The 2018 World Congress on
Advances in Civil, Environmental, & Materials Research (ACEM18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Keynote Paper

The integration of wind and structural engineering

Ashraf A. El Damatty [1)] and F.Y. Elezaby [2)]

1) Department of Civil and Environmental Engineering, The University of Western Ontario, London, Ontario, Canada
2) T.Y Lin International, Miami, Florida, USA
[1)] damatty@uwo.ca

ABSTRACT

The University of Western Ontario in Canada has been leading the science of Wind Engineering since the sixties of the previous century through the research conducted at the Boundary Layer Wind Tunnel laboratory located at this University. The research capabilities at Western has been augmented recently through the establishment of large-scale testing facilities including the Insurance Lab of Better Himes and the Wind Engineering, Energy and Environment (WindEEE) Institute. The existence of such facilities allows more integration between wind and structural engineering pushing the scope of wind testing into assessment of structural capacities and failure modes. Two extensive research projects geared to design structures that can adapt to extreme wind events are conducted using those facilities and are summarized in this paper. Those projects involve studying the behavior of transmission line structures under tornadoes and downbursts and the behavior of wood houses under hurricanes. Those two types of structures have exhibited in the past severe damages under the considered windstorms. The third project presented in this paper is geared towards achieving sustainable design of tall buildings under wind loads by relying on the structure ductility similar to the approach adopted for years in seismic design of structures.

1. INTRODUCTION

Since the establishment of the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario (UWO), Canada, in the early sixties of the previous century, researchers at this university contributed significantly to the field of Wind Engineering. The BLWTL at UWO, established by Professor Alan Davenport, considered to be the father of Wind engineering, was the first wind tunnel in the world designed for testing buildings. Since its establishment, hundreds of tall buildings and long-span bridges have been tested at the BLWTL.
At an early stage of his research career, Davenport (Isyumov (2012)) established what

[1)] Professor and Chair
[2)] Structural Engineer

is called the Davenport Chain in Wind Engineering, which describes the various steps needed to assess the response of a structure to wind effects. This chain is illustrated in Fig. 1 below:

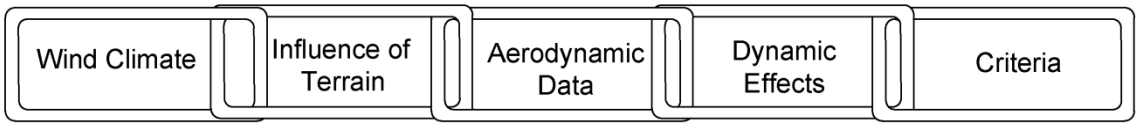


Fig. 1 Davenport Wind Chain

The chain starts by studying the wind climate at the location where the structure is located. This step would lead to an identification of a reference wind speed as well as a distribution of the mean wind velocity. The second link in the chain takes into account the terrain effect influenced by the physical environment surrounding the structure. The terrain can be considered as open, country, sub-urban or urban depending on the surrounding configuration. The wind field is modified based on the type of terrain. Moving from an open to an urban terrain results in reduction in the mean velocity component but introduces more turbulence, which needs to be considered in studying the structure's response. The third link of the chain, which is called Aerodynamic Data, involves the evaluation of the aerodynamic forces acting on the structure due to the applied wind field. At this stage, the structure is assumed rigid and the aerodynamic forces consists of two components; the mean and the background components. The first component is static and results from the mean wind velocity, while the second component varies in a quasi-static manner and is associated with the time-varying turbulence. However, the structure can resonate with the fluctuating turbulence and hence a resonant component is superimposed to the aerodynamic forces, which is calculated in the next link called "Dynamic Effects". Having identified the wind forces acting on the structure, the structural response can be determined. The last step in Davenport's chain involves the establishment of acceptable criteria for the structural response. It should be noted that Davenport established this Wind Chain at a very early stage of his career and spent his life producing knowledge in each link of the chain. Also, researchers all around the world, inspired by this chain, have produced thousands of studies during the past six decades on various aspects related to each link. The photos provided in Fig. 2 provide an illustration of the type of tests that can be conducted in a wind tunnel study as influenced by the Davenport Chain.

In the first two types, the structural model is rigid and the tests are able to simulate the aerodynamic forces associated with the mean and background components. In the first test, only the base shear force and the base overturning moment are measured. The second test involves measuring the pressure on the façade of the building from which the base shear force and the base overturning moment can be calculated as well. Both tests do not capture the resonant component associated with the building dynamic response since the building model is rigid. Following the tests, numerical analysis can be conducted to obtain the resonant component based on the measured quantities and the dynamic characteristics of the structure.

The third type of tests involves a simulation of the building shape (to capture drag forces) as well as the stiffness, mass and damping of the building. This is a full aero-

elastic model, which captures the resonant component of the building response in addition to the mean and background components. Deflections, accelerations and inter-storey drifts can be calculated from the model test results.
Triggered by the problems observed during severe wind storms, research at the UWO in Wind Engineering have evolved significantly during the past two decades. This progress was possible with the advancement of the computational tools in terms of Computational Fluid Dynamics (CFD) coupled with Finite Element Analysis (FEA) as well as the establishment of two unique wind facilities at UWO, which are described below.

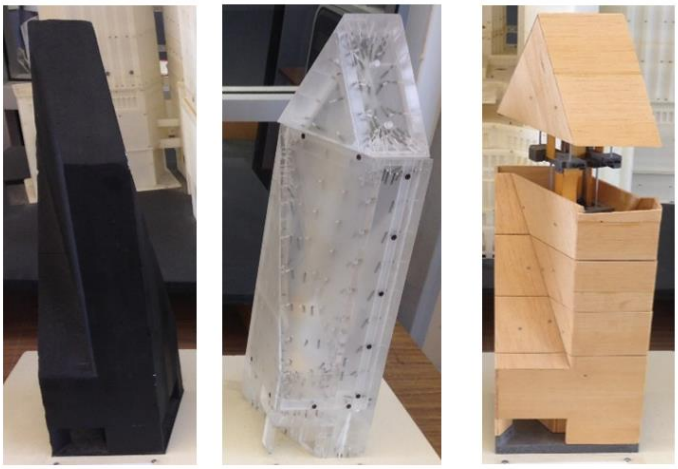


Fig. 2 Different types of Wind Tunnel Tests (a) Force-balance test (b) Pressure test (c) Aeroelastic test.

2. UWO RECENTLY ESTABLISHED WIND TESTING FACILITIES

2.1. Insurance Lab for Better Home (ILBH)

This unique facility (Fig. 3) was established in the early two thousands as a response to the tremendous amount of failures observed for low-rise buildings during hurricane events. The facility allows testing of a full-scale two-storey house under simulated wind loads. The photo in Fig. 3 shows a house that can be moved totally inside the facility. A major type of failure observed during hurricanes result from the uplift pressure acting on the roof. This uplift pressure varies both spatially and temporally. The spatial and time variation of this pressure can be obtained from a wind tunnel test on a small-scale model. The ILBH houses a large number of pressure boxes, which can be used to simulate the spatial and time variations of the uplift wind pressure acting on the roof of a low-rise building. This facility allows observing and studying failure mechanisms, which cannot be studied in a standard wind tunnel.

Fig. 3 Three Little Pigs Facility

2.2. Wind Engineering, Energy and Environment (WindEEE) dome facility

While wind tunnels provide one dimensional wind flow using one large fan, WindEEE can provide a three-dimensional wind field using 106 fans; each can be controlled separately. The facility has a hexagon shape as shown in Fig. 4 with a large number of fans around the perimeter and six large fans at the ceiling. Fig. 5 illustrates the different type of winds that this facility can uniquely produce. By putting two walls inside the hexagon space, a large one-dimensional wind tunnel of a width of 14 m is created allowing testing models under straight wind. The unique capability of this facility is the generation of downbursts and tornadoes. Those events belong to a category of localized windstorms called High Intensity Wind (HIW). They usually occur during thunderstorms. Downbursts result from a jet of cool downdraft of air that impinges to the ground, forms a vortex and produces significant horizontal as well as vertical wind. Tornadoes result from an updraft of hot air that twists and moves upward. Many structural damages have been observed during the past decades due to those localized windstorm events. The mechanism for simulating downbursts at WindEEE involves pressurizing the chamber at the ceiling and then opening its vents together with applying suction at the perimeter, which results in the generation of the downdraft jet of air. The mechanism for creating tornadoes involve rotating the perimeter vent such that the air circulate circumferentially while applying suction at the ceiling.

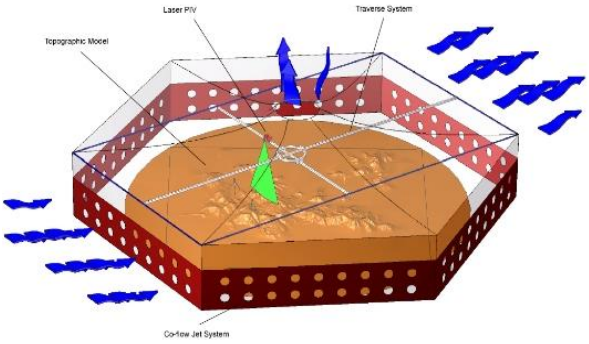
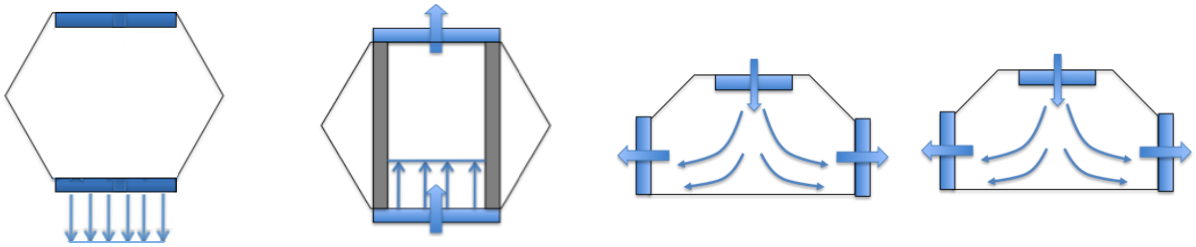


Fig. 4 WindEEE Facility



Straight Closed-Loop Straight Open-Loop Downbursts Tornadoes

Fig. 5 Different types of Wind Generated at WindEEE

3. ADAPTABILTY AND SUSTAINABILTY IN STRUCTURAL WIND ENGINEERING

During the past decades, billions of dollars of financial losses have resulted from severe windstorms, such as hurricanes, tornadoes and downbursts. Some structures, including transmission lines (TLs) and low-rise buildings have exhibited poor performance and were unable to adapt to those storms. Adaptability and sustainability are two key elements that must be addressed in the future design of structures under severe wind loadings. This is particularly important due to the current trend toward increasing both the design wind speed and the structures' height. Therefore, the long-term objective of the research is to evaluate wind loads and their effects on wind-sensitive structures considering their nonlinear behavior and failure modes, culminating in the development of a performance-based design approach under wind loading. Three research project addressing adaptability and sustainability in Structural Wind Engineering are described below.

3.1. Transmission Line (TL) Structures under Downbursts and Tornadoes

As mentioned earlier downbursts and tornadoes belong to a category of windstorms called High Intensity Wind (HIW). It has been reported by Dempsey (1996) that HIW events are responsible for more than 80% of all weather-related TL failures worldwide. The research at UWO on this subject started about twenty years ago following the failures of the Manitoba Hydro towers that happened near Winnipeg in 1996 (McCarthy (1996)). This research was then funded by the company Hydro One, Ontario, as a result of many tower failures that happened at the province of Ontario during downbursts and tornadoes. Other countries that have experienced failures of TLs during HIW events include Australia (Hawes (1993) and Li (2000)), Slovakia (Kanak (2007)), and China (Zhang (2006)).

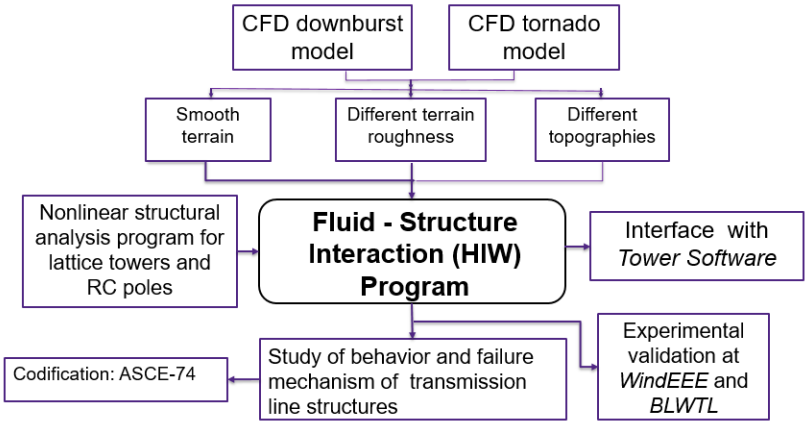


Fig. 6 Research conducted on Transmission Lines under HIW

In the USA, it has been reported by (The White House (2013)) that more than 600 power outages occurred between 2003 and 2012 due to severe weather with economical losses reaching $33 billion. It is apparent that the failure of transmission line structures during HIW events is a worldwide problem.

The conducted research followed the schematic shown in Fig. 6. As shown in the figure, the research consists of various components which interact together in order to achieve the research goals. The first component is the evaluation of the wind fields. The downburst wind field initially relied on a computational fluid dynamics simulation (CFD) conducted by Hangan (2003) and Kim (2007). However, these simulations were limited to the mean component and thus did not include turbulence. Later on, the simulation conducted by Aboshosha (2015), which estimated the turbulence associated with downbursts, was used in the numerical modelling. Shehata (2005) developed a finite element model, which included a simulation of both the towers and multi-span conductors. The wind field obtained from the CFD simulation conducted by Hangan (2003) and then by Aboshosha (2015) was incorporated into the numerical model forming the Software HIW. This model form the basis of many studies conducted on this subject including studying the behavior of guyed (Shehata (2007) and Darwish (2010)), and self-supported (Darwish (2011)) TL systems, and assessing the failure of guyed TLs under downbursts (Shehata (2008)). One of the characteristics of this problem is that it requires conducting a large number of non-linear time history analyses in order to predict the location of the events leading to peak forces in various members of a transmission line structure. Because of the highly non-linear behavior of the conductors and the need for a large number of analyses in the parametric study, the computational time frame to obtain the peak internal forces in a transmission tower due to a HIW event can be significantly high. Accordingly, a semi-analytical solution that can predict the non-linear response of the conductors under a HIW loading, taking into account the non-linearity, sagging and the pretension forces in the conductors as well as the flexibility of the insulators, was developed by Aboshosha (2015a) and Aboshosha (2014). This was incorporated into the numerical model, which significantly increased the efficiency of the software. Regarding tornadoes, Hamada (2010) modified the model developed by Shehata (2005) by replacing the downburst wind field with the

tornado wind developed by Hangan (2008), and thus formed a comprehensive tool for the analysis of transmission line structures under the impact of tornadoes. Hamada (2011) used this model to assess the behavior of guyed transmission line structures under tornadoes in a parametric study similar to that conducted by the same research group under the impact of downbursts. Altalmas (2012) subsequently conducted a similar study on self-supported transmission line structures under tornadoes. Failure studies of individual guyed towers under tornadoes were also conducted by Hamada (2015).

Two major outcomes resulted from this research. The first outcome was the development of a unique structural Software, called “HIW” which can predict the behavior of TL structures under downbursts and tornadoes. The procedure used by the software to determine the critical internal forces acting on the members of transmission tower due to a HIW event is described below:

1. Fig. 7 shows a plan view of a line. In order to estimate the maximum internal forces acting on the tower of interest (Tower A), three conductor spans should be modelled from each side of the tower (according to Shehata (2005)).
2. A parametric study is conducted by moving the location of the HIW event (downburst or tornado) in space. The parameters (R, Dj and θ) define the location of the event. For the downbursts, the value of Dj varies within the practical range of 500 m to 2000 m. For tornadoes, Dj is kept constant depending on the tornado scale using the values specified by the Fujita scale classification. Each HIW configuration will result in a different wind field being experienced by the conductors and the tower of interest.
3. The conductors are first analyzed under the loading resulting from each HIW configuration. The conductors are supported by non-linear springs representing the combined stiffness of the towers and the insulators. The responses of the conductors on the tower of interest are then evaluated and reversed to represent the conductor forces acting on the tower resulting from a specific HIW configuration.
4. The tower of interest is analyzed under the conductor forces in addition to the external loads associated with the specific HIW configuration acting along its height.
5. The member forces are then evaluated, and the peak internal forces obtained from the entire parametric study are subsequently evaluated. It should be noted that for downbursts, a time history analysis is conducted as the wind field varies over time. While for tornadoes, only one analysis is conducted for each configuration as the wind field corresponds to a steady-state and has no time variation. The numerical code was developed to be compatible with the Software “TOWER”, which is widely used by utility companies globally.

The first aero-elastic tests of a multi-span transmission line system under simulated downbursts loading was conducted by Elawady (2017). The results of these tests served to validate the wind field as well as the fluid-structural analysis program developed in the research. By considering many transmission line systems, Elawady (2018) recommended three downburst configurations (load cases), which when considered together, permitted the estimation of the peak internal forces developing in the members of a generic transmission tower. Of those loading cases, Elawady (2016) singled out the “oblique” load case, which caused the maximum longitudinal force acting on a transmission tower. The estimation of this force requires a non-linear analysis of the conductors in a model that takes into account the large deformation,

sagging and pretension force of the conductors, and the flexibility of the insulators. Since this can be a difficult task for practicing engineers, Elawady (2016) developed a set of graphs to be used to estimate such forces. It should be mentioned that those three load cases were examined during the past four years by the ASCE-74 committee responsible for updating of the guidelines pertaining to design loads for transmission line structures. Those load cases are currently in the final considerations for implementation, which will represent the first guidelines in the world to account for downburst loading on transmission line structures. Similar to the case of downbursts, load cases representing the critical effect of tornadoes on generic transmission line structures were developed by El Damatty (2016). Those load cases were subsequently simplified by El El Damatty (2015) and are also in the final stage of implementation in the ASCE-74 guidelines. It should be noted that the tornado studies are focused on F2-tornadoes because the vast majority of observed tornadoes in the world have a scale of F2 or less.

The research is currently progressing by studying the progressive failure for a complete line using a system approach. Tests are currently under preparation to simulate tornadoes acting on transmission line models as well as the study of the progressive collapse of a line experimentally. In addition, the research is moving towards considering the analysis using a probabilistic approach.

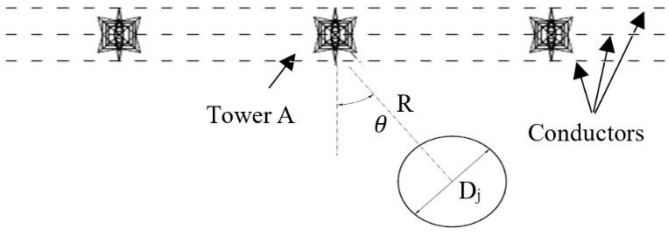


Fig. 7 Transmission line system

3.2. Wooden Houses under Hurricane Loads

Light frame wood houses, especially located in hurricane-prone areas, have a potential of serious damages during strong wind events. One of these damages is primarily due to the wind uplift forces generated on the roofs of wood houses. This wind uplift force or suction pressure tends to detach roof trusses from the supporting walls due to the failure of wood connections to resist the tension forces created by this pressure. In the wood roof skeleton, there are two critical wood connections: roof-to-wall connections (RTWCs) and sheathing-to-truss connections (STTCs) (Jacklin (2014)). These connections resist the suction pressure through their withdrawal capacity, which varies depending on the penetration depth of the nails, the diameter of the nails and wood material conditions. The main concern of this research is the RTWCs with focus to understand how these connections transfer the suction pressure and to come up with an efficient procedure to eliminate possible failure.

One of the previous full-scale experiments used to investigate the behavior of toe-nail connections under simulated wind load was carried out by Morrison (2012). In this experiment, a two-story gable roof house was tested at the Insurance Research Lab for Better Homes (IRLBH) located at the University of Western Ontario. The dimensions of this house was 9 m by 9 m with a roof slope of 1:3 using 16 trusses spaced by 0.6 m, and a roof overhang of 0.5 m in each direction. Each toe-nail RTWC consisted of three

twisted shank nails, either 12d or 16d. The wind load varied spatially and temporally through the utilization of 58 pressure bags that covered the entire roof. The house was tested under mean wind speeds starting at 20 m/sec and increasing by 5 m/sec increments to the point of complete roof failure under 45 m/sec. At each stage of loading, displacement at each RTWC was evaluated to examine at which stage permanent withdrawal had occurred. This test was numerically modelled by Dessouki (2010) where three-dimensional frame elements were used for modelling the trusses, and stud walls while shell elements were used for modelling the plywood sheathings. The nonlinearity of the model was concentrated at the RTWCs, which were modelled as nonlinear springs with load-deflection curves obtained from Reed (1997).

Fig. 8 provides a comparison of the experimental results obtained by Morrison (2012) and the numerical deflection predictions by finite element model with respect to the deflection of all of the RTWCs. The comparison was carried out at applied pressures of wind velocities of 30 m/sec and 35 m/sec. In this range of velocities, the RTWCs start to exhibit inelastic behavior. The nonlinear analysis was performed in a quasi-static time history manner with 1000 time steps. As shown in Fig. 8, good agreement exists between the experimental deflections and the predicted deflections for all RTWCs. The maximum differences between the experimental and the numerical deflection values are 0.3 mm and 0.4 mm for wind velocities of 30 m/sec and 35 m/sec respectively.

By identifying the problem of toe-nail RTWCs, retrofitting techniques were introduced in order to increase the toe-nails RTWCs withdrawal capacity. Some of those techniques involve strengthening of the existing RTWCs through installing hurricane straps. However, these internal techniques are costly and difficult to apply; as they require eliminating the non-structural elements that cover toe-nails RTWCs. A new retrofit technique (Fig. 9) was developed by the author and his research team. The proposed retrofitting system consists of wire cables resting on the top skin of the roof. The wire cables are connected to rigid rods along their edges. The rods are attached to a number of cables (guys) that are in turn connected to small piles anchored to the ground. The cables are stretched by applying a prescribed pre-stressing force through a special loading system. The uplift behavior of the house can be improved through two mechanisms: a) a downward force will be transferred from the cables to the rigid rods to the wires and finally to the roof structure. This downward force will counter balance the uplift force resulting from the strong wind occurring during the storms, b) part of the uplift force will be transferred to the ground though the wires, cable, and pile system. This will reduce the uplift force acting on the connections and will mitigate the failure of those connections. The system will be designed such that the wires remains folded during the normal wind conditions in order to not compromise the aesthetics of the house. Warnings are usually given prior to the occurrence of the windstorms. This will allow installing the system before the wind event.

The validation of this retrofitting system followed three stages. First, the numerical model developed and validated by Dessouki (2010) is extended to include the proposed retrofitting system and the up-lift behavior of full-scale houses with and without the retrofit technique is assessed. Second, structural tests are conducted on a full-scale portion of a house with and without the retrofit system. Third, wind tests are conducted on a one-third scaled model of a full house at the WindEEE facility.

Regarding the numerical model, the rigid bars were modelled as frame elements. The bearing and external cables were modelled as cable elements. The pretension of the retrofit system was simulated by applying target force to the external cables, ensuring an initially taut system. The numerical model predicted the highest mean hourly wind velocity that the structure can withstand before application of the retrofitting system to be 38 m/sec. After this wind velocity, the roof structure became unstable as progressive failure of the RTWCs occurred. The retrofitting system reduced the average deflection of the RTWCs under this pressure distribution by a factor of three, as shown in Fig. 10, resulting in a 45% reduction in the total uplift force transferred by the RTW connections. Regarding the structural tests, a segment of gable-roof house consisting of three typical trusses spanned 9 m and spaced 0.6 m apart with a roof slope of 1:3 was considered. This experiment was conducted by applying simulated uplift wind load with the use of hydraulic jack under two conditions; with and without the retrofit system as shown in Fig. 11. It was concluded that the application of the retrofitting system increases the withdrawal capacity of RTWCs by 40%. The last experiment conducted was the destructive testing of a small-scale light frame wood house. The dimension of this prototype was 3 m by 3 m and it consisted of four typical trusses spaced 1 m from each other. The cross sections of the trusses, the sheathings, and the lateral bracing members were selected based on the assumption that the levels of stress in the prototype members are equivalent to the levels of the stresses in a typical full-scale residential wood frame structure. The stress level was defined as the ratio between the applied stresses in the member and the maximum strength of the member. The RTWCs were also scaled down to be 2D common nails. This prototype was constructed in order to evaluate the capacity of toe-nails connection under a real wind load generated from the Wind Engineering Energy and Environment (WindEEE) Dome at the University of Western Ontario. The prototype was tested with and without the application of the retrofitting system as shown in Fig. 12. It was observed that without the retrofitting system, failure of the RTWCs occurred at mean wind speed of 30 m/sec. After the application of the retrofitting system, and at a maximum fan speed of 36 m/sec, the prototype did not show failure of RTWCs. Fig. 13 shows the load sharing between the RTWCs and the retrofitting system.

To find the optimum design of the retrofitting system components, an optimization tool is developed where the finite element and the genetic optimization techniques are utilized. The design variables in the optimization tool are: (1) Bearing Cable Arrangement, (2) External Cable Arrangement, (3) External cable diameter, (4) External cable inclination angle, (5) Bearing cable diameter, (6) Rigid bar cross section, and (7) Pretension force on external cables. The material cost of the retrofit system components is chosen to be the objective function in the optimization tool. The optimization tool includes constraints on the internal forces developed in the bearing and external cables and rigid bars. In addition, a constraint is included on the tensile forces developed on the RTWCs such that they do not exceed the ultimate capacity of the connection.

The research is currently progressing by developing a closed-form solution model to evaluate the distribution of the uplift wind loads on the supporting trusses with and without the retrofitting scheme. In addition, Monte-Carlo simulations are included to study the effects of RTWCs variability.

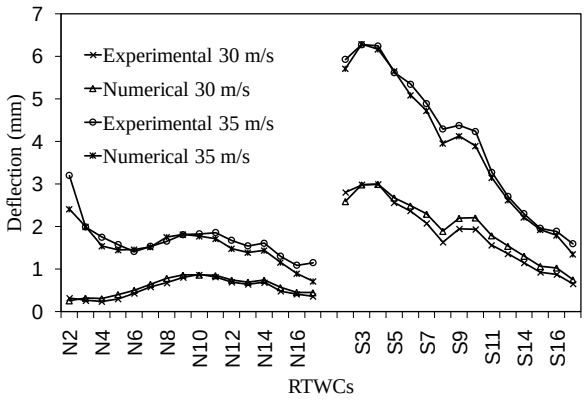


Fig. 8 Deflection values of RTWCs under maximum uplift pressure for wind velocities of 30 m/s and 35 m/s

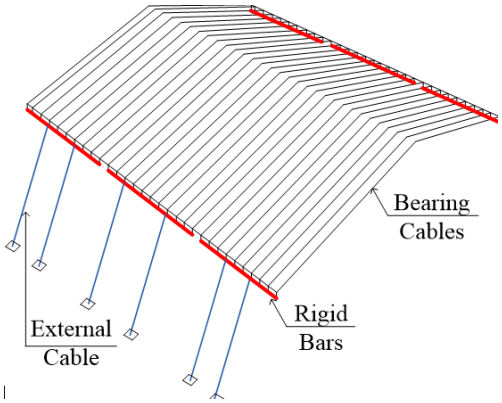


Fig. 9 Retrofitting system proposed by Jacklin (2014)

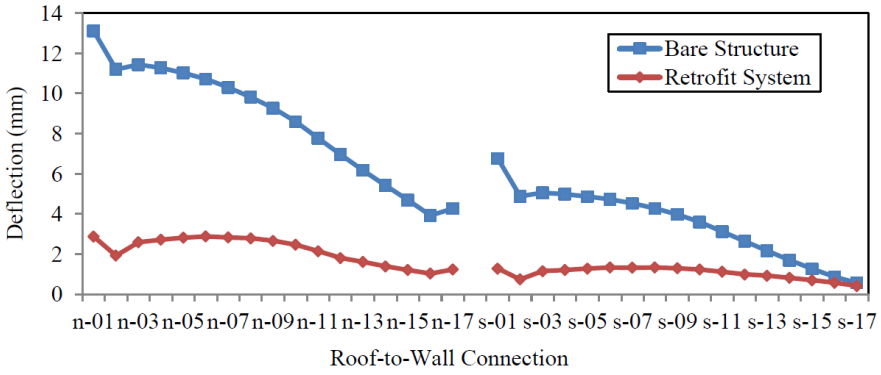


Fig. 10 Deflection of the RTWCs under 38m/sec wind loading

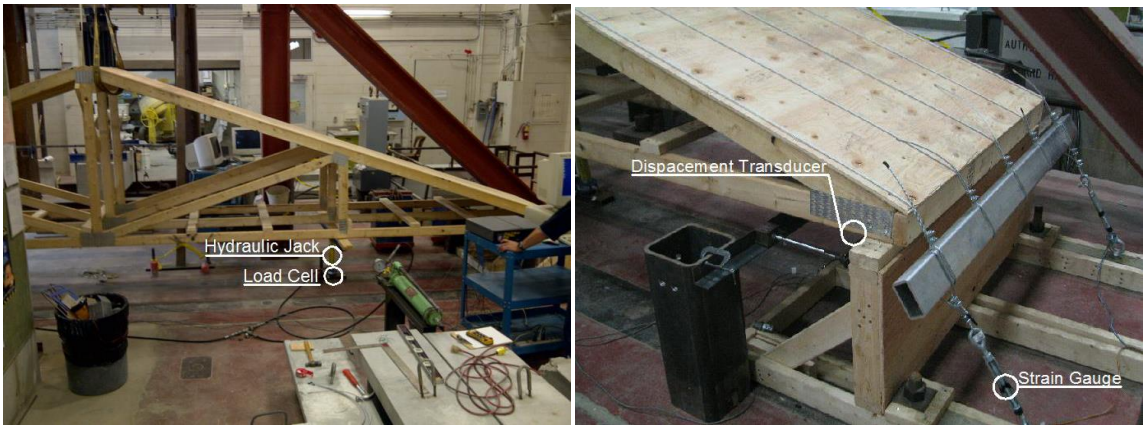


Fig. 11 Structural tests experimental setup

Fig. 12a WindEEE small-scale house tested without the retrofitting system

Fig. 12b WindEEE small-scale house tested with the retrofitting system

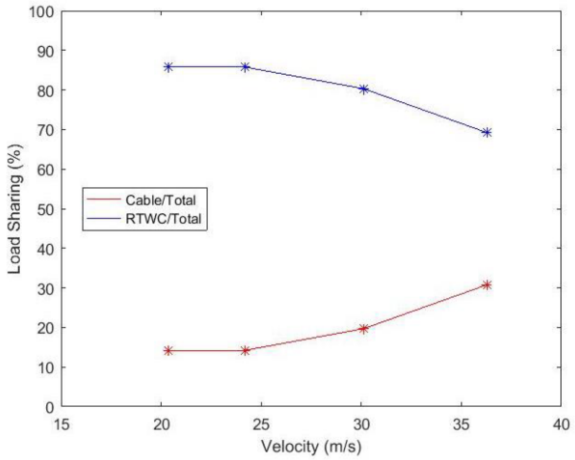


Fig. 13 WindEEE experiment load sharing of RTWCs and retrofit system

3.3. Non-Linear Behavior and Ductility of Buildings under Wind Loads

The wind design of buildings is based on an elastic approach in order to achieve strength and serviceability criteria. Recent trends and modern architectural requirements have pushed towards developing increasingly taller and irregularly-shaped complex buildings, leading to structures that are potentially more susceptible to wind excitations. This, together with the trend of increasing the return period design wind speed, require developing a performance-based technique as an alternative design method. Similar to what is applied in seismic design, inelastic behavior and dynamic effects of the natural hazard are to be considered explicitly in such an approach.

To date, there have been several proposed frameworks for performance-based wind design according to Van (2009), Ciampoli (2011), and Griffis (2012). Bakhshi (2011) performed nonlinear analyses of 20 to 40- story steel frame buildings in a parametric

study comparing earthquake and wind loads, at strength-level hazard intensity. Gani (2012) predicted the nonlinear response of single-degree-of-freedom (SDOF) models using a spectral stochastic method, exhibiting simple behavior (elastic, perfectly-plastic, and bilinear with strain hardening). The previously mentioned studies focused on proposing probabilistic approaches for performance-based wind engineering. Inherent ductility in the structure members has not been explicitly considered before in a defined framework.

This research investigates the application of a ductility-based design approach in wind engineering similar to that applied in earthquake design. Two reasons have triggered the investigation of this ductility-based concept under wind loads. First, there is a trend in the design codes to increase the return period used in wind design approaching the large return period used in seismic design. Second, the structure always possesses a certain level of ductility that the wind design does not benefit from. The load reduction factor that could be applied in wind design might not be as high as its counterpart in seismic design, and it should be applied only on the resonant component of the wind loading. Many technical issues arise when applying a ductility-based approach under wind loads. The usage of reduced design loads will lead to the design of a more flexible structure with larger natural periods. While this might be beneficial for seismic response, it is not necessarily the case for the wind response, where increasing the flexibility is expected to increase the fluctuating response. This particular issue is examined by considering a case study of a sixty-five-storey high-rise building previously tested at the Wind Tunnel Laboratory at the University of Western Ontario using a pressure model.

A three-dimensional finite element model is developed for the building. The wind pressures from wind tunnel testing of a rigid model of the building are applied to the finite element model and a time history dynamic analysis is conducted. The time history variation of the straining actions on various structure elements of the building are evaluated and decomposed into mean, background and fluctuating components. A reduction factor is applied to the fluctuating components and a modified time history response of the straining actions is calculated. The building components are redesigned under this set of reduced straining actions and its fundamental period is then evaluated. A new set of loads is calculated based on the modified period and is compared to the set of loads associated with the original structure. This is followed by a non-linear static pushover analysis conducted individually on each shear wall module after redesigning these walls. Displacement-controlled pushover analysis is carried out to assess the ductility demand of shear walls with reduced cross sections to justify the application of the load reduction factor “R”.

A photo of the wind tunnel test conducted on the on a compound that includes the studied building is shown in Fig. 14.

The plan view of the considered building is shown in Fig. 15. A brief summary of the results of this study is provided below. Table 1 shows the results for one of walls. It shows the total moment before reduction and the value of the resonant component before and after the reduction by the load factor R=2. Based on the value of the reduced moment, it was possible to reduce the thickness of the wall from 35 cm to 28 cm. Similar reductions were achieved for the rest of the walls. The results of the free vibration before and after the reduction of the walls are shown in Table 2. Those results indicate that the increase in the natural period due to the reduction of the walls is not

significant. Table 3 shows the results of the base shear forces for three stages. The first stage is the base shear corresponding to original dimensions. The second stage is the base shear after reducing the resonant component by a load reduction factor R=2. The third stage is the base shear based on the dynamic analysis of the reduced cross sections. The change in the base shear from stage 3 to 2 is not significant. The results of push over analysis of the building with reduced cross sections show a ductility demand values between 1.17 and 1.3. Also, the results show that target performance levels reached for ductile shear walls are mainly in the Immediate Occupancy (IO) range.

Fig. 14 Wind tunnel test for a tall building in a compound.

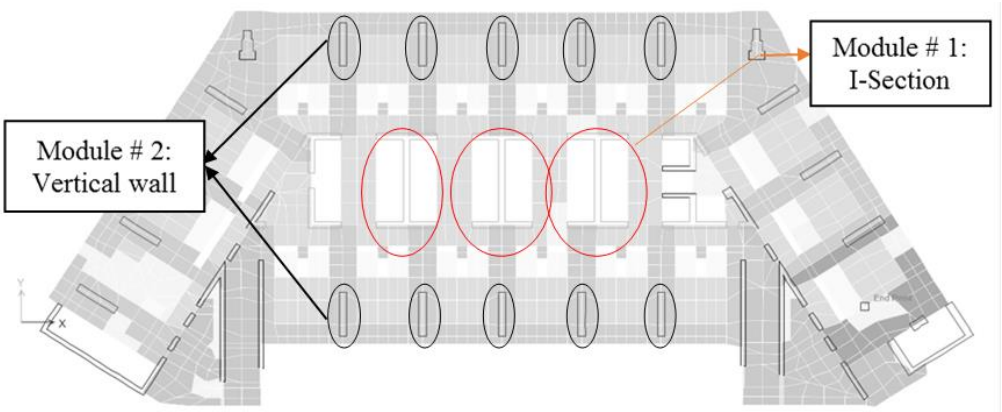


Fig. 15 Plan view of the considered building

Table 1: Summary of reduction procedure on shear walls' straining actions.

Bending moments on Shear Walls:		**(R = 2)**
Module # 1: I-Section	(Thickness = 35 cm)	
Total Moment =	**448626**	kN.m
Quasi-Static (M +BG) =	258982	kN.m
Resonant =	189644	kN.m
Reduced Resonant =	94822	kN.m
New Moment Applied =	**353804**	kN.m
Section is reduced from 35 cm to 28 cm		

Table 2: Modal analysis results before and after reduction.

Modal Analysis Results before reducing cross section					Modal Analysis Results after reducing cross sections				
Mode	Period	UX	UY	RZ	Mode	Period	UX	UY	RZ
	sec					sec			
1	10.882	5.9	10.6	83.5	1	11.563	6.4	5.6	88
2	10.376	0	88.5	11.5	2	10.956	0	93.7	6.2
3	7.38	93.9	0.9	5.2	3	7.527	93.5	0.6	5.9
4	2.657	2.1	12.7	85.2	4	2.909	3.9	2.3	93.8
5	2.557	3.4	82.7	13.9	5	2.71	1.5	95.4	3.1
6	2.198	94.1	4.6	1.2	6	2.268	94.3	2.3	3.4
7	1.21	43.7	1	55.3	7	1.287	4.1	0.3	95.5
8	1.13	16	63.1	20.9	8	1.207	50.5	48.2	1.3
9	1.045	40.2	35.9	23.9	9	1.14	45.2	51.4	3.3
10	0.752	65.7	0.6	33.7	10	0.779	54.7	0.3	44.9

Table 3**:** Base Shear values before and after reduction.

	Structure with initial cross sections, V_T (t)	**Reduced applied load –$V_{T\text{-}I}$ (t) = (V_M+V_{BG}+V_R/2)**	**Structure with reduced cross sections, $V_{T\text{-}II}$ (t)**
Base Shear V_X (kN)	18170	15715	15435
Base Shear V_Y (kN)	32200	26760	24940
DAF for V_x	1.37	-	1.33
DAF for V_y	1.51	-	1.44

4. CONCLUSIONS

This paper summarizes three large projects at the University of Western Ontario in Wind and Structural Engineering. The first project focuses on assessing the behavior of transmission line structures under tornado and downburst loadings. This research is triggered by the tremendous number of failures of transmission line structures that occurred around the world during such events. The research covered various aspects of this problem including the development of the wind fields of those events and the development of numerical tool that simulates the structural behavior of the towers and conductors under those wind fields. The numerical models were validated using the results of the unique experiments conducted at the three-dimensional wind facility, WindEEE. Two major outcomes resulted from this research that will be beneficial for the utility community worldwide. The first is the development of a unique software that can predict the peak internal forces in a transmission tower under spatially variable downburst and tornado events. The second is the development for the first time of load cases that simulate the critical effect of those windstorms on a generic transmission line system which are currently in the final implementation in the ASCE-74 guidelines. The research is currently progressing by considering the progressive failure of an entire line in order to develop a performance based design approach for such structures.

The second project assesses the performance of the roofs of wood houses under uplift pressure. This research is triggered by a common type of failure of roof to wall connections observed during major hurricanes in various locations around the world. The research involved characterization of the uplift pressure using full-scale testing conducted at the Insurance Lab of Better Home at the University of Western Ontario. The results of this unique test are used to validate a three-dimensional finite element model. The research progressed by developing a simple technique for upgrading the uplift resistance of the roofs by developing another load path for the transfer of the wind forces to the ground. The validation of the proposed retrofitting system is conducted though full-scale structural tests of components and reduced-scale wind test of a full house conducted at WindEEE. The results reveal an excellent performance of the retrofitting system. An optimization routine is coupled with the finite element model in order to optimize the design of the retrofitting system in order to achieve maximum performance with minimum cost. The research is progressing by developing a closed-form solution for this up-lift problem, with and without the retrofit system, taking into account the variability of the connection properties using Monte-carlo simulations.

The third project investigates for the first time the usage of a ductility design approach in Wind

Engineering similar to what was applied for many decades in Earthquake Engineering. A real high-rise building that was previously tested at the Wind Tunnel at the University of Western Ontario was considered. The wind forces associated with the mean, background and resonant components were evaluated. The resonant component was reduced by a load reduction factor of 2. The building vertical elements were redesigned under the reduced set of loading resulting in reduced wall thicknesses. Push over tests were conducted to assess the ductility demand of various walls and comparisons were made with the target performance levels. The results indicate that with a load reduction factor of 2, the building performance is mainly in the immediate occupancy range. The results indicate that the applicability of a ductility design approach in wind engineering is very promising.

ACKNOWLEDGEMENTS

The author gratefully acknowledges Hydro One Ontario, Steelcon Engineering, the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ontario Centers of Excellence (OCE) for the financial support provided for this research. The author is grateful for the data and information provided by El Dar Group and the Boundary Layer Wind Tunnel laboratory (BLWTL).

REFERENCES

Aboshosha, H. and El Damatty, A.A., (2014), "Effective technique to analyze transmission line conductors under high intensity winds", *Wind and Structures, An International Journal*, Vol. 18, pp. 235–252.

Aboshosha, H., Bitsuamlak, G. and El Damatty, A.A., (2015). "Turbulence characterization of downbursts using LES". *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 136, pp. 44-61.

Aboshosha, H. and El Damatty, A., (2015a), "Engineering method for estimating the reactions of transmission line conductors under downburst winds", *Engineering Structures*, Vol. 99, pp. 272–284.

Altalmas, A., El Damatty, A. A. and Hamada, A., (2012), "Progressive failure of transmission towers under tornado loading", *Proceedings of the 3rd International Structural Specialty Conference (CSCE)*, Edmonton, Canada.

Bakhshi, A. and Nikhbakht, H. (2011), "Loading pattern and spatial distribution of dynamic wind load and comparison of wind and earthquake effects along the height of tall buildings." In Proceedings of the 8th International Conference on Structural Dynamics (Eurodyn), July 4-6, Leuven, Belgium.

Canadian Wood Council and Canadian Standards Association, (2010), "Wood design manual 2010: The complete reference for wood design in Canada", Ottawa.

Ciampoli, M.. Petrini, F. and Augusti, G., (2011a), "Performance-based wind engineering: towards a general procedure", *Structural Safety*, Vol. 33(6), pp. 367–78.

Darwish, M.M., El Damatty, A.A. and Hangan, H., (2010), "Dynamic characteristics of transmission line conductor and behaviour under turbulent downburst loading". *Wind and Structures, an International journal*, Vol. 13(4), pp. 327-346.

Darwish, M.M. and El Damatty, A.A., (2011). "Behaviour of self-supported transmission line towers under stationary downburst loading". *Wind and Structures, an International journal*, Vol. 14(5), pp. 481-498.

Dempsey, D. and White, H., (1996), "Winds wreak havoc on lines", *Transmission and Distribution World*, Vol. 48(6), pp. 32-37.

Dessouki, A. A. (2010), "Analysis and retrofitting of low rise houses under wind loading", Master Thesis, University of Western Ontario, London, ON, Canada.

Elawady, A. and El Damatty, A.A., (2016), "Longitudinal force on transmission towers due to non-symmetric downburst conductor load", *Engineering Structures*, Vol. 127, pp. 206-226.

Elawady, A., Aboshosha, H., El Damatty, A.A., Bitsuamlak, G., Hangan, H. and Elatar, A., (2017), "Aeroelastic testing of multi-spanned transmission line subjected to downbursts", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 169, pp. 194-216.

Elawady, A. and El Damatty, A.A., (2018), "Critical load cases for lattice transmission line structures subjected to downbursts: economic implications for design of transmission lines", *Engineering Structures*, Vol. 159, pp. 213-226.

El Damatty, A.A., Hamada, M. and Hamada, A., (2015), "Load cases for transmission line structures", 14th International Conference on Wind Engineering (ICWE14), Brazil, June.

El Damatty, A.A. and Hamada, A., (2016), "F2 tornado velocity profiles critical for transmission line structures", *Engineering Structures*, Vol. 106, pp. 436–449.

Gani, F., and Legeron, F., (2012), "Relationship between specified ductility and strength demand reduction for single degree-of-freedom systems under extreme wind events." *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 109, pp. 31–45.

Griffis, L., Patel, V., Muthukumar, S. and Baldava, S., (2012), "A framework for performance-based wind engineering" *ATC & SEI Conference on Advances in Hurricane Engineering*.

Hamada, A., El Damatty, A.A., Hangan, H. and Shehata, A.Y., (2010), "Finite element modelling of transmission line structures under tornado wind loading". *Wind and Structures, an International Journal*, Vol. 13, pp. 451–469.

Hamada, A. and El Damatty, A.A., (2011), "Behaviour of guyed transmission line structures under tornado wind loading", *Computers and Structures*, Vol. 89(11-12), pp. 986-1003.

Hamada, A. and El Damatty, A.A., (2015), "Failure analysis of guyed transmission lines under F2 tornado event", *Engineering Structures*, Vol. 85, pp. 11-25.

Hangan, H., Roberts, D., Xu, Z., and Kim, J., (2003), "Downburst simulation. Experimental and numerical challenges", Proceedings of the 11th International Conference on Wind Engineering, Lubbock, TX, USA.

Hangan, H. and Kim, J., (2008), "Swirl ratio effects on tornado vortices in relation to the Fujita scale", *Wind and Structures, an International Journal*, Vol. 11, pp. 291–302.

Hawes, H., and Dempsey, D., (1993), "Review of recent Australian transmission line failures due to high intensity winds", Proceedings of the Task Force of High Intensity Winds on Transmission Lines, Buenos Aires.

Isyumov, N., (2012), "Alan G. Davenport's mark on wind engineering", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 104-106, pp. 12-24.

Jacklin, R.B., El Damatty, A.A. and Dessouki, A.A., (2014), "Finite-element modelling of a light-framed wood roof structure", *Wind and Structures, an International Journal*, Vol. 19(6), pp. 603-621.

Kanak, J., Benko, M., Simon, A., and Sokol, A., (2007), "Case study of the 9 May 2003 windstorm in southwestern Slovakia", *Atmos. Res.*, Vol. 83, pp. 162-175.

Kim, J., and Hangan, H., (2007), "Numerical simulations of impinging jets with application to downbursts", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 95(4), pp. 279-298.

Li, C.Q., (2000), "Stochastic model of severe thunderstorms for transmission line design", *Probabilistic Engineering Mechanics*, Vol. 15(4), pp. 359-364.

McCarthy, P. and Melsness, M., (1996), "Severe weather elements associated with September 5, 1996 hydro tower failures near Grosse Isle, Manitoba, Canada", Manitoba Environmental Service Centre, Environment Canada.

Morrison, M. J., Henderson, D. J. and Kopp, G. A., (2012), "The response of a wood-frame, gable roof to fluctuating wind loads", *Engineering Structures*, Vol. 41, pp. 498-509.

Reed, T. D., Rosowsky, D. V. and Schiff, S. D., (1997), "Uplift capacity of light-frame rafter to top plate connections", *Journal of Architectural Engineering*, Vol. 3(4), pp. 156-163.

Shehata, A.Y., El Damatty, A.A. and Savory, E., (2005), "Finite element modelling of transmission line under downburst wind loading", *Journal of Finite Element in Analysis and Design*, Vol. 42(1), pp. 71-89.

Shehata, A.Y. and El Damatty, A.A., (2007), "Behaviour of guyed transmission line structures under downburst wind loading", *Wind and Structures, an International Journal*, Vol. 10(3), pp. 249-268.

Shehata, A.Y., and El Damatty, A.A., (2008), "Failure analysis of a transmission tower during a microburst", *Wind and Structures, an International Journal*, Vol. 11(3), pp. 193-208.

The White House, (2013), "Economic benefits of increasing electric grid resilience to weather outages", Executive Office of the President, Washington; Retrieved from http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf

Van de Lindt, J. and Dao, T., (2009), "Performance-based wind engineering for wood-frame buildings", *Journal of Structural Engineering* 9445 (November 2003).

Zhang, Y., (2006), "Status quo of wind hazard prevention for transmission lines and countermeasures", *East China Electric Power*, Vol. 34(3), pp. 28-31.