

10-2014


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Abstract

Despite the destructive effects of tornadoes, limited attempts have been made to quantify tornado-induced loading. The purpose of the study presented here was to investigate the effect of different building geometry on the forces and pressures that low-rise buildings would experience in a simulated tornado with a swirl ratio comparable to what has been measured and recorded for full-scale tornadoes. Measured force and pressure data were then used to judge whether tornado-resistant design for residential structures is feasible. The tornado-induced wind loads were measured on scaled models of buildings in a laboratory-simulated tornado with a core diameter (56 m) and relatively high swirl ratio (2.6) representing an EF3 tornado. The study found that the peak loads vary as a function of eave height, roof pitch, aspect ratio, plan area, and other differences in geometry such as the addition of a garage, roof overhang and soffit. The required strengths of the roof-to-wall and roof sheathing-to-rafter connections were calculated based on the measured loads and compared with their capacities to assess the possibility of failure. It appears that the design of the two critical roof connections in residential construction for tornado-resistant design up to and including EF3 tornadoes can ensure adequate safety cost-effectively by using currently available technology.

Keywords

Tornado effects, Wind loads, Laboratory simulation, Low-rise buildings, Building geometry, Tornado-resistant design

Disciplines

Aerodynamics and Fluid Mechanics | Civil Engineering | Geotechnical Engineering | Structures and Materials

Comments

This is a manuscript of an article published as Case, J., Sarkar, P., & Sritharan, S. (2014). Effect of low-rise building geometry on tornado-induced loads. *Journal of Wind Engineering and Industrial Aerodynamics*, 133, 124-134. doi: [10.1016/j.jweia.2014.02.001](https://doi.org/10.1016/j.jweia.2014.02.001). Posted with permission.

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Effect of low-rise building geometry on tornado-induced loads

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1. Introduction

Various opinions as to whether tornado-resistant design of residential buildings is possible, let alone feasible, have been offered. These opinions have been largely motivated by experience obtained from evaluating structural failure due to strong winds and prejudiced by the awe-inspiring destructive capacity of tornadoes, but they have not been based on the comparison of pressure data obtained from either full-scale or laboratory simulated tornadoes with the capacities of the structural connections and members of typical residential construction. Modern engineering is based on the application of rational and empirical principles, but for tornado-resistant design, there has been little or no data that could be used to form engineering principles. In the past, quantification of pressures on a building envelope and forces on a building structure due to the occurrence of a tornado in its proximity has been limited to forensic investigation and engineering judgments. The reason for this limitation is threefold: the lack of research facilities capable of determining the pressures and forces on structures due to tornadoes; the absence of full-scale data to corroborate the results from laboratory experiments or field structures; and a lack of interest in pursuing tornado-resistant design on the part of many as it was assumed to be cost prohibitive.

A tornado simulator has been constructed at Iowa State University (ISU) to overcome the first challenge (Haan et al. 2008). The ISU tornado simulator is capable of creating a model scale tornado that allows building models to be placed in its path as well as having the ability to travel relative to a building model to be investigated. The ISU tornado simulator also has mechanisms to adjust several different

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1 variables resulting in different types of tornadoes. The second challenge has also been overcome recently
2 with full-scale data obtained from several recent tornadoes (Karstens et al. 2010; Lee and Wurman 2005;
3 Wurman 2002). Subsequent effort has enabled the characteristics of the laboratory simulated tornadoes
4 generated by the Iowa State University (ISU) simulator to be compared with both full-scale data and with
5 computational fluid dynamic models (Sarkar et al. 2005). Work by Thampi et al. (2011) has verified that
6 when the pressures on low-rise building models obtained from a tornado simulated by the ISU simulator
7 are input into a finite element model of a structure, the damage experienced by the corresponding full-
8 scale building in a tornado can be replicated. These advancements enable determination of forces and
9 pressures on a structure and the exploration of cost-effective solutions for tornado-resistant design.

10 This paper presents the results of a study that determined the variation of tornado-induced pressures
11 and forces as a function of the geometry and orientation of the low-rise building. In addition, the uplift
12 load capacities of two of the most vulnerable roof connections in light-framed wood construction, as
13 obtained from the literature, in the context of tornado-induced loads based on tornado-induced pressures
14 measured in the laboratory were studied to investigate the viability of tornado-resistant design.

15

16 **2. Description of simulated tornado**

17 Pressures on low-rise building models obtained from a tornado simulated in a laboratory are useful for
18 investigating the viability of tornado-resistant design only to the extent that the simulated tornado
19 possesses the characteristics of possible full-scale tornadoes. For the purpose of obtaining pressures and
20 forces for the structural design of low-rise buildings, the most important characteristics to reproduce are
21 those that influence the loading on the structure. According to Haan et al. (2010), these characteristics
22 include maximum horizontal wind speed, radius of the core of the tornado and its path, swirl ratio, and
23 translation speed.

1 2.1. *Maximum horizontal wind speed*

2 Based on forensic evidence, around 90% of all tornadoes are rated F2 or less (Bluestein and Golden
3 1993). In the EF (Enhanced Fujita) scale (TTU 2004) this corresponds to an upper bound EF3 tornado,
4 which is estimated to have a maximum velocity of 74 m/s (3-sec gust). The design wind speed for the
5 south-eastern and gulf coasts of the United States for occupancy category II buildings per ASCE 7-10
6 (2010) ranges from 63 m/s to 80 m/s and the basic design wind speed for the same region per the
7 International Residential Code ranges from 54 m/s to 63 m/s (ICC 2012). The design requirement for
8 straight-line wind speeds of this magnitude implies that design for these wind speeds is possible. Based
9 on the fact that building codes require the design of low-rise building structures for wind speeds of
10 similar magnitudes and that most tornadoes are considered to have maximum wind speeds of 74 m/s or
11 less, the target full-scale horizontal wind speed for this study of tornado-induced loads was chosen to be
12 74 m/s.

13 The maximum tangential velocity of the tornado generated by the ISU Tornado Simulator in this
14 study was measured to be 11.6 m/s at a height of 19 mm and a maximum horizontal velocity of 11.7 m/s
15 at the same height. Using a full-scale tornado with a maximum horizontal velocity of 74 m/s (EF3) gives
16 a vortex velocity scale of $\lambda_v = 11.7/74 = 1/6.3$ for a full-scale averaging time equivalent to the model-
17 scale averaging time. A contour plot of the tangential velocity normalized with the maximum tangential
18 velocity is shown in Figure 1.

19 2.2 *Tornado vortex diameter*

20 Brooks (2004) conducted a study using reported tornado damage path lengths and widths to model
21 Weibull distributions of Fujita scale levels. The distributions produced by the study showed the
22 probability of a tornado path width, given the occurrence of a tornado at a specific Fujita scale intensity.
23 This study showed that a tornado's mean path width increased with its Fujita scale rating. According to
24 Brooks for a F1 or a F2 tornado (corresponding approximately to an EF2 or EF3 tornado), the path would
25 be most likely between 100 and 500 m.

1 Assuming that damage occurs at the design wind speed specified in the building codes, which for the
2 Midwestern United States is 40 m/s, and the full-scale horizontal velocity is 74 m/s (EF3), the damage to
3 buildings and other structures may be expected to occur within a diameter where the horizontal wind
4 speed exceeds approximately half of the maximum tangential wind speed. The “0.5” contour in Figure 1
5 is located at 2.2 times the radius of the maximum wind (radius of the core) near the ground. According to
6 the results of the study conducted by Brooks (2004), the radius of the core of an EF3 tornado would have
7 a high probability of being between 45 and 225 meters. The radius of the core for the simulated tornado
8 used in the study presented here was 0.56 meters, which matches with the study done by Brooks (2012)
9 when scaled using a length scale of 1:100.

10 *2.3 Swirl ratio*

11 One of the most commonly used parameters for laboratory and numerically simulated tornadoes is
12 the swirl ratio (Haan et al. 2008; Hangan and Kim 2008). The swirl ratio (S) is the ratio of the tangential
13 momentum to the inflow rate (Q) of the vortex measured at a particular radius ($S = \pi V_{\theta\max} r_c^2 / Q$, r_c is core
14 radius where maximum tangential wind speed $V_{\theta\max}$ occurs). Several studies have shown that the swirl
15 ratio is the parameter that governs the flow characteristics of a tornado (Hangan and Kim 2008; Church
16 et al. 1979). Davies-Jones (1973) demonstrated that the radius of the vortex core is a function of the swirl
17 ratio. Both Davies-Jones (1973) and Church et al. (1979) showed that the vortex structure is related to the
18 swirl ratio; as the swirl ratio increases the vortex breaks down into multiple vortices (Davies-Jones
19 1973).

20 The data from full-scale tornadoes indicate swirl ratio values of 2.0 or greater. For example, when
21 comparing the full-scale data from the Spencer, South Dakota, tornado with 3D numerical simulations
22 Hangan and Kim (2008) found that the best fit was for a swirl ratio of $S=2$. Using data obtained with a
23 Doppler on wheels (DOW), the swirl ratios of the Mulhall tornado were calculated by Lee and Wurman
24 (2005) to be between 2 and 6 for the F4 level tornado. These swirl ratios were measured at the radius of
25 the vortex core (r_c). Based on the latest data obtained by DOW and the best fit of that data with numerical

1 results, it was decided that an attempt should be made to increase the swirl ratio of the tornado used in
2 this study to a value of 2 or greater. In the ISU tornado simulator, a 1.83m (6 ft)-diameter fan creates an
3 updraft. The flow is then directed downward through concentric ducts. Rotational flow is created by
4 several vanes fixed at a given angle with respect to the radial direction that is normal to the tangent of the
5 duct. The swirl ratio of the vortex generated in the Iowa State University's tornado simulator can be
6 increased by increasing the vane angle (Haan et al. 2008). In order to obtain a high swirl ratio the vane
7 angle was set at 75°, resulting in a swirl ratio of 2.6 measured at the core radius or radius of the
8 maximum tangential velocity.

9 *2.4 Translation speed*

10 Various translation speeds of full-scale tornadoes have been reported: 16.5 m/s (Thampi et al. 2011),
11 13 m/s (Lee and Wurman 2005) and 23 m/s (Haan et al. 2008). Based on these reports, pressure
12 measurements on the building models in this study were taken for a tornado translation speed of 0.15
13 m/s. If it is assumed that damage to a building is proportional to the duration of its exposure to the
14 tornado winds then the vortex translation time scale (λ_T) should be equal to one. This results in vortex
15 translation velocity scale equal to the length scale used in modeling. Thus, the translation speed of 0.15
16 m/s at model scale becomes 15 m/s at full-scale for a length scale (λ_L) of 1:100.

17 *2.5 Surface roughness*

18 The ground plane was varnished plywood which was very smooth. No surface roughness blocks were
19 used and therefore this plane represented an open terrain. Since much of "Tornado Alley" is rural
20 farmland, open terrain was considered to be a valid and useful exposure to use in the study.

21

22 **3. Model Description, Instrumentation, and Conventions**

23 *3.1 Building Models*

24 External surface pressure measurements were taken on nine building models with gable type roofs
25 with varying roof pitches (4.6 to 35.5 deg.), eave heights (12.2 to 36 ft), L/B ratios (1.0 and 1.5; where L

1 is the length and B is the width)) and h/L ratios (0.34 to 0.8; where h is the mean roof height), attached
2 garage (with and without) and a variety of test cases (154 total) were conducted that included varying the
3 building orientation angles with respect to the path of the tornado. Each model was fitted with as many as
4 124 pressure taps.

5 Model dimensions were selected such that when scaled using a length scale of 1:100 the models
6 would have realistic low-rise building dimensions and also the effect of roof height, aspect ratio, roof
7 pitch, overhang and an attached garage on the external pressures and forces due to the simulated tornado
8 could be observed. The selection of the dimensions was based on commonly available, simple house
9 plans and a table similar to Figure 6-6 in ASCE 7-10 (2010), where roof pressure coefficients are
10 tabulated as functions of mean roof height divided by the length of the building, wind direction and roof
11 pitch. The model dimensions are given in Table 1.

12 *3.2 Instrumentation*

13 Wind velocity measurements while the simulator was stationary were taken at 78.1 Hz for 26 seconds
14 with a Cobra probe (multi-hole probe, TFI®). Measurements were taken at points spaced at 50.8 mm
15 horizontally and 6.35 mm vertically. The measurements were taken starting at an elevation of 6.35 mm
16 until an elevation of 127 mm and for a horizontal length of 2.64 m at each elevation from the ground
17 plane.

18 Pressure measurements were taken using two high-speed 64-channel ZOC33/64Px pressure
19 transducers (Scanivalve Corporation®) at a frequency of 390 Hz. The static pressure used in both the
20 pressure and the velocity measurements was taken as the laboratory ambient pressure under the ground
21 plane.

22 *3.3 Procedure and Conventions*

23 For each test case the pressures were recorded 10 times. The peak pressures were calculated as the
24 average of the peak pressures from each of the 10 runs. The orientation of the building (building
25 orientation angle, BOA) with respect to the direction of translation of the tornado was varied from 0° to

1 90° with a step size of 15°. The 0° orientation corresponds to the direction of translation of the tornado
 2 being parallel to the ridge of the roof of the building model (along dimension L). The garage models were
 3 tested from 0° to 90° (Orientation 1) and from 180° to 270° (Orientation 2). The taller part of the
 4 garage models experienced the tornado first for Orientation 1 and the shorter part of the model
 5 experienced the tornado first for Orientation 2. For all of the test cases, the tornado translation axis
 6 passed through the center of the building model.

7 The aerodynamic force coefficients were computed along the x (horizontal direction parallel to the
 8 tornado's translation direction), y (horizontal direction perpendicular to the tornado's translation
 9 direction), and z (vertical) directions. An xy force coefficient (C_{Fxy}) which was computed as the square
 10 root of the sum of the squares of the x (C_{Fx}) and y (C_{Fy}) force coefficients was also considered important
 11 as a quantity expressing the total drag force on the low-rise building model. The x and y coefficients
 12 were normalized with an area of the model equal to the height of the ridge of the roof times the length of
 13 the roof ridge (S_v). The z coefficient (C_{Fz}) was normalized with an area equal to the floor plan of the
 14 model (S_z). The equations used to calculate the force coefficients are given as equations 1 through 4.

$$15 \quad C_{Fx} = \frac{F_x}{\frac{1}{2} \rho V_H^2 S_v} \quad (1)$$

$$16 \quad C_{Fy} = \frac{F_y}{\frac{1}{2} \rho V_H^2 S_v} \quad (2)$$

$$17 \quad C_{Fz} = \frac{F_z}{\frac{1}{2} \rho V_H^2 S_z} \quad (3)$$

$$18 \quad C_{Fxy} = \sqrt{C_{Fx}^2 + C_{Fy}^2} \quad (4)$$

1 4. Results

2 The peak pressure and force coefficients were calculated and the time histories of the force coefficients
3 were plotted for each of the models for each building orientation angle. The peak pressure and force
4 coefficients and time histories of the different models were then compared to discover any trends that
5 would demonstrate the effect the different geometric variables had on the tornado-induced forces and
6 pressures. Models with geometry that was similar or exactly the same except for one variable were
7 compared in an effort to isolate the effect of each variable.

8 *4.1 The effect of eave height*

9 Model 1 and Model 2 had the same plan area and plan aspect ratio (L/B), and the same roof slope.
10 The difference between the two models was their eave heights; the eave height of Model 2 (110 mm) was
11 almost twice that of Model 1 (60 mm). For each of the building orientation angles the peak pressure
12 contours of the two models were similar but had different magnitudes. The peak pressures on Model 1
13 were significantly higher. The eave heights of both models were greater than the height at which the
14 maximum tangential velocity was measured (19.5 mm). The maximum tangential velocity at a height
15 equal to the eave height of Model 1 was 10.6 m/s while the maximum tangential velocity at a height
16 equal to the eave height of Model 2 was only 9.6 m/s. This may help to explain the difference in peak
17 pressures as a function of eave height. The average peak pressure contour plots for the 30° building
18 orientation angle of Model 1 and Model 2 can be seen in Figure 4. The C_{Fz} and C_{Fxy} time histories of the
19 two models for the 30° building orientation angle can be seen in Figure 5 and Figure 6, respectively.

20 *4.2 The effect of roof pitch*

21 Models 3, 4 and 5 were compared to observe how roof pitch affects tornado-induced pressures and
22 forces. All three models had the same mean roof height (55 mm), the same plan dimensions, and the
23 same aspect ratios ($L/B = 1.0$ and $h/L = 0.56$). Model 3 had a roof pitch of 4.6° , Model 4 had a roof

1 pitch of 15.95° and Model 5 had a roof pitch of 35.5° . A clear trend occurs in the average peak
2 pressures; as the roof slope increases the peak pressure magnitudes for the roof decrease while those for
3 the walls increase. The peak C_{Fz} for Model 3 and Model 4 occurs for the 45° building orientation angle
4 while for Model 5 the peak C_{Fz} occurs for the 60° BOA. The average peak pressure contour plots for the
5 45° degree building orientation angle of Model 3, Model 4, and Model 5 can be seen in Figure 7.

6 Haan et al. (2010) found that the peak uplift force resulting from tornado-induced loads does not vary
7 with the building orientation. Figure 8 confirms this finding and shows that the peak uplift force also
8 did not vary with roof pitch for building Models 3, 4 and 5. The peak pressures can vary while the peak
9 vertical force coefficient may not vary significantly because the peak pressures do not necessarily occur
10 simultaneously at all locations while the peak force coefficients occur when the integration of the
11 instantaneous pressures results in the largest force coefficient.

12 *4.3 The effect of the ratio of plan dimensions*

13 The lower maximum tangential velocity at the eave height of Model 2 as compared with the
14 maximum tangential velocity at the eave height of Model 1 was considered to have caused the difference
15 in peak pressures and vertical force coefficients. Model 4 had the same roof slope as Models 1 and 2,
16 but had an eave height of 48 mm. The maximum tangential velocity at this height was 10.85 m/s, higher
17 than for both Model 1 (10.6 m/s) and Model 2 (9.6 m/s), but the peak C_{Fz} 's for Model 1 are still higher
18 than for Model 4. The most significant difference between Model 4 and Model 1 was the L/B ratio o,
19 often referred to as the building's aspect ratio. The aspect ratio of Model 1 was 1.5 while Model 4's
20 aspect ratio was only 1.0. The fact that the model's aspect ratio is significant to the magnitude of the
21 tornado-induced forces and pressures acting on it can be seen when the C_{Fz} time history of Model 4 in
22 Figure 9 is compared with the C_{Fz} time history of Model 1 and 2 in Figure 5. The C_{Fz} time histories of
23 Models 1 and 2 show an initial peak followed by a period of lower values for C_{Fz} then another peak as the
24 last part of the simulated tornado passed over the building. This is different than the C_{Fz} time history of
25 Model 4 which has a period of relatively constant C_{Fz} values while the simulated tornado is directly over

1 the model. An aspect ratio greater than 1 allows the tangential velocity to play a clear role in increasing
2 the peak C_{Fz} values for those models.

3 Comparison of the C_{Fz} time history of Model 1 in Figure 5 with the C_{Fz} time history of Model 6 in
4 Figure 13 gives evidence that the cause of difference in the shape of the C_{Fz} time history was due to the
5 aspect ratio and not the building's overall length. Although the length of Model 6 was 221 mm and the
6 length of Model 1 was only 146 mm, the shape of the time history of Model 6 is similar to the other
7 model's with aspect ratios of 1.0.

8 *4.4 The effect of an enclosed overhang and soffit*

9 It was considered important to investigate the effect of an enclosed overhang and soffit on the
10 tornado-induced forces and pressures on low-rise buildings since most low-rise residential buildings in
11 the United States have roofs that extend past the building's walls and many have enclosed soffits. All of
12 the models, except the one which was constructed with a roof overhang and an enclosed soffit (i.e.,
13 Model 7 referred to as the "overhang" model), had sharp corners where the roof met the wall. The
14 overhang model was exactly like Model 1 except for the overhang and soffit. Internal pressures were
15 not considered for either model.

16 Pressures were measured on the underside of the soffit. The peak pressure coefficients for the
17 underside of the soffit ranged from -1.0 to -3.0 depending on the building orientation angle and the
18 region of the soffit. Although the magnitudes of the peak pressures on the overhang model were
19 significantly less than on Model 1, the pressure contour shape on the walls was similar. The distribution
20 of the peak pressure contours on the building walls were less affected by the overhang than those on the
21 roof. Figure 10 shows the peak pressure contour plots for Model 1 and the overhang model for the
22 building orientation angle of 30° .

23 Figure 11 shows how significant the addition of the roof overhang was to the vertical force
24 coefficient. Similar to the peak pressures, the horizontal force coefficients were also less affected by the
25 overhang and soffit than the vertical force coefficients. This is shown in Figure 12.

1 4.5 *The effect of plan area and height to length ratio*

2 Both Model 5 and Model 6 have a roof pitch (θ) of 35.5° , an eave height (h_e) of 37 mm and an aspect
3 ratio (L/B) of 1.0, but had different plan dimensions, 98 mm and 221 mm respectively and different total
4 heights (h_t), 72 mm and 114 mm respectively. These dimensions resulted in a mean roof height to
5 length (h/L) ratio of 0.34 for Model 5 and 0.56 for Model 6. Model 6 was made so much larger than
6 Model 5 in order to maximize the difference in h/L ratios. The large plan dimension of Model 6 is
7 almost 40% of the radius of the core of the simulated tornado. This results in a significantly longer
8 period in which the building's structure must resist the tornado-induced forces as can be seen in Figure
9 13.

10 4.6 *The effect of an attached garage*

11 Most of the residential buildings or houses built in the United States have attached garages. The
12 attached garage is often shorter in elevation and oriented with its roof ridge parallel to the ridge of the
13 roof of the house. Two models with attached "garages" were tested. Model 8 or garage 1 model was
14 an exact replica of Model 5 except with an attached garage. Similarly, Model 9 or garage 2 model was
15 an exact replica of Model 1 except with an attached garage. The dimensions, eave height and roof slope
16 of the "garage" on both models were exactly the same. Similar to the other models, pressures were
17 recorded for the garage models with building orientation angles between 0° and 90° at 15° intervals.
18 This was done twice for each of the garage models. Once where the simulated tornado struck the "house"
19 part of the model first (Orientation 1) and once where the simulated tornado struck the "garage" part of
20 the model first (Orientation 2).

21 The addition of the garage increased the plan aspect ratio (L/B) of the original models. The increased
22 aspect ratio of the garage 1 model resulted in larger peak vertical force coefficients than Model 5
23 (without a garage) for most building orientation angles. While for the garage 2 model the peak vertical
24 force coefficients were larger than the models with aspect ratios (L/B) of 1.0, but for most building
25 orientation angles they were less than those for Model 1.

1 The addition of the garage to the models created more complex geometry which resulted in an
2 interaction between the building model and the simulated tornado. The study of this interaction will
3 require the testing of additional models in order to fully understand the effect of the garage addition.

4 *4.7 The effect of building geometry on roof connection demand*

5 Although not presented here, a comparison of the peak force coefficients, X, Y and Z, for each of the
6 building models and each building orientation angle revealed that without exception the vertical force
7 coefficient was greater than both of the horizontal force coefficients, sometimes by a factor of 2. The
8 peak pressure coefficients also occurred on the roof for all of the models. Both the peak force and
9 pressure coefficients are negative and act away from the roof, subjecting the structural connections in the
10 roof to uplift forces. This agrees with the findings of Haan et al. (2010).

11 In light of these findings, it is not surprising that many damage surveys done after tornado events
12 have found that roof damage is one of the most common types of damage to occur in residential
13 buildings. The occurrence of roof damage is further aggravated by the fact that, for residential
14 construction in the regions of the United States where tornadoes most often occur, the connections in the
15 load path from the surface of the roof to the wall and then to the foundation are almost always nailed.
16 Nailed connections increase the vulnerability of roofs to uplift failure because nails are inherently weak
17 in tension. The loss of the roof increases the vulnerability of the rest of the house, because the exterior
18 walls are composed of diaphragms that are tied together and braced at their tops by the roof structure
19 (Marshall 2002). Therefore, the roof is vital to the survivability of the house and since the connections in
20 the roof are the weak points in the load path due to the nature of tornado-induced loads great
21 improvements in the ability of low-rise buildings to resist tornado-induced forces could be made by
22 improving these connections.

23 Sparks et al. (1988) demonstrated that the roof of low-rise buildings is critical to the integrity of the
24 structure and that for straight-line winds failure of roof connections is dependent not only on wind speeds
25 but also on roof geometry. These researchers also noted that failures of entire residential structures can

1 occur quickly after the loss of the roof. Based on their findings, the connection between the roof trusses
2 and the stud walls was considered to be the critical connection for the survival of the entire house
3 (Sparks et al. 1988). In addition to finding that the roof-to-wall connection (RTWC) was the most
4 critical, they found that for several different roof geometries the toe nailed RTWC would fail at wind
5 speeds as low as 54 mph (3-sec gust) which is much less than the design wind speed of 90 mph (3-sec
6 gust) in boundary layer winds.

7 The other type of connection in residential roof construction that is susceptible to uplift loads is the
8 connection of roof sheathing to the rafters or roof trusses. The roof sheathing has many structural
9 functions including giving lateral support to the roof framing, acting as a surface to which loads are
10 applied and distributed to the roof framing, and as part of the building envelope to aid in keeping the
11 building sealed so as to prevent the inside of the building from becoming pressurized. These functions
12 are critical to the ability of the residential structure to survive a tornado.

13 The sequence of progressive failure of low-rise residential structures in tornadoes is not well
14 understood. Thampi et al. (2011) demonstrated that once the building envelope is breached, either
15 through failure due to wind pressures or debris impact, internal pressures change the sequence of failure
16 and failure mode of the structure. Thampi et al. (2011) also demonstrated that the failure of the roof
17 occurred for a sealed building, but the failure of a door caused failure of the gable end. Therefore, for the
18 purpose of tornado-resistant design, it is useful to understand where the initial failure is most likely to
19 occur. Due to the complexity of failure sequences of low-rise buildings in tornadoes, the analysis of the
20 roof connections below was done assuming that the rest of the structure remained intact until the
21 connections failed.

22 Model 1 and Model 5 were used in the analysis to compare the tornado-induced load on the roof
23 connection with the capacity of the roof connections as reported in the literature, as well as to observe the
24 difference in load on the roof connections for the two models with different dimensions and roof pitch.
25 The pressure time histories of the two models were first converted to pressure coefficient time histories

1 using Equation 5, where P is the recorded pressure (i.e. the total pressure minus the static pressure) at
2 time step i , V_H is the average horizontal component of the wind velocity measured at the radius of the
3 core, and ρ is the density of air.

$$4 \quad C_p = \frac{P_i}{\frac{1}{2} \rho V_H^2} \quad (5)$$

5 *4.7.1 Roof sheathing connection*

6 In the field of aerodynamics terms such as “windward”, “leeward”, “leading”, and “trailing” are often
7 used to describe certain parts of an object immersed in a straight-line flow. These terms are not as easily
8 defined for flow in a tornado, but because of a lack of alternatives they will be used in the following
9 discussion. The terms are defined for the sides of the models for a building orientation angle of 0° and
10 counter-clockwise flow. The sides referred to by the terms do not change with the building orientation
11 angle. The conventions used are as follows:

12

- 13 • Windward: The side of the model that experiences the tangential velocity component first and is
14 parallel to the direction of the translation of the tornado.
- 15 • Leeward: The side of the model that is parallel to and opposite of the windward side.
- 16 • Leading: The side of the model that is perpendicular to the direction of translation and is closest
17 to the tornado before the tornado reaches the model.
- 18 • Trailing: The side of the model that is perpendicular to the direction of translation and is closest
19 to the tornado after the tornado has passed the model

20

21 For the 0° building orientation angle the peak pressures for Model 1 occurred at the leading, leeward
22 corner and roof edge. For building orientations 15° through 75° , the peak pressures on Model 1 occurred
23 at the trailing leeward roof edge and at the windward leading roof edge while for Model 5 the highest

1 peak pressures occur mainly at the leading, windward roof edge and the leading, windward wall edge.
2 For a building orientation of 90° , the pressures are not as high as for other building orientations and the
3 highest peaks for Model 1 occur in the trailing, windward region of the roof and for Model 5 occur in the
4 leading, leeward region of the roof. The maximum peak pressure coefficient from all building orientation
5 angles for Model 1 is -6.1 and for Model 5 is -4.9 .

6 Using the maximum peak pressure coefficients obtained for Models 1 and 5 and the capacity of roof
7 sheathing as reported in the literature for different types of nails and nailing schedules, the required wind
8 velocity for sheathing panel uplift failure can be determined. The full-scale tornado horizontal wind
9 velocities with the same averaging time as the model-scale tornado required to exceed the capacities of
10 sheathing panels with various fastener types and spacing are shown in Table 2. Simply by using 8d ring
11 shank nails spaced at 150 mm along the edges of the panel as well as in the middle of the panel
12 (150/150), the velocity required to create an uplift pressure using the peak pressure coefficients
13 approaches what is considered an EF3 tornado. Installing 8d ring shank nails with a slightly heavier
14 nailing schedule instead of 6d smooth shank nails has an insignificant cost when compared to the total
15 cost of residential construction. Such a small increase in cost is certainly justifiable if the tragedy caused
16 by tornadoes can be lessened.

17 *4.7.2 Roof-to-wall-connection*

18 In order to obtain the full-scale roof-to-wall connection reactions, the maximum model-scale
19 horizontal velocity was scaled to a full-scale velocity of 74 m/s based on the assumption that this full-
20 scale velocity has an averaging time equivalent to the averaging time of the model scale. The time scale
21 (λ_T) was then calculated to be 1:15.9 based on the velocity scale (1:6.3) and length scale (1:100).

22 The dimensions of the models were scaled up to full-scale using a length scale of $\lambda_L = 1:100$. Spacing
23 of the roof trusses at full-scale was 0.6 m (24 inches) on center. The influence functions for these
24 particular models were not available and were beyond the scope of this study; therefore, rectangular
25 tributary areas were used instead. The pressure tap tributary areas were then laid over the truss tributary

1 areas creating a grid. Each area of the grid corresponded to a particular truss (Fig. 14) and a particular
2 pressure tap. Using the pressure coefficient time histories and Equation 5 the full-scale pressures were
3 calculated for each area at each time step. In the analysis the pressures were considered to be uniform
4 over their respective areas on the grid.

5 The resultant forces were calculated for each grid area and their vertical components minus the dead
6 load of the truss and roof sheathing were used to calculate the truss reactions (Figs. 15 and 16) using
7 standard static structural analysis methods.

8 The leeward side of Model 1 experienced higher roof truss reactions than the windward side for each
9 respective truss. The highest value is for the vertical reaction at Truss X (Fig. 14) on the trailing leeward
10 side. The peak reaction for either of the two models was -10 kN. This is almost twice as high as the
11 capacity of a commonly available 18 gauge hurricane tie as reported by Canfield et al. (1991) and 5 times
12 as great as the capacity of a toe-nailed connection using three 16d box nails. This clearly makes the toe-
13 nailed connection inadequate and requires a significant increase in capacity over the use of a single
14 hurricane tie. A possible method of increasing the RTWC capacity would be to incorporate toe nailed
15 connections in addition to hurricane ties. Reed et al. (1997) found that combining the hurricane tie with
16 toe-nails in the same connection increased the capacity of the RTWC to 8.47 kN for one hurricane tie per
17 rafter and 14.35 kN when 2 hurricane ties of the same type were used for each rafter.

18 Canfield et al. (1991) found that for the majority of tests conducted the failure mode of the hurricane
19 tie connection was tearing of the metal hurricane tie. Therefore, another possible solution would be to
20 increase the thickness of the metal used in the hurricane tie from 18 gauge to 16 gauge or even 14 gauge.
21 Tests could be done to determine which sheet metal gauge the connection would not fail by tearing of the
22 hurricane tie, but rather fail by splitting of the wood members in order to optimize the capacity of the
23 hurricane tie without adding significant cost to the connection.

1 The hurricane ties mentioned above are available nationwide at common hardware stores for about
2 US\$0.60 each. The addition of 2 of these ties to each rafter or to each roof truss support is insignificant
3 to the cost of construction of a new low-rise residential structure.

4 **5 Conclusions**

5 The purpose of the study presented here was to investigate the effect of different building geometry on
6 the forces and pressures that low-rise buildings would experience in a simulated tornado with a swirl
7 ratio comparable to what has been measured and recorded for full-scale tornadoes and then to use the
8 force and pressure data to judge whether tornado-resistant design for residential structures is feasible
9 based on hard data rather than opinion and engineering judgment. In order to achieve these goals the
10 pressures on nine low-rise building models were recorded when the models were subjected to a simulated
11 tornado with a swirl ratio of 2.6 using the Iowa State University's tornado simulator. The study found
12 that the peak pressure coefficients, force coefficient time histories and peak force coefficients vary as a
13 function of eave height, roof pitch, aspect ratio, plan area, and other differences in geometry such as the
14 addition of a "garage" and modeling of the roof overhang and soffit. These geometric variables also
15 influence the forces and pressures that would need to be resisted by the structure in tornado-resistant
16 design. It appears that the design of the two critical roof connections in residential construction for
17 tornado-resistant design up to and including EF3 tornadoes can be made to be cost-effective by using
18 currently available technology.

19

20 **Acknowledgment**

21 This research was funded by the National Oceanic and Atmospheric Administration (NOAA) under
22 award # NA09OAR4600222.

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16

17

1 **List of Tables**

2

3 Table 1. Model dimensions

4 Table 2. Required wind velocity for sheathing panel uplift failure

5

6

1 **List of Figures**

2

3 Figure 1. Contour plot of tangential velocity magnitudes normalized with respect to the maximum
4 tangential velocity

5 Figure 2. Building models used in the study

6 Figure 3. Building orientation angle (BOA) with respect to the tornado translation axis (X) and
7 areas (S_v , S_z) used to normalize force coefficients

8 Figure 4. Peak pressure contours for Model 1 (left) and Model 2 (right) for the 30° building orientation
9 angle.

10 Figure 5. Vertical force coefficient time history for Model 1 and Model 2 for the 30° building
11 orientation angle

12 Figure 6. XY force coefficient time history for Model 1 and Model 2 for the 30° building orientation
13 angle

14 Figure 7. Peak pressure contours for Model 3 (left), Model 4 (center), and Model 5 (right) for the 45°
15 building orientation angle.

16 Figure 8. Peak vertical force coefficients for Models 3, 4 and 5 for each building orientation angle

17 Figure 9. Vertical force coefficient time history for Models 3, 4 and 5 for the 30° building orientation
18 angle

19 Figure 10. Peak pressure contours for Model 1 (left) and the Overhang Model (right) for the 30° building
20 orientation angle (Overhang Model - the contours for the long narrow rectangles correspond to the soffit
21 and the contours on the roof include the overhang)

22 Figure 11. Peak vertical force coefficients for Model 1 and Model 7 or overhang model for each building
23 orientation angle

24 Figure 12. Peak horizontal, Y-direction force coefficients for Model 1 and Model 7 or overhang model
25 for each building orientation angle

26 Figure 13. Vertical force coefficient time history for Model 5 and Model 6 for the 30° building
27 orientation angle

28 Figure 14. Location of roof truss connections with respect to the moving tornado for Model 1 (top) and
29 Model 5 (bottom)

30 Figure 15. Peak roof truss reactions for Model 1

31 Figure 16. Peak roof truss reactions for Model 5

32

33