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Laser Tracking Metrology: An Integrated Fabrication Process for Geometrically Complex Facade Systems.

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The geometric complexity resulting from the architectural pursuit of freeform structures is presenting challenges to the construction industry. Curtain wall unit system designs, for example, have morphed in some cases from predominantly flat orthogonal affairs to complex double-curvature multi-layer constructs. Many fabrication tools and processes, however, are only gradually shifting from their linear 2D roots to embrace a truly 3D fabrication environment. The validation and quality assurance of geometrically complex components is problematic in such an environment, potentially compromising both dimensional accuracy and throughput. Three projects are discussed where laser metrology was adopted as a means to facilitate the dimensional measurement of geometrically complex components. For example, one is a high-profile architectural application, a residential building in New York City. The project includes an expansive double-curved surface designed and constructed as a prefabricated unitized system, with opaque units built up from multiple layers of metal panels, insulation, and structural framing. Laser tracking metrology was adopted during the course of project fabrication resulting in accelerating production rates from four to thirty units/week. In addition, drawing requirements were reduced from as many as twelve to zero drawings per unit. Applications, processes, techniques, and findings resulting from the integration of laser tracking metrology in the fabrication process are presented for all three projects.

Keywords: Metrology, Laser Tracking, Complex Facades, Digital Fabrication, Construction Simulation, Curtain Wall

1. Introduction

As defined by the International Bureau of Weights and Measures, metrology is "the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology." (BIPM) Advanced metrology methods have developed as an integral fabrication tool for fields such as the automotive, aerospace, and naval industries. These industries also continue to influence the tools and software that architects and engineers rely on to design and develop vastly complex building systems and geometries. As the vision of these conceptual designs are now becoming a reality, the construction industry must as well increase its dependency on digital tools and advanced metrology methods to successfully and accurately build this new breed of architecture. In doing such, Enclos has relied specifically on laser tracking metrology and spatial analyzing software during the fabrication and installation of many recent projects and research and development efforts.

Laser tracker technology is based on the combination of two techniques: a distance meter to measure absolute distance and angular encoders to measure the laser tracker's two mechanical axes – the azimuth axis and the elevation (or zenith) axis. Laser trackers emit a low power laser beam to a retro-reflective target that is either held or mounted on the object to be measured. Light is reflected off of the target and re-enters the tracker at the same position from which it left. The distance meter (either a laser interferometer or absolute distance meter, ADM) analyzes the light as it re-enters the tracker and measures the distance from the tracker to the retro-reflector. (Meagher)

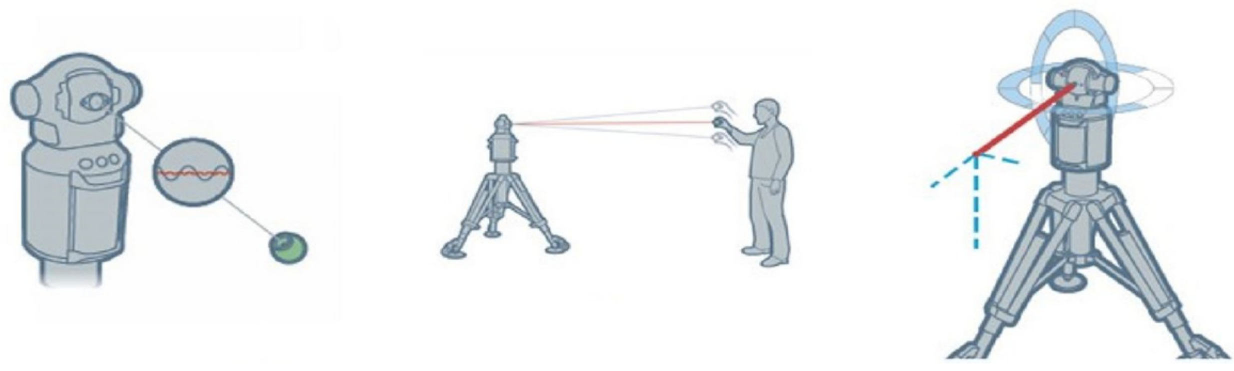

Fig. 1 Laser Tracker Diagram. (Bridges)

2. Laser Tracking Metrology for Fabrication and Quality Control

Located in New York City at 140m tall, this tetrahedron shaped apartment building has a double-curved stainless steel sloping façade comprised of over 1,100 unique curtain wall units (Fig. 2). Due to the hyperbolic shape of the façade, these units are both convex in plan and concave in section - each with a unique radii as well as overall width, height, and twist (Fig. 2-3). The units are anchored to a series of vertical rafters which subdivide the façade into tapering bays. In addition to providing the structural support for the sloped facade, these rafter assemblies also become an integrated part of the complex network of gutters. It is this vertical and horizontal gutter network which creates a male/female connection to the sloped façade units, allowing for a water-tight connection once installed (Fig. 4).

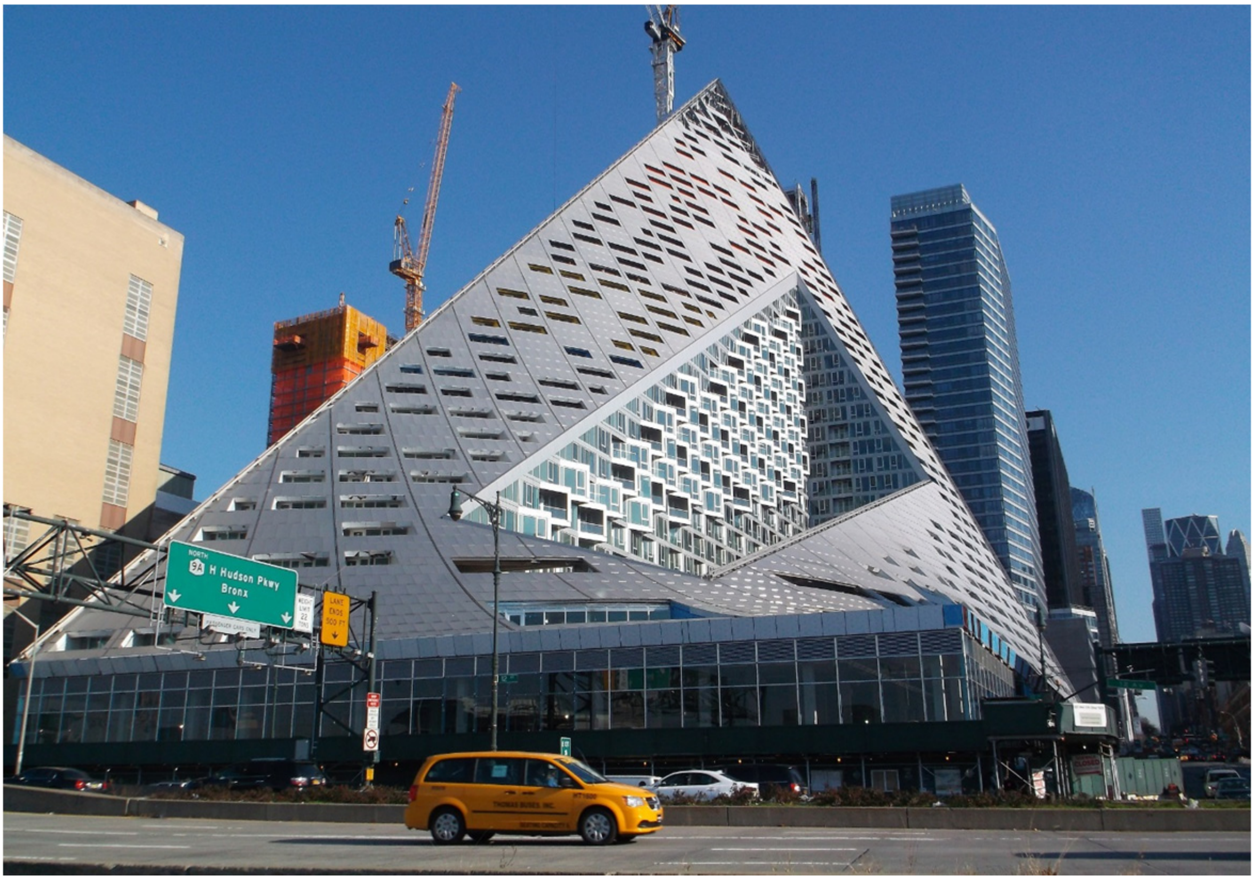

Fig. 2 Sloped Façade Construction as of November 2015.

Fig. 3 Sloped Façade Units.

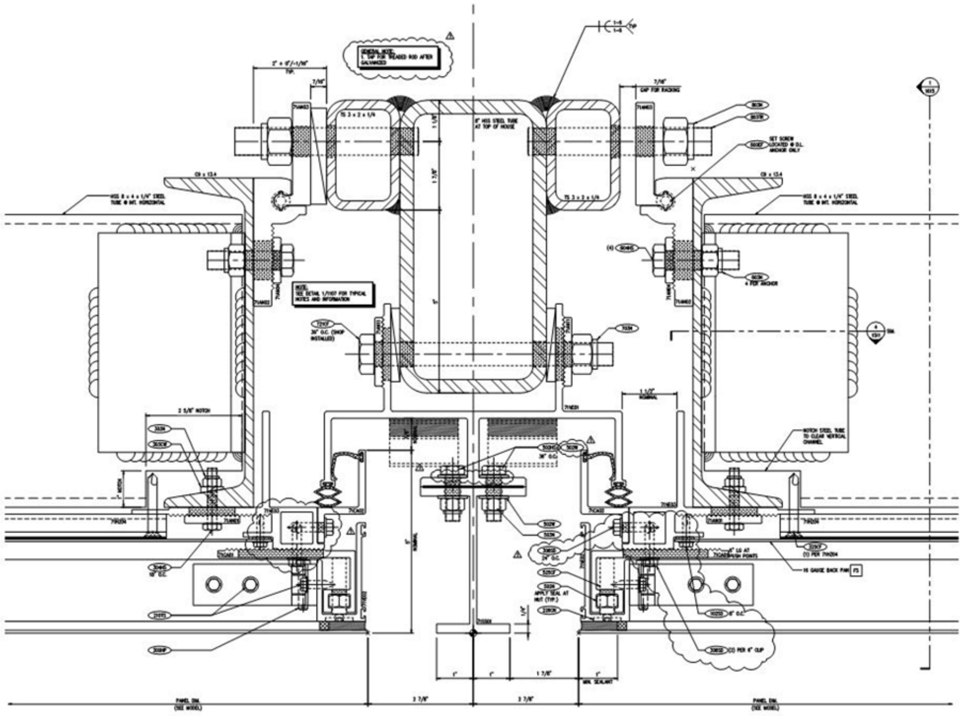

Fig. 4 Sloped Façade Detail of Unitized System and Rafter Assembly

The sloped façade curtain wall system is a layered design starting with a twisted steel truss clad with a perimeter of aluminum extrusions and a series of galvanized steel back pans to create the primary air and water barrier (Fig. 5). To create the final hyperbolic shape of each unit, a series of adjustable height clips are attached above the air and water barrier and a final layer of extrusions are installed which will support the finish stainless steel panels. The adjustable clips are then raised, lowered, or moved laterally to fine-tune the final shape of the unit before the stainless steel panels are glazed to the frame.

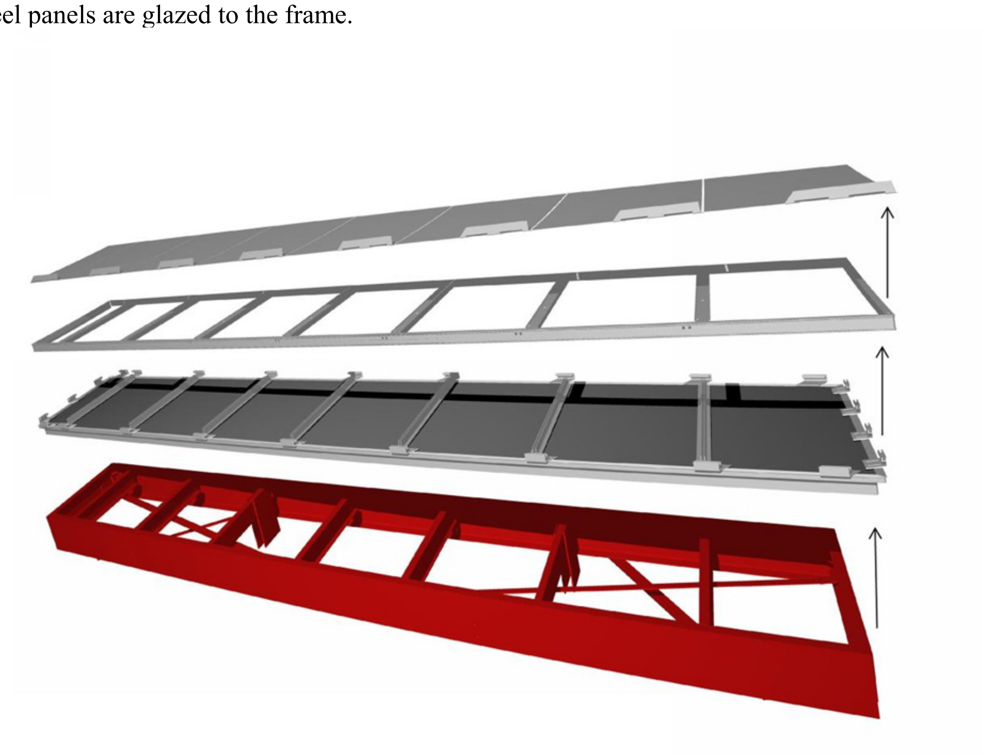

Fig. 5 Sloped Façade Unit Layers Diagram.

To ensure that each layer was fabricated accurately and within its unique tolerances, the laser tracker was utilized at each step of the fabrication process. To begin, each steel truss was measured with the laser tracker and utilizing spatial analizing software, the resulting as built point cloud model was then best fit to the design model and verified for accuracy within the designed tolerances (Fig. 6). Once matched to the design model, shim dimensions could then be determined for all subsequent aluminum extrusions layers- allowing a steel truss with a tolerance of +/- ½" to be fabricated to a fully assembled unit with a final finish tolerance of +/- 1/32". With the introduction of metrology, Enclos manufacturing was able to increase production of unit assembly from 4 to 30 a week.

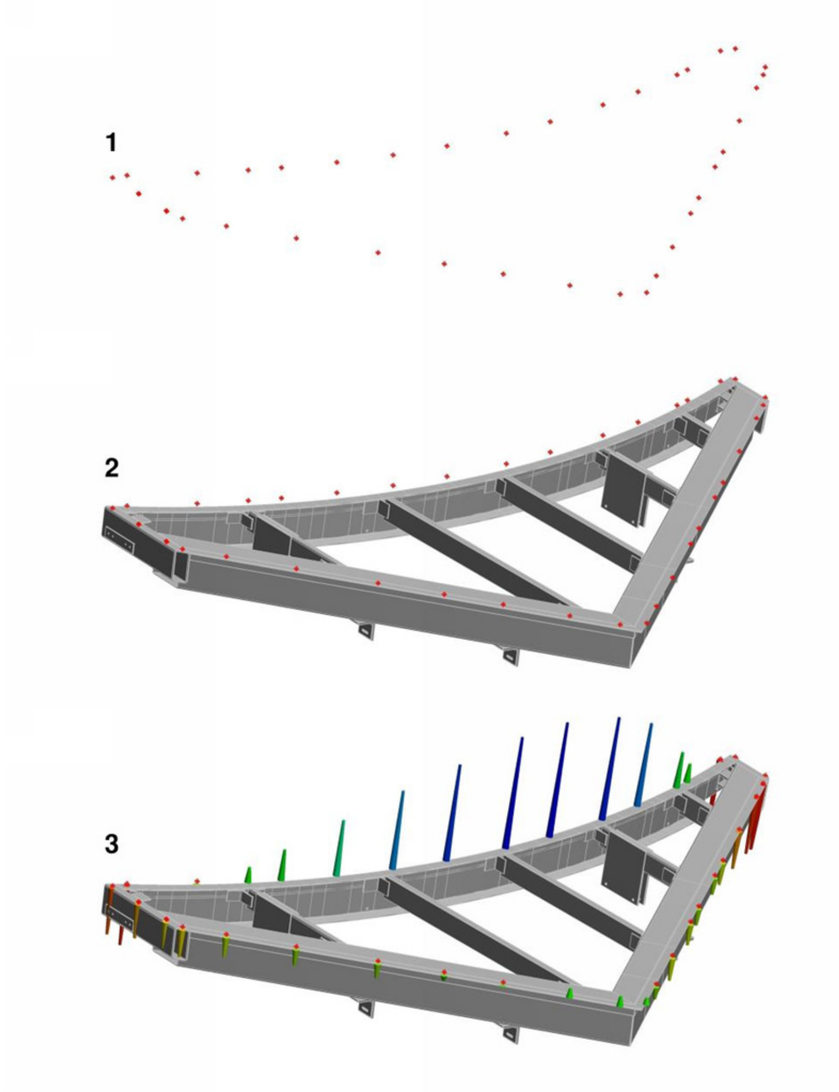

Fig. 6 Steel Truss Scan Utilizing Spatial Analyzing Software.

3. Laser Tracking Metrology for Research and Development of Cold Formed Glazing Limitations

Laser tracking has also become a useful tool for on-going research and development projects at Enclos- specifically our research into the limitations of cold formed glazing. Cold formed glazing is increasingly becoming more recognizable as a feasible construction method to create complex curved geometry. As a result of this process, there are many unpredictable issues such as deformed surface shape, reflective quality, and surface buckling. In an effort to understand and quantify these effects, Enclos prepared extensive finite element analysis and determined that when applied to unitized curtain wall systems, surface buckling was the limiting factor for design.

Fig. 7 Cold Formed Test of 1525mm x 3658mm Glazed Frame.

To verify the accuracy of the finite element analysis, full scale physical tests were performed on a variety of glass thicknesses, sizes, and aspect ratios. For strength and safety, test specimens were fully tempered and monolithic- ranging in thickness from 5mm (3/16"), 6mm (1/4"), and 10mm (3/8"). For each thickness, four different aspect ratios were tested – 1525mm x 1524mm (60" x 60"), 1525mm x 2286mm (60" x 90"), 1525mm x 3048mm (60" x 120"), and 1525mm x 3658mm (60" x 144"). For support, an aluminum extrusion frame was fabricated and added to the perimeter of each of the twelve test specimens using structural silicone sealant.

Fig. 8 Laser Tracker Station and Adjustable Cold Formed Testing Apparatus.

An adjustable test apparatus was designed to support the four different aspect ratios of the glazed frames. The test apparatus allowed for three corners to be fixed and the remaining corner to be displaced or pulled out of plane incrementally- creating a hyperbolic shape which mimicked the various displacement stages of the finite element models (Fig. 7-8). At this step of the testing procedure, the laser tracker was used to scan the perimeter of the test frame and accurately match the corner displacement it to the 3D finite element models within 1/32”. Once the perimeter was matched to the correct displacement, the laser tracker was utilized again to create a point cloud across the surface of the glass, determining any areas with signs of buckling or deformation. This data was captured and graphed in comparison with the digital models, confirming both the onset buckling as well as the deformed geometry generated by finite element analysis (Fig. 9).

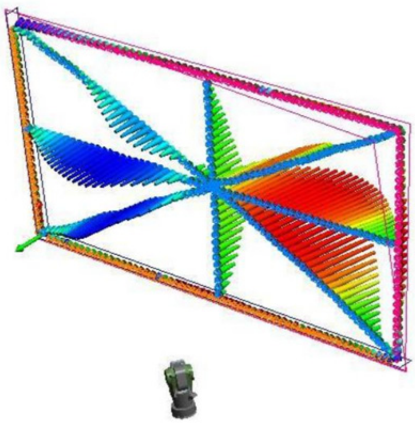

Fig. 9 Results of Onset Buckling Scan of Physical Test as Shown Through Spatial Analysis.

4. Laser Tracking Metrology for Virtual As-Built Construction Models

In addition to the fabrication and quality control benefits of the laser tracking system, Enclos is moving beyond manufacturing with metrology and using existing scanned data to create virtual as-built construction models prior to shipment and installation of unitized curtain wall systems. This allows us to accurately understand the field conditions and tolerances of how the fabricated unitized systems will fit and interact with one another once installed on site.

Enclos is currently designing and testing a system for a multi-faceted glass façade project that will require a series of five to seven unique shop fabricated units to be preassembled in a staging area on site into larger “mega units” that are then hoisted into place on the structure (Fig. 10). During the fabrication and quality control process, the laser tracker system is used to scan all the joinery connection points, the overall shape of the units, and all structural anchor points which will connect to existing steel members on site. By combining the point data of all the unique frames with spatial analyzing software (Fig. 11), Enclos is then able to evaluate beforehand the accuracy of the “mega units” as would be assembled in field. This ensures that all unit to unit connection points align and that all site anchor locations match the as built coordinates provided by field survey input.

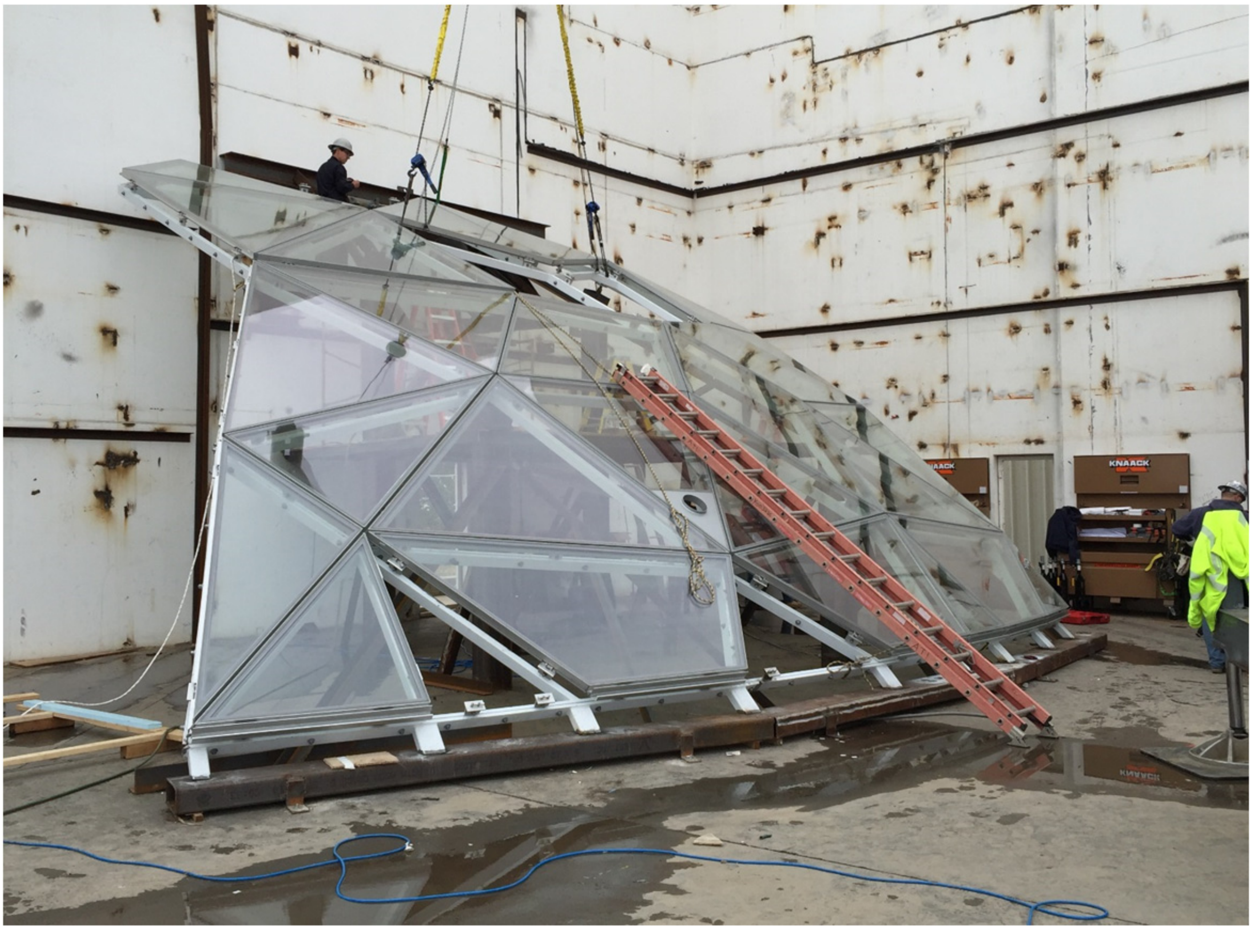

Fig. 10 Construction of Multi-faceted Façade Performance Mockup.

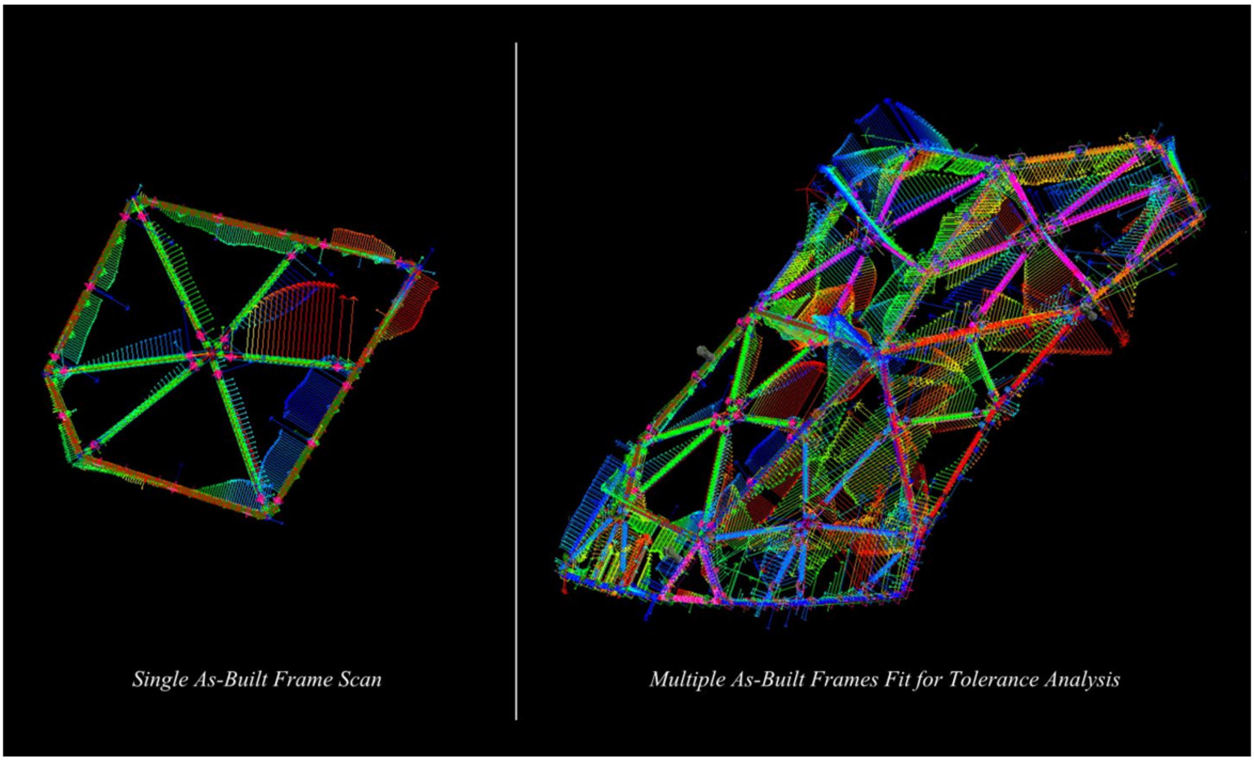

Fig. 11 Digital Model of As-Built “Mega Unit”

5. Conclusion

As proven through these three projects, Laser tracking dimensional metrology is an effective and viable technology in facilitating the implementation of geometrically complex façade designs prefabricated offsite as unitized façade systems. With this increase in project complexity, both design and detailing, Enclos is continuing to expand the use of metrology while educating engineering, manufacturing, and field operations on the usefulness of these applications.

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