Contributions of Wind Tunnel and Full-Scale Studies in Wind-Induced Disaster Mitigation

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ABSTRACT: Wind engineering research is aiming to reduce wind related disasters. Several studies have been conducted in both real and model scales and provided valuable information regarding wind effects on buildings and other structures. The increased number of wind-related catastrophes and their impact on built environment urges for additional research and improvement of the current wind standards and building codes of practice. To demonstrate the connection between experimental studies and contributions to wind-related disaster reduction, two representative studies are presented. The first research project, examines how wind load is transferred through the structural system by conducting field measurements on a low-rise building. The second study describes the wind-induced loads on patio covers using detailed wind tunnel pressure measurements.

KEYWORDS: Wind disasters, wind engineering, wind loads, full-scale, wind tunnel, structural attenuation.

1 INTRODUCTION

Numerous natural catastrophes occurred across the globe over the past few decades. The impact of these events in several cases was disastrous causing thousands of fatalities and billions of dollars in overall and insured losses. Some of the most fatal and costly events were the result of extreme wind incidents. Hurricanes, typhoons and tornadoes were reported and tracked around the globe. The social and economic impact associated to these natural disasters initiated a drastic response from a number of political and academic institutions.

Wind-structure interaction is a special field of engineering, which has as a scope to study the wind effects on buildings. Several studies were conducted specifically to evaluate the effect of wind action on structures, such as residential buildings and other shared public spaces. The contribution of both wind tunnel experiments and full-scale monitoring on the development of modern wind standards and building codes of practice is of great significance. Concepts related to structural integrity during extreme wind events have been studied extensively using boundary layer wind tunnels and verified by monitoring wind-induced responses on real buildings. The concepts of structural attenuation and net wind-induced pressures are two examples of recent research findings that will be discussed in this paper.

2 WIND-RELATED CATASTROPHES

Recent data related to the occurrence of natural catastrophes indicates an increasing trend over the last three decades (see Fig. 1 - Munchener Ruck, 2009). Only in 2009 there were 860 incidents, with most of them being the result of extreme meteorological events. Moreover, wind-related events were responsible for 31% of the fatalities and for the vast majority of the overall and insured losses (Fig. 2). Similar findings were reported for the US region as well. Wind-related events not only take over in the relevant tables (Fig. 3) but show an even more rapid increase in occurrence over the last ten years. The aftermath of recent catastrophic wind events revealed the excessive amount of damage, which translates in billions of dollars, e.g.

hurricane Katrina cost is over 200 billion dollars to the US nation (source: Associated Press, September 2005).

Building codes aim to assist designers to make buildings resist high wind loads. However, in some cases, excessive damage is noticed during hurricane events even if the recorded wind speeds were lower than the maximum recommended by the code design value (Kareem, 1984). Local, national and international building codes have been revised several times over the last few decades but the losses and damages due to wind are still considerably high (ABI 2003, Munchener Ruck 2006). This indicates the importance of wind engineering in the improvement of wind standards and building codes of practice. Two concepts that are currently not adequately addressed in wind standards have been recently studied using full-scale monitoring and wind tunnel modeling of a low-rise building. The first is related to the structural attenuation as wind-induced loads are transferred through the building's components to the foundation. The second study was related to wind loads on attached patio covers and particularly the relaxing effect on the total (net) dynamic load due to simultaneous flow characteristics on the top and bottom surfaces of the patio cover.

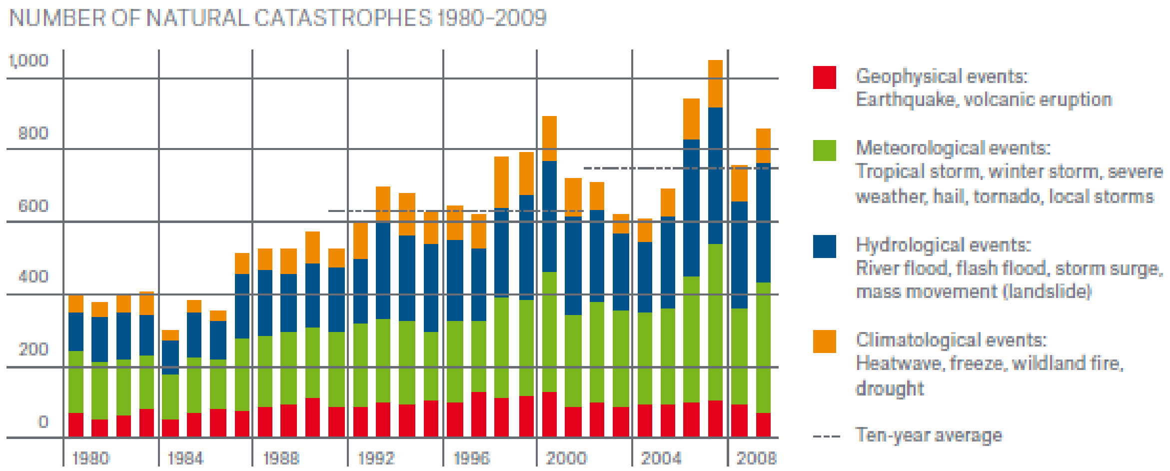

Figure 1. Total number of natural catastrophes occurred during 1980-2009 (Munchener Ruck, 2009).

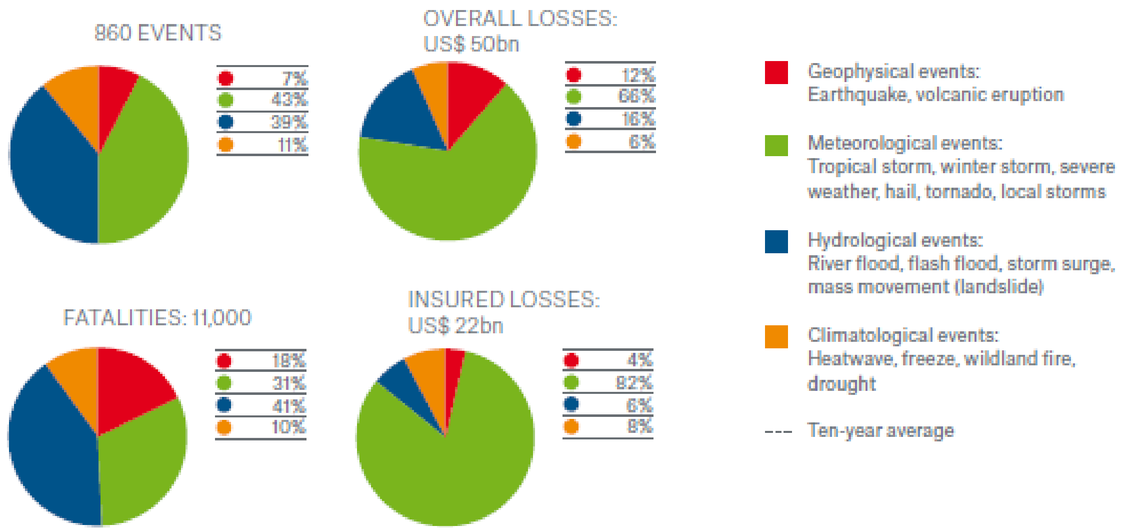

Figure 2. Breakdown of natural catastrophes worldwide in 2009 (Munchener Ruck, 2009).

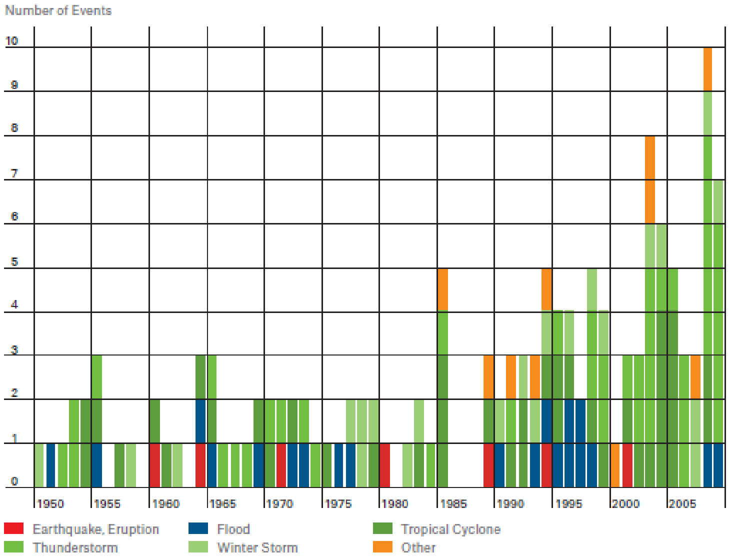

Figure 3. Total number of natural catastrophes occurred in USA during 1950-2009 (Munchener Ruck, 2009).

3 FULL-SCALE AND WIND TUNNEL STUDIES

3.1 *Wind load paths and structural attenuation*

A collaborative effort among Canadian Universities was initiated almost a decade ago and had as main scope to assess the application of environmental loads and their actual transferring through the building elements from the envelope to the foundation. Several experimental approaches were implemented in this study with most important the structural monitoring of a light-frame wood structure subjected to high wind loads. The field facilities include three anemometers and a single-storey test-house constructed according to the needs of the particular research project (Fig. 4). The external dimensions of the house are 8.6m by 17.2m and the roof height is 5.6m. The experimental building is equipped with forty wall and roof pressure taps. In addition, twenty-seven foundation and six roof load cells were placed at key points inside the structural system.

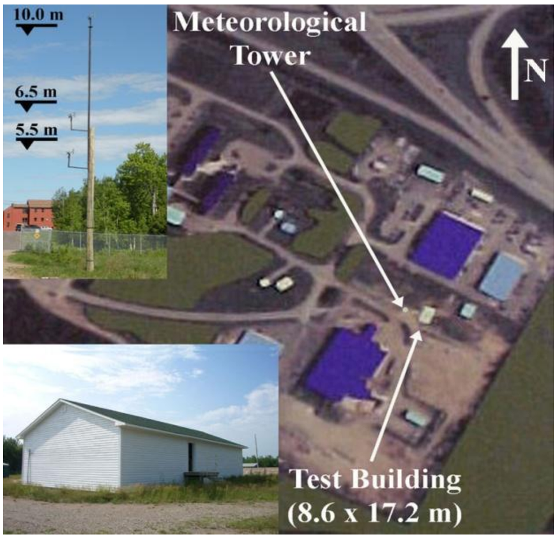

Figure 4. Test house and meteorological tower location.

A unique characteristic of the building is the fact that it is completely isolated from the foundation and the only points of contact with the ground are the 3-D foundation load cells. In parallel with the structural monitoring of this building, wind tunnel tests were conducted in the Building Aerodynamics Laboratory at Concordia University. The wind tunnel model was tested for thirty-six angles of attack and for three different upstream exposures i.e. open, light suburban and heavy suburban terrains. The power law exponents for these simulated exposures were 0.16, 0.22, and 0.28 respectively. Having obtained both full-scale and wind tunnel results, the computer-based analysis provided the opportunity to compare and assess the data of each individual approach. Details regarding the field and wind tunnel data acquisition and interpretation are presented by Zisis (2007) and Zisis & Stathopoulos (2009).

Of particular interest to this study was the evaluation of the wind load transfer mechanisms within the structural system. Current codes account for some attenuation effects by reducing the foundation load by an appropriate factor (e.g. the National Building Code of Canada - NBCC 2005 - reduces by 30% the foundation load due to wind action). In order to evaluate the dynamic response of the particular building through the acquired field data, a 2-D simplified approach was selected. The objective of this approach was to investigate any attenuation effects introduced by the structural system as the wind load travels through the structural and non-structural components to the foundation level. Three frames within the structural system were selected (Fig. 5) based on the location of the instrumentation i.e. all of them are instrumented with roof and wall pressure taps and roof and foundation load cells. This allows real time monitoring of the wind pressure applied on each frame and the resulting force at the roof and foundation levels. A simplified model of the frame was developed and wind load was applied using time-series from each of the pressure taps located on the external surface of the frame. The analysis of each frame resulted in truss and foundation reaction time-series. These results were then compared to the full-scale load cell records for the same reference duration. The comparison of the two individual records was carried out in the form of reduction factors obtained by plotting the load cell and the structural analysis data as scatter plots and applying linear regression. More details about these calculations are provided by Zisis et al. (2009).

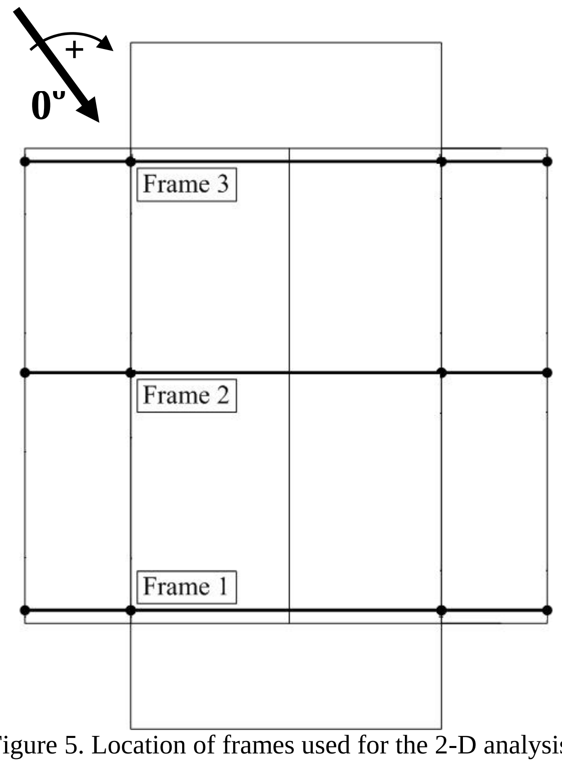

Figure 5. Location of frames used for the 2-D analysis.

The single frame analysis approach was performed on sets from two different records (Table 1). Representative results, from wind speed and direction data from the first record (28th October 2008) for a total duration of 600 seconds are presented in Figure 6. In addition, scatter plots from load cell data extracted and analyzed from the same record are presented in Figure 7. These graphs refer to the comparison between field (FS_LC) and structural analysis (SA_LC) data from Frame 2 for both foundation and roof levels. The reduction (percentage) for this record was 46% and 43% for the roof and foundation levels respectively. For the other examined cases the reduction was found to range from 26% to 46% as the load travels through the roof to the top section of the wall. When the foundation reactions were calculated from the envelope pressures measured in the field by simple structural analysis and compared to those measured directly from the load cells, the reduction was between 21% and 44%.

Set	Date – Time	U_{mean} (km/h)	$U_{stdeviation}$ (km/h)	D_{mean} (deg.)	$D_{stdeviation}$ (deg.)
Oct_28_I	October 28th, 2008 (11:29:23)	16.36	7.67	264.49	26.45
Oct_28_II	October 28th, 2008 (12:16:03)	19.22	6.62	244.85	25.65
Oct_29_I	October 29th, 2008 (15:28:59)	16.11	6.19	254.69	25.57
Oct_29_II	October 29th, 2008 (21:08:59)	10.42	3.25	298.99	19.82

Table 1: Records used for single frame analysis.

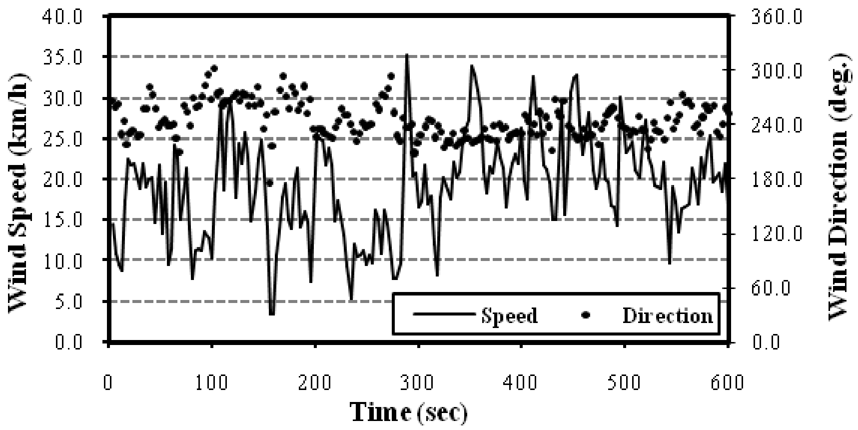

Figure 6. Typical wind speed and direction records.

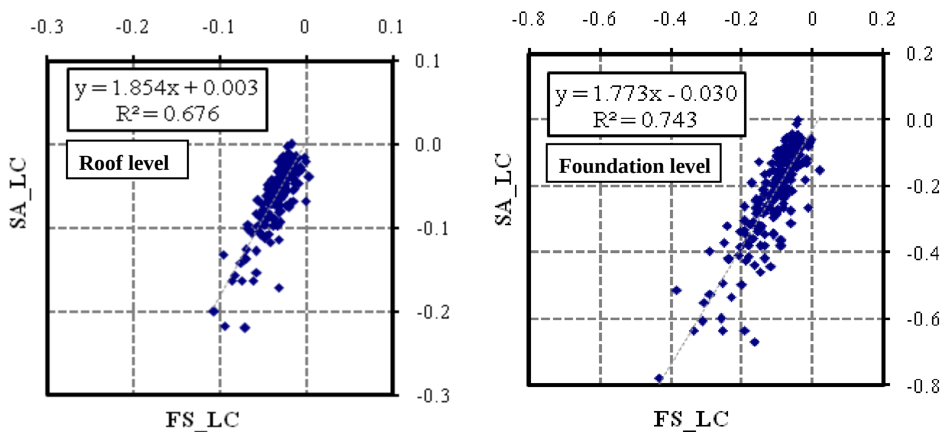

Figure 7. Typical single frame analysis scatter plots (roof and foundation level).

It should be noted at this point, that despite the fact that the above reduction factors have been derived on a conservative basis and refer to the specific structural system (i.e. light-frame wood construction), they are of significant importance as they have been collected on a full-scale building subjected to real wind action. This is a very important observation for purposes of codification as well, for the reason that it is the first time that full-scale findings related to structural attenuation became available. The use of wind tunnel tests provides information related only to envelope pressures and estimation of wind-induced forces is based heavily on structural analysis. The main objective of this study is to use the field observations to collect load cell data which can be used for verification purposes of both wind tunnel tests and structural analysis procedures.

3.2 *Net pressure wind load on patio covers*

Building components that are exposed to wind on both surfaces (e.g. patio covers, overhangs, parapets etc.) require special experimental approaches to precisely define the net wind-induced loads acting on them. The combined effect of top and bottom surface pressure contributions can be examined through correlation analysis of the upper (outer) and lower (inner) pressure traces. Peak values are not likely to occur simultaneously for both surfaces, therefore the applied net pressure is in some cases significantly lower compared to the difference of the individually observed top and bottom pressures.

The case of a low-rise building with an attached patio cover was examined through detailed wind tunnel tests. The experiments conducted in the Building Aerodynamics Laboratory located in the Engineering Complex at Concordia University. The 1:100 geometric scale building model used for the tests has external dimensions of 15 cm by 10 cm by 9 cm (length – width – ridge height) and roof slope of 4:12. The model is equipped with 65 roof pressure taps located both on the top and the bottom of the roof eave. In addition a metallic patio cover model of the same geometric scale (1:100) was constructed and mounted on the existing building model creating the final test model. The patio cover model is 15 cm by 3.65 cm and 0.2 cm thick. In order to consider different building configurations, the patio cover could be attached to two different building heights. Three configurations were examined (Fig. 8); two-storey house with the patio cover at the first floor level, two-storey house with the patio cover at the roof height and single-storey house with the patio cover at the roof height. The patio model was equipped with 30 pressure taps, 15 on the top surface and another 15 on the bottom surface. In total, 28 wind directions were tested (Fig. 9).

Two representative azimuths were selected and correlation coefficients calculated for each pair of top and bottom pressure taps. The results are presented as contour plots for each configuration, for both 30 and 135 degrees wind direction (Fig. 10). Configurations II and III - patio cover at roof overhang level - show a similar pattern which is more pronounced for the case of 135 degrees wind direction. As expected, the two traces are better correlated for the case of 30 degrees rather than the 135 degrees wind direction. Another interesting finding is that when the patio is located on the windward side (30 degrees) higher correlations occur for regions closer to the wall the patio is attached to, as opposed to the case of 135 degrees wind direction that results show higher correlations for the front edge region of the patio.

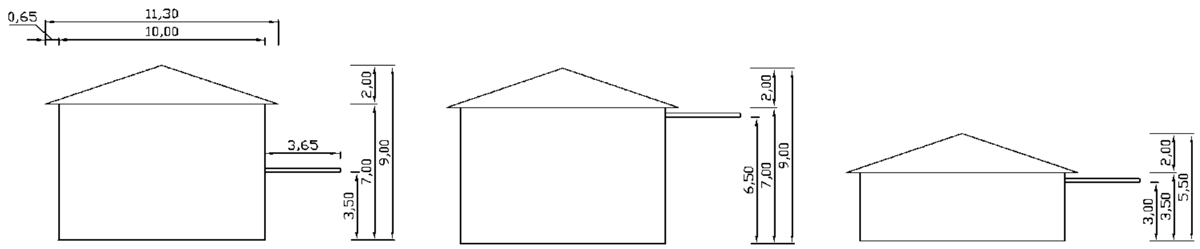

Figure 8. Side views of Configurations I, II and III of the building and patio cover models.

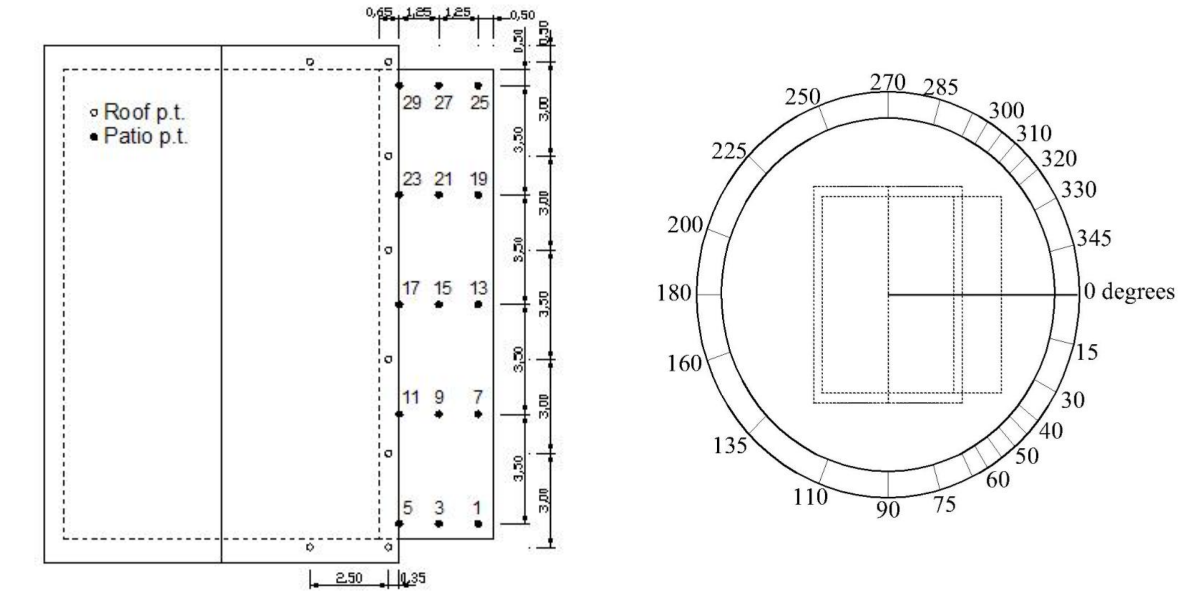

Figure 9. Pressure tap location and notation on the patio cover model and examined wind directions.

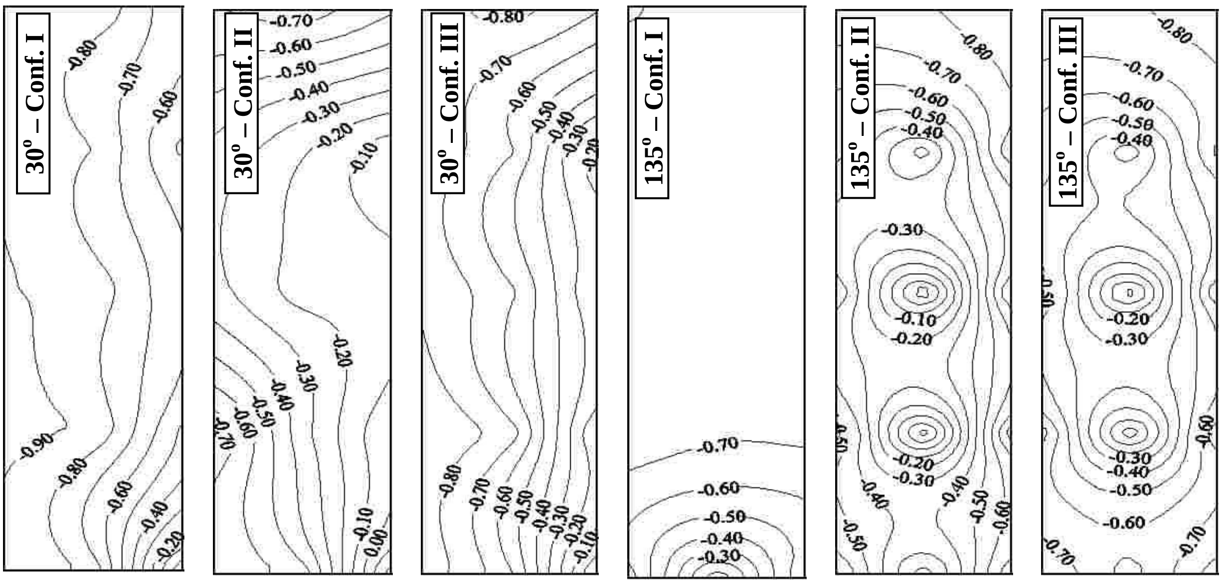

Figure 10. Correlation coefficient contour plots for top and bottom pressure signals (30 and 135 degrees wind direction).

In addition to the results for these two wind directions, the variation of the correlation coefficient versus the wind azimuth for three representative sets of top and bottom pressure taps is presented in Figure 11. The location of these pressure tap pairs is on the corner (pressure taps 1-2), the front edge (pressure taps 13-14) and the patio-to-wall edge (pressure taps 17-18) regions. The results indicate that, in general, Configuration I shows higher correlation values compared to the other two configurations. Moreover, the presence of the patio cover upstream of the actual building results in lower correlation values, especially for the front edge pressure tap sets (1-2 and 13-14). The set of pressure taps located on the patio-to-wall region (17-18) shows the most uniform behavior and least dependent on wind direction.

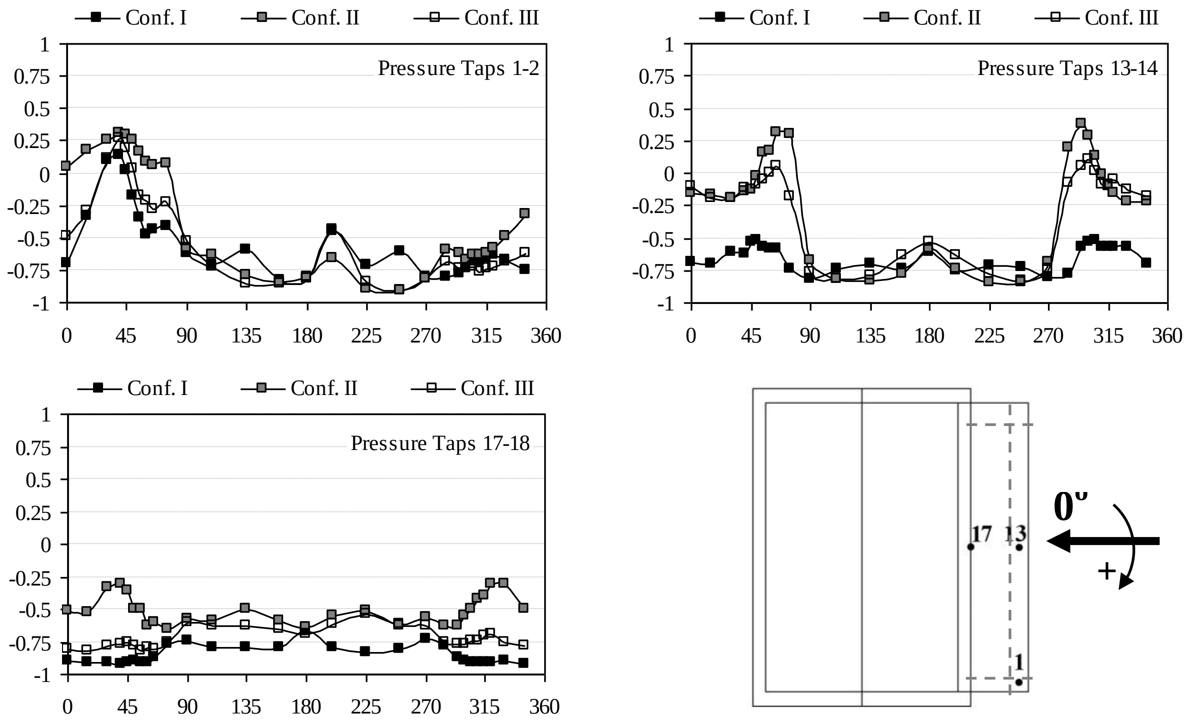

Figure 11. Correlation coefficient variation with the wind direction (pressure taps 1-2, 13-14 and 17-18).

4 SUMMARY AND CONCLUSIONS

Wind-related catastrophes occurred in the recent past were associated with fatalities and excessive amount of damage. The occurrence of these extreme wind phenomena indicates an increasing trend which stresses the importance of wind-induced disaster mitigation measures. Research related to wind-structure interaction is of significant importance when this disaster mitigation is examined. Several wind tunnel and limited full-scale studies have been carried out during the past four decades leading to radical revisions and improvements of national and international wind standards and building codes of practice.

Two of the most recent research projects were initiated due to the lack of appropriate guidance in the wind provisions. The first study examined the effect of structural attenuation in low-rise buildings, as wind-induced loads travel through the superstructure down to the foundation. The second experimental study evaluated the wind load applied to a patio cover attached to a low-rise building. Both findings revealed, for first time, valuable information which can potentially contribute to the development of future building codes.

5 ACKNOWLEDGEMENT

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6 REFERENCES

ABI (2003). The Vulnerability of UK Property to Windstorm damage, London, UK: Association of British Insurers.

Associated Press. < http://www.msnbc.msn.com/id/9281409/>, Retrieved April 2010.

Kareem A. (1984). Wind Speed – Damage Correlation in Hurri-cane Alicia, Hurricane Alicia: One Year Later, Specialty Conference, ASCE – EMD: 81-93. Galveston, Texas.

Munchener Ruck (2006). Knowledge Series, Hurricanes-More intensive, more frequent, more expensive: Insurance in a time of changing risks, 302-04891, Germany: Munich Re Group.

Munchener Ruck (2009). Topics Geo - Natural catastrophes 2009: Analyses, assessments, positions, 302-06291, Germany: Munich Re Group.
NBCC (2005). National Building Code of Canada, National Research Council of Canada (NRC), Ottawa, Canada
Zisis I. (2007). Structural Monitoring and Wind Tunnel Studies of a Low Wooden Building. MASc Thesis, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada.
Zisis, I., Stathopoulos, T., Smith, I., Galal, K. and Doudak, G. (2009). Wind induced structural attenuation in low-rise wood buildings, 11th Americas Conference on Wind Engineering, San Juan, PR, USA.
Zisis, I. and Stathopoulos, T. (2010). Wind-induced pressures on patio covers, J. Str. Eng., Volume 136, No. 9, pp. 1172-1181.