





Outdoor Air Curtain Air enters the cavity from outside and is immediately returned towards the outside. An air curtain forms along the outer skin.

 $\mathbf{\Lambda}$ FIGURE 1 Five modes of double-skin facade ventilation.

## SIMULATION-BASED DETERMINATION OF PRESSURE COEFFICIENTS FOR MULTI-STORY **DOUBLE-SKIN FACADES<sup>°</sup>** JEFFREY VAGLIO, PhD, PE, AIA, LEED AP [BD+C]

This research investigates how various airflow configurations affect the pressure coefficient distribution on multi-story double-skin facades. Multi-story double-skin configurations are the focus due to their prevalence in the United States, as learned following a review of 30 existing projects of which 21 (70%) had a multi-story cavity partitioning and 21 (70%) used an outdoor air curtain ventilation model.<sup>1</sup> For this study, a prototypical geometry is developed and computational fluid dynamic simulations are run for four configurations of airflow inlet and outlet combinations. The simulation method is first calibrated and reviewed against existing wind tunnel studies. The interior skin's coefficient of pressure profile varies considerably depending on the varying inlet configuration.









#### MULTI-STORY DOUBLE-SKIN PROTOTYPE

#### AIRFLOW INLET CONFIGURATION

The outdoor air curtain ventilation mode has been utilized on 17 of the 21 multi-story double-skin facades (81.0%) studied, an increased rate than the 30 project sample of all cavity partitioning configurations. A multi-story double-skin facade with an outdoor air curtain, double-skin height of  $h_{m}$  = 21 m, building height of h = 20 m, width of a= 45 m and cavity depth of s = 1.0 m was deemed the prototype configuration for analysis. In this research the airflow opening and exhaust configurations are treated as variables.



#### 7 FIGURE 2 Multi-story double-skin facade prototype variations: trench inlet (top) and raised inlet (bottom).

#### DEVELOPMENT OF A MULTI-STORY PROTOTYPE

#### DIMENSIONAL TRENDS OF MULTI-STORY DSFs IN THE UNITED STATES

Having identified the multi-story as the predominant cavity partitioning of double-skin facades in the United States,<sup>1</sup> 21 projects were then isolated and evaluated for trends within this subset. The dimensional characteristics a = 46.8 m.

- gathered from projects drawings, technical presentations, journal publications and periodical articles – are summarized:

*Height*: The multi-story cavities range in height from 5.5 m to 69.0 m with an average of *h* = 21.1 m.

Width: The multi-story cavities range in width from 5.5 m to 112.8 m with an average of *Cavity Depth*: The multi-story cavities range in depth from 0.23 m to 3.0 m with an average of s =1.01 m.

Aspect Ratios: The multi-story cavities range in height-to-depth aspect ratio from 6.0 to 101.8 with an average of  $(h_{ad}/s) = 27.8$ . The average cavity height-to-width is  $(h_{ca}/a) = 0.672$  meaning the cavities are more frequently wider than they are tall. The average cavity depth-to-width is (s/a) = 0.031.

closed.



Raised / Entry







Airflow into the double-skin facade cavity may occur through the five generalized opening configurations below. A sealed intake configuration also exhists; this is the mode of many multi-story double-skin facade systems when the operable mechanisms or louvers are

#### AIRFLOW EXHAUST CONFIGURATION

Airflow out of the double-skin facade cavity may occur through the three generalized exhaust, or outlet, opening configurations below. The three exhaust opening configurations all occur at the top of the cavity, or on the adjacent vertical planes, taking advantage of the stack effect. The forward configuration exhausts air over the building's roof through the inner vertical plane while the *return* condition thrusts the air back into the impinging direction via the outer vertical plane.

#### SIMULATION-BASED DETERMINATION OF PRESSURE COEFFICIENTS

The use of simulation for this research requires special attention be given to tuning the modeling process in an effort to preserve the relevancy of the results. Researchers have identified the potential of CFD modeling, when used in conjunction with wind tunnel studies, to tackle challenging design situations. Once standard modeling procedures are established, wind tunnel tests are used to calibrate CFD modeling and predict accurate pressure distributions on facade structures.<sup>2</sup> To evaluate a computational fluid dynamics workflow for determining pressure coefficients for multi-story doubleskin facades, this research aimed to simulate reduced scaled wind-tunnel studies within the simulation domain. The first step in refining an analytical model was to calibrate the method to existing sources of wind tunnel data

#### CALIBRATION STUDIES

The initial calibration step is replicating simulations of existing wind tunnel data for multi-story, single-skin and double-skin facade configurations. Two wind-tunnel studies were conducted to calibrate the CFD modeling in COMSOL Multiphysics. The first calibration exercise was that of a simplified isolated cube in an atmospheric boundary layer wind-tunnel. This experiment was carried out by 12 separate institutions with wind tunnels, results were compared,<sup>3</sup> then carried out separately – and more recently – at full-scale measurements and reduced scale wind-tunnel experiments.<sup>4</sup> Both of these research efforts were summarized in Overview of Pressure Coefficient Data in Building Energy Simulation and Airflow *Network*.<sup>5</sup> The second calibration, presented herein, adopted the most similar physical testing to date: Margues da Silva and Gomes' tests of Gap inner pressures in multi-story double-skin facades.<sup>6,7</sup> An Unsheltered and Sheltered Tower were simulated at a model scale of  $\lambda = 1/40$  in an



open-circuit wind tunnel with a 9 m x 3 m x 2 m

test section. In this paper's research, the Unshel-

tered and Sheltered Towers were simulated and

compared to the aforementioned wind-tunnel

results, maintaining the original studies parame-

ters:  $\lambda = 1/40$ , U = 10.5 m/s,  $\alpha = 0.18$ , and scaled

building configurations dimensions; a = 32.5

cm, b = 20 cm and h = 70 cm, per Margues da

Silva and Gomes.<sup>6</sup> The calibrations maintained

all parameters mentioned, but varied the inlet's

initial turbulence intensity ( $I_x$ ) and floor surface

roughness length ( $z_a$ ) to identify the combi-

nation that generated the most comparable

net pressure coefficients across the double-skin

facade layouts, thus suggesting the most similar

For the simulated models, the three-dimensional

solution domain places the study model - or

building – at the center along the  $L_{\rm m}$  length and

 $W_{uv}$  width, as well as placed with its base at z = 0.

Inlet: The vertical boundary plane at y = 0, the

upstream inlet, has an initial velocity of  $U_{a}$ ,

defined below. The resulting pressure distribution

between the inlet and outlet is variable. The initial

simulated turbulent flow environment.

*Outlet*: The vertical boundary plane at y = 9, or the downstream outlet, is specified as a zero gauge pressure ( $p_q = 0$ ) with no viscous stress.

*Floor*: The floor is defined as a wall function with applied roughness. The surface roughness length ( $z_0$ ) varies based on terrain exposure and is modeled by the equivalent sand roughness ( $k_{S,ABL}$ ).

*Velocity Profile*: The velocity profile varies as a function of the reference velocity  $(U_{ref})$ , height (*z*) and the power law exponent ( $\alpha$ ):

$$U_0 = U_{ref} * \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

SHELTERED TOWERS: Two sheltered tower configurations were used for comparison between the wind-tunnel studies and these simulations. The first, *Layout A*, is best described as a sheltered



0.9

0.8

0.7

0.6

**4** 05 -

0.4

0.3

0.2

0.1

-3

tower on the front and one lateral (left) side where both second skins have a raised/portal inlet, a through outlet/exhaust and unsealed laterally. The second, *Layout D*, is similar to *Layout A*, with the one difference being that the vertical edges of the cavity are closed, making *D* laterally sealed.

The overarching parameters that consistently yielded agreeable (or near-agreeable) results for the multiple layouts considered were an inlet turbulence intensity of  $I_{T_{inlet}} = 0.15$  and a roughness length of  $z_0 = 2.0$  m. The  $C_{\text{num}}$  profiles at x/a = 0.35 and 0.67 for Layout A and Layout D of Margues da Silva and Gomes<sup>7</sup> are shown in Figure 7. The graph shows that for both Layout A and D, the selected set of input parameters yield C<sub>and</sub> profiles that are near-matches for the peak pressures just above the air inlet, 0.1 < z/h< 0.2. For 0.2 < z/h < 0.4, the simulations for both *Layout A* and *D* have a greater magnitude than the wind-tunnel results. For z/h > 0.4, the Layout A simulation follows a near match profile shape through the center of the building height with slight over magnifications at times while Layout D maintains a constant over-magnification for the remaining height of the building.

Layout A (top left) and Layout D (top right).



FIGURE 7  $C_{p,net}$  profiles at x/L = x/a = 0.35 and 0.67 for simulations  $(C_{p,net} = C_{p,int} - C_{p,ext})$  compared to Marques de Silva and Gomes<sup>7</sup> wind-tunnel studies ( $C_{p,net} = C_{p,DSFint} - C_{p,nnik}$ ) with  $U = 10.5 \text{ m/s}, I_T = 0.15, \alpha = 0.18, z_0 : 2.0 \text{ m}, s = 0.8 \text{ m}.$ 

Simulated atmospheric boundary layer wind tunnel configuration. turbulence intensity (  $I_r$ ) and turbulent length scale (  $L_r$ ) are also defined at the inlet.

#### DESCRIPTION OF STEADY-STATE SIMULATION

The steady-state simulations utilized a threedimensional simulation domain representative of the wind-tunnel test section, as shown in Figure 5. The turbulent flow simulations incorporate a Reynolds Averaged Navier Stokes (RANS) turbulence model type with a k- $\varepsilon$ turbulence model with incompressible flow. The simulations maintain the parameters: U = 10.5m/s,  $I_T = 0.15$ ,  $\alpha = 0.18$ ,  $z_0 = 2.0$  m. The building geometry is the same as the multi-story prototype outlined previously: height of  $h_{row}$  = 21 m, width of a = 45 m and cavity depth of s = 1.0 m at a model scale of  $\lambda = 1/40$ .

In this research the airflow opening and exhaust configurations are treated as variables. The inlet and exhaust openings are of equal dimension, maintaining a total area of each at  $s^*a$ . The analysis used twelve DSF models, varying the inlet and exhaust configurations for the following combinations:

- Face-Forward (FF)
- Trench-Forward (TF)
- Raised-Forward (RF)
- Shingled-Forward (SF)
- Face-Through (FT)
- Trench-Through (TT)
- Raised-Through (RT)
- Shingled-Through (ST)
- Face-Return (FR)
- Trench-Return (TR)
- Raised-Return (RR)
- Shingled-Return (SR)

#### RESULTS

The interior and exterior pressure coefficients for each model are extracted; the pressure coefficient contour elevations for each are shown in Figure 8 with a line of symmetry (shown at the left of each elevation) at mid-width (x/a = 0.5).

5

FIGURE 8







#### Exhaust: Return



Each simulation model's pressure coefficient profiles at the center (x/a = 0.5) along both the interior  $(C_{nint})$  and exterior  $(C_{next})$  skins are reported in Figure 9. The  $C_{next}$  profiles possess a similar positive magnitude,  $C_{next} \approx 0.9$ , amongst all four configurations with the *shingled* inlet creating multiple declining profiles at each inlet band and the *raised* configuration halting at z/h =0.25 since it is not full height. Both the *trench* and face inlet configurations follow a similar profile for both the inner and outer skins with slight shifts for near-ground peaks due to the vertical location of the openings. The interior skin profiles vary significantly depending on inlet configuration. The  $C_{p,int(RF)}$  profile for the *raised* configuration is considerably (approximately 40%) less than the  $C_{p,int(FF)}$  or  $C_{p,int(TF)}$  profiles for the face and trench inlets. Furthermore, the shingled interior skin  $C_{n int(SE)}$  increases in magnitude in a step-like manner as it rises up the building towards roof level. At the roof level where the interior skin has the *forward* exhaust, all four inner skins' C<sub>nin</sub> profiles converge around -1.0 to -1.2.

# FIGURE 9

 $C_n$  profiles at x/a = 0.50 for interior  $(C_{n,int})$  and exterior  $(C_{n,ert})$  skins.







The net pressure coefficient,  $C_{nnet}$  (or  $\Delta C_n =$  $C_{next}$  -  $C_{nint}$ ), is calculated across the outer skin for each of the twelve models at  $x/a = \{0.50, 0.67,$ 0.90} in Figure 10. The outer most profiles at x/a= 0.90 for all twelve configurations has the smallest magnitude (as compared to x/a = 0.50and 0.67) for z/h < 0.95. Above that (z/h > 0.95), the x/a = 0.90 profiles increase to be the greatest magnitude, indicative of increased loads in the upper corners. The overall greatest  $C_{nucl}$  values occur just above ground level for the trench- and face-forward configurations, nearing 2.0.

Further detail about each of the twelve analytical configurations' results are summarized in Chapter 9 of the dissertation (Vaglio, 2015).<sup>1</sup>

> FIGURE 10  $C_{n,net}$  profiles at  $x/a = \{0.50, 0.67,$ 0.90} for twelve simulations: *forward* exhaust (top); through exhaust (middle); and return exhaust (bottom);



#### RECOMMENDATIONS

#### DECIDE WHEN IN DESIGN TO CONDUCT WIND TUNNEL TESTS

The primary benefit of conducting a wind tunnel study for a building is that the results in design loads are more accurate than those derived from codes. In an academic sense, or to the structural engineer, this would be the preferred path for determination of wind loads. However, an owner or developer has to weigh the benefits compared to the associated costs of such a study. There is an up-front cost and the time required to conduct these studies, however, the wind loads produced from wind tunnel testing are often lower than those from code, resulting in a more efficient structural framing and glazing assembly. Occasionally, the wind tunnel results can produce loads greater than the building codes, requiring greater safety factors be accounted for in the engineered solution. In both instances, the owner is benefiting from either 1) reduced cost of materials in the enclosure assembly, or 2) mitigating risk and potential damage (as well as replacement) in the long-term performance of the enclosure. For these reasons, as well as the unique geometric and the potential for unusual response characteristics, it is suggested that buildings utilizing a multi-story DSF use wind tunnel testing for the determination of wind loading.

#### SELECT WIND TUNNEL FACILITY

Selecting a credible wind and climate consultant with boundary layer wind tunnel facilities and an established reputation is important. There are not many of these consultancies, so in practice, the field of wind engineering and environmental engineering is dominated by very few.

#### PERFORM SIMPLE GEOMETRY CALIBRATION

Performing a baseline test in the wind tunnel of a regular geometry, such as the Simple Cube.<sup>3</sup> can be used as an initial data set for a computa

#### Inner Skin Pressure (C<sub>n im</sub>)







tional fluid dynamic simulation to be calibrated to. If there is no correlation between wind tunnel and CFD for a simple geometry then there is no chance to develop confidence in the accuracy of the CFD analysis of the DSFs.

#### PRELIMINARY EVALUATIONS USING CFD

Following sufficient calibration of CFD modeling to the simple wind tunnel tests to be used in the final project-specific wind tunnel tests, simulations may be used to compare different configurations, whether they vary in geometry, airflow mode, or another manner. These evaluations are, at a minimum, qualitative comparisons, and in time could prove to have some level of quantitative accuracy. Above are two figures gualitatively comparing results from the twelve simulations conducted for multistory DSFs with varied airflow configurations.

#### RECALIBRATION OF SIMULATION MODEL TO WIND TUNNEL TESTING

The best way to close the gap between the findings of preliminary computational fluid dynamics simulations and the wind tunnel studies of the building configuration with a double-skin facade is to compare the two following the wind tunnel studies, refine the simulation model accordingly, and determine what modeling approaches require altering in future simulations to better emulate the actual wind tunnel's atmospheric boundary layer. In practice, this step is best suited for either the wind engineer or the facade consultant who intends to utilize the same atmospheric boundary layer wind tunnel for future project applications.

#### CONCLUSIONS

In this research, previous wind tunnel studies of multi-story double-skin facade configurations<sup>6,7</sup> were simulated in a CFD domain and showed reasonable agreeability of net pressure coefficient differences for two layouts. These were predecessor studies to a series of twelve multi-story double-skin facade configurations for a prototypical building geometry deduced from a review of built multi-story double-skin facades in the United States. The analytical models varied the airflow inlet and exhaust configurations at the top and bottom, respectively, of the building elevation.

#### DSF IN THE USA

- Double-skin facade applications in the United States are using multi-story configurations at a greater rate than those summarized globally by Perino  $(2007).^{8}$
- Double-skin facade applications in the United States are using the outdoor air curtain ventilation mode at a greater rate than those summarized globally by Perino (2007).8
- Double-skin facade applications in the United States are diverging in scale, gravitating either towards the multistory or box-window solutions.

#### CFD CALIBRATION OF WIND TUNNEL STUDIES

 Computational fluid dynamic models can be tuned to replicate wind tunnel conditions for steady-state analysis of impinging loads on multi-story doubleskin facades.

- characteristics. FOR MULTI-STORY DSFs
  - configurations.

 The greatest variation of multi-story double-skin facade configurations is the  $C_{\rm nim}$  profiles.

• Face and Trench inlet conditions exhibit similar  $C_n$  and the  $C_{nnet}$  profiles.

 Replication of a specific wind tunnel's turbulence characteristics in a computational fluid dynamics model requires special attention and iterative refinement, as these characteristics are unique to each wind tunnel and have a noticeable impact on the results produced from the simulation models.

 Computational fluid dynamics models should be used as a supplemental tool to wind tunnel testing to provide preand post-experimental insights into multi-story DSFs' pressure response

# PRESSURE COEFFICIENT DETERMINATION

 Building codes do not adequately address the determination of wind pressure coefficients for double-skin facades, particularly deeper cavity multistory DSFs and their possible airflow

• A multi-story double-skin facade's outer skin sees greater loads as compared to a single-skin, particularly near the building's edges and airflow openings.

 The airflow inlet configuration has a noticeable impact on the pressure coefficients of multi-story doubleskin facades, particularly the negative pressure on the inner skin within the cavity space.

- and Through Forward exhaust conditions exhibit similar  $C_{-}$  and the  $C_{\rm pure}$  profiles with slight variation near opening regions.
- Inlet conditions that elevate (Raised) or distribute the opening across the height (Shingled) exhibit a reduced magnitude of negative pressure in the cavity space through the lower and center portions of the height.
- Return exhaust configurations exhibit a positive  $C_{nint}$  profile, contrary to the other exhaust configurations that are negative.
- of • The positive  $C_{nim}$ the Return configurations reduces the corresponding  $C_{num}$  profiles.

# PERFORMANCE (CONTINUED)

### SIMULATION-BASED DETERMINATION OF PRESSURE COEFFICIENTS FOR MULTI-STORY DOUBLE-SKIN FACADES

- [0] This article is a reproduction of the research that comprised 1) a preliminary paper under the same title – delivered at the Advanced Building Skins 2015 conference at Graz University of Technology, and 2) the author's dissertation (Vaqlio, 2015).<sup>1</sup>
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# PROCESS

# THE SIGNIFICANCE OF THE WIREFRAME: A DISCUSSION OF COST DRIVERS FOR MODULAR CURTAINWALL CONSTRUCTION VISUAL STORYTELLING: SHOW DON'T TELL!

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