,000 sf with 8 unique facets. The system includes 314 lites derived from 101 unique panel geometries. The maximum nodal coordination, $C_{node,max} = 3$, occurs at numerous locations including the prominent canopy point. Nodal complexity is minimized at this point by terminating the two sloping upper planes with a single underside plane. This system has similar advantages to the unitized tower system, however detailing is significantly exposed.

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4.2 Spertus Institute, Chicago (2007)

Spertus Institute (2007) in Chicago Illinois includes a 161 ft, 10-story faceted window wall construction along Michigan Avenue designed by Krueck &Sexton Architects. The 25,000 sf facade is constructed using an aluminum cassette facade system built from 726 windows of 556 unique geometries which comprise 36 facets (Fig. 4). The facade elevation is approximately 81 ft wide by 160 ft tall. The typical floor to floor spacing is 14 ft to 15 ft, with the ground floor at 18 ft, and 9th and 10th floors at 21 ft.

The crystalline facade form features a protruding architectural ‘skirt’, balcony with glass handrail, a row of cantilevered glass below the 2nd floor, and cantilevered ‘wings’ at the party walls. The framing system is comprised of Y-shaped vertical mullions supporting aluminum-framed insulated glass unit panels. Panels slope from vertical by a small amount, never more than 10° from perpendicular to the vertical mullion in either direction, to achieve the crystalline appearance of the wall.

The facade geometry is defined by a series of faces intersecting along fold lines. Glass panel geometry was generated by projecting a regular system of horizontal and vertical joints on the folded faces. This process results in triangular, rectangular and trapezoidal shaped pieces of glass which are combined to create typical glazed frames approximately 4'-4" wide by 7'-0" tall. Where a face boundary crosses a glazed frame, the frame is folded such that the glass lites it contains lie on the planes of their respective faces. These folds occur between floor slabs exposing the bent vertical mullion condition to the interior space (Fig. 3). Bending the aluminum vertical mullions presented fabrication limitations and sequencing considerations since the resulting bent lengths could not be tempered, painted and prepped in the same manner or sequence as the straight vertical Y-mullions.

Several critical design judgments were exercised early in the design development to limit the complexity of the faceted system into a controlled and manageable fabrica-



Figure 3. Michigan Avenue elevation (left) and interior space (right).

tion and installation process. The first decision was to always orient the vertical Y-mullion orthogonal to Michigan Avenue and the building’s primary structural grid. This allowed the Y-mullions always to remain plumb in elevation. Additionally this limited the number of unique attachment configurations and anchoring conditions to the number of planes - 36 facets. The system was subdivided into a series of manageable co-planar regions with consistent attachment geometries.

The second significant decision was to always align the glass joint centerline with the vertical Y-mullion centerline. With hundreds of variant face of glass to vertical mullion relationships, this logic was achieved by introducing a T-bracket which linked the glazed cassettes to the vertical Y-mullion. The asymmetrical bracket ensures the mullion and glass centerline alignment by interfacing at the Y-mullion with a rotational contact surface which pivots about the face of glass work point (Fig. 5, top right). The T-bracket pieces were prefabricated with screw indicators for each rotational position, improving shop installation efficiency, and were simply flipped to accommodate the mirrored plane condition.

The third momentous choice was to create an independent data model in parallel to

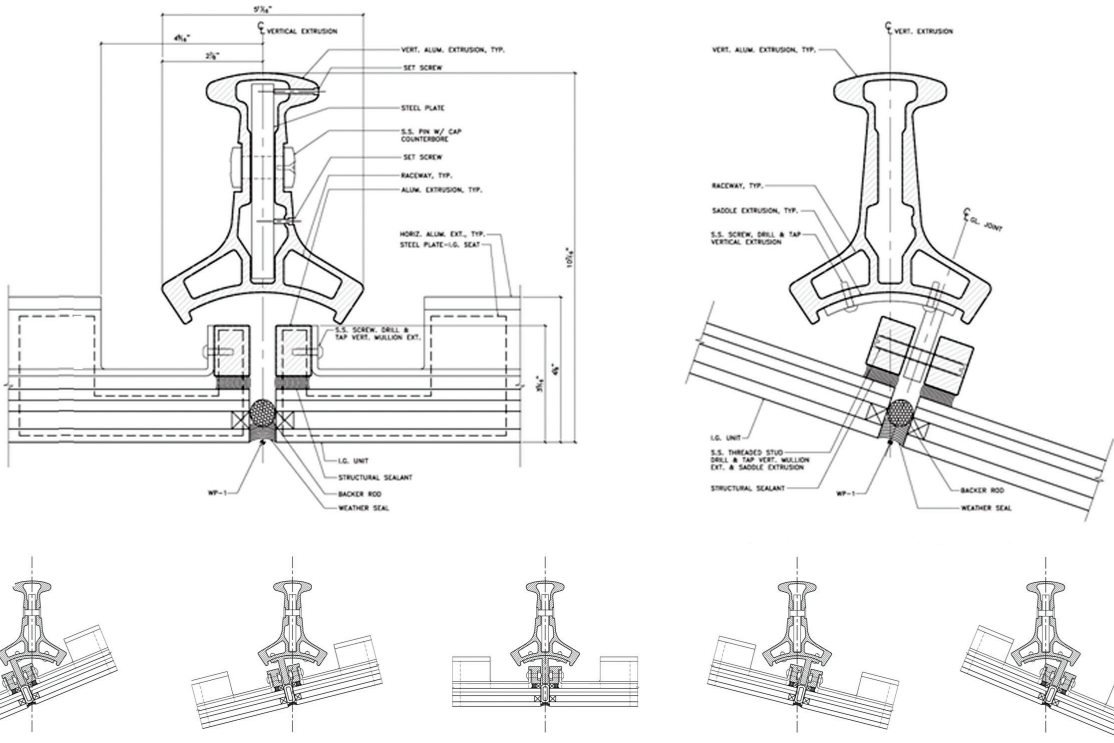
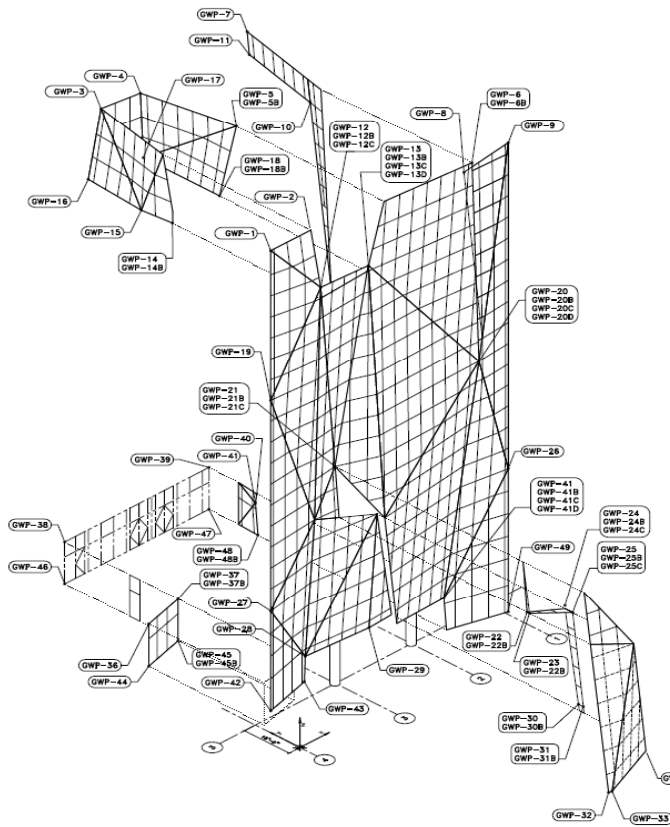
the 3D geometry model to validate the accuracy of all part drawing dimensions and quantities. This information model was generated using Microsoft Excel with the sole common starting point for both models being the 78 geometric work points of the faceted envelope. An automated tool was created in-house to then verify the dimensional and quantity data against AutoCAD drawing sets. This process allowed all entities of the project team to advance with confidence.

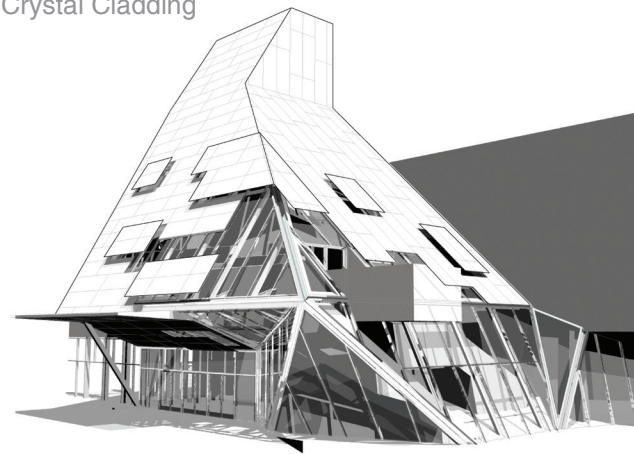
In this project the cassette system permitted a partial kit-of-parts approach where the Y-profile and anchor components remain similar throughout while variation was restricted to the panel geometry, extrusion length, and vertical mullion bend at folds. The main disadvantage with this system was the intensive coordination throughout the entire process resulting from a lack of redundancy.

Opposite Page:

Figure 4 (top). Isometric drawing locating the 78 geometric work points defining 36 facets.

Figure 5 (bottom). Vertical Y-mullion and T-bracket in various rotational configurations.





4.3 LAUSD #9, Los Angeles (2009)

Central Los Angeles Area High School #9 designed by Coop Himmelb(l)au includes an 84 ft tall lobby entrance to the school’s performing arts center expressed through a crystalline volume of glass and metallic forms (Fig. 7). The faceted skin utilizes a stick construction to capture 5900 sf of glass units which emerge from the metallic cladding primarily along the Grand Avenue elevation. The glazing scope includes 176 laminated fully-tempered low-iron glass panels derived from 136 unique geometries to populate 13 distinct faces at different angles and slopes. A magnified level of complexity is the extreme west corner intersection of six planar surfaces converging to a single point.

In this project the geometric massing was prioritized over the systems structural transparency. However, the enclosure design achieves $\tau_{\text{structure}} = 86\%$ from inside looking outward. The glass-fixing system was designed around an off-the-shelf Kawneer sloped glazing system capable of economically accommodating the facade’s negative slopes. An architecturally exposed structural steel (AESS) backer system was then designed to support the faces. The facade system attached to the AESS primary steel using a field-installed anchor (Fig. 8) designed to accommodate field tolerances, ensuring envelope precision.

Three dimensional models were used in lieu of drawings to facilitate design development (Fig. 6). A major role of the model was to coordinate as-built anchor locations

with theoretical work point coordinates to anticipate field conditions that could not be accommodated by the system’s adjustability. Field fixes were minimized by linking as-built survey data with the geometry control model via an automated Excel tool, which simplified the data for field crews to three basic adjustments on circumstances where an anchor location was deemed out of tolerance.

The use of an off-the-shelf glazing system provided an economical solution with proven performance. Challenges were presented by a highly constricted site, necessitating excessive site coordination for the installation of anchor elements and the location of primary steel to acceptable AESS standards. Intricate flashing conditions at nodal convergences were also problematic.

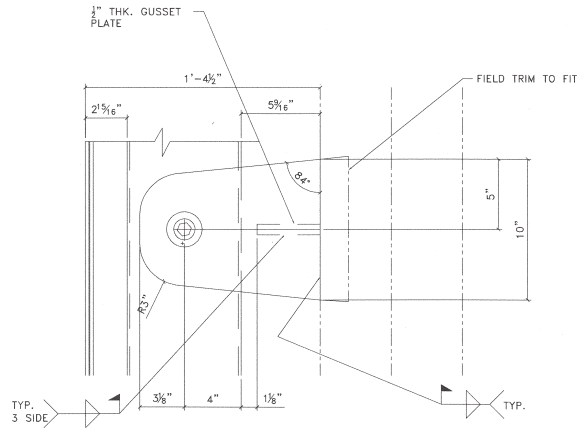


Figure 6 (top left). Lobby geometry control model.

Figure 7 (top right). West elevation of completed lobby.

Figure 8 (below). Section detail of anchor.



4.4 Cathedral of Christ the Light, Oakland

The Cathedral of Christ the Light (2008) designed by Skidmore, Owings and Merrill includes two 88 ft point-supported glass walls, referred to as the Alpha and Omega Walls (Fig. 10a), for a composite 6000 sf of sloped glazing. A total of 308 triangulated glass panels create a faceted representation of a double curvature surface supported by glass bolts at four drilled hole locations offset from each panel corner along two of three edges (Fig. 9a). By offsetting the glazing connection from the vertex of six unique panels towards a quarter point along the panels’ edge reduces the maximum nodal coordination, $C_{\text{node,max}} = 2$. This simplification of glass connection is balanced with a system of completely unique panel geometries. Since the wall occurs twice, there are 154 distinct panels, with each panel type occurring twice.

This system is different from the others because the glass is not continuously supported on four sides and presents magnified issues of warping and adjustability. Tolerance and adjustability are accommodated within the custom stainless steel glass fitting (Fig. 9b), requiring intense and precise field installation. Significant advantages of this system include increased transparency.

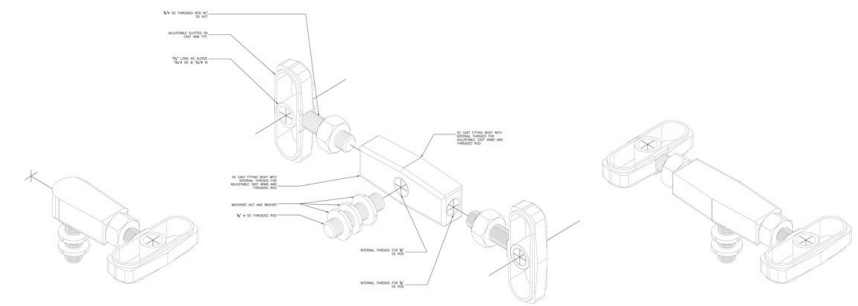
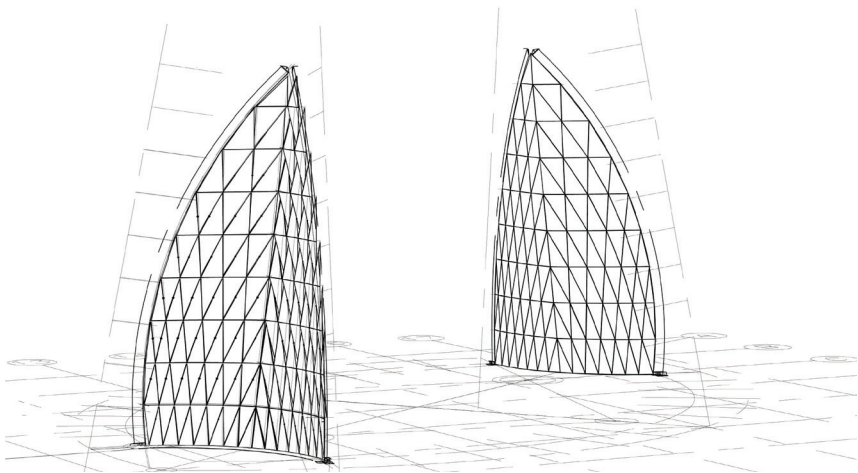


Figure 9a. Photo of Omega Wall (top left).

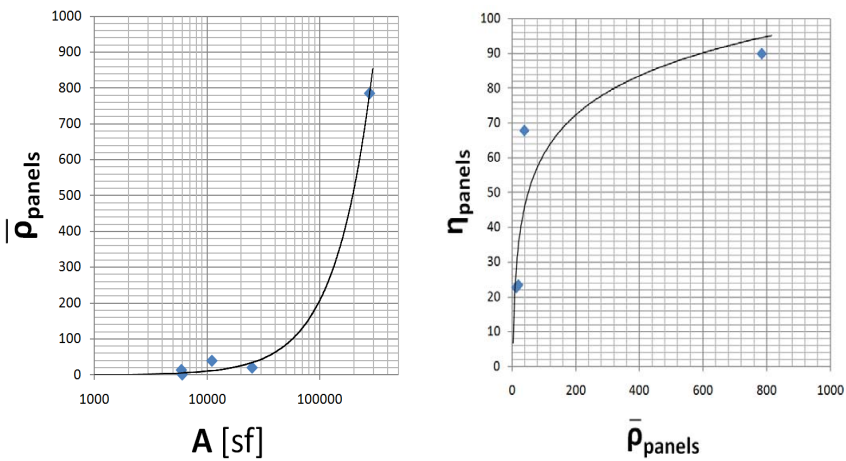
Figure 9b. Glass fitting photograph (top right)

Figure 10a. Iso of Alpha and Omega walls (middle)

Figure 10b. Glass fitting detail (bottom)

Figure 11a (left). Panel density index vs total area.

Figure 11b (right). Panel efficiency vs. Panel density index of faceted aesthetic designs (Oakland Cathedral excluded)



5 RESULTS AND DISCUSSION

The evaluation results for each of the case studies are summarized in Table 1. Further research will increase the sample, but Figures 11a and 11b begin to reveal the types of faceted design trends which can be deduced. Figure 11a shows that a project of larger total surface areas requires a greater number of panels per facet. Figure 11b demonstrates that the more panels per facet, the more efficient the system is geometrically by minimizing the percentage of unique panels to total panel geometries. Trend lines could serve as design guides in future projects.

5.1 Complexity, Scale and Efficiency

One method of understanding complexity of the faceted facades is by evaluating the systems paneling efficiency, η_{panels} . A system which uses the fewest number of unique panel geometries will approach $\eta_{panels}=1.0$. The number of different panel shapes is not adequate alone for comparison of faceted forms; considerations relative to scale must be included. This is evident from the case studies where Cira-Tower contains the most unique geometries, $n_{P,unique} = 791$, but has the greatest efficiency since the geometries are applied across a large facade area. The smallest project LAUSD #9 has the least efficiency, $\eta_{panels} = 0.23$, resulting from many distinct panel geometries across 5900 sf of glazing.

The desire to achieve a complex faceted aesthetic must be balanced with intelligent installation and fabrication strategies.

Most of the faceted examples presented are limited to a small portion of a larger project – typically a lobby feature. The unitized facade of Cira – Tower applies a crystalline form across the entire building, but does so through a rigorous standardization of components and details yielding minimum inventory and maximum diversity. It is intuitive that diversity of part types deters economy; however technological advances with respect to design tools and complex three-dimensional information are improving the management and coordination of complex faceted forms. Many of these technologies are yet to have a significant impact on the building site, so optimization of variation and diversity must be a primary consideration for any crystalline facade.

5.2 Applications

Complex faceted forms are frequently selected to create a striking feature and are prominently located within a project. Project-specific constraints and design priorities must be considered to select an appropriate facade structural system for the faceted aesthetic. The scope of the crystal form tends to be localized to create an architectural focus, such as a point of entrance. The objective of such features is monumental or iconic and exudes a symbolic message greater than the form itself.

6 CONCLUSION

This paper presents an approach for quantifying complexity and rationalization of faceted glazed architectures. This approach is applied to four unique projects. The analysis reveals that variant facade systems can be applied to a broad range of applications to achieve faceted form. As technology progresses and free-form designs become more common, a detailed understanding of applicable systems and panelization logic in the facade engineering process is required to responsibly and economically implement a crystalline vision shared by many of the world’s leading architects.

Table 1. Evaluation Summary

	Project	Facade Typology	nstories	h [ft]	A [sf]	nF	nP,unique	nP,total	Cnode,max	ρ_{panels}	η_{panels} %	$\tau_{structure}$ %
1.1	Cira - Tower	Unitized CW AESS -	29	437	275000	10	791	7852	5	785	90	40-50
1.2	Cira - Canopy	Unitized	4	45	11000	8	101	314	3	39	68	91
2	Spertus Institute	Cassette	10	161	25000	36	556	726	6	20	23	90
3	LAUSD #9	Stick CW Point-Supported	-	84	5900	13	136	176	6	14	23	86
4	Oak. Cathedral		9	88	6000	308	154	308	2	1	50	93

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