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EFFECTS OF TORNADO WIND SPEEDS ON CONCRETE ROAD BARRIERS

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ABSTRACT

Wind speeds can be difficult to measure during tornadoes due to their destructive nature. They pose a significant threat to lives and infrastructure in many parts of Canada and the U.S. The Enhanced-Fujita scale focuses on estimating these wind speeds by observing damage to different types of buildings, but significantly less research has been performed on the damage of other structures. Learning more about the effects of high wind speeds on these structures will help improve the ease and accuracy of future tornado classification. A wind tunnel study was performed at the Boundary Layer Wind Tunnel Laboratory of Western University. The study focusses on estimating the wind speeds that cause overturning in a standard 32” concrete “Jersey” barrier. On April 27, 2014, an EF4 Tornado struck Mayflower, Arkansas, and among the damage, several of these concrete barriers were blown over during the storm. The goal of this study was to find the overturning wind velocity and compare it to other damage in this event. This study was performed by placing a 1:8 scale-model of these barriers in a wind tunnel at a variety of orientations and wind speeds. Through analysis, it was determined that an instantaneous wind velocity of 4.55 to 4.85 m/s would cause overturning. These values correspond to an instantaneous wind speed of 340-360 km/h at full scale. It was estimated that the 3-second gust (used for EF rating) was 300-320 km/h, which sits at the top of the 267-322 km/h classification range for an EF4 tornado.

Keywords: wind loads, tornadoes, EF scale, concrete barrier

1. INTRODUCTION

1.1 Objectives

The objective of this experiment was to determine the wind speeds required to blow over concrete highway barriers. Several wind angles were studied in the wind tunnel and the measured wind speeds were scaled for comparison to real life events.

1.2 Background

Tornadoes pose a significant threat to lives and infrastructure in many parts of Canada and the U.S. This study was performed in light of the 2014 Mayflower, Arkansas Tornado that toppled a string of concrete highway New Jersey barriers. The tornado was estimated to have EF-4 wind speeds of 267-322 km/h (NASA, 2014) but performing wind tunnel tests helped to gather more precise data. The gathered information will be useful for more accurate measurements of wind speeds in future strong wind events.

Figure 1: Overturned barriers from the Mayflower Tornado (Courtesy of Frank Lombardo)

1.3 Scope of the Work

This study focusses specifically on New Jersey concrete highway barriers as those were the type of barriers that were toppled in the Mayflower tornado. The failure wind speeds would vary somewhat depending on the exact dimensions of concrete barrier being modeled, but this report will still be significantly useful for any type of concrete highway barrier. The length of barrier modeled was a standard 10 feet; additionally, further testing of three of these barriers hooked and attached together was performed.

The failure mechanism studied in this report was overturning as it was assumed that failure by overturning would happen before failure by sliding the majority of the time. Due to limited access to the wind tunnel, only "open terrain" was used for the blow over tests. These conditions were the most realistic and were similar to the conditions in which in New Jersey barriers failed in the Mayflower tornado.

2. MODEL DESIGN

The original plan was to do the testing on a model made of concrete but after being unable to topple a 1:20 concrete model, a lighter option was needed. Information on the concrete model can be found in the full report (Jaffe et al., 2015). The final model design was a 1:8 foam model representing a typical New Jersey highway concrete barrier. Wind speeds were directly measured for chatter and overturning failures of the model which, when scaled, approximate barrier failures in real life wind events.

2.1 Model Scale

A scale was chosen that balanced out the advantages and limitations of bigger and smaller models. A bigger model allows for more accurate wind speeds (as long as it does not block a significant portion of the wind tunnel) but are limited by lack of access to materials. The model also has to be light enough, and therefore small enough, to be blown over in the wind tunnel. The weight was not an issue however because the model was made of foam. Due to these factors, a 1:8 model was deemed the most suitable for the experiment.

2.2 Final Model Design

The final foam models were scaled to measure 38.1 cm in length, 10.2 cm in height, and 7.6 cm in base width with a mass of 70.5 g. There were minor inaccuracies due to human error in cutting the foam but not enough to significantly affect any results. Full details of the dimensions can be found in the full report (Jaffe et al., 2015). Initially, the model was to be made of concrete because that would make it identical in density to the prototype. However, a concrete model was deemed impractical because to be light enough for overturning, a very small scale would need to be used, resulting in a model of less than 4 cm in height. The experimental error resulting from using the much lighter foam was far smaller than the error that would have resulted from such a small concrete model. Large foam models were also easier to construct and maintain than the concrete model would have been.

Figure 2: 1:8 foam model

The models were composed of five pieces of foam that ran the length of the model, glued together with silicone (Figure 2). A small amount of glue was also used to fill all the cracks between the pieces of foam to simulate a smoother, more realistic barrier. The silicone glue was heavier than expected resulting in the model being slightly bottom heavy where most of the gluing was done. Since symmetry was maintained, this had no impact on the chattering velocities, and it was assumed to have a negligible impact on the failure velocities. The front faces of the models were slightly simplified from the shape of the prototype. The upper rectangular pieces of foam are a trapezoidal shape in real life with sides angled 6 degrees inwards from the vertical. Simplifying these slopes to make them vertical cost a small amount of accuracy but made these portions of the models much easier to construct.

Figure 3: View of the model and wind tunnel setup for one of the trials

3. EXPERIMENTAL DESIGN AND PROCEDURE

3.1 Wind Tunnel Setup

All of the testing was performed at the Boundary Layer Wind Tunnel II at Western University. The working section of the wind tunnel is 39 m long, 3.4 m wide, and 2.5 m tall. It has a maximum wind speed of approximately 30 m/s. A simulation of an open terrain was used for testing because this is the type of terrain where most concrete highway barriers are located. The open terrain was created in the wind tunnel using spires, adjustable floor roughness elements, and randomly distributed bolt nuts (Figure 3).

3.2 Model Setup

The initial test had the foam barrier placed perpendicular to the length of the wind tunnel for the first set of trials. A cobra probe was placed at either end of the model to measure the wind speeds at the top of the barrier. The tips of the probes were located a foam model barrier's height (about 10 cm) in front of and off to the side of the model (Figure 4). The probes were far enough from the barrier that they would not significant affect the wind flow but close enough to get accurate measurements. Data was collected and analysed from these probes individually and as an average to represent the wind speed across the barrier. A laser transducer was placed behind the model to detect chatter and overturning failures.

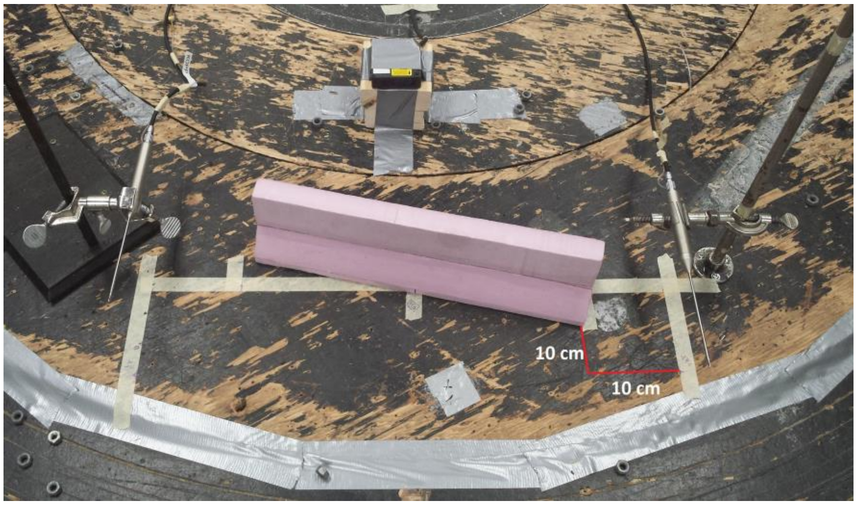

Figure 4: Plan view showing offset distance of cobra probes

For the purpose of this study, it was assumed that the concrete barriers would always fail by overturning before sliding. This assumption was reasonable due to the coefficient of friction between the concrete barriers and the road. To ensure that sliding of the barrier did not occur in the wind tunnel tests, two screws were drilled into the floor behind the model so that their heads would eliminate translation of the barrier along the floor.

The next tests took place in the slower Wind Tunnel 1. The first test was a single barrier to compare to the previous results, then the three models were glued together to represent a single 30' barrier (Figure 5), and finally, they were separated and connected using paper clips to create two hooks equally spaced from the centroid that allow the separate barriers to fall independently (Figure 7).

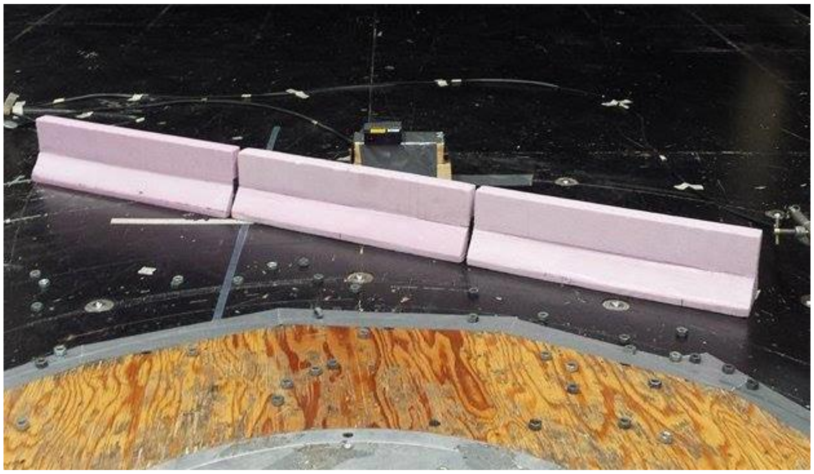

Figure 5 (top left): Glued barrier and Wind Tunnel 1 set up
Figure 6 (bottom left): Hooked barrier set up
Figure 7 (top right): View of two hooks connecting barrier

3.3 Trial Details

Ten trials were done for each of four barrier angles that were tested. The angles were 0, 11.4, 25.2, and 45 degrees and were measured by comparing the barrier's original position to its new position. Each trial began at a wind speed below what was expected to cause failure. A time step of 220 seconds (which represents a time step of ten minutes for the 1:8 model) was used for each wind speed after which the voltage was increased by 0.05V if the barrier had not failed. The wind speed increments were made large enough to be efficient but small enough that the mean speed after increase would not exceed the peak speed of the previous speed setting. Trials were completed at the end of the time step in which overturning failure of the model occurred.

3.4 Definition of Chatter and Failures

There are two types of movements of the barrier that were of interest: chatter, where the barrier began to tip then returned upright, and failures, where the barrier overturned over completely. The beginning of these movements was defined as when the distance from the laser transducer decreases by 1% compared to the average distance of the first 10 seconds of the beginning of the test. The time histories of wind speed and displacement are presented in the full report (Jaffe et al., 2015).

4. RESULTS

4.1 Model Concrete Barrier Results

The first model tested, a 1:20 concrete model, did not overturn in the wind tunnel at the maximum velocity. This test revealed that a full scale wind speed of 203 km/h was insufficient to cause either chatter or failures in the concrete barrier. The full calculations for this conclusion can be found in the full report (Jaffe et al., 2015).

4.2 Foam Model Failure and Chatter Velocities

The instantaneous velocity was recorded as the maximum wind speed in the 10 milliseconds just before the beginning of movement. A maximum of two chatters were recorded per test. The table below presents the average failure and chatter wind speeds for all four configurations, with each probe recorded separately, then averaged. The difference between the average failure and chatter speeds are compared below.

Table 1: Summarized model test results

Angle (Degrees)	Probe 311 Failure Velocity (m/s)	Probe 311 Chatter Velocity (m/s)	Probe 313 Failure Velocity (m/s)	Probe 313 Chatter Velocity (m/s)	**Average Failure Velocity (m/s)**	Failure Velocity Standard Deviation (m/s)	Average Chatter Velocity (m/s)	Chatter Velocity / Failure Velocity
0	5.162	4.826	4.548	4.277	**4.855**	0.552	4.552	93.8%
11.4	4.539	4.519	4.547	4.280	**4.543**	0.576	4.400	96.8%
25.2	5.165	4.817	4.520	4.483	**4.843**	0.552	4.650	96.0%
45	5.035	4.669	4.360	4.390	**4.698**	0.538	4.530	96.4%

These results showed that wind speeds causing failure were 3-6% greater than those that would cause chatter. They also suggest that orientation angles up to 45° had little impact on the failure velocities.

4.3 Full Scale Instantaneous Failure Velocities

Using equation [1], the overturning moment coefficient of the model can be obtained, which should match that of the full scale barrier. This coefficient can be used to calculate the full scale failure velocities, which are provided below. The velocity used was the directly measured maximum velocity at the top of the model, rather than the average velocity that could have been calculated using the profile.

[1] $T = \frac{1}{2}\rho A r C_M V^2$

Table 2: Average full scale instantaneous failure velocities

Orientation Angle (Degrees)	Average Model Instantaneous Failure Velocity V_M (m/s)	Overturning Moment Coefficient C_M	Average Full Scale Instantaneous Failure Velocity V_P (m/s)	Average Full Scale Instantaneous Failure Velocity V_P (km/h)
0	4.855	0.456	100	**361**
11.4	4.543	0.520	94.0	**338**
25.2	4.843	0.458	100	**361**
45	4.698	0.486	97.2	**350**

4.4 Full Scale Average Failure Velocities

Note that since the 1:8 foam model has a different density than the actual barrier, an exact time scale cannot be easily established. As such, the results above are the maximum gust speeds rather than the more commonly used 3-second average. Figure 8 shows a graph of average wind failure velocities normalized over the instantaneous maximum, for varying time lengths and centered around the failure points.

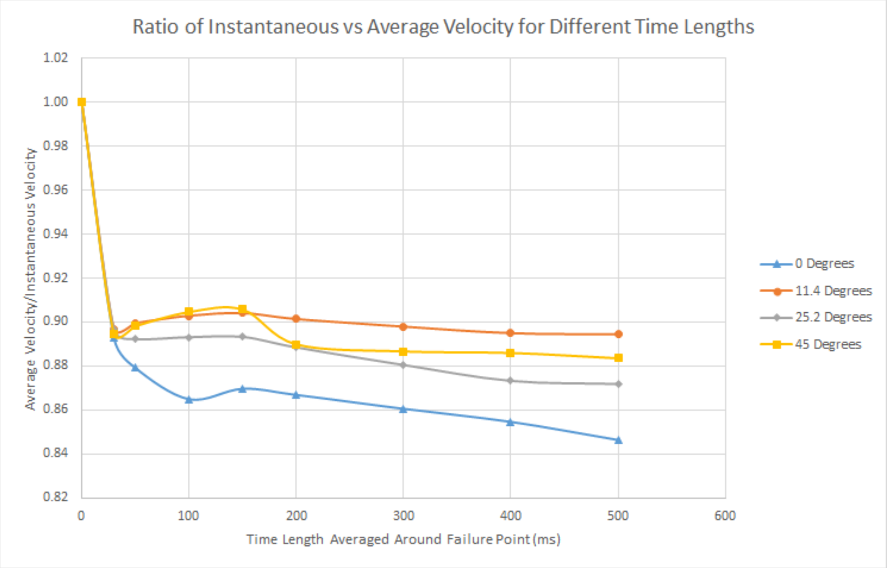

Figure 8: Graph of normalized average failure velocities

This figure shows that when the velocity is averaged over any time length, it drops to 85-90% of the instantaneous maximum. If it is estimated that the 3-Second Gust Velocity is 88%, the following results are found.

Table 3: Assumed average full scale 3-second gust failure velocities

Orientation Angle (Degrees)	Average Full Scale Instantaneous Failure Velocity V_P (km/h)	Assumed Average Full Scale 3-Second Failure Velocity $0.88*V_P$ (km/h)
0	361	318
11.4	338	297
25.2	361	318
45	350	308

4.5 Multiple Model Tests

The following tests we performed in Wind Tunnel 1, a slower wind tunnel. The terrain was open, set to be as similar to the one used in Wind Tunnel 2 as possible. Nevertheless, a single barrier was tested for comparison. Three barriers glued together and three hooked together were then tested at 0 and 25.2 degrees.

Table 4: Summarized multiple model test results

Setup and Angle (Degrees)	Probe 311 Failure Velocity (m/s)	Probe 313 Failure Velocity (m/s)	**Average Failure Velocity (m/s)**	Failure Velocity Standard Deviation (m/s)	Probe 311 Chatter Velocity (m/s)	Probe 313 Chatter Velocity (m/s)	Average Chatter Velocity (m/s)
One: 0°	4.034	4.158	4.096	0.627	3.777	3.935	3.856
Glued: 0°	4.197	4.044	4.120	0.651	4.494	3.989	4.241
Glued: 25.2°	4.107	4.365	4.236	0.607	4.206	4.058	4.132
Hooked: 0°	3.886	4.001	3.944	0.621	4.094	4.274	4.184
Hooked: 25.2°	4.014	3.799	3.907	0.713	3.979	4.120	4.050

Table 5: Average full scale instantaneous failure velocities for multiple model tests

Setup and Angle (Degrees)	Average Model Instantaneous Failure Velocity V_M (m/s)	Overturning Moment Coefficient C_M	Average Full Scale Instantaneous Failure Velocity V_P (m/s)	Average Full Scale Instantaneous Failure Velocity V_P (km/h)	Single Model Failure Velocity / Multiple Model Failure Velocity
One: 0°	4.096	0.640	84.72	**305.0**	
Glued: 0°	4.120	0.722	79.72	**287.0**	94.1%
Glued: 25.2°	4.236	0.683	81.97	**295.1**	
Hooked: 0°	3.944	0.729	79.36	**285.7**	93.7%
Hooked: 25.2°	3.907	0.743	78.62	**283.0**	

5. CONCLUSIONS

The analysis of the wind tunnel data has led to the following conclusions:

1. A powerful instantaneous gust is required to overturn a concrete barrier, ranging from about 340-360 km/h. If this gust is about 4% less than this range, it can cause the barrier to start to tip but return to the upright position.
2. These tests revealed no clear relations between barrier orientation and failure velocities. Between perpendicular to wind and 45°, the random variations in the wind seemed to have a much greater impact on the failure velocities than the orientation.
3. The multiple barrier tests revealed that attached barriers tipped at wind speeds about 6% lower than the individual barriers. Whether they were rigid (glued) or flexible (hooked) seemed to have little impact on the reduction of the failure speed.

Comparing these results to the 2014 Mayflower, Arkansas Tornado, the full scale wind velocities were determined. Estimating that the 3-second gust failure velocities are 88% of the instantaneous, a failure range of 300-320 km/h was found, which sit at the high end of the 267-322 km/h range of an EF4 tornado. The official classification of the Mayflower Tornado was an EF4, and the results of these tests appear to agree with this.

6. FUTURE WORK

This study has been useful in determining the approximate instantaneous failure speeds of a concrete barrier; however, there are several gaps and errors apparent in these tests.

1. While not an error, a minor miscalculation led to the use of 11.4° and 25.2° orientations rather than the 15° and 30° that were planned.
2. The most critical flaw was the small number of tests that were run. 30-40 trials per orientation would give more accurate data and may reveal a relationship between orientation angles and failure wind velocities.
3. Many of these trials failed to capture the barrier overturning in the data. Ensuring that the overturning was captured before moving on would help increase the number of tests and give a greater statistical reliability.
4. Any new foam models should be cut using a table saw, rather than the band saw used in this study, to ensure dimensional accuracy.

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