INFLUENCE OF ARCHITECTURAL FORM ON THE WIND-INDUCED RESPONSE OF TALL BUILDINGS

BY

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THESIS

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ABSTRACT

Architectural form of a tall building can be the most influential factor in its performance under the action of wind. Traditionally, tall building projects include early stage architectural design that is often decoupled from engineering considerations. When wind tunnel testing of a set architectural form reveals any undesirable behavior, it must be mitigated through engineering modifications. These modifications typically include addition of structural material or supplementary damping devices. Modern-day awareness of the potential environmental impacts of construction has caused emphasis to be placed on economically and materially efficient building design, prompting designers to utilize preexisting material in innovative ways. Intelligent design of architectural forms enables the shape of a tall building to be a part of the solution to its crosswind excitation problem rather than worsen its effect.

The phenomenon of vortex shedding is widely identified as the dominant cause of crosswind excitation in tall buildings. Reducing the coherence of vortex shedding along a building’s height, modifying separated shear layer structure, and stabilizing the near-wake region of a building have subsequently been identified as response mitigation techniques. Practically applicable aerodynamic treatments such as single- and double-vents, chamfering of corners, and addition of fins to a portion of the building were explored as a means to reduce crosswind excitation of a prismatic square building. In total, 43 architectural forms were tested at Skidmore, Owings & Merrill’s in-house boundary layer wind tunnel facility. The effect of freestream turbulence was also considered through the simulation of flows over both open and suburban terrain. An ‘influence zone’ was identified around 20-40% of the way down from the roof of prismatic square buildings. Optimal locations for single- and double-vents were determined
within this influence zone. Double-vent treatments, at any two locations along a building’s height, were typically observed to be more effective than a single vent placed at either of those locations. Incremental chamfering and addition of different corner fins were applied to the top half of prismatic square buildings. Effectiveness of aerodynamic treatments in reducing the crosswind response of prismatic square buildings was evaluated and potential full-scale impact was assessed.
ACKNOWLEDGEMENTS

I owe a debt of gratitude to several people for playing their part in my story so far. Special mention must be made for those few who were instrumental in this research becoming a reality:

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Next, I must highlight the contribution of Skidmore, Owings & Merrill, who generously funded this research. Thanks especially to Jim Pawlikowski for kickstarting this collaborative study and bringing me to SOM almost two years ago. Thanks also to Brad Young and Austin Devin for providing invaluable guidance in shaping this study and being incredibly patient with me for the past year. Onwards and upwards from here!

I recognize that I owe this and everything else I achieve to my family. My parents, Anuksha and Rajesh, and my sister, Ruchika, have all played influential roles in my life so far. Thank you for making me the person I am today.

And finally, a huge shout out to my colleagues at the Wind Engineering Research Laboratory at UIUC. Thank you for taking the time to provide constant encouragement and quality feedback throughout my time as a graduate student. Good luck to you all!
To my family
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CHAPTER 1: INTRODUCTION

The performance of a tall building under the action of wind can be greatly influenced by its architectural form. The core objective of this research was to determine the effectiveness of various aerodynamic treatments in reducing crosswind excitation of a prismatic square tall building. Background information on concepts that are essential to this research project and a detailed structure of content covered in this thesis are provided below.

1.1 Background and Organization

The traditional tall building design process includes early stage architectural design that is often decoupled from engineering considerations. In such a process, it may be necessary for the engineer to modify the structure to mitigate any undesirable effects that the building’s shape has on its wind-induced response. These response mitigation strategies typically comprise of stiffening the building through addition of structural material or introducing supplementary damping devices. The along-wind response is largely static in nature and is accounted for through the choice and design of an appropriate lateral system for the structure. The crosswind response, on the other hand, is dominated by dynamic effects that are dependent on several influencing factors including the architectural form of the building. With a set architectural form, control of a building’s motion under wind excitation requires adjusting the dynamic properties of the building. Often such response mitigation efforts take place at a later stage in the development of the design. Changes to the structure at such a time can be expensive, extremely disruptive to the programmatic requirements, or simply impossible. A greater understanding of the influence of architectural form on the wind-induced response of tall buildings is therefore essential in
avoiding situations where last-minute response mitigation strategies are required. Over the years, experimental data from wind tunnel laboratories has shed light upon several different types of aerodynamic treatments. Results from such research studies serve as experimental validation of shaping strategies that may be potentially implemented by tall building designers. It is important for researchers to continue augmenting the growing number of cataloged wind tunnel tests that compare different aerodynamic treatments and evaluate their effects on a building’s response to wind. Early integration of wind tunnel test results into the design process, through a review of published research, allows for designers to take advantage of a building’s interaction with fundamental fluid flow phenomena and optimize the design for enhanced performance under wind excitation.

When dealing with wind effects on a structure, engineers divide the structural response into drag, lift, and twisting components. Each classification is further subdivided into a static and dynamic portion that combine to form the structure’s peak response. The drag or along-wind response is a combination of static displacement caused by a mean drag force exerted by wind on a building and the dynamic action of freestream turbulence. International codes and standards have sufficiently dealt with along-wind dynamics through the gust factor approach (Davenport, 1967). Engineers are equipped with the knowledge of building stiffness and mass distribution, and understand relatively well how to resist base overturning moments generated from the along-wind response to wind loading. The dynamic response of lift, or crosswind excitation, is much more complicated and requires wind tunnel testing to accurately predict. Fluid-structure interaction is complex due to its stochastic nature and inherent variability. Phenomena such as vortex shedding, buffeting, galloping, and fluttering are all affected by approach flow conditions and in turn affect the dynamic response of the structure. A review of these phenomena and some
basic wind flow fundamentals are provided in Chapter 2. Twisting, or torsion, results from the spatial non-uniformity of incident wind loads on a building, or asymmetry in the building’s architectural shape or structural skeleton. Torsional effects compounded with the along- and across-wind dynamic response can result in increased building motions. Wind-induced torsional effects are accentuated by eccentricity in the center of mass or rigidity and through the coupling of various degrees of freedom. Hence, most structures aim to minimize torsional concerns through symmetric architectural forms and structural configurations.

Once any undesirable crosswind behavior has been identified and its source understood, the next step is to recognize ways in which it can be mitigated. Reducing the coherence of vortex shedding along a building’s height, modifying separated shear layer structure, and stabilizing the near-wake region of the building have all been previously explored as techniques to reduce wind-induced response. Such response-mitigation techniques, and commonly researched aerodynamic treatments that implement them like tapering, chamfering, and slotting are reviewed in Chapter 2.

All wind tunnel testing for this study was conducted at Skidmore, Owings & Merrill’s (SOM) wind tunnel facility in Chicago, IL. A calibration exercise was conducted to compare results from the SOM wind tunnel to an international benchmark established as a result of the 12th International Conference on Wind Engineering in Cairns, Australia (Holmes & Tse, 2014). The specifics of that exercise are discussed in Appendix B. After the calibration study was completed, two terrain types – open and suburban – were simulated in the SOM wind tunnel for this research study. These were used to assess the impact of flow turbulence on the effectiveness of any applied aerodynamic treatment studied. Established flow simulation criteria highlighted in literature are identified in Chapter 2 and simulation results are compared to published targets in
Chapter 3. Details of the SOM wind tunnel and overall experimental setup including a
description of all models tested are also presented in Chapter 3. All analysis results are shown in
Chapter 4. Concluding remarks and suggested future work are mentioned in Chapters 5 and 6
respectively. Finally, additional figures and tables of collected data can be found in Appendix A
while Appendices C and D contain important aspects of data processing techniques used in this
study.

1.2 Objectives and Novel Contribution

The objectives of this research were to:

1. Accurately simulate realistic wind environments in the wind tunnel
2. Understand fluid-structure interaction fundamentals
3. Experimentally verify the effectiveness of various aerodynamic treatments applied to
   a prismatic square building in reducing crosswind excitation

As reviewed in Chapter 2, aerodynamic treatments used to reduce crosswind excitation
have been researched previously. Corner modifications such as chamfering and addition of fins
(vanes), although previously explored (Gu & Quan, 2004; Kwok & Bailey, 1987; Tamura &
Miyagi, 1999), were now investigated further to determine the effect of incremental chamfering
applied to part of the building cross section. Fins were applied to corners at varying angles as
compared to the traditional guide vane-type orientation. Building openings and slots (Dutton &
Isyumov, 1990; Kwok, 1988; Miyashita, Katagiri, & Nakamura, 1993; Zdravkovich, 1981) were
additionally explored through the practical lens of vented, or blow-through, floors following the
successful implementation of such aerodynamic treatments in real-world projects (Kamin, 2017).
The ‘optimal’ location for placing a single vent along a building’s height was determined.
Dependence of single-vent treatment effectiveness on building slenderness and the value of adding a second vent were also evaluated as part of this research project.

The architectural forms studied as part of this research were specifically chosen as practical means to reduce crosswind excitations of tall buildings. Knowledge of fluid-structure interaction and response mitigation techniques was coupled with professional expertise provided by industry collaborators to narrow down a potentially never-ending list of possible architectural configurations that could reduce crosswind excitation. Opening of one or two vented spaces was considered a conceivable option for real-world tall building projects. Incremental chamfering was tested to evaluate the benefit of smoother corners without sacrificing leasable space at all stories of the building. Finally, fins at 45° were tested as a means of mimicking chamfering without the loss of space and fins at 90° were added as an irregular geometry.

Apart from the wanting to study realistic solutions to crosswind excitation problems, this research initiative was also motivated by the desire to provide an accessible report that aims to experimentally validate the effect of various architectural forms on crosswind excitation. The majority of wind-influenced architectural ideas implemented in real-world projects are tested in wind tunnels during the design process. However, such wind tunnel reports are not accessible to the public due to the confidential nature of tall building projects. This research aims to bridge the gap between project-based and scientific research – providing the reader with a quantitative idea of reduction in wind forces that may be attained through intelligent design.
CHAPTER 2: LITERATURE REVIEW

This chapter contains an overview of previously published works that serve to both inspire and guide the three objectives of this project – accurately simulating the atmospheric boundary layer (ABL) in a wind tunnel, understanding fundamental fluid flow phenomena, and exploring the effectiveness of various aerodynamic treatments at improving a building’s response to wind loading.

2.1 ABL Simulation in a Wind Tunnel

To achieve meaningful and scalable results through any simulation, it is important to accurately simulate conditions that are expected in reality. Generating atmospheric boundary layer flow in wind tunnels requires the use of flow augmentation devices such as spires, barrier fences, and 2-D or 3-D roughness elements that are arranged depending on desired terrain properties (Counihan, 1969). Simulation quality is also judged based on widely accepted ‘conditions for similarity’ criteria (Cermak, 1971, 1982; Cook, 1982; Counihan, 1975) that include the following:

- Mean velocity ($\bar{U}$) profile (and corresponding power law exponent)
- Longitudinal turbulence intensity ($I_{uu}$) profile
- Integral length scale ($L_u$)
- Spectra of longitudinal turbulence
- Surface roughness length ($z_0$)
- Tunnel blockage
• Minimum Reynolds number requirements (different for building model and roughness elements)

Trapezoidal or triangular spires are used to generate vortices and introduce large-scale turbulence to the flow inside a wind tunnel. Precise determination of spire geometry is based on the dimensions of the wind tunnel, available fetch length, and desired boundary layer thickness (Irwin, 1981). Spires also influence the attainable mean velocity of flow simulated in a wind tunnel. Surface roughness is another dominant factor on both turbulence intensity and mean velocity of wind flow (Davenport, 1971). Although the importance of terrain in shaping ABL profiles is widely known, laying out of roughness elements in wind tunnel ABL simulations still requires a trial-and-error approach guided by the researcher’s judgement. Published experimental wind tunnel simulations contain guidelines on selecting the shape, height, and density of roughness elements but case-specific fine tuning is almost always necessary (Burton, 2001; Gartshore & De Croos, 1977; Wooding, Bradley, & Marshall, 1973). Roughness element layouts are usually adjusted until satisfactory mean velocity and turbulence intensity profiles are obtained. In addition, layout specifics also determine flow simulation parameters including surface roughness, $z_0$, when they are calculated by morphometric (geometric) methods (Grimmond & Oke, 1999; Lettau, 1969).

Although the precise nature of the physical characteristics of ABL flow is still debated, it is generally agreed that the mean velocity distribution with height of full-scale ABL flow follows a power or log law. For the convenience of the reader, governing equations for these laws, along with variable definitions, are reproduced below.

**Power law formulation** (Davenport, 1960; Hellman, 1916):

$$
\bar{U}(z) = \bar{U}_{ref} \left( \frac{z}{z_{ref}} \right)^n
$$

(1)
where $\bar{U}_{ref}$ and $z_{ref}$ are the mean velocity and height at a fixed reference point (typically taken as model height for such simulations), $z$ denotes height above ground level, and $n$ is the power law exponent.

*Log law formulation* (Sutton, 1949):

$$\bar{U}(z) = \frac{u_*}{\kappa} \ln \left( \frac{z - d}{z_0} \right)$$

(2)

where $u_*$ is the shear velocity, $d$ is the zero-plane displacement height, $z_0$ is the surface roughness length, and $\kappa$ is von Kármán’s constant (typically assumed to be 0.4 for such simulations). This law has been previously assumed to be accurate only up to the height of the Atmospheric Surface Layer (ASL), which is approximately $0.10\delta$ (ASCE, 2012; Panofsky & Dutton, 1984). Gradient height, $\delta$, denotes the thickness (height) of the Atmospheric Boundary Layer (ABL). The log law formulation was further modified to improve its applicability to heights above the ASL:

*Log law formulation (modified)* (Deaves & Harris, 1978):

$$\bar{U}(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right) + a_1 \left( \frac{z}{h} \right) + a_2 \left( \frac{z}{h} \right)^2 + a_3 \left( \frac{z}{h} \right)^3 + a_4 \left( \frac{z}{h} \right)^4$$

(3)

where $a_1 \approx 5.75$, $a_2 = 1.87$, $a_3 = -1.33$ and $a_4 = 0.25$ are universal constants determined theoretically and $h$ is the height of the Planetary Boundary Layer (PBL). At the height of the PBL, mean wind speed is equal to the geostrophic wind speed implying that the Coriolis force and pressure gradient force are in equilibrium (Lettau, 1939). It is noted that although log law formulations are widely used in meteorological applications, most wind tunnel facilities, and international codes and standards utilize a power law to determine similarity of simulated profiles with theoretical ones (ASCE, 2012, 2017; Simiu & Yeo, 2019).
Turbulence intensity profiles are much harder to simulate as compared to mean velocity profiles. This is in part due to the nonlinear nature of wind turbulence and the use of statistical models to study turbulent behavior (Panofsky & Dutton, 1984). Simulation of turbulence in boundary layer wind tunnels requires artificial generation of freestream fluctuations. Spires and barriers, used as mixing devices, introduce large scale turbulence into the wind flow by mimicking the presence of a sufficiently long fetch length required for natural ABL development (Cermak, 1982; Cook, 1982). The layout and density of surface roughness further complicates turbulence generation through isolated-, wake-interference-, or skimming-type flow around individual elements (Grimmond & Oke, 1999). Very dense roughness elements essentially act as a large-scale obstruction, where individual elements begin to shelter one another causing skimming-type flow to occur. Sparsely spaced elements generate individual wakes that are isolated from those generated by surrounding obstructions. The flow regime in between these two extremes, termed wake-interference flow, is likely the most turbulent of the three (Grimmond & Oke, 1999).

Along with prescribing power law exponents for different exposures, ASCE provides a constant-exponent power law to describe longitudinal turbulence intensity profiles (ASCE, 2017). The power law is of the form:

$$I(z) = c \left(\frac{10}{z}\right)^{1/6}$$

(4)

where the coefficient $c$ is dependent on exposure category (0.30 for Exposure B and 0.20 for Exposure C). The constant power law exponent value of 0.167 is close to that used in describing mean velocity profiles over open terrain (Exposure C). Thus, this equation provides a realistic profile for Exposure C simulations but not for flows over rougher surfaces. The greater turbulence generated by built-up environments of suburban and urban terrains would decrease at
a faster rate with height as the influence of surface roughness diminishes. To judge simulation quality with respect to turbulence profiles, this study makes the imperfect assumption that fluctuation in the recorded velocity profile is independent of height – allowing both the mean velocity and longitudinal turbulence intensity profiles to have the same power law exponent (Zhou & Kareem, 2002). A similar approach has also been adopted by other international codes (CEN, 2005; National Standards Committee, 2012; NRCC, 2005) and can be seen in exponents tabulated in Table 2.1.

Table 2.1. Power law exponents for mean velocity & turbulence intensity profiles specified in international codes

<table>
<thead>
<tr>
<th>Code or Standard(a)</th>
<th>Open Terrain</th>
<th>Suburban Terrain</th>
<th>Urban Terrain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$U$ profile</td>
<td>$I_{uu}$ profile</td>
<td>$U$ profile</td>
</tr>
<tr>
<td>ASCE 7-16</td>
<td>0.15</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>GB 50009-2012</td>
<td>0.15</td>
<td></td>
<td>0.22</td>
</tr>
<tr>
<td>NBC 2005</td>
<td>0.14</td>
<td>0.25</td>
<td>0.36</td>
</tr>
</tbody>
</table>

(a) Eurocode (CEN, 2005) specifies a log law profile (exposure dependent) for $I_{uu}$ profiles

Power Spectral Densities (PSD) provide the distribution of energy as a function of frequency. For the practice of wind engineering, spectra help delineate the turbulent energy contained in the flow across various frequencies or eddy sizes (Panofsky & Dutton, 1984). Various types of spectra exist for the comparison of simulated longitudinal turbulence to observed or theoretical values. One of the most well-known wind spectra formulations is reproduced below.
Simplified von Kármán spectra (ASCE, 2012; von Kármán, 1948):

\[
\frac{fS_u(z, f)}{\sigma_u^2} = \frac{4 \frac{f^x L_u}{U}}{\left[ 1 + 70.8 \left( \frac{f^x L_u}{U} \right)^2 \right]^{\frac{5}{6}}}
\]

where \( fS_u(z, f) \) is the PSD normalized by variance of the longitudinal velocity, \( \sigma_u^2 \). This formulation requires estimation of the integral length scale, \( ^xL_u \), from the determined surface roughness length, \( z_0 \) (Counihan, 1975). Note that \( f \) denotes frequency in hertz.

Roughness length, \( z_0 \), is another important descriptor of simulation similarity to actual flow. The value of roughness length is indicative of turbulent eddy size at the surface (Panofsky & Dutton, 1984). Roughness lengths for various terrain types were identified by several researchers (Cook, 1986; Davenport, 1960; Oke, 1978) and have been adjusted and compiled (Wieringa, 1993) into a widely-accepted list shown in Table 2.2.

Table 2.2. Roughness lengths for homogeneous terrain (ASCE, 2012)

<table>
<thead>
<tr>
<th>Surface type</th>
<th>( z_0 ) (m)</th>
<th>ASCE Class</th>
<th>ASCE Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open sea</td>
<td>~0.0002</td>
<td>1</td>
<td>D</td>
</tr>
<tr>
<td>Mud flats</td>
<td>0.005</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Open terrain</td>
<td>0.03</td>
<td>3</td>
<td>C</td>
</tr>
<tr>
<td>Low crops</td>
<td>0.10</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>High crops</td>
<td>0.25</td>
<td>5</td>
<td>B</td>
</tr>
<tr>
<td>Parkland or bushes</td>
<td>0.50</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Dense low buildings</td>
<td>1.0-2.0</td>
<td>7</td>
<td>A</td>
</tr>
<tr>
<td>City center</td>
<td>&gt; 2</td>
<td>8</td>
<td>-</td>
</tr>
</tbody>
</table>

The estimation of surface roughness for wind tunnel simulations can be made using either of two approaches – morphometric or anemometric. The morphometric approach depends on the size, shape, density and distribution of surface roughness elements (Grimmond & Oke, 1999). The earliest formulation of estimating surface roughness from roughness element geometry
distributed in regular arrays, provided in Eq. (6), was developed for homogeneous element layouts (Lettau, 1969):

\[ z_0 = 0.5 H_{ob} \frac{S_{ob}}{A_{ob}} \]  

(6)

where \( H_{ob} \) is the average effective obstacle height, \( S_{ob} \) is the average silhouette (vertical frontal) area of an obstacle, and \( A_{ob} \) is the average area (in plan) occupied by an obstacle including the area surrounding it. Additional information about these variables is provided in Chapter 3. A similar formulation was applied to layouts created using LEGO blocks with additional tests accounting for changes in element density (Counihan, 1971). This formulation was later modified to account for the nonlinear decrease of roughness due to higher roughness element densities (MacDonald, Griffiths, & Hall, 1998) that led to defining flow regimes based on element density into isolated-, wake-interference, and skimming-type flows described earlier in this section. The anemometric approach uses velocity measurements made at multiple heights within the ASL along with the assumption of a log law profile described in Eq. (2) earlier. This method can result in large errors in roughness length estimation if slight errors are present in velocity measurements (Simiu & Yeo, 2019) especially when the zero-plane displacement height, \( d \), is large (Panofsky & Dutton, 1984).

Approach flow can be classified as laminar or turbulent based on its Reynolds number, which is a measure of the ratio between inertial and viscous forces:

\[ Re = \frac{\rho UL}{\mu} \]  

(7)

where \( \rho \) and \( \mu \) are the density and dynamic viscosity of a particular fluid respectively, and \( L \) is a characteristic dimension (typically transverse side dimension of a bluff body in flow). To maintain exact dynamic similarity between full-scale and simulated flows, it would be ideal to
match Re values to ensure similar vortex shedding and, hence, crosswind behavior (Cermak, 1981). However, due to the high fluid density, extremely fast simulation velocities, or unfeasibly large model sizes required to match Reynolds numbers of wind tunnel simulations to full-scale flows it was deemed sufficient to meet minimum thresholds instead (Cermak, 1971). Minimum Re criteria exist for both the model and roughness element scales used in the simulation (ASCE, 2012):

\[
\frac{\rho u^* z_0}{\mu} \geq 2.5 \quad (8a)
\]

**Roughness element Re criterion** (Schlichting, 1979):

\[
\frac{\rho U L}{\mu} \geq 1.1 \times 10^4 \quad (8b)
\]

Note that the roughness element criterion uses a modified Re equation with shear velocity, \(u^*_\), and roughness length, \(z_0\) (both at model scale).

Flows simulated in the SOM wind tunnel for this research were checked for adequate similarity using the criteria reviewed in this section. This comparison is provided in Chapter 3.

### 2.2 Fundamental Fluid Flow Phenomena

When a fluid stream approaches a bluff body, flow separation occurs at the windward edges of the body. These separated shear layers circulate in the form of vortices along the sides of the body, creating a wake of turbulent air behind it. The vortex formation process and wake region width are dependent on both the geometry of the bluff body (Scruton & Flint, 1964) and the approach flow conditions, i.e. if the flow is laminar or turbulent. Vortices formed along the sides of the body grow stronger as more air is entrained within their vorticity, eventually drawing
vortices from the opposite side across the near-wake (Bearman, 1984; Gerrard, 1966). As vortices continue to strengthen and engulf those from opposite sides of the body, a stable configuration of vortex shedding begins from alternating sides of the body. When the body is flexible, as is the case for tall buildings, this phenomenon of vortex shedding induces dynamic oscillations in the direction normal to the incident wind (Bearman, 1984; Scruton & Flint, 1964). This crosswind excitation of tall buildings could possibly result in safety and occupant comfort-related concerns.

Increasing turbulence in the freestream flow has been shown to reduce flow separation and promote quicker reattachment of separated shear layers, thus impairing the organized shedding of vortices and reducing wake excitations (Laneville, Gartshore, & Parkinson, 1975; Nakamura & Ozono, 1987). While this effect requires a sufficiently long projection, termed afterbody, of the body behind its windward face, turbulent flow also distorts separated shear layer structure causing an overall reduction in the crosswind excitation of most bluff bodies. Although still affected by freestream turbulence, characteristics of vortices shed from sharp-edged bluff bodies, such as prismatic square buildings, are typically not as strongly dependent on flow conditions due to the fixed nature of flow separation points concentrated at the sharp edges (ASCE Task Committee, 1961; Cermak, 1971; Scruton & Flint, 1964).

Another important descriptor of wake excitation characteristics is the frequency of vortex shedding or Strouhal number (in reduced form):

\[
St = \frac{f_0 B}{U}
\]

where \( f_0 \) is the frequency of vortex shedding and \( B \) is the across-wind dimension of the building. Reduced frequency is the inverse of reduced velocity, meaning higher Strouhal numbers correspond to lower critical velocities that can cause vortices to shed at their natural frequency.
When a building’s natural frequency is equal to the vortex shedding frequency, resonant oscillations can occur. Close alignment between the vortex shedding frequency and a building’s natural frequency results in the phenomenon of ‘lock-in’, which increases the range of critical velocities that can cause a structure to resonate (Bearman & Davies, 1975). The phenomenon of vortex shedding is portrayed, on vastly different scales, in Figure 2.1.

Buffeting occurs due to the presence of wind gusts, or turbulence, within the freestream and affects both the along- and across-wind response of a building. In terms of a building’s along-wind response, buffeting affects pressure distributions on the windward and leeward faces of a bluff body that in-turn alter drag dynamics. Designers of tall buildings account for buffeting effects on along-wind loads through the gust factor approach (Davenport, 1967). The crosswind response, largely resulting from the phenomena of vortex shedding, is also affected by buffeting as it alters the structure of freestream flow. Buffeting effects on tall buildings can be amplified due to the fluid flow interference from other structures in the vicinity, also known as proximity effects (Bailey & Kwok, 1985). Such effects have been characterized using buffeting factors to judge the impact of different configurations of upwind buildings (Saunders & Melbourne, 1979).

A third type of wind forcing mechanism can be attributed to the aerodynamic instability of a structure’s response to wind loading. Such unstable behavior, like galloping and fluttering, requires consideration of a structure’s dynamic properties to fully understand. While of importance to long-span and cable-stayed structures such as bridges, these effects are often not a factor in tall building design.
2.3 Aerodynamic Treatments & Fluid-Structure Interaction

The advancement in structural engineering and architectural practice along with rising urban population, improved economic feasibility, and aspirational client demand has led designers to build taller buildings over time. Oscillation-type responses of tall buildings to wind excitation were traditionally mitigated through increased stiffness achieved either by adding
structural material or introducing supplementary damping devices. With a greater awareness of the potential environmental impact of construction activities, emphasis in the modern day has been placed on economically and materially efficient building design. This has prompted designers to utilize preexisting material in innovative ways, in-turn encouraging researchers to study the impact of a building’s form on its response to wind excitation. Organized periodic shedding of vortices is the most dominant factor causing crosswind building oscillations. Hence, researchers have thoroughly investigated aerodynamic modifications to buildings that disrupt the phenomenon of vortex shedding in order to mitigate crosswind excitations. ‘Major’ modifications covered in literature include shaping strategies such as tapering, twisting, and addition of setbacks. ‘Minor’ modifications include introduction of openings and application of localized modifications like chamfering and recessing of corners (Sharma, Mittal, & Gairola, 2018).

Reducing the correlation of vortices shed along a building’s height spreads the energy present in vortices over a larger bandwidth, instead of concentrating it around the Strouhal number. Most major modifications aim to implement this response mitigation technique – reducing vortex shedding coherence with height. Tapering of buildings has been found to be more effective in reducing crosswind excitations in less turbulent approach flows (Y. M. Kim & You, 2002). Tapering also affects the along-wind response of a building by altering leeward face pressure distribution as compared to a prismatic square building (Y. C. Kim & Kanda, 2010). Further research included the effects of mass and stiffness eccentricity on the dynamic response of a building with setbacks (Y. C. Kim, Kanda, & Tamura, 2011). Such wind-influenced shaping of a building’s main architectural form has also been successfully implemented in real world projects such as the Burj Khalifa in Dubai, UAE (Baker, Pawlikowski, & Young, 2009) and the
CTF Finance Centre in Tianjin, China (Lee, Baker, Rhee, & Johnson, 2016). Photographs of these prominent tall buildings are provided in Figures 2.2 and 2.3.

Figure 2.2. The Burj Khalifa, pictured in downtown Dubai, was designed to “confuse the wind” (Nick Merrick © Hedrich Blessing, image compliments of SOM)
Figure 2.3. The tapering and streamline form of the CTF Finance Centre in Tianjin, China
(© Tim Griffith, image compliments of SOM)
Another way to influence the vortex shedding phenomenon around a typically bluff building form is to alter separated shear layer behavior around the windward and leeward edges of a building. This technique is best adopted through the use of corner modifications that directly affect separation points in the flow. Early wind tunnel test data exploring slotting of corners and vertical fins (guide vanes) is available for aeroelastic models tested in an open terrain (Kwok & Bailey, 1987). Fins protruded out along the building diagonal in the form of guide vanes from the corners of a prismatic square building. Additionally, models with gaps between the fins and building corners were also considered. Apart from increasing the drag response of the building tested, such fins were found to not alter or disrupt the formation of vortices. Instead, an increase in critical velocities (reduction in Strouhal number) was observed, altering the flow conditions needed to potentially trigger a resonant response in the modified building. The introduction of slots was found to be a more effective way to disrupt organized vortex shedding. This study explores addition of fins to sharp corners at angles different from the traditional guide vane orientation.

Chamfering of corners promotes both a reduction in flow separation at the windward edges and an increase in flow reattachment around the leeward edges of a bluff body. As a relatively simple corner modification, chamfering has long been a commonly tested aerodynamic treatment applied to square building cross sections. A chamfer of around 10% appears to provide maximum crosswind response reduction, while that of approximately 20% begins to show Strouhal number changes due to the octagonal shape of the modified cross section (Gu & Quan, 2004). Corner modifications such as chamfering and rounding also result in a reduction of wake region width. Wake region width reduction is further facilitated by more turbulent approach flows that promote increased reattachment of the separated shear layers. The effects of flow
turbulence on vortex shedding and wake excitations are well documented for prismatic buildings with both sharp (Laneville et al., 1975) and modified (Tamura & Miyagi, 1999) corners. Dependence of chamfering treatment effectiveness on the incident wind angle of attack has also been evaluated (Miyashita et al., 1993). This study investigates chamfering of corners as applied incrementally to different portions of a prismatic square building.

Near-wake stabilization techniques have also been investigated as an effective way to reduce vortex shedding excitations (Zdravkovich, 1981). The main difference in the way such aerodynamic treatments impact crosswind response, as compared to separated shear layer modifiers like chamfering and other corner modifications, is that they affect the interaction of vortices at the confluence point in the wake of the building. Openings in the building allow positive pressures to vent through the building, alleviating negative pressures acting on the side and leeward faces (Dutton & Isyumov, 1990). This study adopts such a pressure bleeding technique through the use of vented, or blow-through, floors and evaluates the impact of vent location along the building’s height. It is interesting to note that although covered minimally in research (Kwok, 1988), vented floors have been effectively employed in tall building construction in New York’s 432 Park Avenue and Chicago’s Vista Tower (Kamin, 2017). The super-slender 432 Park Avenue is pictured in Figure 2.4.
Various unconventional building forms have also been evaluated as ways to mitigate excessive crosswind excitation in tall buildings. Emphasis has been placed on cross-sectional variation with height and the impact of wind climate on the effectiveness of a given modification. Helical twists, in particular, were noted for their effectiveness being essentially independent of the incident wind direction (Tanaka, Tamura, Ohtake, Nakai, & Kim, 2012). Many of the studies discussed here, among several others, have been recently summarized for comparison purposes (Sharma et al., 2018).
CHAPTER 3: EXPERIMENTAL SETUP

Details about the experimental setup are provided in this chapter. Specifics about the wind tunnel, flow simulations, model fabrication, and overall experimental methodology of research are included.

3.1 Wind Tunnel and Flow Simulation Specifics

All testing for this study took place at SOM’s open-circuit boundary layer wind tunnel facility in Chicago, IL. A schematic view of the tunnel shown in Figure 3.1 provides information about the layout of the tunnel including relative location of flow augmentation devices, surface roughness elements, and the model test section.

![Figure 3.1. Schematic view of the SOM boundary layer wind tunnel](© SOM)

The rectangular tunnel cross section is 1.4 m (55 in) tall by 1 m (40 in) wide, allowing for various scales of tall building models to be tested without requiring blockage corrections. A fetch length of roughly 5.5 m (18 ft) is available between the spires and test section, classifying the
tunnel as a short boundary layer wind tunnel (Cermak, 1981). Tunnel dimensions are shown in Figure 3.2.

Two flow simulations, suburban and open, were developed for this study in line with ASCE classifications of Exposure B and Exposure C (ASCE, 2012, 2017). Exposure C (open) terrain conditions were replicated through the use of trapezoidal spires and an evenly smooth floor surface made up of LEGO base mats shown in Figure 3.3(a). Spires used have a base width of 0.23 m (9”) that tapers to a width of 0.09 m (3.5”) at the top. Two full-height (55”) spires spaced at 0.43 m (17”) on center were required to generate open terrain flow simulations in the SOM wind tunnel. Additional turbulence required to simulate the suburban conditions of Exposure B was generated with roughness elements laid out using a morphometric approach (Grimmond & Oke, 1999). More details of the roughness element layout configuration and methodology used to achieve desired turbulence for suburban terrain simulations are presented in the next section. Photographs of the wind tunnel for both terrain simulations are shown in Figure
3.3. Mean velocity and longitudinal turbulence intensity profiles, normalized to reference values measured at building height, are shown in Figure 3.4.

![Wind tunnel layout for open terrain flow simulation](image)

(a) Wind tunnel layout for open terrain flow simulation

![Wind tunnel layout for suburban terrain flow simulation](image)

(b) Wind tunnel layout for suburban terrain flow simulation

**Figure 3.3.** Photographs of tunnel configurations for different terrain simulations
Figure 3.4. Mean velocity and longitudinal turbulence intensity profiles for simulated flow over open (left) and suburban (right) terrain
In addition to matching mean velocity and turbulence intensity profiles, other flow similarity criteria described earlier (see Section 2.1) were evaluated for simulated profiles and compared to values provided in published literature. This comparison is presented in Table 3.1 below.

Table 3.1. Flow similarity comparison between simulated flow and ASCE provisions (ASCE, 2012, 2017)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Open Simulation</th>
<th>Exposure C (ASCE 49-12)</th>
<th>Exposure C (ASCE 7-16)</th>
<th>Suburban Simulation</th>
<th>Exposure B (ASCE 49-12)</th>
<th>Exposure B (ASCE 7-16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$ (a)</td>
<td>0.13</td>
<td>0.14</td>
<td>0.15</td>
<td>0.20</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>$xL_u$ (m) (b)</td>
<td>116</td>
<td>110</td>
<td>152</td>
<td>82.9</td>
<td>64</td>
<td>98</td>
</tr>
<tr>
<td>$z_0$ (m) (c)</td>
<td>0.067</td>
<td>0.03</td>
<td>0.02</td>
<td>0.28</td>
<td>0.25</td>
<td>0.30</td>
</tr>
</tbody>
</table>

(a) Mean hourly power law exponent
(b) Integral length scale at 10 m (33 ft) height (full scale)
(c) Roughness length calculated differently for suburban and open terrain

The use of a uniformly smooth surface to simulate open terrain in the wind tunnel did not permit the utilization of Eq. (6) (morphometric approach) to determine surface roughness. Instead, multiple velocity measurements within the simulated ASL were used with the log law formulation provided in Eq. (2) to determine surface roughness values (anemometric approach) shown in Table 3.1.

Finally, turbulence spectra were compared to von Kármán’s spectral density model in Figure 3.5 to demonstrate similarity in flow structure. Spectra used in the comparison were obtained from a velocity record, $U_{ref}$, measured at model height, $z_{ref}$. Note that no smoothing was applied to the spectra obtained from wind tunnel measurements.
Figure 3.5. Longitudinal turbulence spectra similarity for different terrain simulations
3.2 Development of Surface Roughness

The SOM wind tunnel was already equipped with spires to accurately simulate flow over open terrain conditions at a geometric scale of 1:700. These spires, described in the previous section, can be seen in the background of tunnel photographs shown in Figure 3.3. In order to investigate the effects of freestream turbulence on aerodynamic treatment effectiveness, a suburban terrain was specially developed as part of this research. A morphometric approach was used to determine appropriate spacing of roughness elements in the wind tunnel. Standard 2x4 peg LEGO blocks were used on a LEGO base mat to mimic a variety of surface roughness conditions. Figure 3.6 shows a schematic view of roughness blocks in the tunnel, indicating both relevant spacing parameters and element dimension variables. Variables shown were used in conjunction with Eq. (6) to determine the surface roughness for each layout tested. A summary of all roughness element layouts tested is provided in Table 3.2. Each roughness layout configuration tested was named with the following naming convention – X-\(\gamma\)-Y, where ‘X’ could be ‘R’ or ‘S’, indicating a rectangular or square element layout, ‘\(\gamma\)’ indicates how high the blocks were stacked (for example, \(\gamma = 3\) would indicate \(3H_{ob}\) high blocks with \(H_{ob}\) being the height of a standard LEGO block), and lastly, ‘Y’ was either ‘a’ or ‘c’ and indicated whether an in-line (a) or staggered (c) grid was used. Visual description of the types of grid layouts used are also shown in Figure 3.6.
Table 3.2. Summary of different surface roughness configurations tested

<table>
<thead>
<tr>
<th>Layout</th>
<th>Grid Type</th>
<th>Aspect Ratio</th>
<th>$B_{ob}$ (in)</th>
<th>$L_{ob}$ (in)</th>
<th>$H_{ob}$ (in)</th>
<th>$D_{ob}$ (in)</th>
<th>$D_{ob}/H_{ob}$ Ratio</th>
<th>$z_0$ (m)</th>
<th>$n$ (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1a</td>
<td>In-line</td>
<td>2:1</td>
<td>1.25</td>
<td>0.625</td>
<td>0.4 (1H)</td>
<td>5</td>
<td>12.5</td>
<td>0.071</td>
<td></td>
</tr>
<tr>
<td>R2a</td>
<td>In-line</td>
<td>2:1</td>
<td>1.25</td>
<td>0.625</td>
<td>0.8 (2H)</td>
<td>5</td>
<td>6.25</td>
<td>0.285</td>
<td>0.19</td>
</tr>
<tr>
<td>R2c</td>
<td>Stag.</td>
<td>2:1</td>
<td>1.25</td>
<td>0.625</td>
<td>0.8 (2H)</td>
<td>5</td>
<td>6.25</td>
<td>0.285</td>
<td>0.20</td>
</tr>
<tr>
<td>R3a</td>
<td>In-line</td>
<td>2:1</td>
<td>1.25</td>
<td>0.625</td>
<td>1.2 (3H)</td>
<td>5</td>
<td>4.17</td>
<td>0.640</td>
<td>0.23</td>
</tr>
<tr>
<td>R3c</td>
<td>Stag.</td>
<td>2:1</td>
<td>1.25</td>
<td>0.625</td>
<td>1.2 (3H)</td>
<td>5</td>
<td>4.17</td>
<td>0.640</td>
<td>0.25</td>
</tr>
<tr>
<td>S3c</td>
<td>Stag.</td>
<td>1:1</td>
<td>1.25</td>
<td>1.25</td>
<td>1.2 (3H)</td>
<td>5</td>
<td>4.17</td>
<td>0.640</td>
<td></td>
</tr>
<tr>
<td>R4a</td>
<td>In-line</td>
<td>2:1</td>
<td>1.25</td>
<td>0.625</td>
<td>1.6 (4H)</td>
<td>5</td>
<td>3.13</td>
<td>1.138</td>
<td></td>
</tr>
<tr>
<td>R4c</td>
<td>Stag.</td>
<td>2:1</td>
<td>1.25</td>
<td>0.625</td>
<td>1.6 (4H)</td>
<td>5</td>
<td>3.13</td>
<td>1.138</td>
<td></td>
</tr>
</tbody>
</table>

(a) $z_0$ calculated per morphometric approach using Eq. (6). Note that $A_{ob}$ has been highlighted in Figure 3.6 above and $S_{ob} = B_{ob} \times H_{ob}$

(b) mean hourly power law exponents were not calculated for layouts resulting in poor flow simulation similarity to ASCE Exposure B (ASCE, 2012; ASCE, 2017)

It is important to note that fewer velocity measurements were made for layouts showing poor similarity to desired parameters. Power law exponents resulting from such roughness element layouts are therefore not provided to due to difference in resolution of the various profiles. The roughness element layout specified in R2c was eventually determined to be the best overall simulation for ASCE Exposure B (ASCE, 2012; ASCE, 2017) and was chosen as the configuration for ‘suburban’ terrain in this study. Model-scale Reynolds number for the suburban
roughness element layout (R2c) was 10.15 which is greater than the minimum limit prescribed in Eq. (8a). Key takeaways from tests conducted to accurately simulate suburban flow were:

- Switching from an in-line grid to a staggered one had only a slight effect on simulated mean wind speed and longitudinal turbulence intensity profiles.
- Roughness elements alone cannot increase turbulence for the entire height of the simulated boundary layer. Depending on wind tunnel height and model scale, spires need to be modified to achieve desired turbulence intensity at model heights.
- Square elements (in plan) were found to reduce the turbulence generated at lower heights.

### 3.3 Models Tested

This study employed the well-developed High Frequency Force Balance (HFFB) method (Tschanz & Davenport, 1983). Lightweight models were fabricated using special high-stiffness industrial-grade ROHACELL® 71 foam. Model faces were cut on a Computer Numerical Control (CNC) mill and joined to create different architectural forms. This ensured that while exact architectural forms could be modeled on the outside, model weight was minimized as they were kept hollow. All models were tested on a six degree-of-freedom force balance to determine wind-induced base overturning moments acting on the structure. The use of the HFFB method concentrates primarily on the architectural form of buildings tested while dynamic properties of the structure itself are considered analytically via post-processing of experimental data. Wind-induced motion effects such as higher mode contributions to the structural response and aerodynamic damping are typically not considered in the HFFB method (Kareem & Gurley, 1996) and are therefore out of the scope of this study.
A total of 43 tall building architectural forms (3 baseline + 40 with aerodynamic treatments) were tested in both open and suburban terrain to understand the impact of each aerodynamic treatment and its effectiveness in different flow environments. All 43 building configurations are shown in Table 3.3 with dimensions and additional details provided in Table 3.4. Models were fabricated at a 1:700 geometric scale that not only enabled proper velocity, time, and frequency scaling of full-scale parameters (see Appendix C) but also ensured that blockage values were kept to below 5% per ASCE guidelines (ASCE, 2012). Model height, H, remained constant for all 43 schemes with a full-scale value of 410 m (1344 ft). All reference measurements were made at a consistent height inside the wind tunnel which equaled the height of all models tested. Three slenderness ratios of 7:1, 8.5:1, and 10:1 corresponding to full-scale base widths of 58.5 m (192 ft), 48 m (158 ft), and 41 m (134 ft) respectively were tested as part of this study. Each model was tested for a single wind angle of attack – incident wind perpendicular to side dimension of square models. This orientation is shown in Figure 3.7. On a model scale, the Reynolds numbers for 7:1, 8.5:1, and 10:1 slenderness baseline models were $3.89 \times 10^4$, $3.19 \times 10^4$, and $2.72 \times 10^4$ respectively. Note that these are all greater than the minimum limit prescribed in Eq. (8b). A modification length, L (in terms of building height), was used to describe the location where a certain aerodynamic treatment was applied to create a distinct architectural form. Modification lengths describing various architectural forms are indicated in Table 3.4
<table>
<thead>
<tr>
<th>SLENDERNESS RATIO</th>
<th>MODELS TESTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:1</td>
<td></td>
</tr>
<tr>
<td>8.5:1</td>
<td></td>
</tr>
<tr>
<td>10:1</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.3. Matrix of all models tested*
Figure 3.7. Typical model orientation and wind angle of attack

For vented models, L indicated the distance from roof height to the bottom of the vent and could range from 0.1H to 0.6H. Models of 7:1, 8.5:1, and 10:1 were all tested with single-vent openings. Additionally, 8.5:1 models were also tested with all double-vent configurations shown in Table 3.3. All vents were kept at a constant height of 12 m (40 ft). Vented floors contained solid obstructions to wind flow in the form of a core and perimeter columns. The core covered 25% of the floor area, while all 8 perimeter columns were 2 m x 2 m (7 ft x 7 ft) square.

Chamfering was applied to 16.7% of the building width at building corners. Only 8.5:1 slenderness models were tested with various chamfer configurations – L values ranged between 0.1H and 0.5H that defined the portion of building height that was chamfered.

The 8.5:1 slenderness models were also tested with the addition of fins to sharp corners. Fins were applied at an angle of 45° (analogous to chamfers) and 90° as measured from the building side. Both finned configurations were created by attaching fins to the top half of the 8.5:1 baseline prismatic square building. Fins applied were 1.2 m (4 ft) thick and extended a length, \( B_f \), equal to 3.5 m (11.5 ft) out from the building corners.
Table 3.4. Detailed description of aerodynamic treatment types tested

<table>
<thead>
<tr>
<th>Treatment Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Baseline</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Single Vented</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>0.5 B</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Double Vented</td>
<td>L1</td>
</tr>
<tr>
<td></td>
<td>L2</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>0.5 B</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Chamfered</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>B/6</td>
</tr>
<tr>
<td>Finned</td>
<td>0.5H</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
</tbody>
</table>
Full-scale moment calculations require estimation of dynamic properties applicable to actual buildings. The fundamental period, $T_0$, (inverse of natural frequency) for two sway modes and the critical damping ratio, $\zeta$, were assumed for full-scale buildings of the different slenderness ratios tested. These values are provided along with other full-scale building dimensions in Table 3.5 below. These dynamic properties are utilized in the calculation of full-scale peak crosswind moments discussed in the next chapter.

### Table 3.5. Full-scale parameters for baseline prismatic square buildings

<table>
<thead>
<tr>
<th>Slenderness Ratio</th>
<th>H (m)</th>
<th>B (m)</th>
<th>$T_0$ (sec)</th>
<th>$\zeta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:1</td>
<td>410</td>
<td>58.5</td>
<td>8.5</td>
<td>2</td>
</tr>
<tr>
<td>8.5:1</td>
<td>410</td>
<td>48</td>
<td>9.0</td>
<td>2</td>
</tr>
<tr>
<td>10:1</td>
<td>410</td>
<td>41</td>
<td>9.5</td>
<td>2</td>
</tr>
</tbody>
</table>
CHAPTER 4: ANALYSIS OF ARCHITECTURAL FORMS

In order to thoroughly investigate the wind-induced response of all architectural forms tested, it was important to establish some comparison criteria. The primarily dynamic response of crosswind excitation was therefore broken up into three criteria to facilitate meaningful comparisons between model results:

- Crosswind response spectra
- Crosswind dynamic moment coefficients
- Peak crosswind moments (full-scale)

Crosswind response spectra provide a measure of the strength of vortex shedding oscillation that can occur at critical reduced velocities. Prismatic square buildings have a Strouhal number of about 0.1 (Steckley, 1989) that corresponds to a critical reduced velocity value of 10. Aerodynamic treatments can potentially cause a reduction of peak energy of vortex shedding, widening of the response bandwidth, or changing of the Strouhal number. Any or all of these effects could be useful for response mitigation depending on the wind climate of a particular proposed building.

Crosswind dynamic overturning moments, $\vec{M}$, represent the fluctuating component of the moment response measured in the wind tunnel. These moment values are nondimensionalized into dynamic moment coefficients, $C_{\vec{M}}$, per Eq. (10) below:

$$C_{\vec{M}} = \frac{\vec{M}}{\frac{1}{2} \rho \bar{U}_H^2 BH^2}$$  \hspace{1cm} (10)

The denominator is comprised of model dimensions, and the dynamic pressure exerted by incident flow, $\frac{1}{2} \rho \bar{U}_H^2$, where $\rho$ is the density of air and $\bar{U}_H$ is the mean velocity in the tunnel at
model height. Note that static moment coefficients can be similarly calculated by normalizing the
mean value of the measured moment response, $\vec{M}$. Separate from the spectral response,
crosswind dynamic moment coefficients provide a measure of the effectiveness of a given
aerodynamic treatment in reducing the crosswind response of a building. To facilitate
comparison between various aerodynamic treatments, crosswind dynamic moment coefficients
were normalized to those obtained from baseline square models as follows:

$$\text{Normalized } C_{\bar{M}} = \frac{C_{\bar{M}}}{C_{\bar{M}_0}}$$

(11)

where $C_{\bar{M}}$ is the crosswind dynamic moment coefficient for any architectural form calculated per
Eq. (10) and $C_{\bar{M}_0}$ is the crosswind dynamic moment coefficient obtained from a baseline
prismatic square model of identical slenderness.

Next, it is useful to compare the quantitative change in design forces that may be realized
due to certain aerodynamic treatments. For this reason, full-scale peak moments were calculated
in the crosswind direction by combining the static and dynamic overturning moments, along with
the spectral component of the dynamic response (Tschanz & Davenport, 1983):

$$\bar{M} = |\bar{M}| + g \bar{M} \sqrt{1 + \frac{\pi}{4} \left( \frac{f_s S_M(f_s)}{\sigma_{\bar{M}}^2} \right) \frac{1}{\zeta}}$$

(12)

where $\bar{M}$ and $\bar{M}$ are the full-scale static and dynamic moments obtained from scaling the
response measured in the wind tunnel, $g$ is the peak factor (Davenport, 1967) typically taken as
3.75 for such simulations, $\zeta$ is the critical damping ratio, and $\left( \frac{f_s S_M(f_s)}{\sigma_{\bar{M}}^2} \right)$ is the spectral component
corresponding to a frequency $f_s$ that depends on the full-scale velocity, $V_h$, building width, and
building natural frequency, $f_0 = \frac{1}{T_0}$. This equation is better grasped by breaking down the
dynamic contribution into its background, $g\tilde{M}$, and resonant, $g\tilde{M} \sqrt{\frac{\pi}{4} \left( \frac{f_{s}S_{M}(f_{s})}{\sigma_{M}^{2}} \right) \frac{1}{\zeta}}$, components.

The background component is dependent solely on model geometry and wind tunnel simulation while the resonant component scales the measured response with respect to estimated dynamic properties of the full-scale building. Comparing peak moments for various architectural forms tested indicates that the effectiveness of a given aerodynamic treatment is strongly dependent on wind climate. This dependence is due to the impact wind climate has on the dynamic moment response of the building. As seen in crosswind response spectra, the magnitude of a building’s response is dependent on the reduced velocity of incident wind. Therefore, an aerodynamic treatment might be more or less effective depending on the location of the proposed building project. Note that full-scale peak moments were also normalized to square baseline model results per a similar procedure to that outlined in Eq. (11).

The rest of this chapter contains experimental results obtained from testing the various models described in Tables 3.3 and 3.4 previously. Different aerodynamic treatment types (vents, chamfers, fins) are first investigated in detail with a generalized overall comparison made in the last section of this chapter. Additional results are provided in Appendix A.

### 4.1 Vent Study

Three slenderness ratios were tested with venting treatments – 7:1, 8.5:1, and 10:1. As can be seen in Figure 4.1, opening a single vent across a building has multiple effects on the energy spectra of a building’s crosswind moment response. First, vents placed at 0.3H, 0.4H, or 0.5H from the top of the building reduce the maximum energy of vortex shedding-induced excitations. This effect is more prominent in the less turbulent flow simulated over open terrain. Vents opened at 0.1H, 0.2H, or 0.6H down from building roof height do not have a similar effect
of spreading energy within the response over a larger bandwidth of frequencies. This hints at an ‘influence zone’ existing around 0.3H to 0.5H down from the roof height of the building. The influence zone represents possibly critical locations for a single vent to be placed in order to reduce the magnitude of a prismatic square building’s crosswind response. Similar results were seen for buildings of 7:1, and 10:1 slenderness tested with single-vent treatments. PSD plots for those model responses are located in Appendix A.

Crosswind dynamic moment coefficients were calculated for all vented models per Eq. (10). These coefficients were normalized to the response of baseline square buildings with identical slenderness ratios per Eq. (11) to evaluate the effectiveness of a certain vent location on buildings with varying slenderness. Normalized crosswind moment coefficients as a function of vent location are shown in Figure 4.2 for both suburban and open terrain simulations. Most vented building configurations were observed to be more effective in open terrain conditions, suggesting that turbulence in the freestream reduced the near-wake stabilization effect of a single vent. Of the vent locations tested, buildings of 7:1 and 8.5:1 slenderness have an ‘optimal’ vent location of 0.3H down from the top of the building. For the 10:1 building, this location shifts upward along the building cross-section to 0.2H down from the roof height. This change in optimal location could potentially be further investigated using capped or sectional models where flow is restricted from passing over the top of the model. Unlike energy spectra in Figure 4.1, crosswind dynamic moment coefficients indicate that the influence zone along a building’s cross-section is around 0.2H to 0.4H down from the roof height.
Figure 4.1. Crosswind response spectra for 8.5:1 models with single-vent treatments
To further explore the effect of freestream turbulence on the effectiveness of single-vent treatments, normalized moment coefficients were plotted separately for buildings with different slenderness in Figure 4.3.

**Figure 4.2.** Normalized dynamic moment coefficients for single-vent models in different environments
Figure 4.3. Normalized dynamic moment coefficients for single-vent models of varying slenderness

Freestream turbulence appears to have a similar effect on all slenderness ratios tested. Vents placed at 0.2H or below the top of the building were marginally less effective in the suburban flow simulation.

Buildings of 8.5:1 slenderness were also tested with 15 possible double-vent combinations (0.1H to 0.6H) shown in Table 3.3. A summary of normalized crosswind dynamic moment coefficients resulting from various single- and double-vent configurations is provided in Table 4.1. The results from double-vented tests further emphasize the influence zone seen in single-vented results. ‘Optimal’ double-vented configurations for open terrain flow conditions are formed by a first vent opened at 0.2H with another at either 0.3H or 0.4H measured down
from roof height. Note that both these combinations require both vents to be within the influence zone identified previously.

Table 4.1. Normalized dynamic moment coefficients comparing double-vented scenarios (open terrain)

<table>
<thead>
<tr>
<th>Vent #2 Location (L2)</th>
<th>Vent #1 Location (L1)</th>
<th>No vent</th>
<th>0.1H</th>
<th>0.2H</th>
<th>0.3H</th>
<th>0.4H</th>
<th>0.5H</th>
<th>0.6H</th>
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<td>No vent</td>
<td>1.000</td>
<td>0.848</td>
<td>0.738</td>
<td>0.724</td>
<td>0.769</td>
<td>0.830</td>
<td>0.884</td>
<td></td>
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<tr>
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<td>0.848*</td>
<td>0.689</td>
<td>0.642</td>
<td>0.654</td>
<td>0.695</td>
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</tr>
<tr>
<td>0.2H</td>
<td>0.738</td>
<td>0.689</td>
<td>0.738*</td>
<td>0.605</td>
<td>0.602</td>
<td>0.623</td>
<td>0.674</td>
<td></td>
</tr>
<tr>
<td>0.3H</td>
<td>0.724</td>
<td>0.642</td>
<td>0.605</td>
<td>0.724*</td>
<td>0.642</td>
<td>0.655</td>
<td>0.687</td>
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</tr>
<tr>
<td>0.4H</td>
<td>0.769</td>
<td>0.654</td>
<td>0.602</td>
<td>0.642</td>
<td>0.769*</td>
<td>0.717</td>
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<tr>
<td>0.5H</td>
<td>0.830</td>
<td>0.695</td>
<td>0.623</td>
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<td>0.812</td>
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<td>0.6H</td>
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<td>0.674</td>
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<td>0.742</td>
<td>0.812</td>
<td>0.884*</td>
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</tbody>
</table>

*values along diagonal indicate single-vent scenario where L = L1 = L2

While having two vents open at a time is usually better than a single vent at either of those locations, it is important to judge the added benefit of adding a second vent to a single-vented building. As seen in Figure 4.4, wherever possible, an additional vent at 0.2H, 0.3H or 0.4H (within the influence zone) tends to improve the response of single-vented buildings. Vents in the top half of the building are only improved marginally, if at all, by a second vent opened in the lower half (at 0.6H down from the roof) of the building. This indicates that, depending on the wind climate governing the design of a proposed project, opening an additional vent at 0.6H might not be worth the loss in usable space.
Figure 4.4. Effect of adding a second vent to single-vented models

(a) Vent #1 at 0.1H, 0.2H or 0.3H
Figure 4.4 (cont.). Effect of adding a second vent to single-vented models

(b) Vent #1 at 0.4H, 0.5H, or 0.6H
The effects of single- or double-vent treatments to a building on the response spectrum and dynamic moment coefficient are combined when analyzing full-scale peak moments. Per Eq. (12), peak moments for the 8.5:1 single-vented models were calculated over a range of wind speeds and presented in Figure 4.5. For mean hourly full-scale wind speeds below 100 mph (45 m/s), single-vent treatments have little effect on the peak moment response of a square prismatic building of 8.5:1 slenderness. A drastic shift is first seen around 130 mph (58 m/s), which aligns with the Strouhal number of the response spectra seen in Figure 4.1. As the peak response is proportional to the magnitude of the wind velocity squared, at wind speeds greater than the critical velocity, the overall response of baseline and modified buildings increases while the effectiveness of a given aerodynamic treatment usually decreases. The effect of increased turbulence on aerodynamic treatment effectiveness is again observed when comparing the peak moments experienced in different flow conditions. The Strouhal number peak is less evident in both Figures 4.1(b) and 4.5(b). Similar figures were generated for 7:1 and 10:1 models and are located in Appendix A.
Figure 4.5. Normalized peak moments for 8.5:1 models with single-vent treatments
4.2 Chamfer Study

Chamfering of corners was applied incrementally along the height of the 8.5:1 baseline building to determine effectiveness of both altering separated shear layer behavior (from chamfering of sharp corners) and reducing coherence of vortex shedding along its height (from a portion of the building having a different cross-sectional geometry). Figure 4.6 shows the crosswind response spectra for chamfered model configurations in both open and suburban flow simulations. Increased turbulence in incident wind is again seen to suppress effectiveness of the aerodynamic treatment in reducing a square baseline building’s crosswind response. Unlike single- and double-vent treatments, chamfering does not appear to lose effectiveness when applied below 0.4H from the top of the building. As a larger portion of the building’s corners (with respect to height) are chamfered, crosswind excitation is spread over a larger bandwidth. Apart from spreading spectral energy over a wider bandwidth, chamfering of building corners halfway down from the roof height also increases the Strouhal number. This behavior is due to the influence of the building’s new octagonal cross-section which, at L=0.5H, now accounts for the top half of the building. Note that chamfering down to 0.2H from the roof height does not affect the spectral response significantly, again indicating an influence zone exists starting between 0.2H and 0.4H down from the roof height.
As seen previously, crosswind dynamic moment coefficients were most affected by vents opened within the influence zone (0.2H to 0.4H down from roof height). A point of diminishing
returns is seen around 0.4H down from the top of the building. For the modification lengths tested, chamfering of building corners does not reveal a similar point diminishing return. It is possible, however, that further chamfering down below 0.6H from the roof height could result in lower effectiveness as the variation in cross-sectional geometry is lost. Normalized crosswind moment coefficients as a function of chamfer height are shown in Figure 4.7 for both suburban and open flow simulations. Figure 4.8 shows peak moments for the 8.5:1 chamfered models as a function of wind speed.

Figure 4.7. Normalized dynamic moment coefficients for chamfered models
Figure 4.8. Normalized peak moments for 8.5:1 models with chamfered corners

Similar to single-vented configurations in Figure 4.5, the maximum peak moment response value is first observed around 130 mph (58 m/s). The effect of chamfering to 0.3H and below on the Strouhal number is seen again, with the full-scale response reducing by approximately 60%
around the critical velocity when corners are chamfered to halfway down the building. Irrespective of simulated terrain conditions, increasing the proportion of building cross section that is chamfered improves the performance of a building for wind speeds greater than 110 mph (49 m/s).

### 4.3 Fin Study

3D printed fins were attached to sharp corners of 8.5:1 baseline prismatic square models for the top half of the model height. Two fine angles – 45° (analogous to chamfering) and 90° were tested. Fins (or vanes) tested previously have been applied to the entire building height (Kwok & Bailey, 1987; Zdravkovich, 1981). Such modifications often result in an increased along-wind response due to an increase in windward surface area. Placing fins along half the building height was done to determine the effectiveness of such a cross sectional change in reducing coherence of vortex shedding along the building’s height. Figure 4.9 shows crosswind response spectra for finned model configurations in both open and suburban flow simulations to compare the effect of fins on a prismatic square building. Fins placed at 45° result in similar energy dissipation effects that are seen in the implementation of chamfering down to 0.5H from the roof height. This result is intuitive as fins at this acute angle were intended to have a chamfer-like effect on the phenomenon of vortex shedding. Separated shear layer behavior is altered due to smoothening of sharp corners that exist in a prismatic square building. Interestingly, fins at 90° also result in a reduction in wake excitation energy similar to fins at 45°. Although the body is not made any less bluff due to the addition of fins at 90°, corner geometry is much different to that of a prismatic square building.
The effect of fins on full-scale peak moments can be observed in Figure 4.10. While fins at 45° provide a reduction in peak moments for wind speeds above 110 mph, the reduction is
much less than that obtained from chamfering of corners halfway down the building. Fins at 90° do not appear to be an effective aerodynamic treatment to reduce the peak crosswind response of a prismatic square building, especially in more turbulent approach flows.

Figure 4.10. Normalized peak moments for 8.5:1 models with corner fins
4.4 Overall Comparison

In total, 3 prismatic square buildings (7:1, 8.5:1, and 10:1 slenderness ratios) were used as the baseline to evaluate the effectiveness of 40 different aerodynamic treatment configurations. Treatments tested include opening of one or two vents, chamfering corners, and adding corner fins at different angles. While the previous sections allowed for detailed comparison restricted to within a certain aerodynamic treatment type, this section makes a general comparison of all architectural forms tested at a slenderness of 8.5:1. Along-wind static moment coefficients and crosswind dynamic moment coefficients determined for all architectural forms tested at 8.5:1 slenderness were normalized to those obtained from the 8.5:1 baseline square building. This overall comparison is shown in Figure 4.11. Although reducing crosswind excitation has been emphasized in this study, looking at the relative impact of various aerodynamic treatments on a building’s along-wind response provides a holistic understanding of the potential benefits a given aerodynamic treatment can possess. It was observed that along-wind static moment coefficients are most affected by chamfering-type modifications. Double-vented treatments perform the next best to chamfers, with effectiveness being marginally dependent on vent locations. Fins at 90° have the least impact on the along-wind response of a prismatic square building, with such a configuration actually causing the response to increase in suburban flow simulations. Opening two vents within the influence zone (0.2H to 0.4H from the top of the building) was determined to be the most effective way to reduce the crosswind dynamic response of a prismatic square building. Chamfering of corners for the top half of the prismatic square building has a similar effect on the crosswind dynamic response while being much more effective in reducing the along-wind static response. Again, attaching fins at 90°
showed the least benefit, with tests in both terrain types resulting in such fins actually worsening the response of a prismatic square building.

Finally, the best configurations within each aerodynamic treatment type tested are compared in detail similar to that of previous sections within this chapter. Crosswind spectra and full-scale peak moments are compared for the most effective single-vent (at 0.3H), double-vent (at 0.2H & 0.4H together), chamfer (down to 0.5H), and finned (at 45°) configurations of 8.5:1 slenderness. These have again been normalized to the response of an 8.5:1 prismatic square model. Response spectra and peak moments obtained in open terrain simulations are shown in Figure 4.12. Similar results for suburban terrain simulations are presented in Figure 4.13. Response spectra for both terrain conditions suggest that the aerodynamic treatments are all effective in reducing the peak energy of vortex shedding-induced wake excitations as compared to a prismatic square building. Although energy content is spread over a wider bandwidth of similar magnitude for all aerodynamic treatments shown, chamfering down to 0.5H from the building roof and opening vents at 0.2H and 0.4H simultaneously result in the largest Strouhal number change as compared to a prismatic square building. Again, increased turbulence of flow over suburban terrain is observed to have an impact on all treatments compared. For wind speeds above 110 mph, irrespective of terrain type, the peak crosswind response of a square building is most improved by the double-vent configuration shown (0.2H & 0.4H). Chamfering halfway down from roof height and opening a single vent at 0.3H down from the roof are the next best aerodynamic treatments tested. Finally, fins at 45° were determined to have the least effect on the peak crosswind response of a prismatic square building, with the effect becoming virtually nonexistent at high wind speeds.
Figure 4.11. Normalized moment coefficients for all 8.5:1 models tested in open (above) and suburban terrain (below)
Figure 4.12. Crosswind response in open terrain flow simulations for most effective aerodynamic treatment types
Figure 4.13. Crosswind response in suburban terrain flow simulations for most effective aerodynamic treatment types.
CHAPTER 5: CONCLUDING REMARKS

Accurate simulations of open and suburban terrain flow were generated at the SOM wind tunnel to test various aerodynamic treatments that were applied to prismatic square buildings. A morphometric approach was used to determine the best roughness element layout configuration to simulate suburban terrain. The increased turbulence of flow over suburban terrain was observed to influence most aerodynamic treatments tested. Fluid-structure interaction was studied to determine the possible ways to disrupt organized vortex shedding in flow around prismatic square tall buildings. Reducing the coherence of vortex shedding along the building’s height, modifying separated shear layer structure, and stabilizing the near-wake region of the building were identified as possible response mitigation techniques. All three of these techniques were implemented through the use of different aerodynamic treatments such as opening of vents, chamfering of corners, and addition of corner fins tested in this research.

In total, 43 architectural forms were tested at the SOM wind tunnel to determine influence of architectural form on the wind-induced response of tall buildings. Single- and double-vents, chamfering of corners, and addition of fins were all explored in both suburban and open terrain flow environments. An ‘influence zone’ was identified to exist between 0.2H and 0.4H down from the roof height of prismatic square buildings tested. Vent-type aerodynamic treatments were observed to be most effective in reducing crosswind excitation when applied within this influence zone. The influence zone was observed to be shifted slightly upwards for buildings of 10:1 slenderness. However, this shift must be further explored through the use of sectional models. A vent opened at 0.3H down from the roof was the most effective of all single-vent treatments tested, while a combination of one vent at 0.2H and another at 0.3H or 0.4H
down from roof height were optimal double-vent configurations. Having two vents open at a
time was also seen to be better than a single vent at either of those locations. The most effective
of all aerodynamic treatments tested were double-vent combinations located within the influence
zone (0.2H to 0.4H) and chamfering applied to the top half of the building. Chamfering also had
the added benefits of reducing along-wind response and altering the Strouhal number of baseline
prismatic square models more than any other aerodynamic treatment tested. Fins at 45° reduced
the crosswind response spectral energy of a prismatic square building similar to the effects of
chamfering of corners to halfway down the building. Of all aerodynamic treatments tested, fins
applied at 90° was the only one observed to potentially worsen the response of a square baseline
building. This effect was amplified in suburban terrain simulations.
This research is part of an ongoing collaboration between the Wind Engineering Research Laboratory at UIUC and Skidmore, Owings & Merrill LLP. The work done as part of this study is intended to be developed further into a scientific publication that may be utilized by practitioners and researchers alike. It is understood that while chamfering has been explored in the work of previous scientific researchers, venting is a relatively novel concept with important real-world applications. Based on the experimental results achieved during this research, the following ideas have been identified as possible topics to further explore:

- Test the chamfered and vented building models at other wind angles of attack to investigate the effect of these aerodynamic treatments in such conditions.
- Continue incremental chamfering from the halfway point to the base of the building to identify a point of diminishing returns that may be reached due to the loss of cross-sectional variation (from octagon to square) with height.
- Study the impact of porosity on vented floors – addition of porous screens with varying openings to understand effect on reduced air flow through vents. This topic is especially relevant to the application of vented floors in real-world projects.
- Lastly, recognize ‘optimal’ vent dimensions within realistic limits.
REFERENCES

ASCE. (2012). Wind tunnel testing for buildings and other structures. (ASCE 49-12). Reston, VA.


APPENDIX A: ADDITIONAL TABLES & FIGURES

Figure A.1. Crosswind response spectra for 7:1 models with single-vent treatments
Figure A.2. Crosswind response spectra for 10:1 models with single-vent treatments
Figure A.3. Normalized peak moments for 7:1 models with single-vent treatments
Figure A.4. Normalized peak moments for 10:1 models with single-vent treatments

(a) Response in open terrain flow simulations

(b) Response in suburban terrain flow simulations
<table>
<thead>
<tr>
<th>Slenderness Ratio</th>
<th>Model Type</th>
<th>Modification Length</th>
<th>Along-Wind Static Moment Coefficient</th>
<th>Crosswind Dynamic Moment Coefficient</th>
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</thead>
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<td>N/A</td>
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<th>Crosswind Dynamic Moment Coefficient</th>
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<td></td>
<td>Suburban Terrain</td>
<td>Open Terrain</td>
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<tr>
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<td>Baseline</td>
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<td>1.00</td>
</tr>
<tr>
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<td>1.00</td>
</tr>
<tr>
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<td>@ 45</td>
<td><strong>0.91</strong></td>
<td><strong>0.89</strong></td>
</tr>
<tr>
<td>8.5</td>
<td>Finned</td>
<td>@ 90</td>
<td>1.04</td>
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</table>

* Note that models with greatest dynamic moment reduction for each aerodynamic treatment type tested are highlighted in bold
APPENDIX B: CALIBRATION OF THE SOM WT

For the purpose of benchmarking against an industry standard, a calibration exercise was undertaken at the SOM wind tunnel. Results obtained were compared to those published in an international high-frequency base balance benchmark study (Holmes & Tse, 2014). This portion of the appendix is meant to serve as a standalone calibration to match other wind tunnels around the world. The experimental setup (spires, model scale, etc.) of the calibration exercise was separate from that described in Chapter 3 and these results have no influence on those generated for the rest of this research. The goals of the calibration exercise were to achieve similar results to an international standard while also understanding flow dynamics inside the SOM wind tunnel facility through extensive testing of a relatively simple building form. Lessons learned from the calibration exercise helped improve simulation and experiment quality for the rest of this research.

A.2 Experimental Setup & Comparison Criteria

To match prescribed ‘urban’ terrain flow conditions specified in the benchmark study, special spires were used upstream of the test section. A geometric scale of 1:500 was used to create a model per ‘basic building B’ specifications provided in the calibration study. Model details and global axes used in the SOM wind tunnel are shown in Figure B.1. The rectangular building model was rotated clockwise in 10° increments through 360° with response calculated in terms of the model’s local axes. A description of this local axis coordinate system and incident wind direction is given in Figure B.2.
(a) Model dimensions & local axes orientation

(b) Photograph of the building model inside the SOM wind tunnel

Figure B.1. Model used for ‘Basic Building B’
The velocity profile provided in the benchmark study was digitized and compared to that obtained in an urban flow, with a power law exponent of 0.23, simulated at SOM. This comparison is provided in Figure B.3. Longitudinal turbulence intensity at model height was measured at 18%, which was higher than the prescribed value of 14.3%. This increased turbulence of the simulated urban environment generated additional buffeting effects that were not seen in aerodynamic treatment tests in open and suburban environments for the rest of this research. Mode shapes were assumed to be linear for the basic building and were not corrected. Finally, it must be noted that the global axes used in this calibration exercise do not match those used in the benchmark study. Wherever used, plots digitized from the benchmark study have been adjusted to facilitate comparison between the industry benchmark and SOM results.
A.3 Results

Mean moment coefficients for both sway directions are compared to the benchmark study in Figure B.4. Since only static and peak response data is provided, there was no way to specifically compare the dynamic response.

Figure B.3. Mean velocity profile for simulated urban terrain
Both sway directions show good correlation between test data from the SOM wind tunnel and results from the benchmark study. Wind incident at corner points of the building appear to cause the most discrepancy in results – tests at angles around 45°, 135°, 225°, and 315° provide the least correlated results to those seen in the benchmark study. A possible rationale for this behavior is the larger turbulence simulated in the SOM wind tunnel compared to that specified in the benchmark study. It must be noted that although the measured response does deviate from benchmark curves at these angles, symmetry is still maintained in the obtained results, indicating that the urban flow simulation was laterally uniform.

Peak response calculation involves the use of observed model response along with prescribed full-scale dimensions and dynamic properties. Although the full-scale properties used in this calibration exercise are identical to those specified in the published benchmark study, spectral measurements could not be validated from the calibration study. Differences in frequency-domain data processing such as use of windows and smoothing could alter the resonant dynamic response used in peak response calculation. Also, simulated urban flow
conditions had a longitudinal turbulence intensity of 18% at the building height (180 m in full-scale) as compared to a lower value of 14.3% prescribed in the international benchmark paper. Figure B.5 provides a comparison of peak full-scale moments obtained in the SOM wind tunnel to those published in the international calibration study.

![Figure B.5: Full-scale peak moment comparison in both sway directions](image)

(a) Peak (min) moments in the X-direction

(b) Peak (max) moments in the Y-direction

**Figure B.5.** Full-scale peak moment comparison in both sway directions
While a similar trend to the benchmark results can be seen in both sway directions, peak (max) moments in the Y-direction have better correlation to the benchmark overall. Note that the two benchmark curves indicate an upper- and lower-bound of data published in the benchmark study. Peak moments are obtained through the combination of static and dynamic (background and resonant) components per Eq. (12) described previously. A comparison to dynamic data would be required to determine the exact reason for the lack of correlation seen in peak (min) moments in the X-direction. A more traditional method of looking at wind tunnel results through full-scale static and peak moments is shown in Figure B.6 for both sway directions. Again, symmetry in the peak response is seen, indicating that both the static and dynamic responses obtained from the SOM wind tunnel were symmetric. The calibration exercise served to not only corroborate results obtained in the SOM wind tunnel to an industry benchmark but also to help build intuition of flow around simple bluff bodies in the wind tunnel. Lessons learned from this exercise laid the foundation for the architectural form study conducted in this research.
Figure B.6. Full-scale (max-mean-min) moments in both sway directions
APPENDIX C: TIME AVERAGING OF WIND SPEEDS

To ensure proper scaling of wind tunnel simulation results to full-scale response estimates, it was important to maintain similarity between simulation and full-scale parameters. The following dimensionless parameter was defined:

\[
\left( \frac{L}{UT} \right)_m = \left( \frac{L}{UT} \right)_p
\]

where the subscripts \( m \) and \( p \) denoted the model and prototype (full-scale) parameters respectively. While the length scale, \( \frac{L_p}{L_m} \), was fixed at 700, the time, \( \frac{T_p}{T_m} \), and velocity, \( \frac{V_p}{V_m} \), scales varied to allow for calculation of full-scale peak moments over a range of wind speeds. \( T_p \) was chosen to be 1 hour (3600 sec) to employ full-scale mean hourly time averaging of wind speeds. \( U_m \) was fixed at 7 m/s (15.6 mph) which was recorded at model roof height for flow over both suburban and open terrains simulated in the wind tunnel. Table C.1 lists the possible scaling combinations (values of \( T_m \) and \( U_p \)) required to maintain the desired 1:700 geometric scale.

<table>
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<tr>
<th>( T_p ) (sec)</th>
<th>( T_m ) (sec)</th>
<th>( \frac{T_p}{T_m} )</th>
<th>( \frac{U_p}{U_m} )</th>
<th>( U_m ) (m/s)</th>
<th>( U_p ) (m/s)</th>
<th>( U_p ) (mph)</th>
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<td>2.92</td>
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<td>20.4</td>
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</table>

Cobra Probe (TFI, 2015) measurements were made to determine mean wind speed readings at several heights in the wind tunnel. Such mean wind speed profiles are shown in Figure 3.4 previously. Wind speeds were typically recorded for 5 minutes (300 seconds), but to
ensure geometric scaling while attaining reasonable full-scale speeds, averaging times of 20 to 90 seconds were used in the calculation of peak moments discussed in Chapter 4. A typical 5-minute wind speed record in the SOM wind tunnel, along with shorter time averages of wind speed are shown in Figure C.1. The coefficient of variance for both mean velocity and longitudinal turbulence intensity values for the various averaging times was within 5% of values calculated from a full 5-minute record. Thus, proper scaling of parameters was ensured.
Figure C.1. Time averaging applied to a wind speed record measured at model height (open terrain simulation)
APPENDIX D: DATA FILTERING

The high frequency force balance technique requires stiff and lightweight models (i.e. models with high natural frequencies) to accurately predict full-scale response based on model geometry. This is done to prevent the model’s local response from affecting the vortex shedding-induced excitation generated by the geometry of the model. All model tests in the wind tunnel were conducted at a high sampling rate of 500 Hz to determine any model resonance effects. This response was then filtered through an 8th order low-pass Butterworth filter during post-processing in MATLAB. A sample crosswind moment response time history for the baseline square model is shown in Figure D.1 to demonstrate the effects of such filtering of the data in the time domain.

The low-pass frequency cutoff was set to 25 Hz for all models tested. This value was set by examining PSDs for all 43 models to satisfactorily delineate between the geometric body’s
aerodynamic response to wind loading and the model’s resonant response. Data was not
decimated (down-sampled) to retain the resolution of high-frequency sampling. Figure D.2
shows a sample spectrum for the square baseline model capturing the effect of such a filter in the
frequency domain.

Full-scale peak moment calculations involved the use of terms obtained from such
spectra. Such calculations were only made for a range of speeds that were within the maximum
reduced frequency limit of 0.2. Hence, for the 7:1, 8.5:1, and 10:1 buildings, the minimum full-
scale wind speed was 34 m/s (76 mph), 27 m/s (60 mph), and 22 m/s (48 mph) respectively.

![Figure D.2 Crosswind moment response spectral density for 8.5:1 baseline model](image)

Sample MATLAB code used to filter time history data in such a way is provided below:

```matlab
fs = 500; % original sampling frequency (Hz)
fsl-cut = 25; % low-pass cutoff frequency (Hz)
order = 8; % filter order

[b,c]=butter(order,(fc/(fs/2))','low'); % create low-pass filter

x_fil = filtfilt(b,c,x); % filter data (x = original)
```