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FULL-SCALE EXPERIMENTAL TESTING TO INVESTIGATE WIND-INDUCED VIBRATIONS ON CURTAIN WALL SYSTEMS

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Curtain walls are dominant cladding components of mid to high-rise buildings in modern architecture. However, the curtain wall systems have been observed highly susceptible to vibrations leading to component or system-level failure during recent extreme wind events. This paper studies the complex mechanisms of wind induced vibration (WIV) functionality at the system- and component-levels. A wind testing experiments for a full-scale single-skin façade panel was conducted at the Wall of Wind experimental facility (WOW EF) at Florida International University (FIU). Effect on the vibration of the curtain wall due to the addition of sunshade fin is also studied. The experimental protocol included testing the samples (with and without sunshade fins) at various wind speeds from 22.3 m/s to 40.1 m/s with 8.9 m/s intervals in open terrain. Effect of wind direction is also considered varying from 0 to 180 degrees with 45-degrees interval. The tests were performed on two sets of panels: (1) a polycarbonate panel (with the geometric properties maintained) to obtain dynamic wind pressure data; (2) actual glazing units that are instrumented with accelerometers and strain gauges at critical sensing locations. The experimental results indicate that the sunshade fins have a stiffening effect on the joints of the curtain walls while overall increasing the wind pressure on the panel. Dynamic amplifications on the glazing were in the order of 1.1 to 1.8 which underline the importance of studying dynamic effects on the façade systems.

Keywords: Extreme wind events, Single skin façade, Sunshades, Fins, Water ingress, Wall of wind.

1 INTRODUCTION

Curtain walls are primarily used as environmental separators for mid to high-rise buildings. While considered as non-structural elements, the system needs to have enough capacity to resist against wind loading. The use of glass for curtain wall systems to transmit natural light has become popular in the last century, with the Hallidie Building in San Francisco being the first in 1918. Since then, many buildings including the Burj Khalifa have adopted glass curtain walls to accommodate the increasing demand of lighting and architectural aesthetics. The wind induced vibration (WIV) to the curtain wall systems remains to be better understood. For example, severe damages were made to the Capital One Tower during Hurricane Laura that made landfall on Louisiana, USA in 2020 as a Category 4 storm, has underlined the importance of understanding the WIV. ASCE 7 (2016) suggests that dynamic wind excitation does not need to be considered for the structures with a natural frequency greater than 1 Hz. However, the frequent failure of non-structural elements and cladding systems evidences the design guidelines developed for a typical building scale are not necessarily applicable to building envelopes including facades, solar panels, and metal roofs. Previous tests performed at FIU Wall of Wind EF (Chowdhury *et al.* 2018) on solar panels and standing seam metal roofs evidenced significant amount of vibrations while the respective natural frequencies were 13 Hz (Moravej *et al*. 2015, Naeiji 2017) and 8.1 Hz (Habte *et al*. 2015, Azzi *et al*. 2020) greater than 1 Hz criteria specified by ASCE 7(2016). This study extends the previous investigations to the façade systems, for which a full-scale single skin curtain wall sample is constructed and instrumented with accelerometers and strain gauges on the glass and frames (mullions) supporting the glass, respectively, and tested in a wind tunnel setting.

The shading devices such as vertical fins have been added to the curtain walls due to the demand for thermal and visual comfort of occupants. However, very little attention has been paid to the effect of these shading devices on the wind pressure distribution over the curtain walls (Rofail and Kwok 1999) except some tall and complex structures that are typically tested in a wind tunnel. The current wind loading provisions such as ASCE 7(2016), do not provide proper guidance on the design of these curtain wall systems with the protruding elements. There are many incentives of conducting a full-scale wind tunnel testing to understand the effect of the protruding elements on the wind-induced response of curtain wall systems because it enables a) to consider precise geometric and structural element details of the curtain wall panels, b) to adequately instrument and c) to simulate exact Reynolds number as in the field to avoid any scaling effects. This paper studies the effect of vertical fins using the Wall of Wind experimental facility (WOW EF) at Florida International University (FIU).

This paper highlights the experiment results obtained during the full-scale wind tests performed at the FIU WOW EF. Section 2 describes the tested specimen, layout of instrumentation, and testing protocol. Section 3 discusses on the results. Some key findings are summarized in Section 4.

2 EXPERIMENTAL TESTING IN WIND TUNNEL

A full-scale single skin curtain wall specimen is constructed at the WOW EF as shown in Figure 1(a), (b), (c), and (d). The specimen is built on using a steel frame and the final dimension is 3.66 m (W) × 1.83 m (L) × 3.05 m (H). The sidewall of the building is composed of three different curtain wall panels; one center panel with a width of 1.83 m joined by two adjacent curtain walls of 0.915 m. There are two vertical joints between the center panel and adjacent panels at which mullions (the main vertical frames) are located. A geometrically similar façade panel is built on the other side of the steel frame using polycarbonate glass for the wind pressure measurement. Considering it is hard to drill the glass on the actual façade to place the pressure taps, another panel with polycarbonate glass is adopted for the pressure testing.

The specimen with two sides is held in place on a rotating table at the WOW and capped with a wooden roof and two sides to create an enclosed building model. A total of 110 holes are drilled to the polycarbonate glass (hereafter called ‘static side’) to locate the pressure taps to measure external pressure and 2 pressure taps are placed inside the building model to measure internal pressure. The curtain wall side (hereafter called ‘kinetic side’) is instrumented with 3 tri-axial accelerometers on the center glass panel and 1 tri-axial accelerometer on each of the adjacent side panels. The mullion frames are instrumented with uni-axial strain gauges along the length (i.e., vertical direction). After testing the “No Fin” configuration, two vertical fins are added to the same model to build “With Fin” configuration. The fins are attached at the mullions between the center panel and adjacent panels on both static and kinetic sides, and 18 additional holes are drilled to attach pressure tubing on the static side fins. The instrumentation layout is illustrated in Figure 2(a) and 2(b).

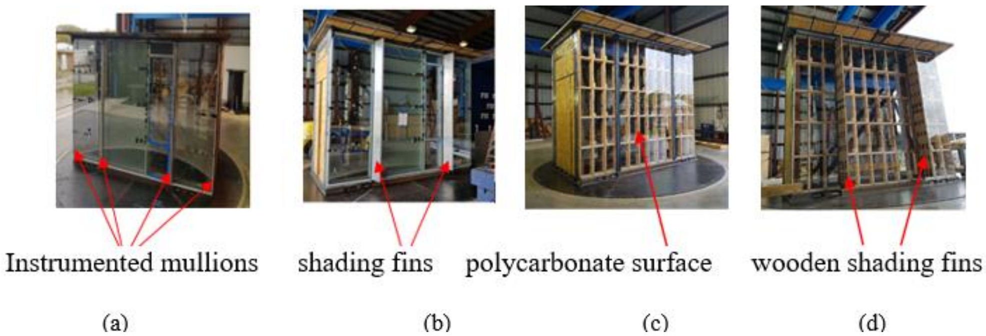
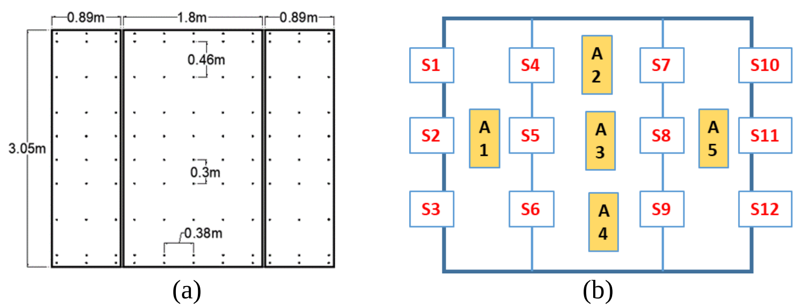


Figure 1. Tested panels: (a) No Fin configuration on the kinetic side, (b) With Fin configuration on the kinetic side, (c) No Fin configuration on the static side, and (d) No Fin configuration on the static side.



(A- Accelerometer on the glass, S- Strain gauge on the mullion)

Figure 2. Instrumentation layout: (a) Pressure taps shown with dots, (b) accelerometers and strain gauges.

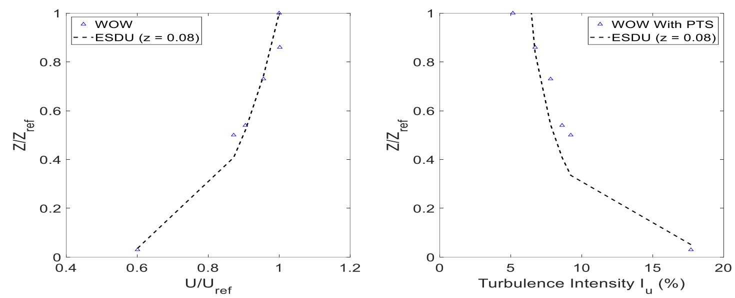
The testing protocol included testing at three different wind speeds 22.35 m/s (for 10 mins.), 31.30 m/s and 40.23 m/s (for 5 mins. each). The terrain roughness was calculated to be open terrain based on matching ESDU (1985) data at roof height with roughness length of 0.08 m. The turbulence intensity and wind speed profiles were well aligned with ESDU (2016) data as shown in Figure 3(a) and 3(b). These wind speeds were chosen based on the typical wind gusts that would be experienced by a tall building in New York City (ASCE 7 2016). The static side is tested at 22.35 m/s (for 1 min.) to measure the pressure coefficient. The underlying assumption is that mean and peak pressure coefficients would not change with change of wind speed which then can be used to estimate the pressure for different wind speeds. The same tests are repeated for the "With Fin" configuration after adding fins to the specimen. Table 1 summarizes all performed tests. Figure 4(a) shows the Wall of Wind test section with the turn table where the façade specimen is located, and Figure 4(b) shows the orientation of the façade system and tested angles.

3 TEST RESULTS AND DISCUSSION

The dynamic pressures obtained from the experiments are converted into mean and peak pressure coefficients using Eq. 1 and Eq. 2.

$$Cp_{mean} = P_{mean} / (0.5 * \rho * U_{mean}{}^{2}) \tag{1}$$

$$Cp_{peak} = P_{peak} / (0.5 * \rho * U_{3\text{-sec}}^{2}) \tag{2}$$

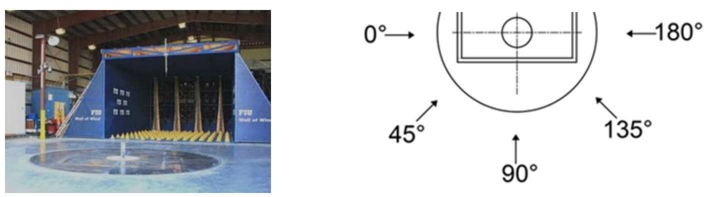


(a) (b)

Figure 3. WOW ESDU (2016) comparison (a) Vertical Velocity profile, (b) Turbulence Intensity profile.

Table 1. Testing protocol per configuration.

Test Type	Wind Speed (m/s)	Wind Direction (degree)	Duration (mins.)
Pressure	22.35	0,15,30,45,60,75,90,105,120,135,150,165,180	1
Kinetic	22.35	0,45,90,135,180	10
Kinetic	31.30	0,45,90,135,180	5
Kinetic	40.23	0,45,90,135,180	5

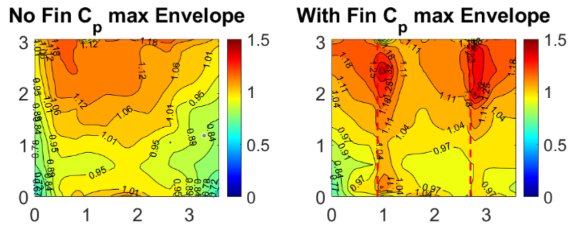


(a) (b)

Figure 4. FIU WOW EF testing: (a) Test section showing turntable, (b) Wind direction.

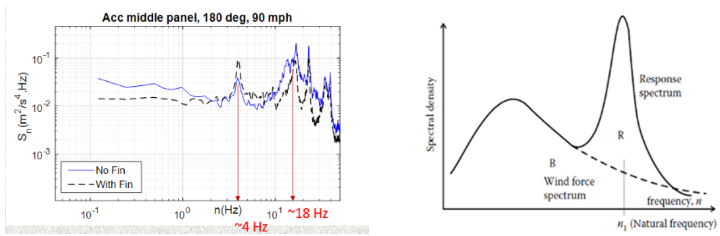
Peak pressure coefficients (Cp) for the "With Fin" case showed up to a 20% increase compared to the "No-Fin" case around fin positions as shown in the Cp contour plots in Figure 5. This indicates the need for more wind loading data to consider the effect of the protruding elements on the façade systems. The power spectral density (PSD) plots of acceleration showed that the first mode of vibration (natural frequency of curtain wall) occurred at 4.15 Hz and the second mode occurred at ~18 Hz as shown in Figure 6(a). The spikes in the PSD plots indicating the dynamic and resonance response of the system evidence the importance of considering the Dynamic Amplification Factors (DAF) in the design of curtain wall systems. Accelerometer data can be split into three components of mean, background (from wind spectra) and resonant (due to dynamic excitation) response components as shown in Figure 6(b) by which DAFs can be computed using Eq. 3. The effects of wind speed and wind direction for both "With Fin" and "No Fin" configurations are presented in Figure 7(a) and 7(b) respectively. The figure shows that the maximum DAF of accelerations is as high as 1.8.

Figure 8 shows the strain values at the strain gauge 5 (S5) and strain gauge 2 (S2) on the mullion (See Figure 2b). Maximum strains are observed at 90° for S5 while maximum strains are observed at 45° for S2 due to their position relative to the wind angles. The strain results also indicate that the fins increase the stiffness of the joints, as lower strains were recorded in 'With Fin' configurations at joints that have fins (e.g. joint where S5 is located) as shown in Figure 8(a).



(a) (b)

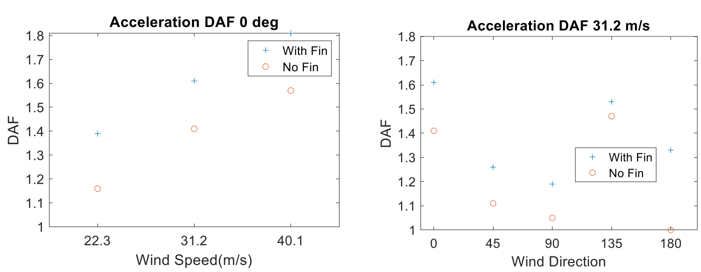
Figure 5. Envelope of Peak Pressure coefficient (Cp) (a) Peak Cp on 'No Fin Configuration' (b) Peak Cp on 'With Fin Configuration.



(a) (b)

Figure 6. Accelerometer Analysis (a)PSD plots to show the system natural frequency (b) Splitting spectral density into the background (wind force) and resonant response (Holmes 2007).

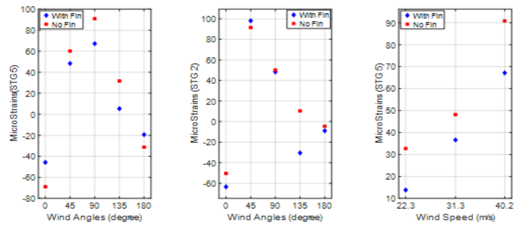
$$DAF = MaximumPeak\,Response / MaximumQuasiStatic\,Response(Mean + Background) \quad (3)$$



(a) (b)

Figure 7. Dynamic Amplification Factors (DAF) (a) Wind Speed (b) Wind Direction.

At mullion joints where there are no fins (e.g. joint where S2 is located), the "With Fin" configuration shows higher strains as expected due to the increased pressures observed in with-fin configurations, except at 90° wind angle where the fins do not have a lot of impact on the flow. At the marked difference in strain direction at 135° for S2 is due to flow separation occurring because of the fins. No dynamic amplifications were observed in the mullions of the model tested. An increase in strains with increasing wind speeds was observed as expected.



(a) (b) (c)

Figure 8. Mean Strains Plots (a) Wind Angles vs S5 strains (b) Wind Angles vs S2 strains (c) Wind Speed vs S5 strains (at 90° wind).

4 CONCLUSIONS

This paper discusses the effect of wind induced vibration on the single skin façade system via full-scale wind tunnel testing. The effect of vertical fins on the façade response is also studied.

- The peak pressure coefficients showed an increase of up to 20% for the "With Fin" case which therefore needs to be considered in the design and standards.
- The natural frequency of the tested curtainwall system was as high as 4.15 Hz, greater than 1 Hz criteria specified by ASCE (2016). This finding calls for the attention to revisit the criteria and the importance to account for the dynamic effects for building facades.
- The acceleration dynamic amplification factor (DAF) values were in the order of 1.1-1.8, which indicates a significant increase in the dynamic response of the glazing.
- Fins increase the stiffness of the joints and hence reduction in strains in the mullions.

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