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Optimizing Glass Design: The Role of Computational Wind Engineering & Advanced Numerical Analysis

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Wind induced pressure is a major design consideration for glazing design. However, the effects of façade geometry and urban terrain on wind loading are often difficult to quantify without costly and time-consuming wind tunnel testing. Accurate 3-dimensional data, covering most major cities, is becoming increasingly accessible, and such models are ideal to support numerical modelling of environmental effects on the built environment, especially if such modelling attempts to capture the geometric effects of the cityscape. A new methodology to assess the effects of wind loads on the structural strength of glass using transient, geometrically non-linear analyses and improved glass failure prediction models is presented. A description is provided for both the calculation of wind-induced façade loads, and the development and employment of a finite element (FE) solver to model façade performance.

Keywords: curtainwall, wind loads, design, computational fluid dynamics (CFD), finite element analysis (FEA)

1. Introduction

The design of buildings and structures requires an accurate assessment of wind loads on the structural system and cladding elements to ensure efficient and reliable design. Loads obtained from building code provisions cannot account for the effects of building shapes significantly different from rectangular, nor for the effects of wind channeling or buffeting caused by nearby structures or terrain. For wind-induced cladding loads, the complex interaction between the building and the wind typically results in large areas of the façade having design pressures less than those required by the building codes, as well as local areas with design pressures higher than the requirements of the building code. An accurate determination of cladding wind loads permits an economical facade design that provides strength where it is needed.

Pedestrian acceptability of sidewalks, entrances, plazas, and terraces is often an important design parameter of interest to the building owner and architect. Acceptability assessment of the pedestrian-level wind environment is desirable during the project design phase so that modifications can be made, if necessary, to improve areas found to be excessively windy. Analytical methods such as computational fluid dynamics (CFD) are now able to estimate wind pressures, structural system loads, or windiness in pedestrian areas. The techniques presented herein have been developed to allow computational modeling of buildings to determine overall structural loading, wind pressure on cladding and windows, and wind velocities in pedestrian areas. The authors have developed a customized CFD solver and the wind modeling process has been validated during several engineering studies. This report includes discussion of computational modeling methodologies, calculation of wind pressures, and discussion of glazing design. All calculations were performed in accordance with the American Society of Civil Engineers (ASCE) Manual of Practice Number 67 on wind-tunnel testing (1999), and with the ASCE Standard 7-05 on wind loads (2006).

2. Numerical Investigation

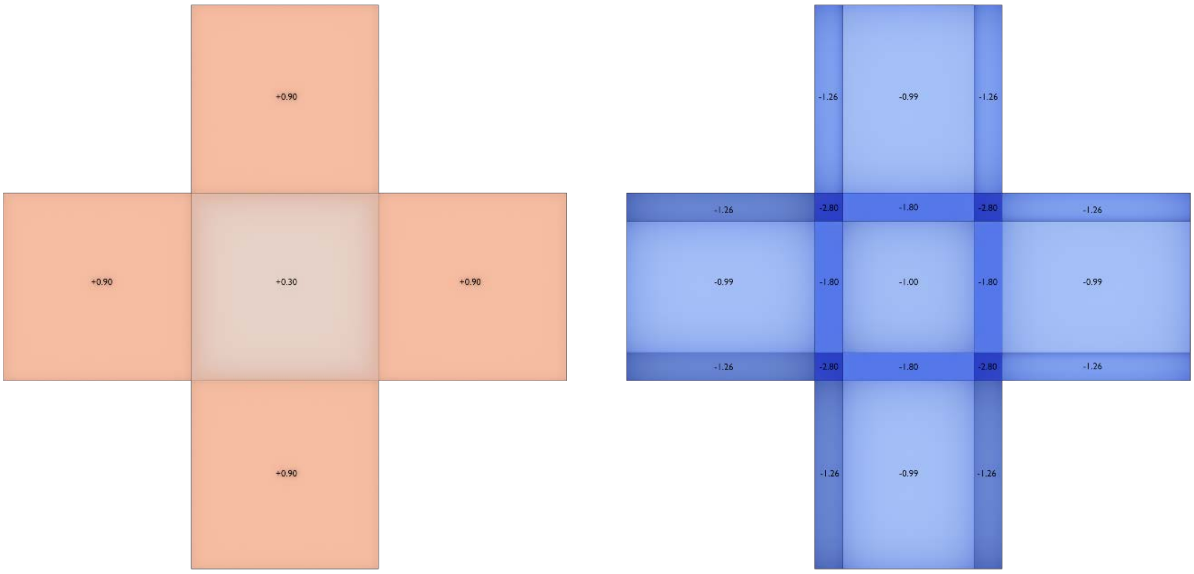
Further to the analytical comparison work conducted by Overend (2006), a simple test case was required to make an objective comparison of the methods described later in the paper and to quantify the accuracy of these methods. Data from a full-scale and widely validated test performed by researchers at the Silsoe Research Institute (SSI) are used as a control reference point. The SSI experiment comprised a simple 6m cube in a natural atmospheric boundary layer in an open country site in Bedford, UK. Two cases were considered, one with wind arriving normal to one of the cube faces and another with wind arriving at 45˚ to a cube face. This relatively simple experiment generates most of the complex flow features encountered around building structures. The measured 10-minute mean wind speed was of 10m/s at a height of 10m and this was used for the analyses reported in this paper.

3. Initial CFD Simulations

The computational domain used for the CFD simulation was 120m(L)x60m(W)x30m(L), comprised of approximately 2 million tetrahedral elements, with a blockage ratio of 2%. The outlet distance was selected to be far enough to develop equilibrium with the inlet conditions. Following a parametric mesh sensitivity analysis, a steady state simulation was used to calculate structural pressure loads using a Reynolds-averaged Navier-Stokes (RANS) k-ε turbulence model. The final transient analyses were performed using a large-eddy simulation (LES) turbulence model.

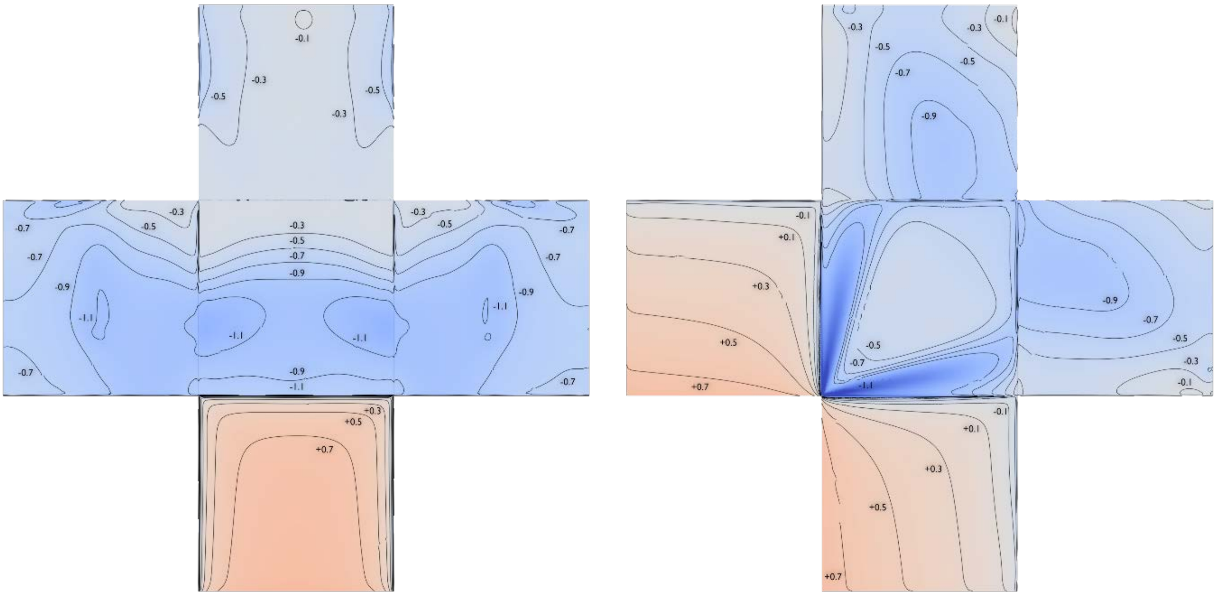
4. Results

Numerical results of the various analyses are best compared using non-dimensional, external aerodynamic pressure coefficients (C_{pe}). These values are multipliers to the dynamic pressure at a particular location. The multipliers exist due to the effective peak gust speed and are normally used directly for design purposes. This direct combination of gust speed and C_{pe} is based on quasi-steady theory, where it is assumed that all load fluctuations are due to gusts of the boundary layer, thus ignoring turbulent fluctuations generated by the building. Figure 1 shows the values of C_{pe} predicted by ASCE 7-05. The values represent an envelope for the most onerous values evaluated for wind directions of -45˚ through to +45˚. Figure 2 shows the results of the transient CFD analysis. C_{pe} values are based upon the mean of 135 values calculated for each of the two simulations. The initial conditions for the transient LES simulation were provided by the initial steady-state RANS calculation.



a) b)

Fig. 1a) Positive, b) Negative C_{pe} values from ASCE 7-05

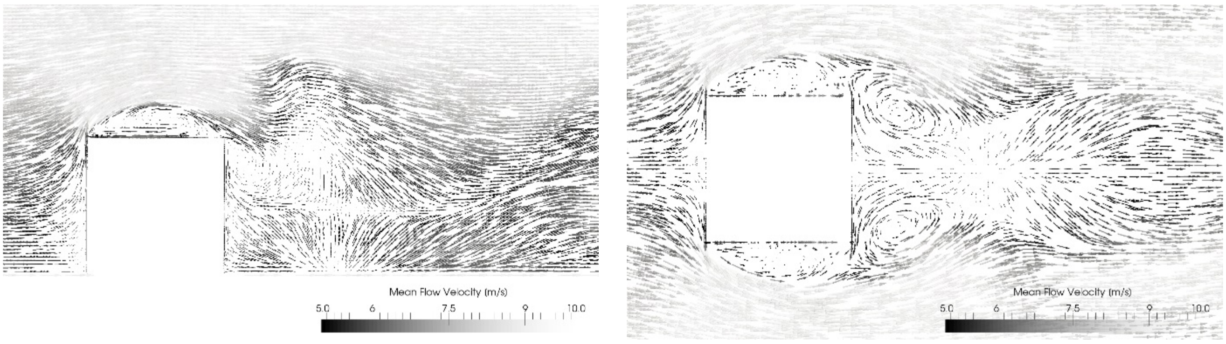


a) b)

Fig. 2a)CFD C_{pe} values for wind normal to cube, and b) wind at 45° to cube

5. Comparison and Discussion

Comparisons between the ASCE 7-05 C_{pe} code values (Figure 1) and those shown in Figure 2 provide an indication of the simplifications adopted by the codes of practice. This gives an insight as to how complex pressure distributions can be, particularly in dense urban contexts. However, this would be difficult to codify into a standard since each large building modifies the urban wind flow thereby modifying the pressure distribution over surrounding buildings. The possibility of new tall building construction further complicates the problem, increasing the number of load cases. The general flow characteristics, such as flow separation and reattachment, were all simulated as shown in Figure 3 and this is reflected in the correct distribution of surface pressures.



a)

b)

Fig. 3a) Vertical, and b) horizontal section through flow normal to cube

Despite being limited to simple geometries in this study, ASCE Standard 7-05 was found to significantly overestimate façade pressures for the simple notional cube. This overestimation is most pronounced in local pressure calculations, which are critical for designing façade elements.

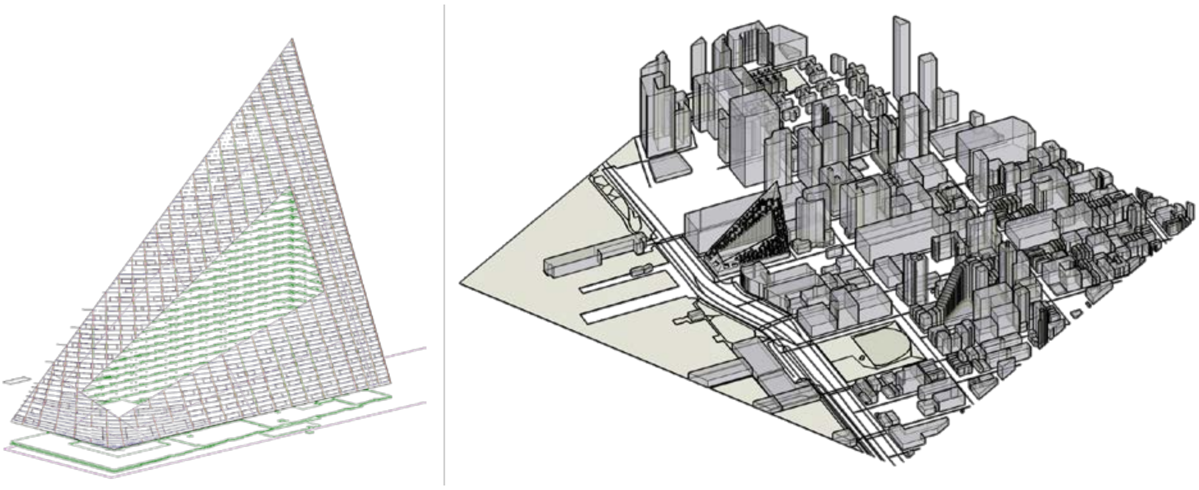
As demonstrated, CFD can be a very useful tool in façade design as this computational method produces a level of flow field detail that would be very difficult to extract from a wind tunnel. Such information can be used to inform the geometrical design of the façade and give indications of new construction effects on surrounding buildings along with pedestrian comfort predictions.

6. Complex Wind Model Development

Accurate 3-dimensional data, covering most major cities, are becoming increasingly accessible, and these models are ideal for numerical modeling—especially if such modeling attempts to capture geometric effects of the cityscape. However, there is still considerable complexity involved in converting the raw geometric data into a format suitable for numerical analysis. The authors have developed methods to address this technical requirement, and these methods often entail leveraging models that have been developed and optimized for less demanding computational tasks (i.e., map viewing). This has real benefits for the availability and accessibility of geometric data, but it also means that modeling data can be fast, cost-effective, accurate and as up-to-date as mapping data (see Figure 4).

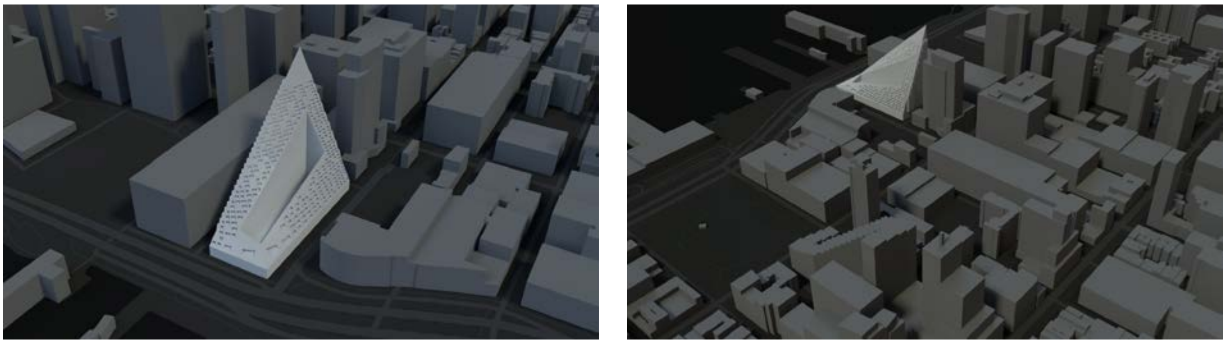
Raw geometric data used to construct urban models can be collated from several sources and typically leverages photogrammetric 3D technology, geo-located high-resolution aerial imagery, and LIDAR. Pre-processing of the original facetized geometry includes non-destructive reconstruction to optimize performance by reducing the vertex/face count of the mesh and removing unnecessary vertices and edges (see Figure 5).

An appropriate mesh generation utility is required to discretize (i.e., mesh) the case geometry with a high degree of automation and good parallel efficiency. Hex-dominant meshes with an octree topology are preferred, whereby a background cubic mesh is subdivided a number of times as the ground and building surfaces are approached. At the building surfaces, the cells are modified to snap to the underlying geometry of the urban cityscape (see Figure 6).



a) b)

Fig. 4a) A structural façade imported from CAD, and b) Model used for the computational study



a) b)

Fig. 5a), and b) Renderings of the cityscape model used for the computational study

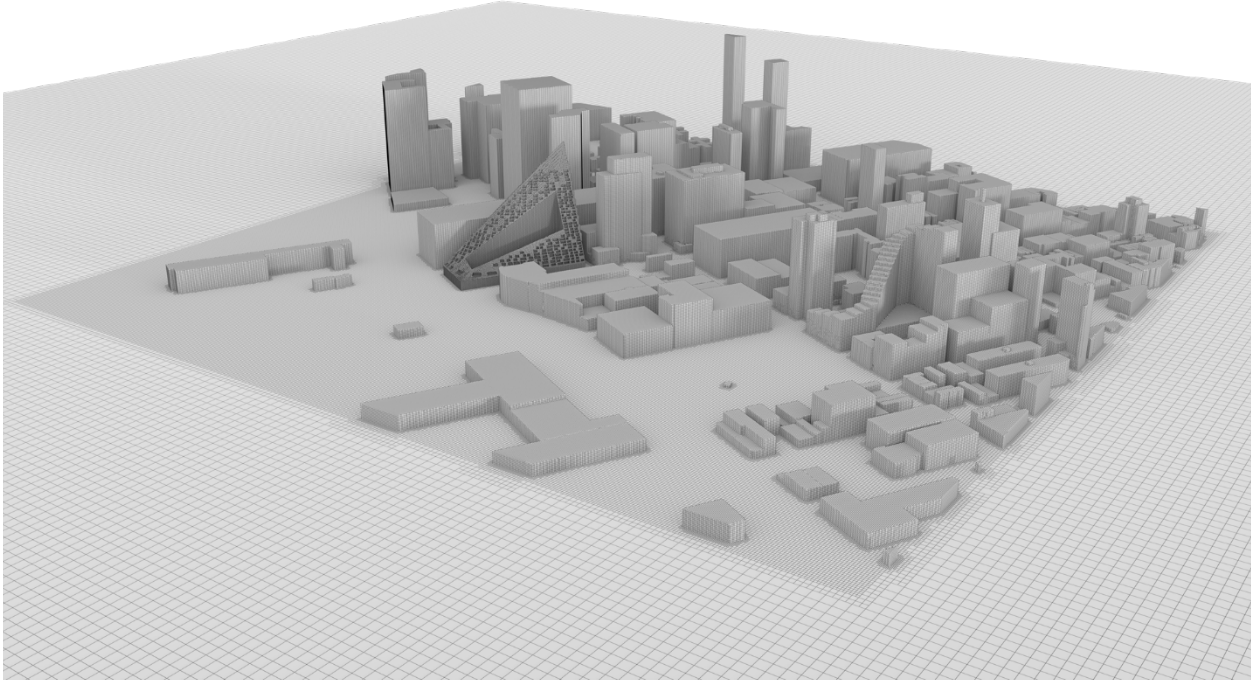


Fig. 6 Cityscape model domain & discretization (meshing). The model domain is 9840(W)x9840(D)x6560ft(H) and composed of 33.2 million cells. Additional refinement is provided in the regions of interest (i.e., around the buildings and ground plane).

7. Sample Wind Load Calculation

For smaller domains (e.g., single buildings) and internal flow problems, it is possible to use a LES approach. However, for wind calculations within urban cityscape environments, a steady-state solver for incompressible turbulent flow is used, which employs the semi-implicit method for pressure-linked equations (SIMPLE) algorithm. Input parameters for the CFD calculation are shown in Table 1, with the simulation outputs shown in Figures 7 through 9.

Table 1: Calculation input parameters

Inputs	Parameters	Data Source
Basic Wind Speed	V = 98mph	Project Specific Data
Importance Factor	I = 1.00	Project Specific Data
Mean Roof Height	h = 500ft	Project Specific Data
Exposure Category	Exp = B	ASCE 7-05, Section 6.5.6.3
Velocity Pressure Exposure Coefficient	$K_z = 1.56$	ASCE 7-05, Table 6-3
Topographic Factor	$K_{zt} = 1.0$	ASCE 7-05, Section 6.5.7
Directionality Factor	$K_d = 0.85$	ASCE 7-05, Table 6-4
Enclosure Classification	Enclosed	ASCE 7-05, Section 6.2
Dynamic Pressure:		
$q_z = 0.00256 \times K_z \times K_{zt} \times K_d \times V^2 \times I$	$q_z = 32.6$ psf	ASCE 7-05, Equation 6-15
Equivalent Wind Velocity	$v_z = 113$mph	Flow velocity used in simulation

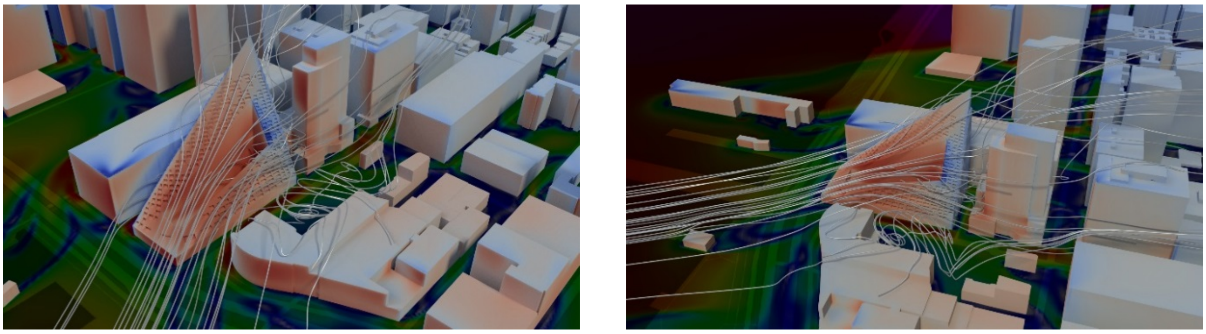


Fig. 7 Calculation outputs. Pressure loads shown on the building exteriors (red – positive, blue – negative) Velocity fringe shown on the ground plane. Stream tracers indicate flow within the domain.

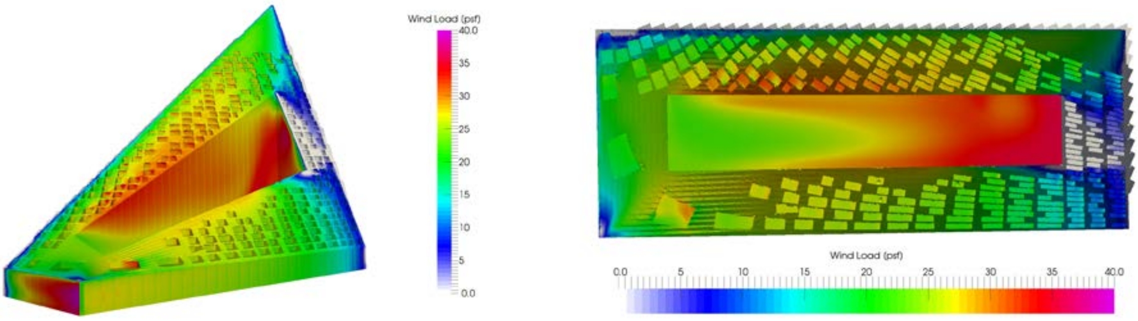


Fig. 8 3D fringe plots indicate positive pressure loads calculated from a single wind direction.

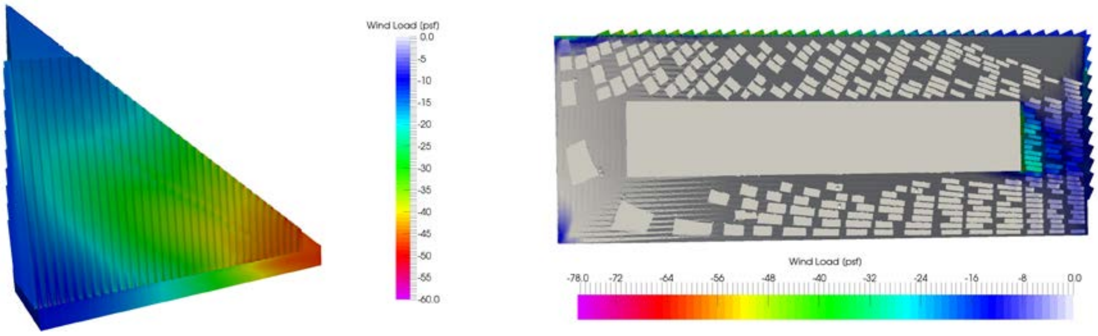
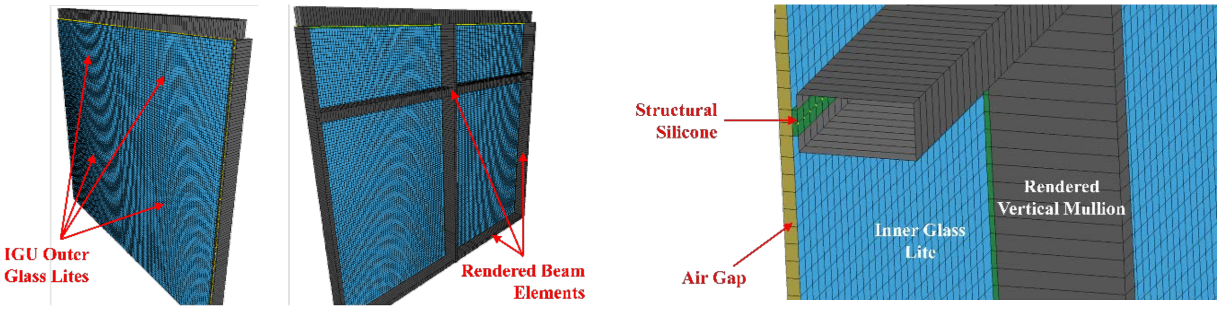


Fig. 9 3D fringe plots indicate negative pressure loads calculated from a single wind direction.

8. High-fidelity Glazing Design

Leveraging the modeling and analysis capabilities of finite element computational codes, a novel approach for evaluating the performance of architecturally complex glazed facades under dynamic loading conditions such as wind has been developed. The modeling approach offers design-level fidelity to maximize computational efficiency (i.e., minimize run time) whilst retaining adequate fidelity and accuracy to capture key aspects of system behavior. For this modeling approach, structural mullions are represented through the use of Timoshenko-type beam elements while glass lites, interlayers, and IGU spacers are modeled with reduced-integration shell elements. Constant stress solid elements are used to represent the IGU air gaps and structural silicone. Using this mixed element approach, a design-level fidelity is achievable, facilitated through the use of unique user-defined constitutive models (UMATs) for glass, PVB interlayer, and structural silicone. An example design-level finite element model of a standard 4-IGU curtain wall cassette is presented in Figure 10.



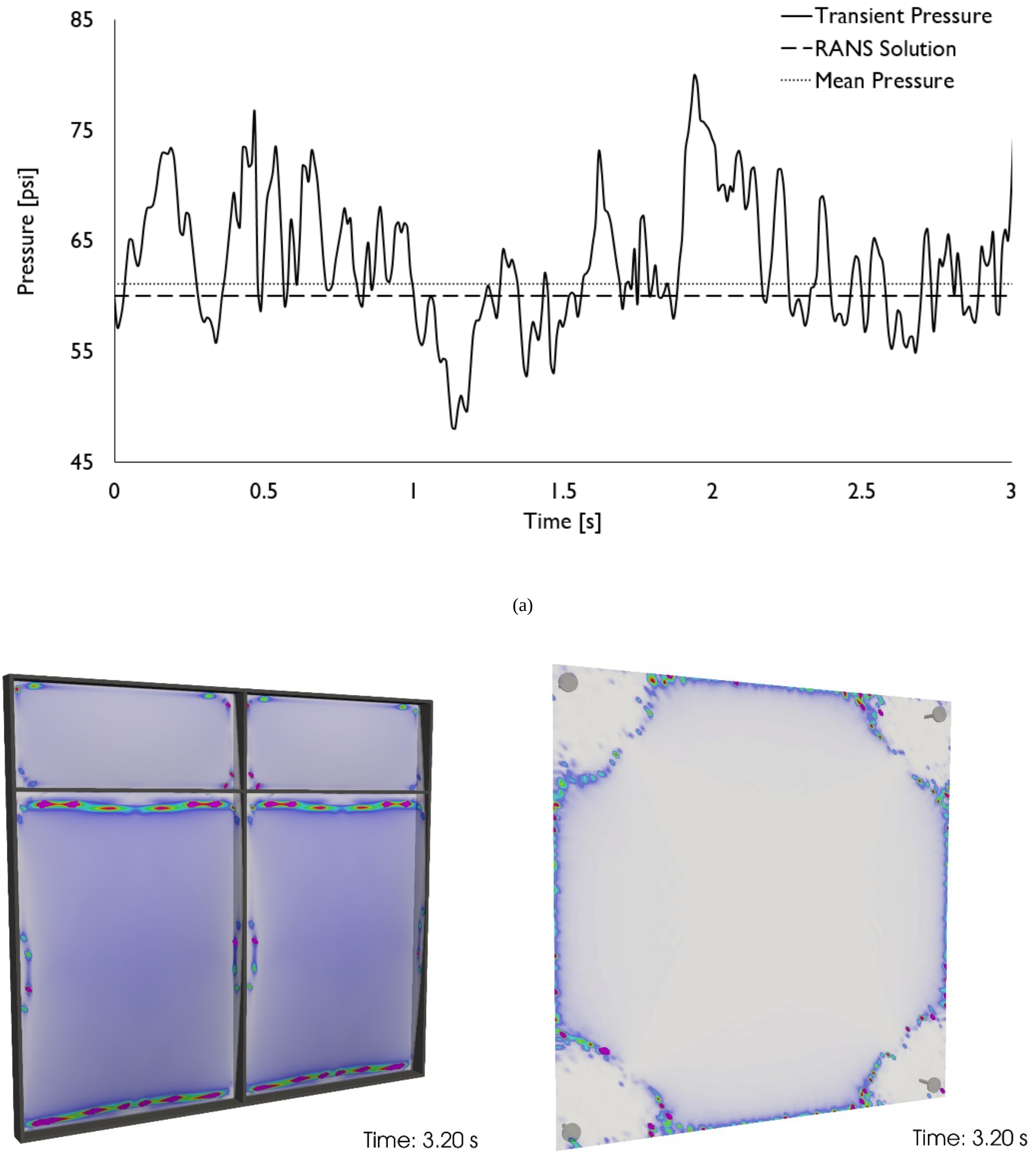
a) *b)*

Fig. 10 Example finite element model construction for a standard 4-IGU glazed curtain wall cassette

This work builds upon previous work conducted for the Air Force Research Laboratory (AFRL) and PPG Industries to validate a modeling approach capable of predicting glass failure for both static and dynamic loads. The new glass UMAT features an elastic constitutive model with a surface-flaw based probabilistic failure criterion derived from Beason and Morgan's (1984) Glass Failure Prediction Model (GFPM) and extended to be compatible with a finite element based explicit numerical solver. Use of the GFPM glass failure theory is consistent with the current state-of-the-practice and future vision of ASTM E1300 *Standard Practice for Determining Load Resistance of Glass in Buildings* (ASTM 2012). The new PVB interlayer UMAT captures post glass-break, strain-based tension stiffening due to the interaction between PVB and adhered glass shards, and it also incorporates a dynamic increase factor that is dependent on both strain and strain rate. The new structural silicone UMAT features a hyper-elastic constitutive model that accounts for dynamic strength increase due to both strain and strain rate (supported by experimental data for the DOW 983 two-component product).

Current dynamic design approaches typically use single-degree-of-freedom (SDOF) methods to analyze the performance of window glazing and mullions. The flexural resistance and mass of each component must be identified to define the SDOF representation. Then, the resistance curve must be calculated based on span, support conditions, cross sectional stiffness, assumed deformed shape, and a failure criterion. SDOF methods have significant limitations when used for analysis of complex and/or geometrically playful glazing systems, such as storefronts, curtain walls, cable-supported facades, and curved glass. Coupling effects—the interaction between the glazing and the support system—are ignored in SDOF methods, and only single assumed modes of response can be considered. The use of finite element analysis (FEA) techniques can eliminate assumptions on mass distribution and deformed shape, facilitate spatial fracture prediction at appropriate points on the glass surface, and can explicitly capture coupling effects. FEA can also ultimately remove geometric restrictions of typical SDOF analysis techniques, thus providing a viable and robust approach for predicting the performance of non-rectilinear and curved glass.

In the work carried out herein by the authors, façade pressures are taken at 25Hz for a period of 3 seconds from the transient LES CFD calculations described earlier. The mean pressure during this sample time was 61.08 psi, with the RANS calculation converging at a pressure of 60 psi. Examples of transient glazing response analysis for a typical curtain wall sub-assembly and a point-supported lite are shown in Figure 11. This analysis was conducted using the outputs of the CFD wind calculation whereby a 3-s period in an area of high negative pressures (also shown in Figure 11) was extracted and used as input to the glazing response analysis. The response analysis was conducted to assess the suitability of the proposed glazing design and to potentially optimize the design, if at all possible.



(a)

(b)

(c)

Fig. 11 High-fidelity physics based (HFPB) modeling two glazing designs. The negative-pressure (suction) load history (a) was used as the input loading function for the HFPB calculations for the standard glazed curtain wall cassette (b) and the point-supported glass model (c). The time step color fringes show 'stress-biaxiality' within the glass (i.e., the ratio of the minimum and maximum principal stresses). This metric is used as a key input parameter ASTM. 2016. E1300-16 GFPM.

9. Conclusion and Future Work

The potential for finding optimized building solutions is unfolding through enormous development in computational design tools. CFD software, as detailed herein, enables the assessment of wind loads on complex building geometries by simulating wind flow in a virtual wind tunnel using a customized CFD solver. This process has been developed and validated during several engineering studies. The model of any 'building of interest' can be extracted from existing CAD/BIM models (e.g., Revit) and the surrounding cityscape geometry developed from GIS data. The space occupied by air is modeled using a hex-dominant finite volume mesh after which the surfaces and regions of flow circulation are refined. Post processing of the simulation facilitates visualization of flow patterns in the vicinity of the investigated building. Influences from nearby buildings and aerodynamic properties can be qualitatively assessed, and velocity and pressure fields give insight into the turbulent vortex structures occurring downstream of buildings.

The CFD simulations can be used to calculate peak wind loading on the structure using time periods of several wind storms to assess statistically safe extreme values. Furthermore, pedestrian level wind conditions can be investigated and compared to criteria for human comfort and safety, and mitigation measures such as wind screens and massing changes can be quickly evaluated.

Ongoing and future work will extend the CFD solver to analyze façade appendage hum/whistle by means of aeroacoustic analysis. The general approach currently under development utilizes an Eulerian code to calculate the flow field, vortices, surface interaction, etc. around the appendages. An acoustic analogy is then used to translate the surface noise sources (dipoles) and flow field noise sources (quadruples) from the CFD calculation into sound emitters/sources and FEA methods used to propagate the noise through a bounding surface/volume. The results of this calculation are integrated to calculate the generated sound power and frequencies to determine the potential for wind-induced nuisance hum/whistle from the appendages.

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