Hindcasting the damage of Ottawa-Gatineau tornado outbreak of September 2018: a coupled CFD and FEA computational approach

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1. Introduction

The recent Ottawa-Gatineau tornado outbreak of September 2018 caused 23 injuries, damaged over 2000 houses and electrical infrastructure causing a power outage that affected over 200,000 people for days following the storm. Dunrobin was identified as one of the worst hit neighbourhoods in the aftermath of the event. A closer look of the damage pictures from Dunrobin revealed that some houses in the neighborhood performed better than the others. Figure 1 shows the case-study neighbourhood before and after damage. This raises the following questions: was there a certain feature in the structural design of those houses that prevented their collapse? Or was it a mere coincidence that those structures were positioned in a way that they got shielded from the effect of intense winds?

There are various wind damage assessment analysis studies of low-rise light-timber structures on tornados, such as the studies by Thampi et al. (2011), Kumar et al. (2012), Peng et al. (2016), He et al. (2017). Nevertheless, limited information is available on the characteristics of tornado wind field near the ground and the damage. In this study a Computational approach comprising computational fluid dynamics for tornado simulation and Finite Element Analysis for structural modeling has opted to explain some of the damage patterns observed in Dunrobin. To this effect, a preliminary study has been conducted with the following objectives (i) replicating the Dunrobin tornado wind field using CFD to accurately model the exposure and its aerodynamic interaction with the buildings in the neighborhood, (ii) conducting a detailed finite element analysis (FEA) of certain representative buildings along the tornado path. The specific buildings that are being investigated are shown in Figure 1. A more detailed study is underway.

Before damage (South-view) After damage (South-view) After damage (West-view)

Figure 1: *Aerial view of case-study neighbourhood before and after tornado damage*

2. Tornado Modeling

In the first stage of the study, the vortex size, tangential velocity, line of center, translation speed and direction are inferred from evidence based on damage patterns, post damage reports, video footage from security cameras and recollection of events from witnesses since there are no radar measurements available. Ideally, wind speed measurements from doppler radar would be required to match the velocity profiles or at the very least the location of maximum velocity in the simulated vortex. However, due to the absence of such data (at least during the study period), visual appearance of the vortex from video footages and pictures of the tornado were used to aid in qualitatively matching the flow-structure. For instance, video footage as shown in Figure 3 indicates a more "turbulent and fuzzy" looking vortex which is a characteristic of multi-cell structures achieved at higher swirl ratios as opposed to "laminar looking" single cell structures at low swirl ratios. As a result, a vortex of appropriate size and swirl ratio of 0.75 was simulated to match the appearance. Such vortices have multiple "pressure hotspots" due to the presence of sub-vortices within the main vortex that can cause increased damage to buildings as seen in Figure 3.

Further, since the Dunrobin tornado was rated EF3, wind speeds in the near ground region (5-20 m) are targeted to be in the range of 62.5m/s to 73.5 m/s (3-s gust). The tornado size from the damage is estimated to be in order of 200-250 m, therefore the size of the simulated vortex is targeted to be in that range as well. Figure 3 shows that the maximum wind speeds for the simulated vortex at 5m-20 m above ground level are in the range of 68-74 m/s and its radius is about 110 m (220 m in diameter). At this stage of the study, Large Eddy Simulations (LES) of stationary vortex of different sizes (175m-250m) are conducted for various locations of the vortex center following the method discussed in Gairola and Bitsuamlak (2019). Details of These stationary tornado simulations are used to aid in matching the wind field and designing proper mesh for more robust translating vortex simulations. In the next stage, simulations of translating vortex over the Dunrobin neighborhood will be conducted to obtain the wind loads.

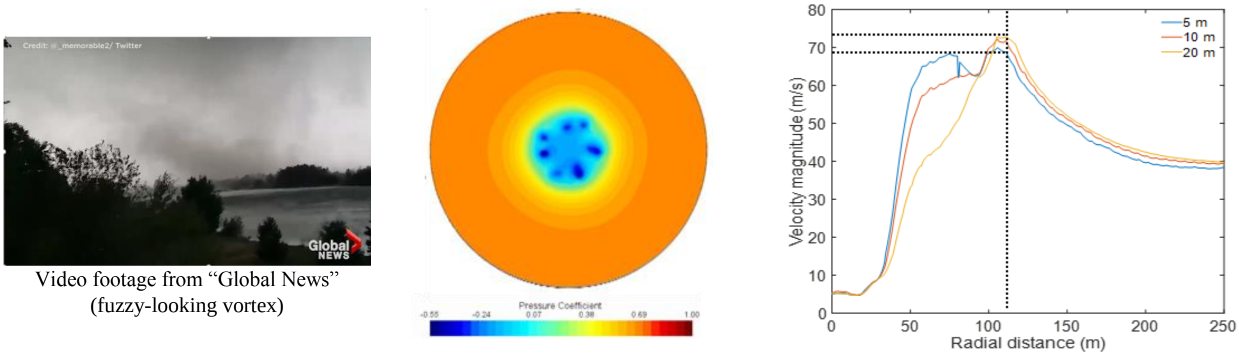
Manitoba, 2007

CFD (smooth-looking, single cell, low swirl ratio of 0.2)

El-Reno, 2013

CFD (fuzzy-looking, multi-cell, high swirl ratio of 0.7)

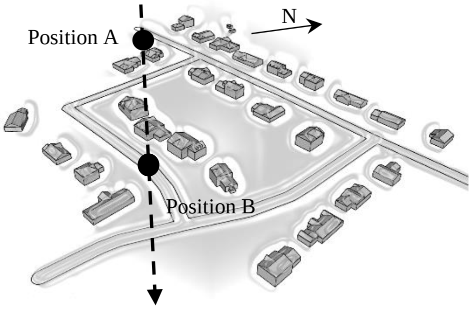
Figure 2: *Control of swirl-ratio to obtain the specific type of tornado from media sources*



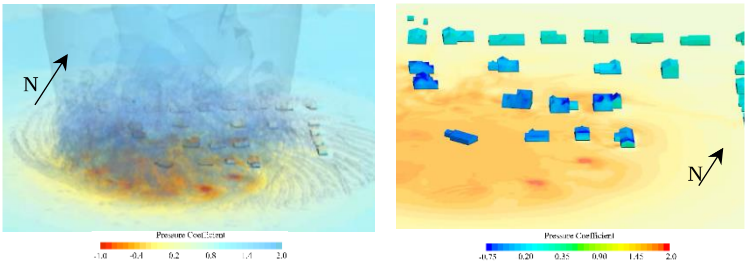
Video footage from "Global News" (fuzzy-looking vortex)

Pressure hot-spots in multiple-vortex

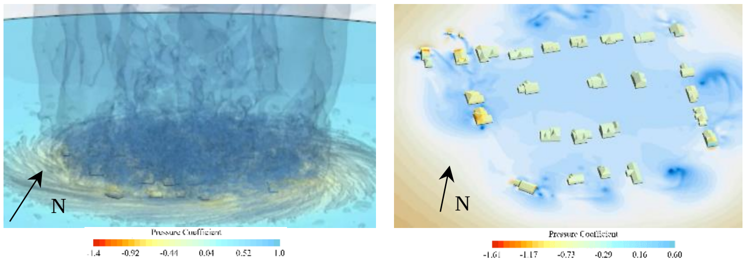
Figure 3: *Identification of multi-cell vortex tornado that most likely happened in the case-study*



Dunrobin neighbourhood with approximate tornado path and two static cases tornado center at Position A and B



Tornado center at Position A

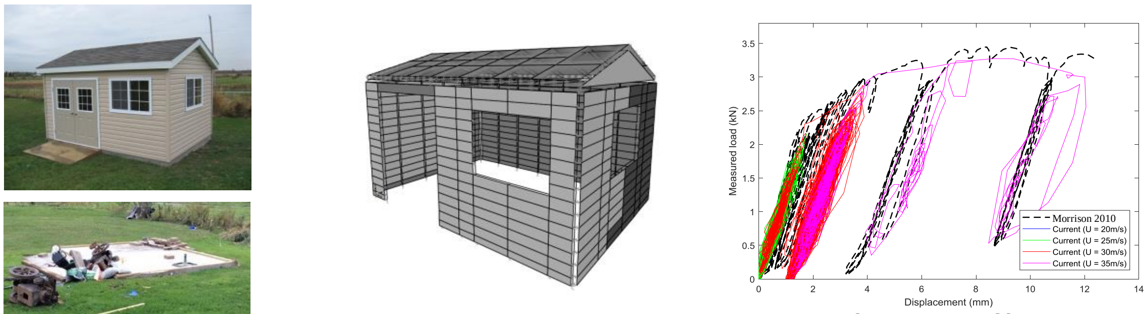


Tornado center at Position B

Figure 4: *Neighbourhood model and two stationary positions of simulated tornado*

3. Damage Modeling

In the second stage of this study, a detailed finite element analysis (FEA) of the representative buildings in the neighbourhood is conducted to analyze their structural design and response to the numerically generated load time histories obtained from the CFD simulation. Structural aspects such as connections, structural redundancy, load path and load direction (lateral or uplift) play an important role in the performance of houses during tornados. The garden-shade was the first structure modeled to calibrate the finite element modeling scheme as well as explain why the observatory stood the tornado load while the garden-shade was fully damaged. The picture of the garden-shade and its FEA model are shown in ***Figure 5***. Damage surveys in the past have shown that connections are the weakest components of light-timber structures. In the current stage of the study, sheathing-to-purlin connection (STPC), roof-to-wall-connection (RTWC), and wall-to-foundation-connection (RTFC), are considered to fail.



Garden-shade

FEA model of garden-shade

Non-linear RTWC calibration after Morrison 2010's tests

Figure 5: *FE modeling of the garden shade with non-linear roof-to-wall-connection (RTWC) behavior*

The FEA model was built using commercial software SAP2000. The studs and roof internal elements were modeled as beam elements while all sheathings were modeled as shell elements.

The material properties were defined as linear elastic isotropic. The connection behaviors were calibrated based on information from literature. The calibration of RTWC, for example, is based on connection test conducted by Morrison 2010 as shown in ***Figure 5***. The modeling of the other structures is in progress following the same procedure to replicate the damage observed in the field.

4. Summary and Future Work

Numerical replica of the Dunrobin tornado, that was rated EF3 based on damage survey, was simulated along with the neighbourhood. The features of the tornado were compared to video footages due to lack of more accurate measurements such as Doppler radar. The current simulations are limited to stationary vortices at various locations in the neighborhood. The authors are now extending this work to include translating vortices of various translational speeds to obtain more representative wind loads. The FEA modeling of the structures is underway for the buildings starting with calibration of connections with experimental results. Future work will include application of the dynamic load obtained from translating tornado simulation applied to the FEA model of the case-study buildings to estimate the damage. Comparison with the observed damage will be made as well.

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