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Implementing BIM and Finite Element Analysis in a Structural Integrity Investigation of Curtain Walls

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ABSTRACT

Evaluating the structural integrity of curtain walls during the life cycle of a building project can assist architects in developing better designs, help contractors establish better installation methods, and allow facility managers make informed maintenance decisions. This paper presents an effort to develop a process which combines three types of technologies: 3D laser scanning, Building Information Modeling (BIM), and Finite Element Analysis (FEA), to evaluate the structural integrity of a curtain wall. In a case study, a 3D laser scanner was used to scan the curtain wall, the resulting set of point clouds was used to create an actual as-built BIM model. This "as-is" BIM model is different than a construction as-built BIM model in that the former model captures existing deformations developed during construction, installation, and maintenance phases. Then further analysis was completed using simulation with FEA using the BIM model to potentially predict any future structural issues. Wind loads on the building façade and their effect on unintentional stresses built into the glass panel were studied. The final results inform of deformities in the curtain wall and show the amount of wind load the structure can support before there is a risk of structural damage. The contribution of this study is that the harmonious three-step technique quickens the entire process of identifying the risks to a building element. An additional use for these common software packages would be beneficial to all the stakeholders involved in the life cycle of the building, especially those concerned with the facilities management and the building life cycle.

Keywords: Three Dimensional Laser Scanning; Finite Element Analysis (FEA); Building Information Modeling (BIM); Curtain Wall; Structural Integrity

INTRODUCTION

Glass panels are used extensively in today's curtain wall systems bifurcating the interior from the exterior of the building. At the same time, they provide transparency and clear sight of the outdoors to the occupants. Aesthetic glass panels are generally more appealing (especially in a commercial front) than other building façade types, hence their need has increased over time (Kwon et al., 2004). Installation techniques and sealants used have shown modern glazings to be quite robust. However, their structural reputation cannot be completely trusted (Kwon et al., 2004). In the past, architects and engineers were combating difficulty with glass design processes, due to the inability to perform failure prediction analysis (So & Chan, 1996). Therefore, it is important to pay more attention to the structural integrity in not only for design, but also for the construction process, and maintenance management, which is the root cause of the numerous failures in the industry (Lam, 2000; Epaarachchi, Stewart, & Rosowsky, 2002; Puente, Azkune, & Insausti, 2007; Hu & Zhang, 2011).

The failure of a curtain wall's structure can lead to glass fragments on the sidewalks or streets below, leading to serious injuries or fatalities. Apart from its heavy dead load, the curtain wall system is mostly at risk by strong wind loads throughout its normal life. Due to the brittle nature of glass, and under strong dead load and wind action, the glass panels deflect considerably and there can be breakage without any warning (So & Chan, 1996). Therefore, being able to predict the deformities in the structural as-built model through structural analysis can aid in monitoring potential risks and predicting maintenance needs of the curtain wall system. Understanding the potential structural integrity issues beforehand can help stakeholders take remedial actions on time, and ultimately save the owner money on corrective or reactive maintenance. The necessity for precise as-built data is also essential for operation and maintenance (O&M) tasks throughout the lifecycle of the building (Liu, Eybpoosh, & Akinci, 2012). It is a time-consuming and costly effort to manually measure the geometry of the building elements, including curtain walls, for the as-built data.

A set of dense laser scanning point clouds can capture the geometric complexity of the structure (Barazzetti et al., 2015). These point clouds can then be used by the Building Information Modeling (BIM) technology to develop a 3D virtual model. BIM is defined as a "shared digital representation of physical and functional characteristics of any built objects" ("ISO Standard," 2010). A new consideration for the BIM model is the capture of all the characteristics and geometric data required for structural analysis and monitoring. The integration of BIM and laser scanning by automatically recognizing the construction objects from the point clouds and extracting them into a BIM model is the first step in this structural analysis. Computer-aided-engineering (CAE) can be used to conduct the Finite Element Analysis (FEA), and the simple approximation developed for each element is used to model the entire problem and calculates by assembling all the finite elements (Ren et al., 2018). These tools are typically used during the design phase but there are also needs for their use during the operations and maintenance (O&M) phase as well.

The focus of this paper is to integrate the three technologies of 3D laser scanning, BIM and FEA for determining the structural abnormalities and defects developed over-time in a building element, so that further precautions can be applied to reduce possible risks that might be encountered during the life cycle of a building.

This is a three-step study with an expected goal at every step.

Step 1: Conducting a 3D laser scanning. The objective is to scan the entire building with an expected level of accuracy. Performing heat mapping to quickly identify the existing deflections in the curtain wall without performing FEA is an added benefit of the software use.

Step 2: Creating an as-built BIM model. The goal is to automatically recognize building elements from point clouds to create a complete BIM representation with all the characteristic data stored in the model so that it could be further used for structural analysis in step 3.

Step 3: Performing FEA on the BIM as-built model. The objective of this study is to perform a FEA on a curtain wall model and to understand wall deformation for potential damage when subjected to typical loads over-time, and a method to monitor changes to storefront and curtain walls for potential issues. The loads taken into consideration in this step were the dead load of the curtain wall system and the wind load.

LITERATURE REVIEW

In the early 2000s, the Architectural/Engineering/Construction and Facilities Management (AEC/FM) industry recognized that quick, precise and automated project progress tracking is needed (Bosché et al., 2015). Case studies have shown that by creating a 3D model, the project team can minimize risks, errors and save time and costs on labor-intensive jobs, while simultaneously recuperate the project quality (Eastman et al., 2008). New technologies advancing the construction business are inevitable since saving money and time is the priority of any business. As a result, the integration of 3D laser scanning, BIM and FEA, will benefit those already using these technologies to provide additional benefits for the industry.

While BIM provides an innovative way of presenting the designed building information, it cannot also be used to showcase prevailing deformities and issues which appeared over time. The location of failure in any building element can be significant and considerations should include how loads act more crucially depending on its location and the length of a span. Location-based measurements and documentation help in recognizing and recording the inspection results (McGuire et al., 2016). However, if these measurements are collected manually the results are unreliable and subjective. Subjectivity brings in unpredictability between the actual outcome and its interpretation (Phares et al., 2004). This issue can be addressed by quantifying the amount and location of deterioration through field measurements. However, additional field measurements require additional labor and time which can increase the overall cost. If the measurements of the deterioration are computerized and stored in a centralized location, it not only helps accelerate the measuring process but also saves costs in maintenance planning.

Three dimensional laser scanning started to rapidly gain momentum as there has been an ever-increasing requirement of measuring a building's geometry, appearance, and other characteristics and then converting those quantities into innovative visual depictions, that are open to interrogation (Mahdjoubi, Moobela, & Laing, 2013). A laser scanner sweeps its entire surrounding space with laser light to acquire 3D data point with high accuracy, high density and great speed (Bosché & Guenet, 2014). As laser scanning has progressed, the focus in recent years has been on the accuracy of the scans. The U.S. Institute of Building Documentation (USIBD) released Version 2 in 2016 for their Guide for Level of Accuracy, which has become a resource for those needing to articulate and reference an accuracy level of their scans (USIBD, 2016). However, Park et al. (2007) identified 3D scanning as a method to monitor not only the construction process but also a means to detect deflection and deformation.

The structural analysis of a building aids in determining the subsequent state of danger and in predicting the behavior of the structure in the future (Guarnieri, Milan, & Vettore, 2013). The finite element method has been popularly used, that has large acceptance rate in various engineering applications, and its application in structural analysis is a very effective numerical method which is globally recognized (Barazzetti et al., 2015). One of the most important numerical techniques used by structural designers for physical phenomenon simulation is the FEA which simulates the natural behavior of solids, liquids, and gases as well as their interaction. Through FEA dynamic as well as static analysis of structures can be analyzed with

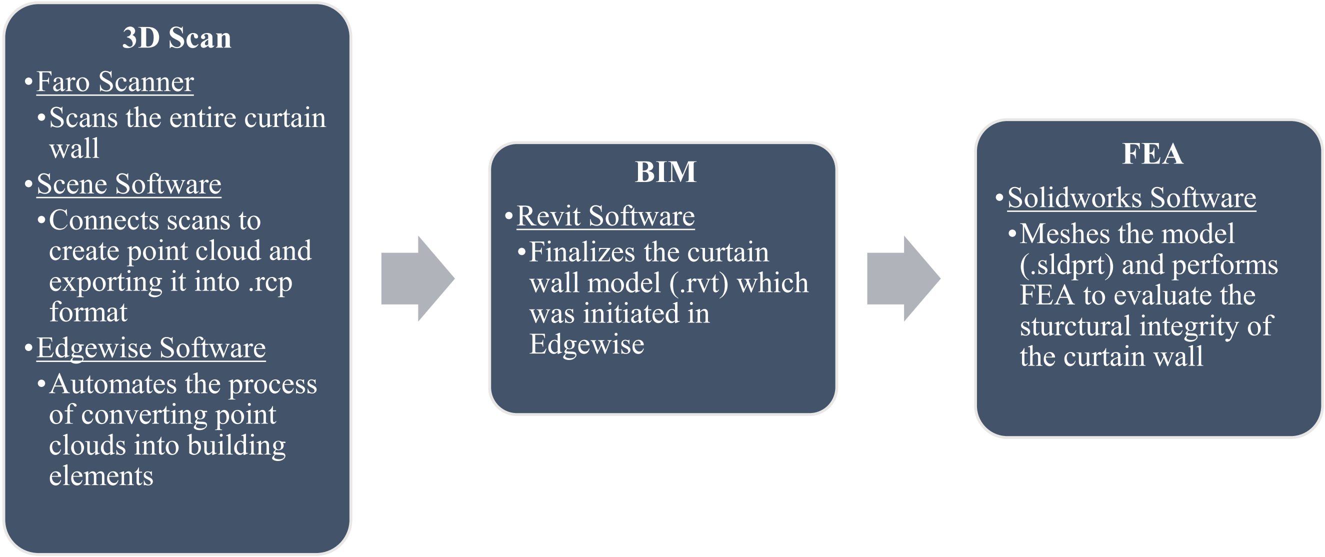

FIGURE 1.—Workflow of the Research.

high accuracy. The process, however, requires some manual inputs. Interoperability of FEA and BIM assists in simulating the structural behavior of a structure before, during and post construction until the end of its lifecycle (Fedorik, Makkonen, & Heikkilä, 2016).

METHODOLOGY

The integration of the proposed three-step technique, namely SCAN-BIM-FEA, involved scanning a curtain wall of an academic building, converting it into an as-built BIM model, and performing FEA on the model. Figure 1 shows how the integration of SCAN-BIM-FEA was adopted using various software to achieve the transference of files from the first step to the last.

Performing Three Dimensional Laser Scanning

The first step was to scan the curtain wall which can be used to develop an as-built BIM model. The instrument used was a Faro Focus3D Lidar Scanner that scans up to a maximum distance of 420 feet from its scanning head. The

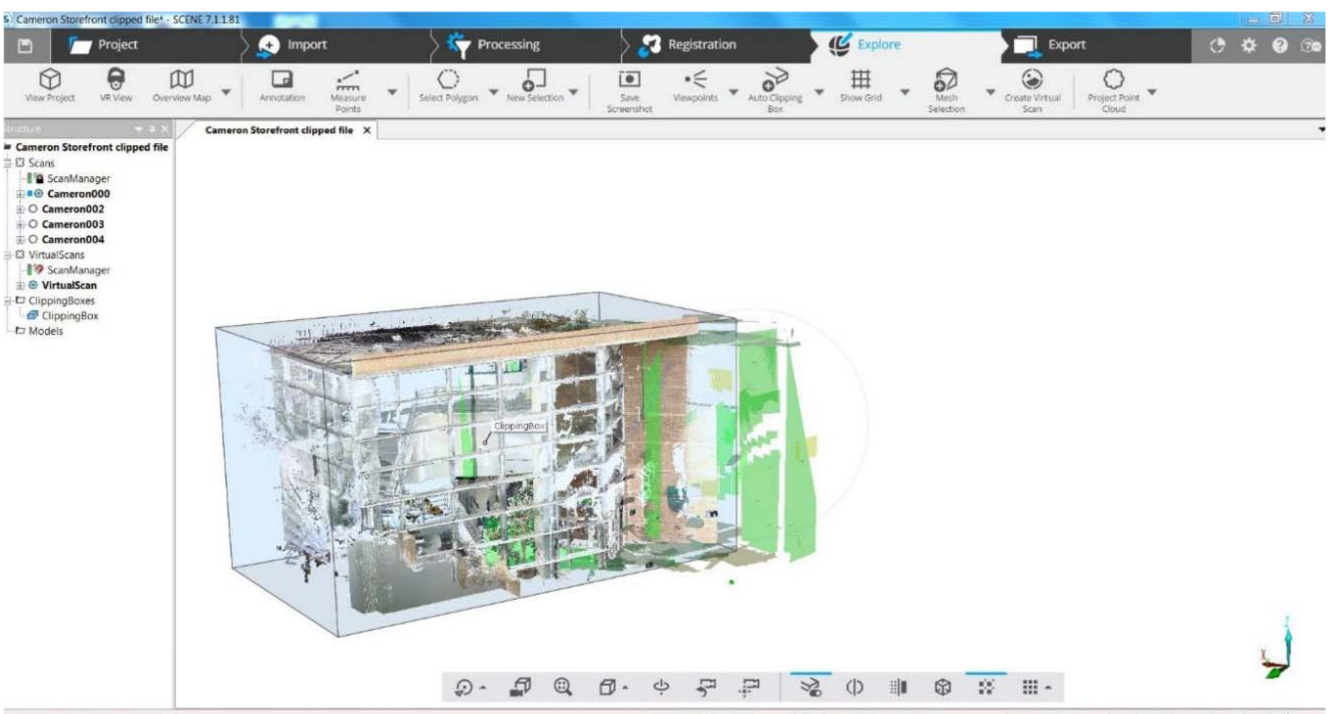

FIGURE 2.—Registration of Point Clouds.

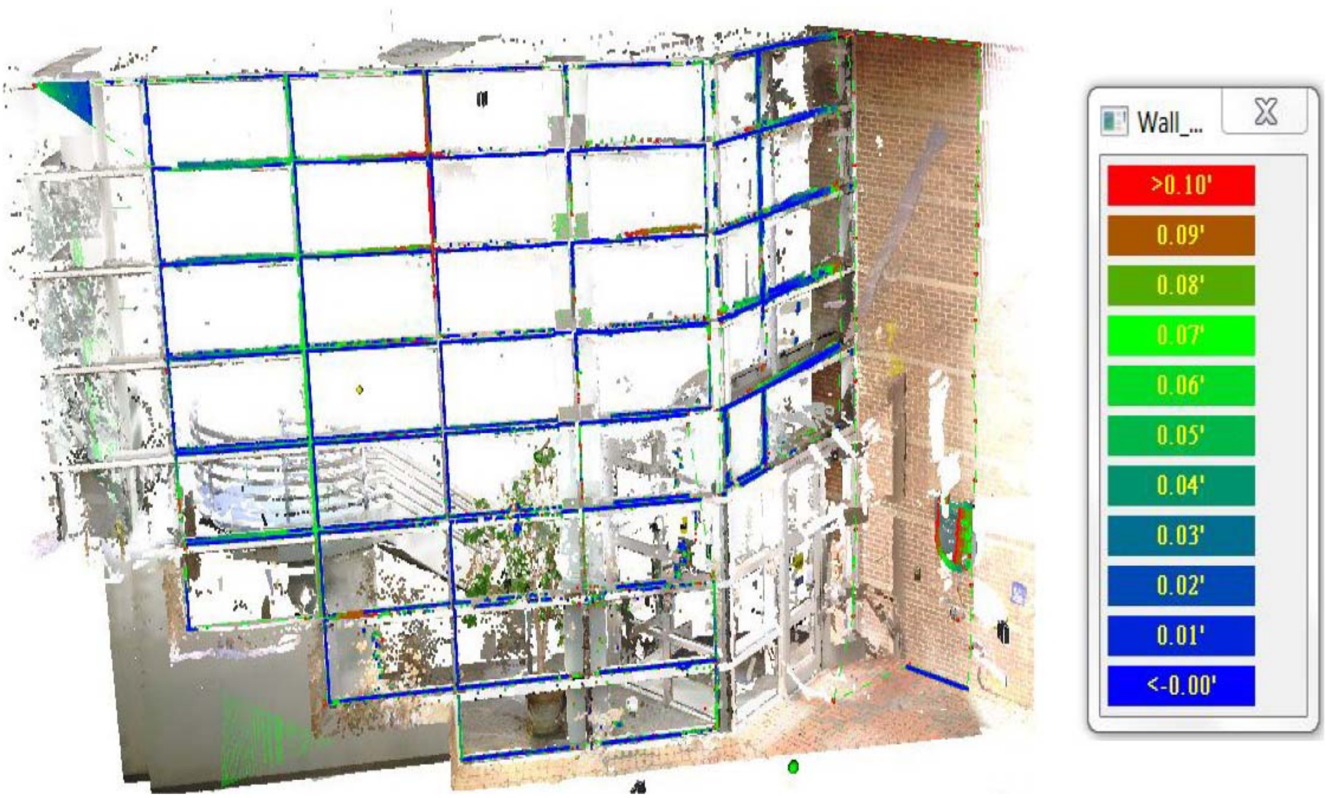

FIGURE 3.—Heat Map of the Curtain Wall.

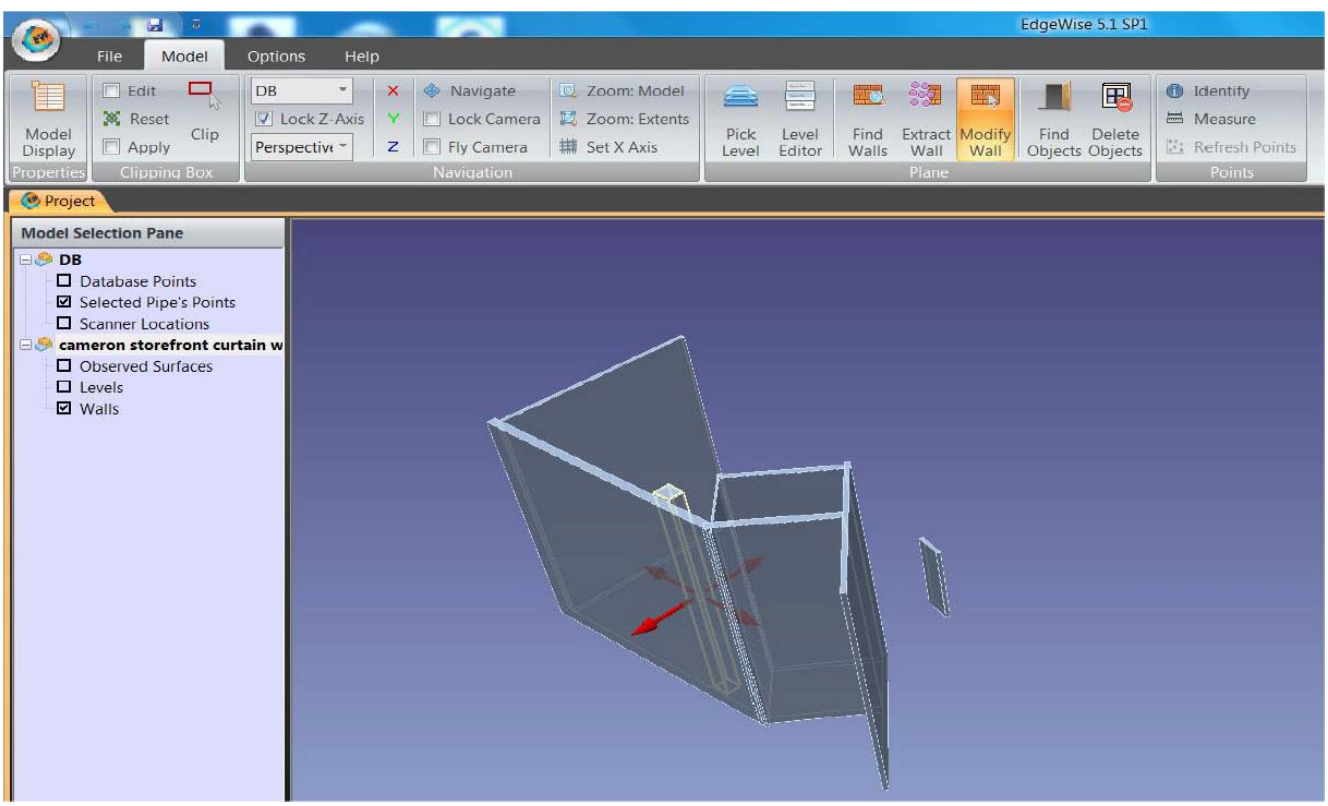

FIGURE 4.—The Initial Curtain Wall Model in Edgewise.

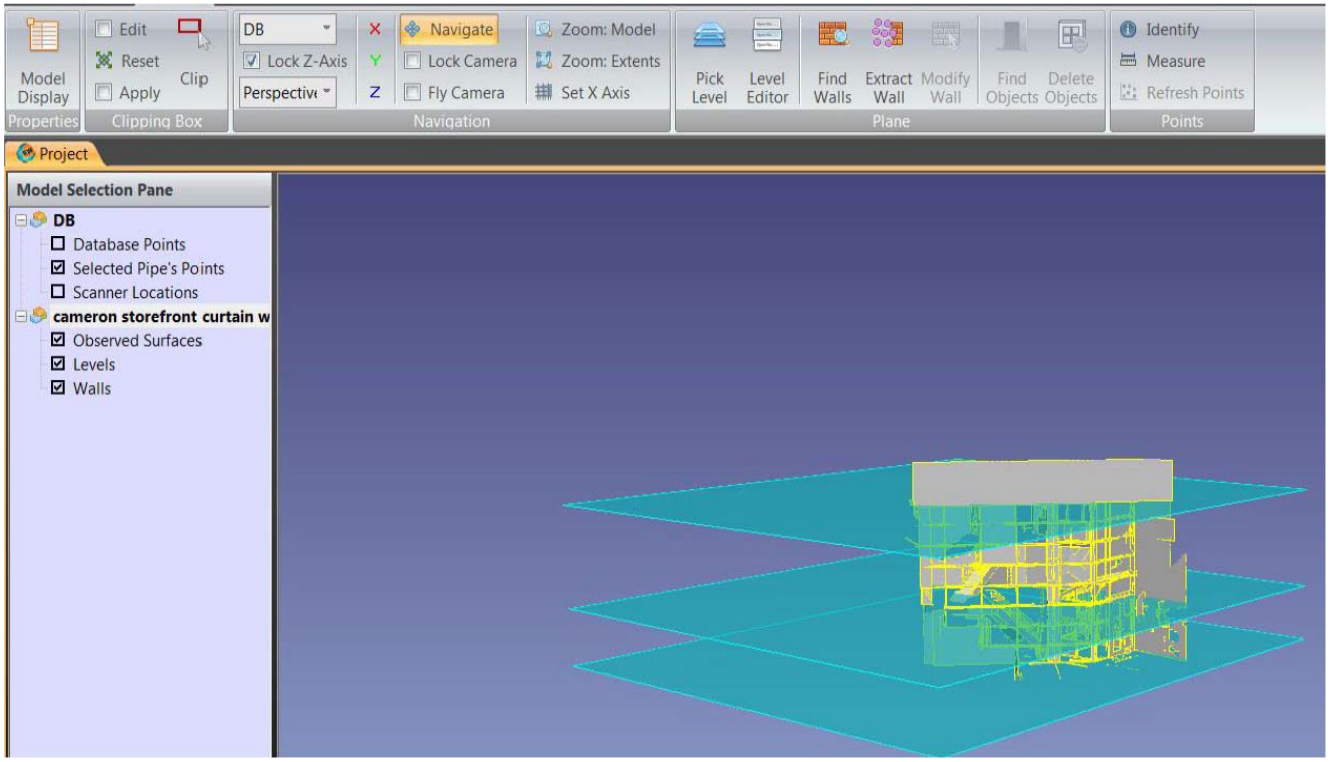

FIGURE 5.—Levels in Edgewise.

scanner is a "volumetric" measuring and imaging tool that distributes the laser beam at a vertical range of 305^0 and a horizontal range of 360^0, has a ranging accuracy with a scanning distance of approximately 98 feet between each scan and a surface reflectivity higher than 10% which is always greater than 0.043 inches ("FARO Focus | FARO Technologies," 2017). This scanner provides two options for registering the individual scans, either using targets for scanning or performing target-less scans. In this study, 5 spherical targets were used to properly orient and combine the scans. The scanner was fixed on a light-weight tripod and moved around the building to capture the scans from various vantage points. To ensure capturing the required point cloud and registering the scans without any loss of information, the vantage points were within 30 feet of each other. Since the resolution of the laser scanner camera was

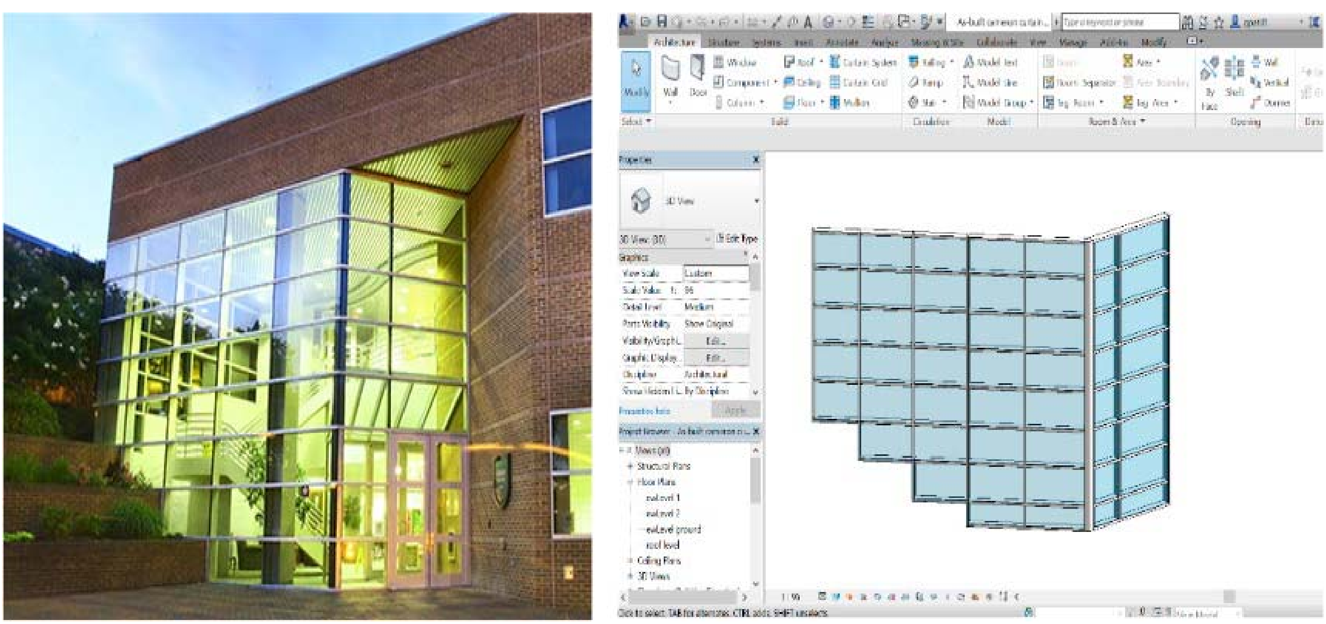

FIGURE 6.—Curtain Wall: Actual Wall (left) vs. As-built Model (right).

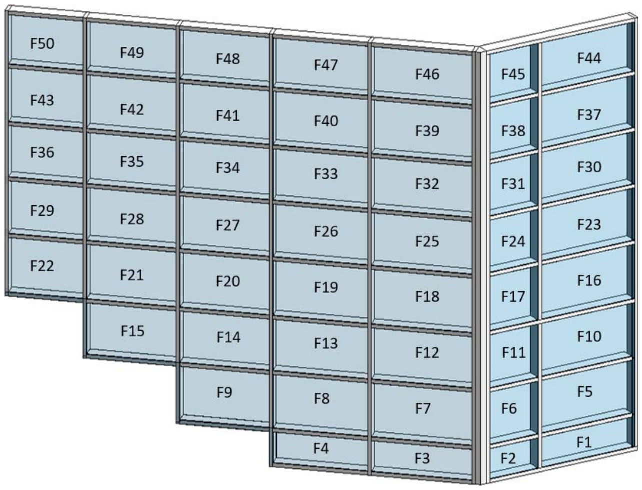

FIGURE 7.—Curtain Wall Panels.

up to 70 megapixels, the process took about 5-8 minutes for each scan to document the space at every vantage point.

The point clouds collected from these different scans were combined by the process known as registration (Xiong et al., 2013). Scene software (Faro 3D Laser Scanner Software | SCENE Software, 2017) (Figure 2) was used to complete the registration process and all five scans were imported for use with the unnecessary components removed. For a seamless transition of the final point cloud into the Revit software, the Scene file needed to be exported into a .rcp file. This .rcp file is later read by Revit to create a BIM model.

Heat Mapping

One feature of the Scene software is its capacity to generate heat maps, which can be used to visually determine the existence of structural defects in addition to performing FEA. This is achieved by detecting the distance of the surface of glass from the curtain wall frame consisting of vertical and horizontal mullions. The color coding shown in Figure 3 shows that the wall deforms maximum in its central top half.

Developing the As-Built BIM Model

The second step was to develop an as-built BIM model using the final point cloud file. Edgewise software was used to automatically generate basic architectural elements such as walls, windows, and doors, from point clouds registered in Scene, by grouping all the points on one plane as one component. This software provides a head start to create an as-built BIM model by coarsely modeling from the point clouds without any details. However, this methodology creates an "as-is" model for the glazing locations, with all the existing deformities that occurred over the years due to loading. As seen in Figure 4, Edgewise is capcable of modeling a basic solid wall, which has to be further modeled as a curtain wall in Revit. Once the scans are processed in Edgewise, the levels can be added manually (Figure 5), so that when this model is transferred to a BIM

TABLE 1.—Wind Loads for the As-built Model (Case 1: 12 mph)

Number	Area (sf)	Pressure (lb/sf)	Cd	Kz	Gh	Wind load (lb)
F1	10	0.28	1.6	0.258	1.721	2.0
F2	5	0.28	1.4	0.258	1.721	0.9
F3	10	0.28	1.6	0.258	1.721	2.0
F4	9	0.28	1.6	0.258	1.721	1.9
F5	17	0.28	2.0	0.376	1.581	5.8
F6	9	0.28	1.8	0.376	1.581	2.8
F7	17	0.28	2.0	0.376	1.581	5.7
F8	16	0.28	2.0	0.376	1.581	5.4
F9	15	0.28	2.0	0.376	1.581	5.1
F10	17	0.28	2.0	0.451	1.519	6.8
F11	9	0.28	1.8	0.451	1.519	3.2
F12	16	0.28	2.0	0.451	1.519	6.3
F13	15	0.28	2.0	0.451	1.519	6.0
F14	15	0.28	2.0	0.451	1.519	5.6
F15	15	0.28	2.0	0.451	1.519	5.7
F16	18	0.28	2.0	0.503	1.479	7.5
F17	10	0.28	1.8	0.503	1.479	3.6
F18	17	0.28	2.0	0.503	1.479	7.3
F19	16	0.28	2.0	0.503	1.479	6.9
F20	16	0.28	2.0	0.503	1.479	6.5
F21	16	0.28	2.0	0.503	1.479	6.6
F22	13	0.28	2.0	0.503	1.479	5.4
F23	17	0.28	2.0	0.544	1.451	7.7
F24	9	0.28	1.8	0.544	1.451	3.7
F25	17	0.28	2.0	0.544	1.451	7.5
F26	16	0.28	2.0	0.544	1.451	7.1
F27	15	0.28	2.0	0.544	1.451	6.7
F28	15	0.28	2.0	0.544	1.451	6.7
F29	12	0.28	2.0	0.544	1.451	5.5
F30	17	0.28	2.0	0.579	1.429	8.0
F31	9	0.28	1.8	0.579	1.429	3.9
F32	16	0.28	2.0	0.579	1.429	7.7
F33	15	0.28	2.0	0.579	1.429	7.2
F34	15	0.28	2.0	0.579	1.429	6.8
F35	15	0.28	2.0	0.579	1.429	6.9
F36	12	0.28	2.0	0.579	1.429	5.7
F37	17	0.28	2.0	0.609	1.411	8.3
F38	9	0.28	1.8	0.609	1.411	4.0
F39	17	0.28	2.0	0.609	1.411	8.3
F40	16	0.28	2.0	0.609	1.411	7.8
F41	15	0.28	2.0	0.609	1.411	7.4
F42	15	0.28	2.0	0.609	1.411	7.5
F43	13	0.28	2.0	0.609	1.411	6.1
F44	16	0.28	2.0	0.635	1.397	8.1
F45	9	0.28	1.8	0.635	1.397	3.9
F46	16	0.28	2.0	0.635	1.397	7.9
F47	15	0.28	2.0	0.635	1.397	7.4
F48	14	0.28	2.0	0.635	1.397	7.0
F49	14	0.28	2.0	0.635	1.397	7.1
F50	12	0.28	2.0	0.635	1.397	5.8
Transoms	22	0.28	1.4	0.528	1.397	6.4
Mullions	30	0.28	1.4	0.528	1.397	8.8

software, it automatically has the required levels and heights recorded.

Revit is one of the most commonly used BIM software due to its interoperability and offering of custom families and user-defined parameters; therefore, Revit was the preferred software for this study. In Revit, the exported Scene file in .rcp format and the Edgewise model both are imported to create an "as-is" BIM model. The solid wall

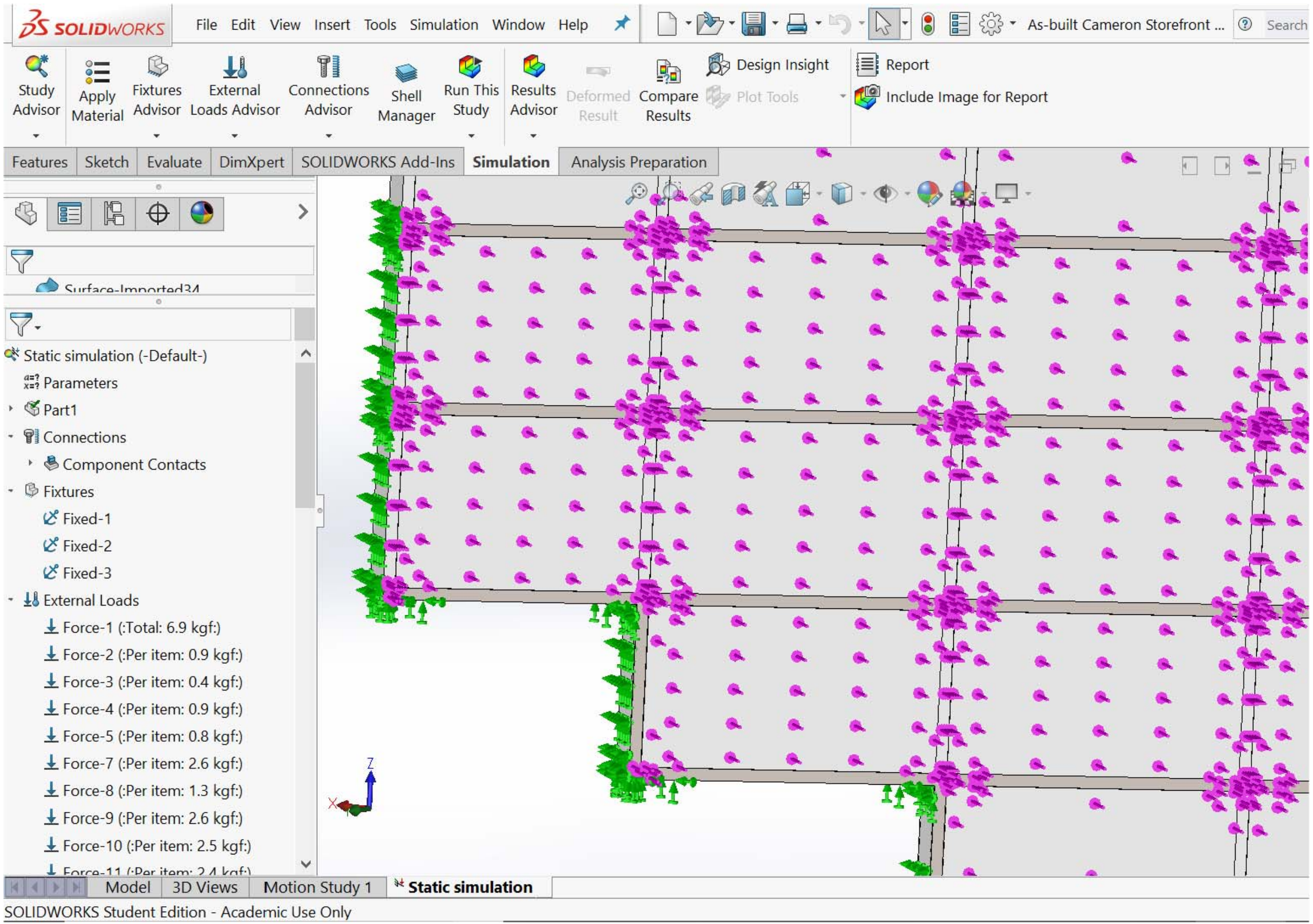

FIGURE 8.—Uniformly Distributed Wind Loads.

generated in Edgewise was converted into the storefront curtain wall, from the curtain wall family in Revit. Further, with the help of the point cloud data, information about the thickness and the position of the mullions, transoms and glass panels was extracted and used. It should be noted that even though the materials for the curtain wall were recorded in Revit for the mullions and transoms and glass for the panels, they had to be manually input into SolidWorks again for performing FEA on the model. As seen in Figure 6, the as-built model and the actual curtain wall are comparable in geometry.

Conducting Finite Element Analysis (FEA)

Selection of Software: The last step in the SCAN-BIM-FEA process is developing a structural model of the curtail wall with proper boundary parameters and loading conditions, and then performing finite element analysis to evaluate its structural integrity. For Step three, multiple software options were considered: i.e., ANSYS, Autodesk Robot Structural Analysis (ARSA), and SolidWorks. Each software option was piloted whereby two options failed and SolidWorks emerged successful. Since only the student version of ANSYS was available for this study, which has a limitation of generating up to 20,000 meshing entities, the software was not used because it could not mesh the entire curtain wall. Although ARSA provides a direct tab to convert the model from Revit to ARSA, its user interface was quite difficult to handle, and it led to a lot of errors which could not be resolved. As a result, ARSA was also not chosen. SolidWorks proved to be successful in finely meshing the curtain wall and providing proper deformation results.

Load Calculations: In this study, the dead load and wind loads are both considered to analyze the structural integrity of the curtain wall. In SolidWorks, the dead load of the entity is calculated depending on the materialistic property of the entity and by applying gravitational force. The lateral wind load was calculated manually for each glazed panel of the curtain wall. The formula used for calculating wind load is as follows:

$$WindLoad = A * P * C_d * K_z * G_h \tag{1}$$

In Equation 1, A is the area of the glass panel (sf), P is wind pressure (lb/ft^2), C_d is the drag coefficient, K_z is the exposure coefficient, and G_h is the gust response factor.

Using this Formula, wind loads from the bottom panel to the top panel of the wall were calculated for different wind speeds ranging from 12 mph up to 70 mph, i.e., 12

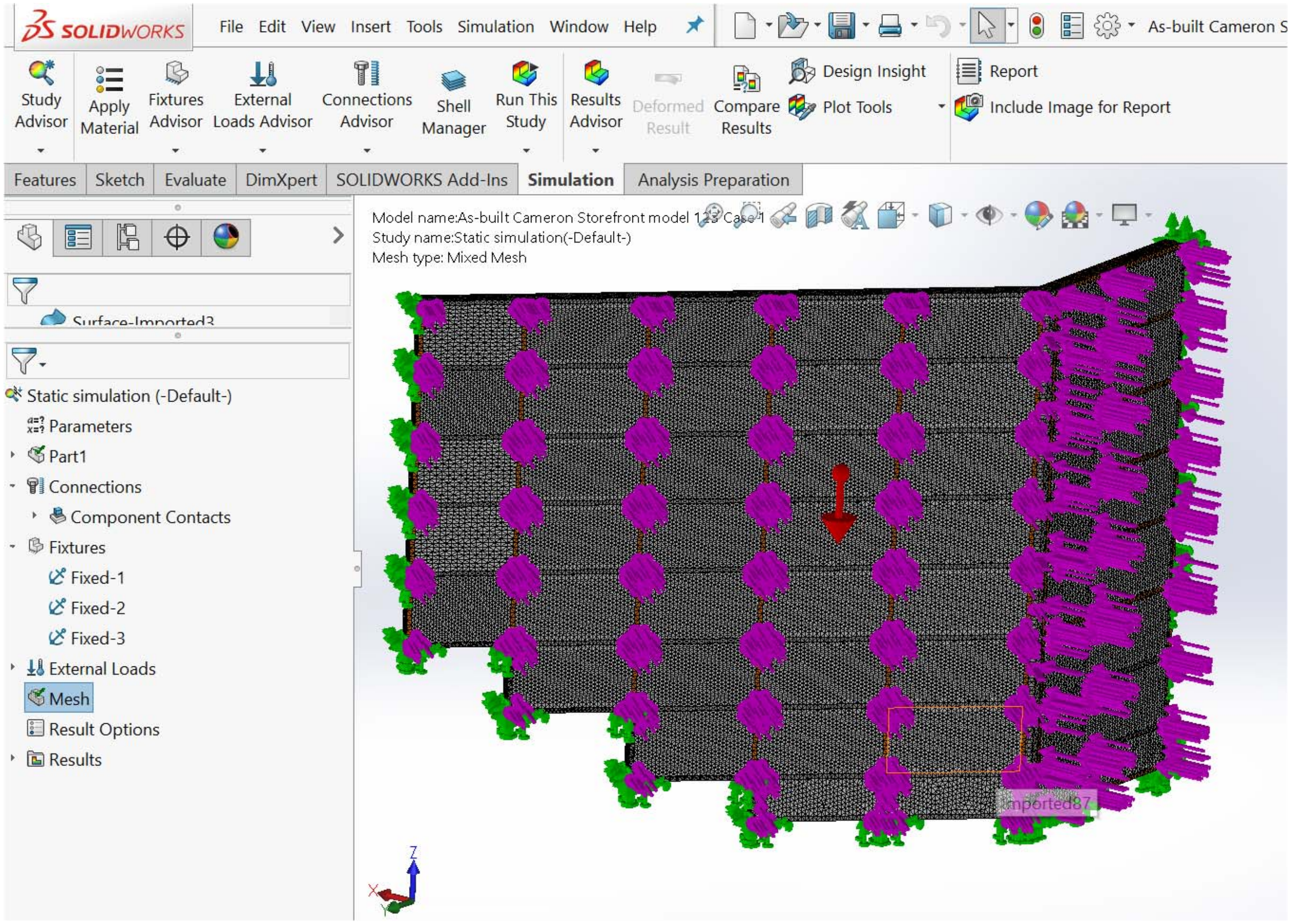

FIGURE 9.—Meshed Curtain Wall.

mph, 20 mph, 25 mph, 30 mph, 35 mph, 40 mph, 45 mph, 50 mph, 55 mph, 60 mph, 65 mph, and 70 mph. Twelve mph is the typical wind speed at the local area, and 70 mph represents an extreme windy situation. The reason of using various wind speeds (a total of 12) within this range was to evaluate the structural integrity of the curtain wall under different wind load situations. Curtain wall panels were numbered as shown in Figure 7. Wind loads under a 12-mph wind speed are included in Table 1.

FEA Analysis Using SolidWorks: In this step, the Revit file was directly imported into SolidWorks in standard ACIS format or. sat format. This provides a one-step direct link from Revit to SolidWorks (BIM-FEA). The material used for glazed panels was glass with elastic modulus of 9.9 x10^6 psi, while the mullions and transoms were made up of stainless-steel casting with elastic modulus of 2.8x10^7 psi. The calculated wind loads (Table 1 as one of 12 wind load cases) were applied as uniformly distributed area loads to the glass panels, as shown in Figure 8. Boundary conditions were defined and applied to the curtain wall.

In SolidWorks, the curtain wall was meshed into smaller components, with each component sized at 3.5 mm by 65 mm (Figure 9). Then FEA was performed on 12 wind load cases, and results are reported in the next section.

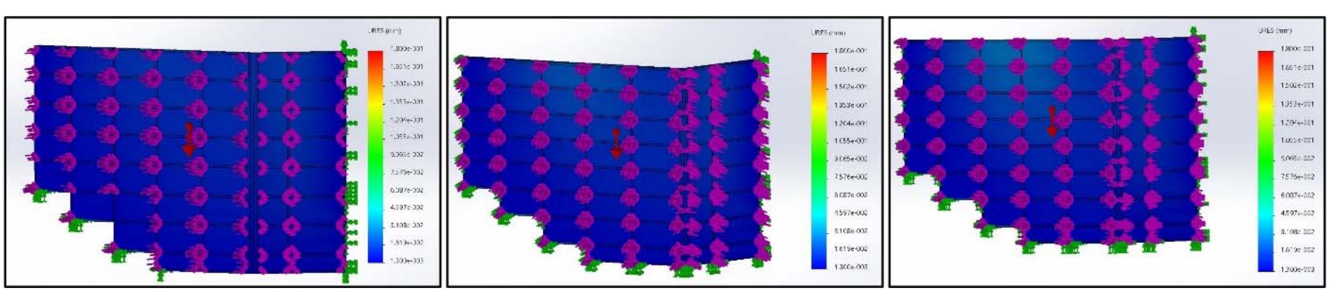

FIGURE 10.—Deformation of the As-built Model (Left: 12mph; Middle: 20mph; Right: 25mph).

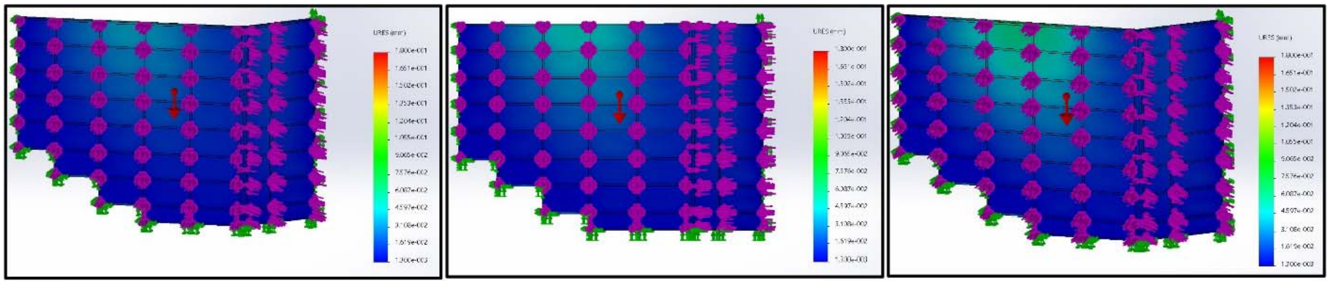

FIGURE 11.—Deformation of the As-built Model (Left: 30mph; Middle: 35mph; Right: 40mph).

RESULTS AND DISCUSSION

After performing FEA on the curtain wall, the resulting deformation can be visualized. Excessive deformation indicates the existence of potential structural integrity issues. In this study, deformation of the curtain wall was analyzed under 12 different wind loads and the selected results are included in Figures 10 through 13. As seen in the legend, the areas which are red color-coded have the maximum deformation while the blue areas have the least deformation.

The figures show that as the wind load increases, larger deformation is observed in the curtain wall, and that the maximum deformation occurs at the top part of the curtain wall. From the heat map (Figure 3), the top part of the curtain wall has existing deformation, possibly due to defective materials, improper installations or maintenance errors. This existing deformation was captured by the 3D laser scanner and stored in the as-built BIM model. As shown in Table 2, when this model is gradually loaded in FEA, the existing deformation triggers a larger and more severe deformation (reaching a maximum of 0.0060 mm per mph when the wind load is increased to 70 mph), becoming the starting point of a potential structural integrity issue.

It is evident that the proposed SCAN-BIM-FEA process is able to not only capture and document existing structural integrity issues, identify the potential failure mechanism through FEA, but also help engineers specify better panel designs and help contractors select proper installation methods.

This process is also useful to facility managers in planning and scheduling the preventative maintenance based on the actual conditions of the asset. Typical maintenance planning horizons and review processes should still be used, but the SCAN-BIM-FEA process will provide the FMs with real-time information that can be used to update maintenance and/or capital budgets. This process, however, does require a financial investment both in the software and hardware, as well as appropriate training.

CONCLUSION AND RECOMMENDATIONS

Monitoring the integrity of structures is an important concern in the AEC/FM industry, and would substantively assist designers, engineers, contractors, property developers, homebuyers, sellers, manufacturers, and facility managers in their decision-making processes. The application of 3D laser scanning for buildings has accelerated the speed and enhanced the accuracy of building information captured for geometric definition and creation of as-built 3D models. The integration of 3D laser scanning, BIM and FEA would not only help the designers and engineers improve the structural integrity of the curtain wall but can also help facility managers to continuously monitor changes and predict potential issues with the curtain wall, a part of a predictive maintenance program for facilities management.

A case study was performed to validate the proposed SCAN-BIM-FEA process. Discussions with industry technology users provided evidence that there are no optimum methods for using BIM for FEA and that the process has not been considered by facility managers as a tool. The as-built BIM model successfully captures the existing deformation, and the transfer of relevant information to the FEA software. Further deformations caused by the rated wind loads in a particular geographical area were calculated and

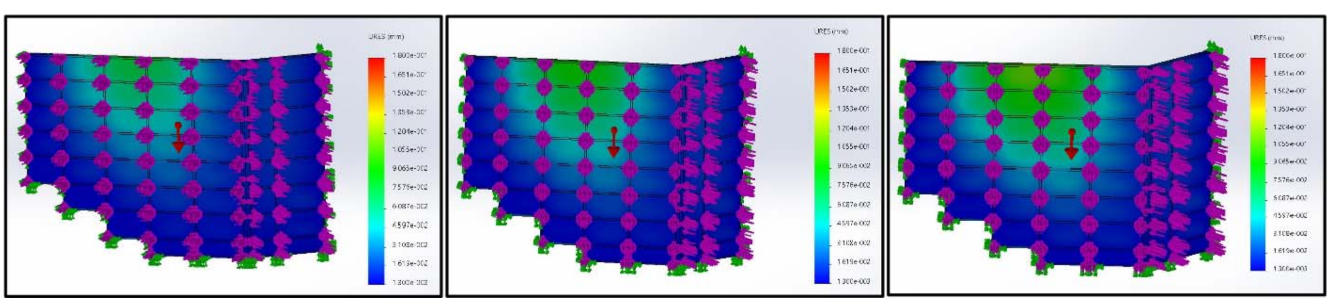

FIGURE 12.—Deformation of the As-built Model (Left: 45mph; Middle: 50mph; Right: 55mph).

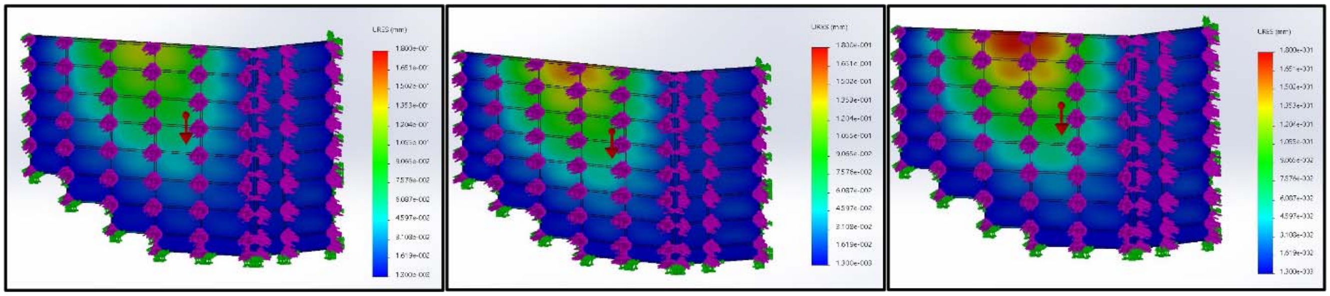

FIGURE 13.—Deformation of the As-built Model (Left: 60mph; Middle: 65mph; Right: 70mph).

TABLE 2.—Wind Speeds and Max. Deformation

Wind Speed (mph)	Max. Deformation (mm)	Increase Rate (mm/mph)
12	0.0013	
20	0.0020	0.0001
25	0.0136	0.0023
30	0.0261	0.0025
35	0.0395	0.0027
40	0.0560	0.0033
45	0.0733	0.0035
50	0.0907	0.0035
55	0.1155	0.0050
60	0.1353	0.0040
65	0.1502	0.0030
70	0.1800	0.0060

presented in a graphical format. These detailed and accurate results aid in identifying the structural risks of a building element and furthermore, can assist architects in developing better designs, inform manufacturers on the needs to produce stronger building elements, help contractors establish better installation methods, and allow facilities managers make informed predictive maintenance decisions regarding potential risk areas.

The work carried out in this study is only the beginning of automating the process of performing FEA on an as-built model developed in BIM. At various points, manual corrections and inputs were necessary due to algorithmic lack in the software. The integration of SCAN-BIM-FEA is not fully seamless when it comes to complete automation. Future work is needed especially on the programming of the Laser scanning and BIM software, to accommodate the smooth transition between different formats and recognition of a variety of shapes and geometry.

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