ANALYSIS OF LOAD PATHS IN RESIDENTIAL HOUSES

By

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ANALYSIS OF LOAD PATHS IN RESIDENTIAL HOUSES

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Abstract: The Moore tornado on May 20th 2013 caused severe damage to numerous residential homes. A research team was sent to rate the damage and collect information about load paths during tornadic events. The team found that the load paths of the houses were insufficient and that failure was occurring in the connections. Using the information they collected a relationship between the centerline of the tornado path and EF rating could be seen. This could be used to see how and where the failure occurs. In addition to a statistical analysis a theoretical analysis was also done to support the information from the research team. This analysis also included the comparison of nailed and metal connection to see the benefit they provide.

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CHAPTER I

INTRODUCTION

Section 1.1: Introduction

On May 20th 2013 several tornados touched down in Oklahoma. One that was located in Moore was rated an EF5 by the National Weather Service and had winds estimated at just over 200 mph. This tornado cause catastrophic damage to numerous residential houses in the area. The RAPID Deployment Damage Assessment Team was sent to collect information about the damage.

In a tornado it is almost impossible to measure wind speed during the event. That is why the EF scale is based on damage and the wind speed is only estimated. The failures that occurred could be attributed to inadequate load paths.

Sections 1.2: Load Paths

For any structure load paths are important. Much like water, loads cannot jump from point to point the load must flow through the system. Failure of a structure usually is not cause by failure in the members. The failure occurs at the connections. Usually the connections cannot carry as much load as the members anyway but also they are often loaded in both shear and tension/compression which lowers the efficiency of the connection.

For residential houses the load path begins in the roof. All of the uplift load must be transferred from the roof to the top plate. The top plate then transfers it to the studs and the sheathing. Then depending on how many stories the house has it will either go to the joists or the bottom plate. Once it has reached the bottom plate it is transferred to the anchorage into the foundation. The horizontal wind loads cause on overturning moment. This moment is resisted by dead load and the tie downs to the foundation.

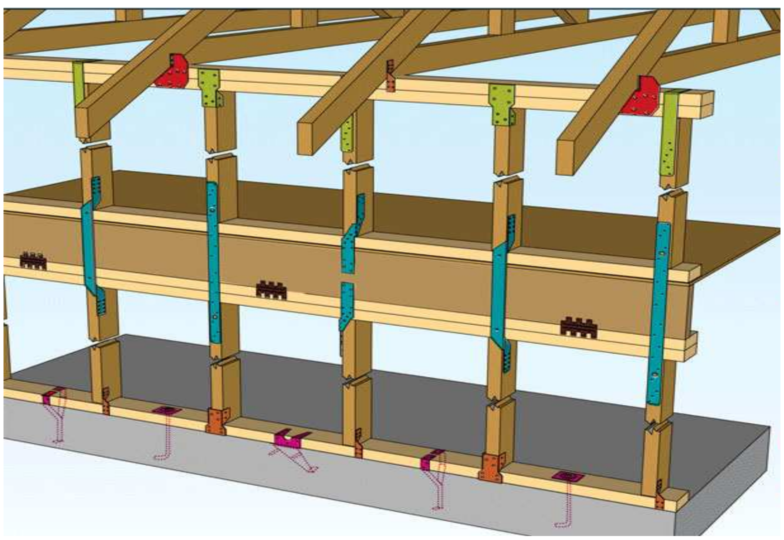

Figure 1: Load Paths (Radaractive)

To study how load paths behave during a tornado and where failure might occur, two things were done. First the information collected by the RAPID team was used to determine relationships between damage and distance from the center of the tornado. This would give an idea of what failure modes control. Second a mathematical analysis was done to reinforce these find and also see the benefits of using metal connector if any.

Section 1.3: Failure Modes

Several different failures can occur in the path between the roof and the foundation. The most common failures are discussed below in detail. They include roof to top plate failure, the connection of the stud to the plates and the failure of the bottom plate. Other failures included shear failure of the anchor bolts, tension failure in the anchor bolts and racking of the wall system.

The roof to top plate connection is where the load path begins. This connection has to transfer the uplift load from the roof to the top of the stud walls. This connection is one of the most important because of two reasons. One the dead load of the roof is obviously smaller than the rest of the house. Since this helps resist the uplift forces it requires better connections. Secondly if these connections fail the house loses its ability to behave as a diaphragm, greatly lowering the capacity. Figure 2 below shows this failure mode.

Figure 2: Roof Failure

When the connection between the studs and the bottom plate fail, the wall and roof systems are removed leaving the bottom plate anchored to the foundation as seen in Figure 3. Typically for this connection you will see the used on end nails. This is done for ease of construction. However since these nails are parallel to the grain they provide no withdrawal design capacity. Sheathing helps transfer the load from top to bottom plate as well if it is adequate. The sheathing is loaded in shear so the connection is much stronger .

Figure 3: Failure of Stud to Bottom Plate Connection

The bottom plate would fail if the connections above it are adequate and the wood fails before the bolt reaches capacity. This type of failure leaves the anchor bolt in the foundation but removes the bottom plate. The difference between the stud connection failure and bottom plate failure can be seen in Figures 4 and 5. Notice in Figure 5 the bolts are bent but still have the nuts attached. This type of failures could be prevented several different ways such as decreasing anchor spacing, using larger pieces of lumber for the bottom plate, larger washers. All of these solutions increase the amount of surface area being loaded thus lowering the stress. This type of failure could also occur if the roof system is removed and the walls began to act as a moment arm about the bottom plate. This would put pressure perpendicular to the grain and could cause the wood to fail. This would explain the bending of the anchor bolts.

Figure 4: Bottom Plate Anchored to Foundation

Figure 5: Failure of Bottom Plate

The second type of failure that occurs at the bottom plate is a bolt failure. Instead of the plate failing the bolt is the failure mechanism. The two failure types in this case were shear failure and thread failure or slippage. Shear can be observed in Figure 6. The two ways to resolve this issue is to either increase the size of the bolt or decrease bolt spacing. The problem with increasing the bolt size is that it would require a larger hole to be drilled in the bottom plate thus reducing the cross sectional area of the wood member increasing the probability of failure. In Figure 7 the anchor bolt is still attached but the nut has slipped. Again this could be prevented by decreasing bolt spacing. Also this could have occurred due to inadequate bolt length and not enough extra thread was provided for the nut.

Figure 6: Shearing of Anchor Bolt

Figure 7: Failure of Bolt Thread

Section 1.4: EF Scale

The Enhanced Fujita (EF) scale estimates the wind speed of a tornado by the damage it causes. Damage is assessed and compared to a list of Damage Indicators (Dis) and Degrees of Damage (DoD). (National Weather Service) The scale ranges from an EF0 to EF5 lowest to highest wind speed. The EF scale is shown below in Table 1.

Table 1: EF Scale

EF SCALE	
EF Rating	3 Second Gust (mph)
0	65-85
1	86-110
2	111-135
3	136-165
4	166-200
5	Over 200

CHAPTER II

METHODOLOGY

Section 2.1: Tornado Data

The information collected by the RAPID Deployment Damage Assessment Team for the Moore tornado, which is located at http://esridev.caps.ua.edu/MooreTornado/MooreTornado.html, was used to develop statistics about the tornado. Data was collected for 120 houses at varying locations for relation to the center of the tornado path, EF rating and damaged sustained. This data was used to determine the relationship between EF rating/damaged sustained and how close the house was to the center of the tornado. Also the relationship between EF rating and failure modes was determined.

The path of the tornado was broken down in to five equal strips running parallel to the path. Depending on the width of the tornado path at the time the strips were about 1/10-2/10 of a mile in width. The houses could be rated as one of three locations; center, off center or edge. The EF rating given by the team was recorded, then using the on-site photos damage sustained and failure modes were determined. Assuming that higher wind speeds would be seen at the centerline then as you move away from it the failure modes would change. This would give insight into what failure modes occur at certain wind speeds.

Figure 8: Tornado Path

The damage was put into six categories. The first was roof damage which was anything that was not structural such as shingle damage. Next was partial roof damage which was if part of the roof failed but all the walls were still intact. Next there was roof failure but no wall damage. Then there was partial roof and wall damage this was if only part of the roof and a part of the wall system was damage. Next was complete roof failure and partial wall damage. Lastly there was complete failure where only the foundation was left.

Section 2.2: Theoretical Analysis of Failure Wind Speeds

A simple house was analyzed to give an estimate of what wind speeds would cause a house to fail and where the failure occurs. The house was 36’x36’ and one story with a wall height of 9’ and a total height of 15’. The dimension remained the same throughout the calculations with only the total dead load and the connections capacities changing. The dead load was changed between whether the house was assumed to have brick veneer or not. The connections capacity changed depending on if the connections were nailed or if a metal connection was used and which type was used.

It was assumed that failure would not occur in the members but at the connections. This was assumed because the information collected by the RAPID team pointed to failures in the connections. The shear capacity of the house was not calculated because all of the connections had a higher shear capacity than withdrawal capacity. This in combination with the house acting as a diaphragm would cause the shear capacity of the system to always be higher than the uplift or overturning capacity.

In analyzing the data from the RAPID team three connections were shown to be the critical connections. The connections were the roof system to the top plate, top/bottom plate to the studs and bottom plate to the foundation. In calculating the allowable load for these connections all of the nailed connections were assumed to be toenailed. This was done because if the connections were end nailed they would provide no design capacity. The metal connections in the roof system were assumed at every connection. The first two tension ties (see Figure 9) they were only assumed at the corners. For the second pair of tension ties (see Figure 10) they were assumed at every connection. For the capacities of the metal connectors Simpson Strong-Tie design information was used. The connections used can be seen in Figures 9, 10 and 11. The images are from strongtie.com.

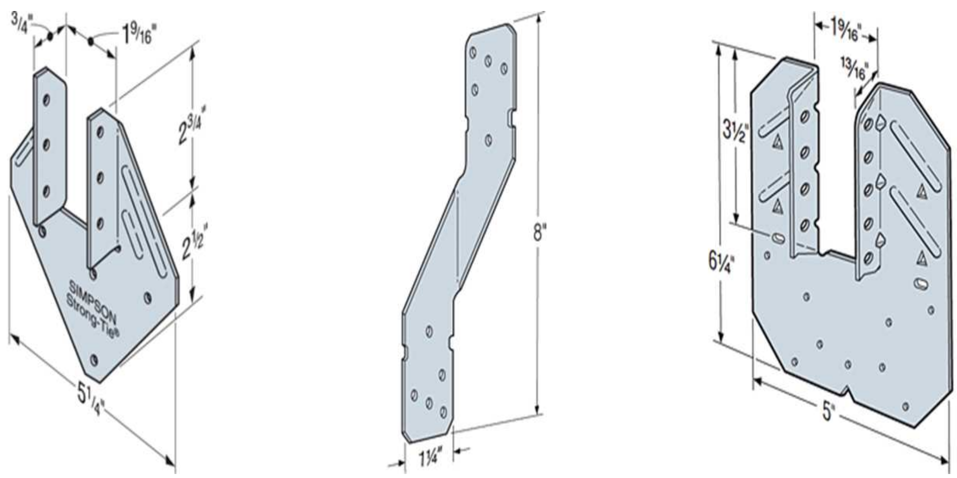

Figure 9: Hurricane ties H1, H8 and H10A

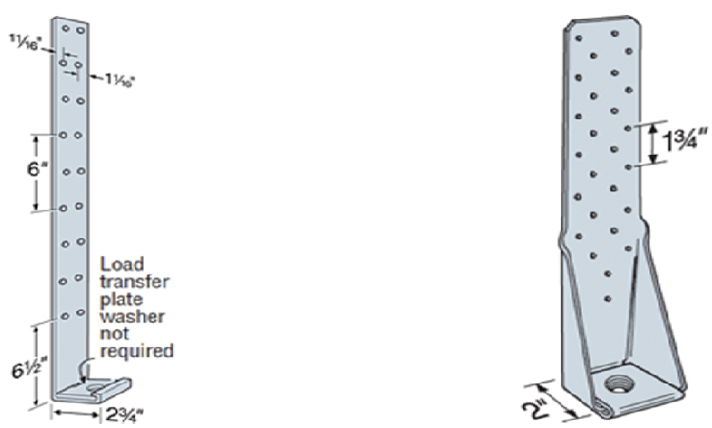

Figure 10: Tension ties LTTI31 and HTT5

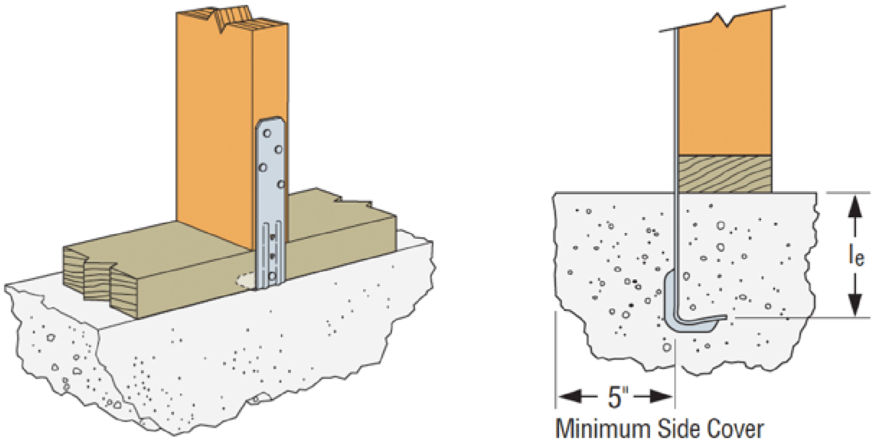

Figure 11: SSP and PA Strap Connections

Table 2: Metal Connector Capacities

Metal Connector	Tension Capacity (lbs)
H1	585
H8	745
H8 (x2)	1490
H10A	1140
SSP	420
PA51	2025
LTTI31	1350
HTT5	4350

The two failures that would occur were overturning of the roof and overturning of the house. Both of these are calculated using summation of moments. Figure 12 shows the free body diagram for overturning of the house. After the allowable load for each connection was calculated the house dead load was estimated. This was done using ASCE 7-02 Section C3.0. Using the allowable loads for the connections and the dead leads of the house the resisting moment for roof overturning and house overturning were calculated. The horizontal and the uplift pressure cause the overturning moment. Using ASCE 7-02 Figure 6-2 the horizontal and uplift pressure were found to have a linear relationship. Also there is a second order polynomial relationship between horizontal pressure and wind speed. Failure wind speed was then guessed and then the resulting overturning moment was checked against the resisting moment to see if failure had occurred.

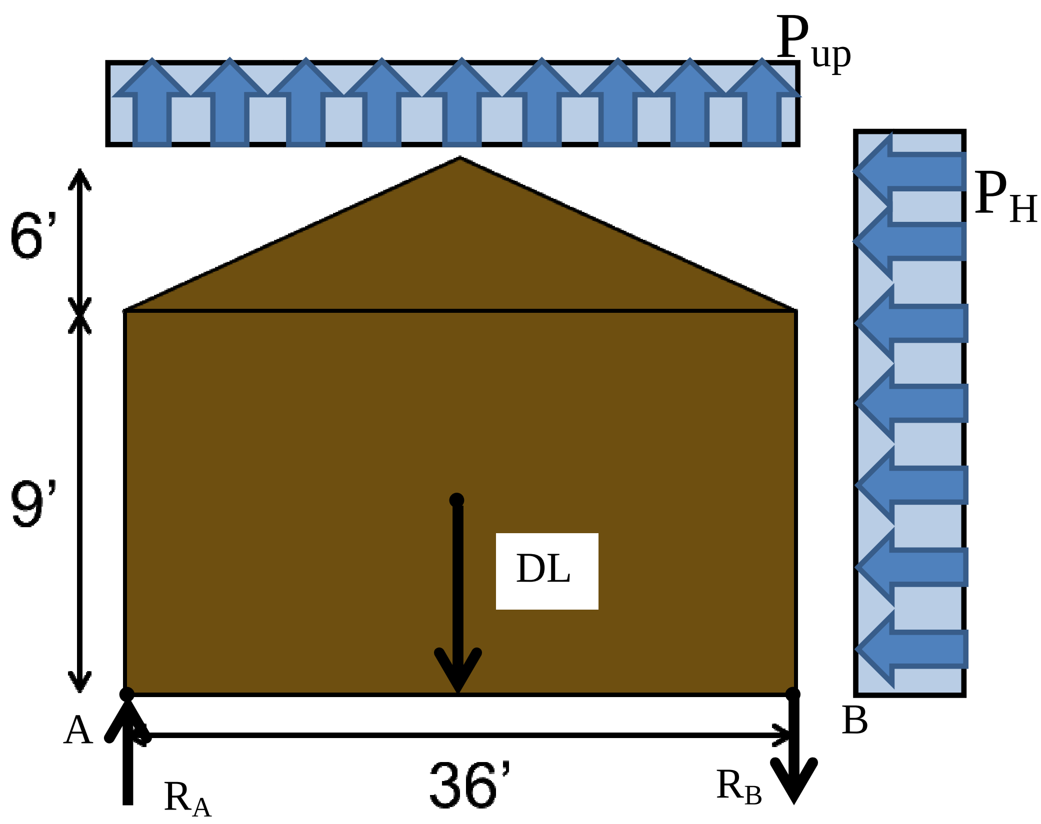

Figure 12: FBD for House Overturning

CHAPTER III

FINDINGS

Section 3.1: Results of Tornado Data

This section contains the results from information collected by the RAPID team. The data for this section can be seen in the appendix pages 24-29. Below Table 3 shows the total number of house that was recorded for each EF rating. Table 4 shows that EF rating has a tendency to increase as the centerline of the tornado path is approached.

Table 3: Total Number of Sample Houses and Their EF Rating

	EF 0's	EF 1's	EF 2's	EF 3's	EF 4's	Total
Houses	25	17	46	5	27	120

Table 4: Location vs. EF Rating

	Relation to Center vs. EF Rating (%)				
	EF0	EF1	EF2	EF3	EF4
Edge	80.0	17.6	2.2	0.0	0.0
Off Center	16.0	52.9	54.3	0.0	25.9
Center	4.0	29.4	43.5	100.0	74.1

Below Table 5 shows that there is a relationship between the distance to the centerline of the tornado and the severity of the damage sustained. Figure 13 shows the same information in a bar graph.

Table 5: Damage Sustained Compared to the Location of the House

	Damage vs. Relation to Center (%)		
	Edge	Off Center	Center
Roof Damage	95.8	26.7	11.8
Partial Roof Failure	0.0	22.2	11.8
Roof Failure	0.0	0.0	5.9
Partial Roof and Wall Failure	4.2	22.2	11.8
Full Roof and Partial Wall Failure	0.0	13.3	33.3
Complete Failure	0.0	15.6	25.5

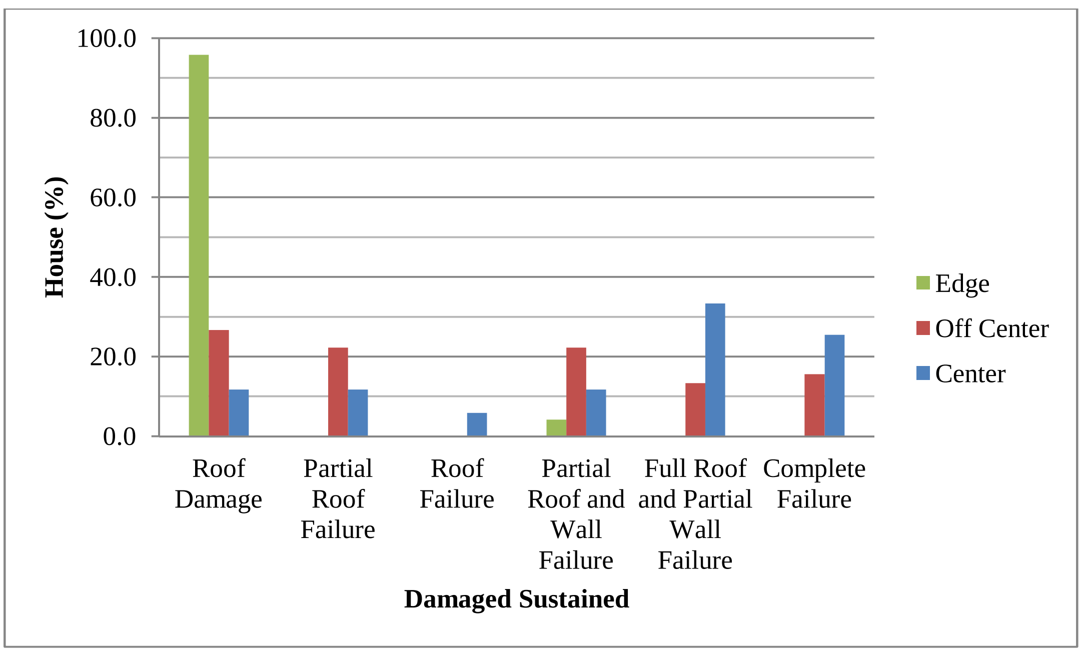

Figure 13: Percent of Houses vs. Damaged Sustained Based on Location

Table 6 shows the relationship between the EF rating a particular house was given and the damage that it sustained. Figure 14 shows this same information in graph form.

Table 6: Damage Sustained Compared to the EF Rating

	Damage vs. EF Rating (%)				
	EF 0's	EF 1's	EF 2's	EF 3's	EF 4's
Roof Damage	100.0	76.5	6.5	0.0	0.0
Partial Roof Failure	0.0	17.6	28.3	0.0	0.0
Roof Failure	0.0	0.0	6.5	0.0	0.0
Partial Roof and Wall Failure	0.0	5.9	28.3	0.0	11.1
Full Roof and Partial Wall Failure	0.0	0.0	23.9	60.0	33.3
Complete Failure	0.0	0.0	6.5	40.0	55.6

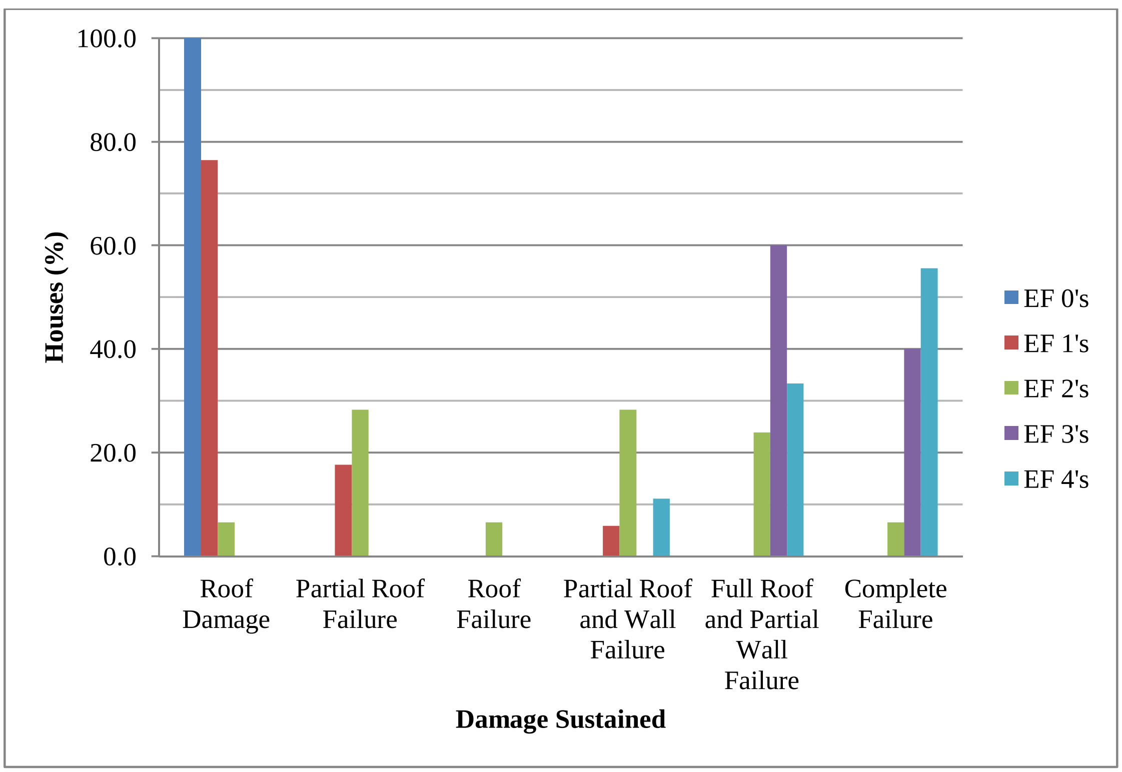

Figure 14: Percent of Houses vs. Damage Sustained Based on EF Rating

Section 3.2: Results of Theoretical Analysis

This section contains the results from the mathematical analysis of the example house shown in Figure 11. The complete calculations for this section can be seen in the appendix pages 30-62. Below Table 7 lists the different failures types and what wind speed would be necessary to cause failure.

Table 7: Failure Wind Speed for Nailed Connections and the Corresponding EF Rating

	Wind Speed at Failure (mph)	Tornado Category
Roof Failure	100	EF1
House Overturning w/o Brick Veneer	140	EF3
House Overturning w/ Brick Veneer	185	EF4
Bottom Plate w/o roof	40	EF0

Table 8 shows the comparison between nailed and metal connections. It also gives the EF rating for the failure wind speed.

Table 8: Failure Wind Speeds for All Connection Types

	Connection Capacity (lb)	Roof overturning (mph)		House Overturning w/o brick veneer (mph)		House Overturning w/ brick veneer (mph)	
Toenailed	86	100	EF1	140	EF3	185	EF4
H1	585	145	EF3	-	-	-	-
H8	745	155	EF3	-	-	-	-
H8 (x2)	1490	205	EF4	-	-	-	-
H10A	1140	180	EF4	-	-	-	-
LTTI31*	1350	-	-	145	EF3	190	EF4
HTT5*	4350	-	-	160	EF3	200	EF4

***Only located at corners**

Table 9 shows the failure wind speeds if the sheathing capacity was assumed to be zero and the nailed connections were end nailed.

Table 9: Failure Wind Speeds for Dead Load Only

	Connection Capacity (lb)	House Overturning w/o brick veneer (mph)		House Overturning w/ brick veneer (mph)	
Dead Load Only		105	EF1	155	EF3
SSP	420	135	EF2	180	EF4
PA51	2025	220	EF5	250	EF5

CHAPTER IV

CONCLUSION

Section 4.1: Conclusion of Tornado Data

The data collected from the Moore tornado shows several things. The most obvious is that the closer the house is to the centerline of the tornado, damage sustained is more severe. This can be seen throughout the data. When examining Table 4 it shows that EF rating increases as the centerline of the tornado is approached. Using this idea and Table 6 and Figure 14 it shows that the controlling connection is the roof to the stud walls. It shows that even in areas of damage ratings as low as EF1 there was partial roof failure occurring. So if roof failure can occur further away from the centerline and since lower winds speeds are seen as you move away from the centerline it is reasonable to conclude that roof failure occurs first. Table 5 and Table 13 suggest the same conclusion. The houses that were located in the off center strips were more likely to sustain partial roof and partial wall damage or less. Only full roof and partial wall failure, and complete failure have a higher percentage of houses located at the center. However when considering the load paths the walls are able to stand without the roof since a load path still exists, the roof on the other hand cannot stand once the walls have failed. The lack of severe damage away from the centerline seems to indicate that it is the roof that fails first. This is why a mathematical analysis was done to support the data.

Section 4.2: Conclusion of Theoretical Analysis

The theoretical analysis showed that the load paths will typically fail in the roof to top plate connections first. This is due to the fact the other connections have the benefit of more dead load. The greatest benefit of metal connectors was seen in the roof, going up from 100 mph to as high as 205 mph. Considering the rarity of even and EF4 tornados this would greatly improve safety. All of the metal connections used for the roof would be sufficient for an EF2.

For house overturning the best prevention is to have a brick veneer. The difference between with and without the veneer was 45 mph. With the brick veneer the house dead load is large enough by itself to resist a 185 mph wind with only nailed connections. There is benefit in adding tie downs at the corners. However the increase in wind speed is only 15-20 mph. This is why Table 9 was evaluated. This table shows several things. First the benefit from adequate sheathing increased the wind capacity by 40 mph. Considering the difference between EF ratings is about 25-35 mph this is considerable. Next it shows that if smaller metal connections were used at every stud in can greatly increase capacity. However if the roof connections fail this benefit is useless. This is shown in the calculation of the wall without the roof system if it is rotated about the bottom plate. A 6’x 8’ section fails at 40 mph. If the roof connections have failed, the wind speed would most likely be high enough to fail the wall system.

Section 4.3: Overall Conclusions

After reviewing both the tornado data and the theoretical analysis it is obvious that the roof system is where the load path fails. Once this failure occurs it depends on the conditions how much of the wall system will fail but given that low speeds can cause damage at this point it could be considerable. Metal connections for the roof should be required and smaller rafter spacing should be used if possible. House overturning failure was greatly affected by whether veneer was used and sheathing capacity. Quality sheathing should always be used especially in houses without brick veneer. The failure wind speed for overturning of the house should always be higher than required to fail the roof. If the roof fails first there is the hope of smaller pieces of debris rather than if the entire house failed at once.

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APPENDICES

The following four pages contain the data from the interactive map at http://esridev.caps.ua.edu/MooreTornado/MooreTornado.html. The houses are listed from 1-120 on the left hand side. The house information includes the EF rating and the relation to center. The EF rating ranges from 0-4. The relation to center ranges from 1-3, where 1 is at the center, 2 off center and 3 at the edge. The damage information is broken down into six categories that were listed and explained in the Chapter II: Methodology. The house is given a 1 for yes and 0 for no. The right hand column has notes about the house locations. The totals are listed at the bottom of the fourth sheet.

	House Information		Damage						Notes
	EF Rating	Relation to Center	Roof Damage	Partial Roof Failure	Roof Failure	Partial Roof and Wall Failure	Full Roof and Partial Wall Failure	Complete Failure	
House 1	2	2	0	0	0	1	0	0	SW 152nd Pl. West of Western on south side of path
House 2	1	2	0	1	0	0	0	0	
House 3	0	3	1	0	0	0	0	0	
House 4	1	3	1	0	0	0	0	0	
House 5	0	3	1	0	0	0	0	0	
House 6	2	1	0	0	0	0	1	0	149th and Kyle Dr. then go south
House 7	2	1	0	0	0	0	1	0	
House 8	2	1	0	0	1	0	0	0	
House 9	2	1	0	0	0	0	1	0	
House 10	2	1	0	0	1	0	0	0	
House 11	2	1	1	0	0	0	0	0	
House 12	2	1	0	1	0	0	0	0	
House 13	1	1	0	1	0	0	0	0	
House 14	2	1	0	1	0	0	0	0	
House 15	2	1	0	1	0	0	0	0	
House 16	1	1	1	0	0	0	0	0	
House 17	2	1	0	1	0	0	0	0	
House 18	2	2	0	1	0	0	0	0	
House 19	2	2	1	0	0	0	0	0	
House 20	1	2	1	0	0	0	0	0	
House 21	0	2	1	0	0	0	0	0	
House 22	2	2	0	1	0	0	0	0	
House 23	2	2	0	1	0	0	0	0	
House 24	1	2	1	0	0	0	0	0	
House 25	1	2	1	0	0	0	0	0	
House 26	2	2	0	1	0	0	0	0	
House 27	2	2	0	1	0	0	0	0	
House 28	1	2	1	0	0	0	0	0	
House 29	2	2	0	1	0	0	0	0	
House 30	1	2	1	0	0	0	0	0	
House 31	1	2	1	0	0	0	0	0	

	House Information		Damage						Notes
	EF Rating	Relation to Center	Roof Damage	Partial Roof Failure	Roof Failure	Partial Roof and Wall Failure	Full Roof and Partial Wall Failure	Complete Failure	
House 32	0	3	1	0	0	0	0	0	154th and Acacia Rd
House 33	0	3	1	0	0	0	0	0	
House 34	0	3	1	0	0	0	0	0	
House 35	2	1	0	0	0	1	0	0	149th Pl. just south of 149th St.
House 36	4	1	0	0	0	0	0	1	
House 37	4	1	0	0	0	0	1	0	
House 38	0	1	1	0	0	0	0	0	
House 39	4	1	0	0	0	0	1	0	
House 40	4	1	0	0	0	0	1	0	
House 41	4	1	0	0	0	1	0	0	
House 42	4	1	0	0	0	0	1	0	
House 43	4	1	0	0	0	0	1	0	
House 44	4	1	0	0	0	1	0	0	
House 45	2	1	0	0	1	0	0	0	
House 46	1	2	1	0	0	0	0	0	151st and Stone Meadows
House 47	0	2	1	0	0	0	0	0	
House 48	0	2	1	0	0	0	0	0	
House 49	0	2	1	0	0	0	0	0	
House 50	3	1	0	0	0	0	1	0	Hudson Ave to Sante Fe, North of 149th
House 51	3	1	0	0	0	0	0	1	
House 52	4	1	0	0	0	0	0	1	
House 53	4	1	0	0	0	0	0	1	
House 54	4	1	0	0	0	1	0	0	
House 55	2	1	0	0	0	1	0	0	
House 56	1	1	1	0	0	0	0	0	
House 57	1	1	1	0	0	0	0	0	
House 58	2	1	1	0	0	0	0	0	
House 59	2	1	0	1	0	0	0	0	
House 60	0	3	1	0	0	0	0	0	

	House Information		Damage						Notes
	EF Rating	Relation to Center	Roof Damage	Partial Roof Failure	Roof Failure	Partial Roof and Wall Failure	Full Roof and Partial Wall Failure	Complete Failure	
House 61	0	3	1	0	0	0	0	0	Hudson Ave to Sante Fe, North of 149th
House 62	0	3	1	0	0	0	0	0	
House 63	1	3	1	0	0	0	0	0	
House 64	2	2	0	0	0	1	0	0	
House 65	4	2	0	0	0	0	1	0	
House 66	4	2	0	0	0	0	1	0	
House 67	2	2	0	0	0	1	0	0	
House 68	2	2	0	0	0	0	1	0	Sante Fe and 12th St. East down 12th St.
House 69	1	2	0	1	0	0	0	0	
House 70	2	2	0	0	0	1	0	0	
House 71	2	2	0	0	0	1	0	0	
House 72	2	2	0	0	0	1	0	0	
House 73	2	2	0	0	0	1	0	0	
House 74	2	2	0	0	0	0	0	1	
House 75	2	2	0	0	0	1	0	0	
House 76	2	2	0	1	0	0	0	0	
House 77	2	2	0	0	0	0	0	1	
House 78	2	2	0	0	0	1	0	0	
House 79	2	2	0	0	0	0	0	1	
House 80	2	2	0	0	0	0	1	0	Sante Fe and 13th St. East down 13th St.
House 81	3	1	0	0	0	0	1	0	
House 82	3	1	0	0	0	0	1	0	
House 83	2	1	0	0	0	0	1	0	
House 84	1	1	0	0	0	1	0	0	
House 85	4	1	0	0	0	0	0	1	
House 86	4	1	0	0	0	0	0	1	
House 87	3	1	0	0	0	0	0	1	
House 88	4	1	0	0	0	0	0	1	
House 89	2	1	0	0	0	0	1	0	
House 90	4	1	0	0	0	0	0	1	

	House Information		Damage						Notes
	EF Rating	Relation to Center	Roof Damage	Partial Roof Failure	Roof Failure	Partial Roof and Wall Failure	Full Roof and Partial Wall Failure	Complete Failure	
House 91	2	1	0	0	0	0	1	0	Sante Fe and 13th St. East down 13th St.
House 92	2	1	0	0	0	0	1	0	
House 93	4	1	0	0	0	0	0	1	
House 94	4	1	0	0	0	0	1	0	
House 95	4	1	0	0	0	0	0	1	
House 96	2	1	0	0	0	0	1	0	
House 97	4	1	0	0	0	0	0	1	
House 98	4	1	0	0	0	0	0	1	
House 99	0	3	1	0	0	0	0	0	Edge and Penn Lane going south
House 100	0	3	1	0	0	0	0	0	
House 101	0	3	1	0	0	0	0	0	
House 102	0	3	1	0	0	0	0	0	
House 103	0	3	1	0	0	0	0	0	
House 104	0	3	1	0	0	0	0	0	
House 105	0	3	1	0	0	0	0	0	
House 106	0	3	1	0	0	0	0	0	
House 107	0	3	1	0	0	0	0	0	
House 108	2	3	0	0	0	1	0	0	
House 109	1	3	1	0	0	0	0	0	East of Sante Fe and North of 19th. SW 10th St.
House 110	0	3	1	0	0	0	0	0	
House 111	0	3	1	0	0	0	0	0	
House 112	0	3	1	0	0	0	0	0	
House 113	2	2	0	1	0	0	0	0	Eagle Dr and SW 10th
House 114	4	2	0	0	0	0	0	1	
House 115	4	2	0	0	0	0	0	1	
House 116	4	2	0	0	0	0	1	0	SW 6th and Telephone Rd.
House 117	4	2	0	0	0	0	0	1	
House 118	2	2	0	0	0	0	1	0	
House 119	2	2	0	0	0	1	0	0	
House 120	4	2	0	0	0	0	0	1	
	Statistics	**Total**	**41**	**16**	**3**	**17**	**23**	**20**	

The tables below have the totals from the previous data. The percentage tables are in Chapter III: Findings.

Table 10: Total Number of Sample Houses and Location

	Center	Off Center	Edge
Houses	51	45	24

Table 11: Total Number of Sample Houses and Location vs. Damage

	Damage vs. Relation to Center		
Damage	Edge	Off Center	Center
Roof Damage	23	12	6
Partial Roof Failure	0	10	6
Roof Failure	0	0	3
Partial Roof and Wall Failure	1	10	6
Full Roof and Partial Wall Failure	0	6	17
Complete Failure	0	7	13

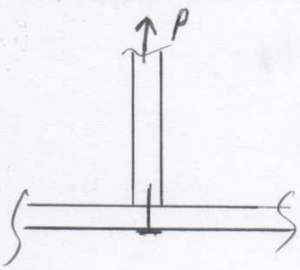
Table 12: Total Number of Sample Houses and EF Rating vs. Damage

		Damage vs. Rating				
Damage	**Total**	EF 0's	EF 1's	EF 2's	EF 3's	EF 4's
Roof Damage	41	25	13	3	0	0
Partial Roof Failure	16	0	3	13	0	0
Roof Failure	3	0	0	3	0	0
Partial Roof and Wall Failure	17	0	1	13	0	3
Full Roof and Partial Wall Failure	23	0	0	11	3	9
Complete Failure	20	0	0	3	2	15

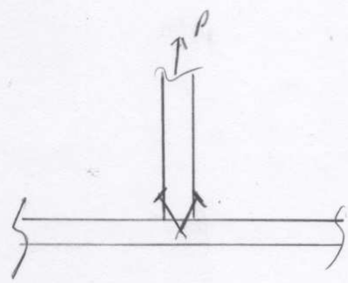
Connection Capacities

The following pages show the hand calculations for the connection capacities.

Stud to plate connection



Since nail is in withdrawal parallel to grain this connection has no design capacity.



Assume

Wood : DF #2

$G = 0.46$

Nails : two toenailed 8d nails

$\phi = 0.131''$

$l = 2.5''$

penetration length

$$p_w = l - \frac{l/3}{\cos(30°)} \leq \frac{t_m}{\cos(30°)}$$

$$2.5'' - \frac{2.5''/3}{\cos(30°)} \leq \frac{1.5''}{\cos(30°)}$$

$$p_w = \underline{1.54''} \qquad \leq 1.73''$$

Continued ↓

1/10

Stud to plate connection

Load capacity

Table 11.2C NDS

For $G = 0.46$, $\phi = 0.131''$

$w = 26$ lb/in

$W = p_w(w) = 1.54''(26 \text{ lb/in})$

$W = 40$ lb/nail

2.3 NDS

$C_D = 1.6$

$C_t = 1.0$

$C_{tn} = 0.67$

$W' = W(C_D)(C_t)(C_{tn})$

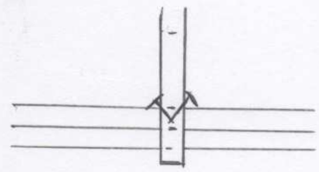
$W' = 40 \text{ lb/nail}(1.6)(1.0)(0.67)$

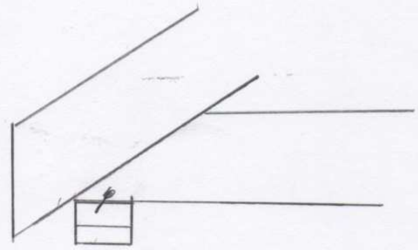
$W' = 42.88$ lb/nail

$P_{allow} = W'N = 42.88 \text{ lb/nail}(2 \text{ nails}) = \boxed{86 \text{ lb}}$

2/10

Roof to top plate in withdrawal





Assume

Top plate: DF #2 2x4's

Roof system: DF #2 2x6's

Nails: two toenailed
8d nails
$\phi = 0.131''$
$l = 2.5''$

penetration length

$$p_w = l - \frac{l/3}{\cos(30°)} \le \frac{t_m}{\cos(30°)}$$

$$2.5'' - \frac{2.5''/3}{\cos(30°)} \le \frac{3''}{\cos(30°)}$$

$$p_w = 1.54'' \le 3.5''$$

Load capacity

Table 11.2C NDS

For $G = 0.46$, $\phi = 0.131''$

$w = 26\ ^{lb}/_{in}$

$W = p_w(w) = 1.54''(26\ ^{lb}/_{in})$

$W = 40\ ^{lb}/_{nail}$

Continued ↓

3/10

Roof to plate in withdrawal

2.3 NDS

$C_D = 1.6$

$C_t = 1.0$

$C_{tn} = 0.67$

$W' = W(C_D)(C_t)(C_{tn})$

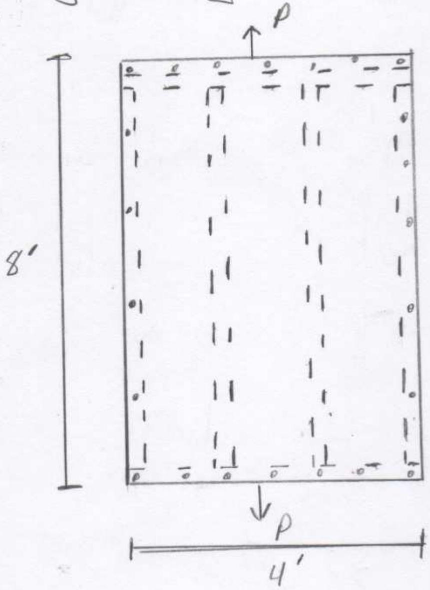
$W' = 40 \text{ lb/nail} (1.6)(1.0)(0.67)$

$W' = 42.88 \text{ lb/nail}$

$P_{allow} = W'N = 42.88 \text{ lb/nail} (2 \text{ nails}) = \boxed{86 \text{ lb}}$

4/10

Sheathing connecting top + bottom plate



Assume

side panel: $G = 0.50$

$t = 7/16''$

interior: 2x4 DFS

$G = 0.46$

nails: 10d @ 6" spacing

$\phi = 0.148''$

$l = 3$ in

Table 11Q ASD

$Z = 84$ lb

$$Z' = Z(C_D)(C_m)(C_t)(C_g)(C_\Delta)(C_{di})(C_{tn})$$

$= 1.0$

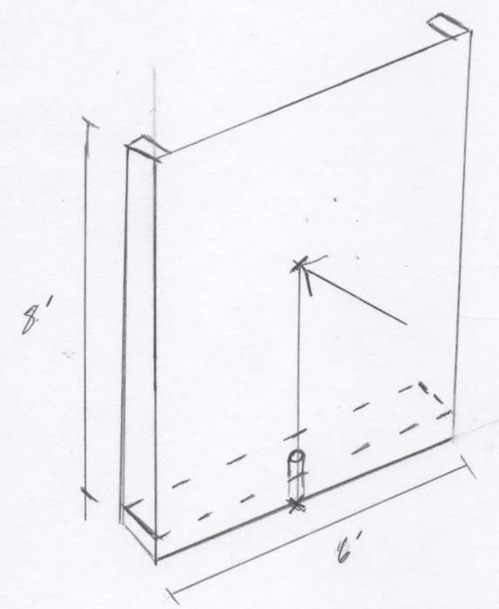
$$Z' = 84\text{ lb}(1.6) = 134.4 \text{ lb/nail}$$

$$P_{allow} = NZ' = 9 \text{ nails}(134.4 \text{ lb/nail}) = \boxed{1210 \text{ lb}}$$

5/10

Bottom plate failure

Assume that anchorage is sufficient. Failure shouldn't occur until system has changed. If roof was removed wall acts as moment arm.



Assume

6'x8' wall section

2x4's DFS

1/2" anchor bolts

6' bolt spacing

For bottom plate 2x4

From wood handbook

$F_{t\perp} = 350\ psi$

$$I = \frac{72''(1.5'')^3}{12} = 20.25\ in^4$$

Continued ↓

6/10

Bottom plate failure

$$\sigma = \frac{My}{I}$$

$$M = \frac{\sigma I}{y} = \frac{350psi\,(.75'')}{20.25\,in^4}$$

$$M = 4450\ lb\text{-}in$$

$$\circlearrowleft + \sum M = 0 = 4450\ lb\text{-}in - P_H(48'')(8ft)(6ft)$$

$$P_H = 4.1\ psf$$

$$P_H = 0.0022V^2 - 0.0022V + 0.82$$

$$\boxed{V = 40\ mph}$$

7/10

Example House

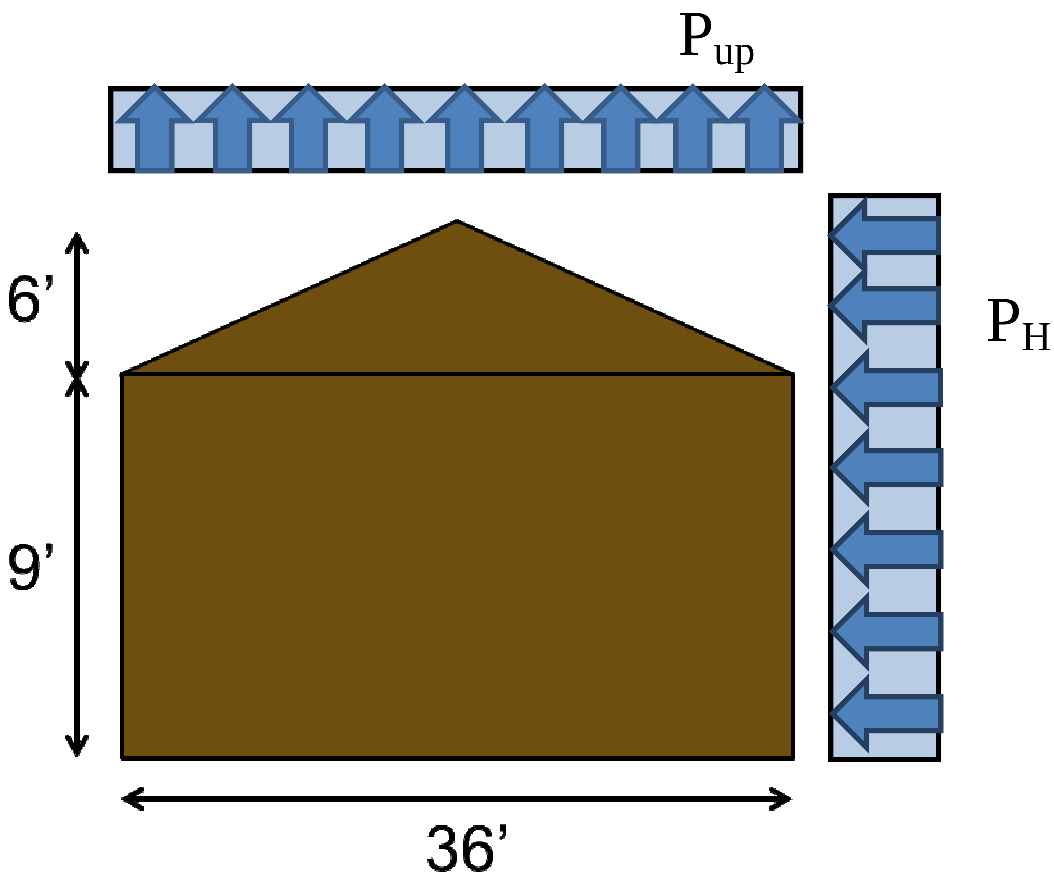


Figure 15: Example House and Wind Loads

Assumptions:

- The house is 36’ x 36’
- Douglas fir-South
- 2x4’s used for frame walls
- 2x6’s used for the roof system
- Stud spacing 16” on center
- Side sheathing is plywood
- 5/8” gypsum board for ceiling
- 5/8” plywood used for roof sheathing
- Roof is shingled
- It is a hip roof

House Dead Load

From ASCE 7-02 Section C3.0

gypsum board (per mm thickness) = 0.55 psf   5/8" = 15.875 mm
Asphalt shingles = 8 psf
plywood (per 1/8" thickness) = 0.4 psf

exterior stud walls

2x4 @ 16", 5/8" gypsum insulated, 3/8" siding = 11 psf

stud wall w/ brick veneer = 48 psf

Exterior walls

8 ft height
36' x 36' = 144' perimeter

11 psf x 8 ft x 144 ft = **12,672 lb w/o veneer**
48 psf x 8 ft x 144 ft = **55,296 lb w veneer**

Ceiling

36' x 36 = 1296 ft^2

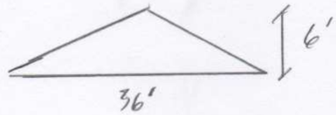
0.55 psf/mm (15.875 mm)(1296 ft^2) = **11,315 lb**

8/10

House Dead Load

Roof system

- estimate amount of wood



bottom chord

$36'\left(36'\left(\frac{16''}{12''}\right)\right) = 972\ ft$

top chord

$l = \sqrt{\left(\frac{36'}{2}\right)^2 + (6')^2} = 18.97'$

$18.97'(2)\left(36'\left(\frac{16''}{12''}\right)\right) = 1025\ ft$

total = 1997 ft

If 2x6 DF is used

$34\ pcf\ (1997\ ft)\left(\frac{1.5''}{12}\right)\left(\frac{5.5''}{12}\right) = 3890\ lb$

- plywood 5/8"

$0.4\ psf/_{1/8''}\ (5)(36')(36') = 2592\ lb$

- shingles

$2\ psf\ (36')(36') = 2592\ lb$

9/10

House Dead Load

Wall DL = 55,300 lb (w/ brick)
Wall DL = 12,200 lb (w/o brick)
Ceiling DL = 11,300 lb
Roof DL = 9000 lb

Total DL = 75,000 lb (w/ brick)
Total DL = 32,900 lb (w/o brick)

10/10

The table below is from ASCE 7 Figure 6-2 for a 20° roof slope. The example house has a roof slope of 18.75° so these numbers are conservative.

Basic Wind Speed (mph)	85	90	100	110	120	130	140	150	170
Horizontal pressure (psf)	15.9	17.8	22	26.6	31.6	37.1	43.0	49.4	63.4
Uplift pressure (psf)	13.8	15.4	19.1	23.1	27.4	32.2	37.3	42.9	55.1

The following graphs were developed using the table above.

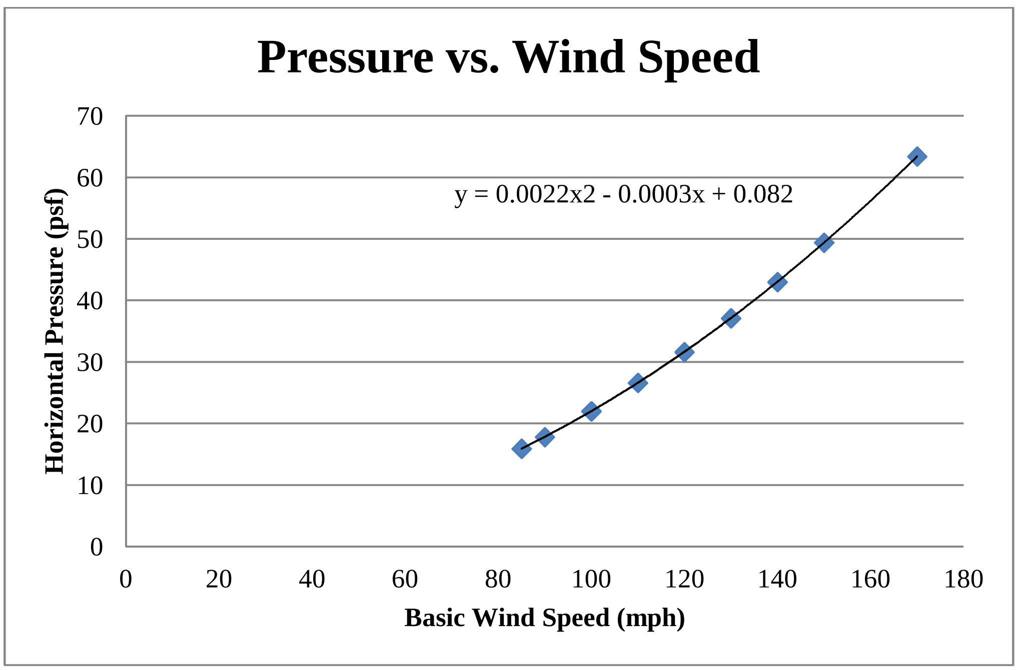


Figure 16: Equation Relating Wind Speed to Horizontal Pressure

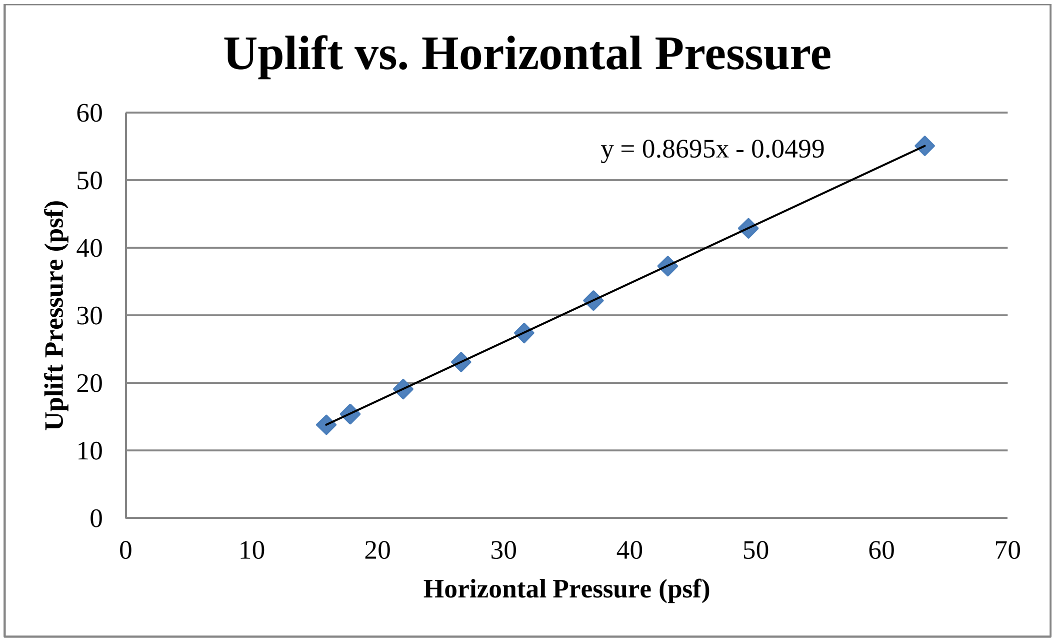
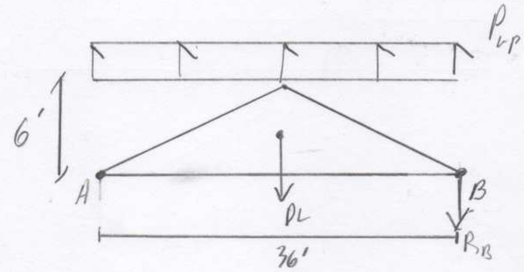


Figure 17: Equation Relating Horizontal and Uplift Pressures

Calculation of Failure Wind Speeds

The following pages show the calculations of the wind speed that would cause failure at different points. The first of these pages is a hand calculation showing the method used. All following calculations use the same method but were done in an Excel spreadsheet.

Roof overturning w/ Nailed connections



Roof DL = 20,300 lb

Overturning controls

$86\ ^{lb}/_{connection}\,(27\ \text{connection}) = 2322\ \text{lb}$

$+\circlearrowleft \Sigma M_A = 0 = 2322\ \text{lb}\,(36') + 20{,}300\ \text{lb}\,(18') - F_{up}\,(18')$

$F_{up} = 24{,}944\ \text{lb}$

$P_{up} = \dfrac{24{,}944\ \text{lb}}{(36')(36')} = 19.25\ \text{psf}$

Equation developed from ASCE 7 Fig 6-2

$P_{up} = 0.8695\,(P_H) - 0.0499$

$P_H = \dfrac{(19.25\ \text{psf} + 0.0499)}{0.8695}$

$\underline{P_H = 22.2\ \text{psf}}$

Continued

1/2

Roof overturning w/ nailed connections

Equation developed from ASCE 7 Fig 6-2

- Check 100 mph

$$P_H = 0.0022V^2 - 0.0003V + 0.082$$

$$P_H = 0.0022(100\,mph)^2 - 0.0003(100\,mph) + 0.082$$

$$P_H = 22.05\,psf < 22.2\,psf \quad \underline{OK}$$

- check 101 mph

$$P_H = 0.0022(101\,mph)^2 - 0.0003(101\,mph) + 0.082$$

$$P_H = 22.5\,psf > 22.2\,psf \quad \text{Failure}$$

$$\underline{V_{fail} = 100\,mph}$$

2/2

Roof Overturning with Nailed Connections

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**101**	**mph**				
horizontal 0-30ft	22.4	psf	806	plf	12092	lb
uplift	19.4	psf	699	plf	25168	lb

overturning moment	**543721**	**lb-ft**	**just uplift moment**	**453032**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	86	lb		
metal connection	0	lb	metal connections	0
sheathing capacity	0	lb	sheathing connections	0
dead load	20300	lb		

Moments (Roof Only)

wall connections	86688	lb-ft	
roof dead load	365400	lb-ft	
resisting moment	**452088**	**lb-ft**	**ROOF FAILURE**

Roof Overturning with Metal Connections (H1)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**147**	**mph**				
horizontal 0-30ft	47.4	psf	1705	plf	25575	lb
uplift	41.1	psf	1481	plf	53306	lb

overturning moment	**1151326**	**lb-ft**	**just uplift moment**	**959511**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	585	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	20300	lb		

Moments (Roof Only)

roof to plate connections	589680	lb-ft	
roof dead load	365400	lb-ft	
resisting moment	**955080**	**lb-ft**	**ROOF FAILURE**

Roof Overturning with Metal Connections (H8)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**159**	**mph**				
horizontal 0-30ft	55.4	psf	1994	plf	29916	lb
uplift	48.1	psf	1732	plf	62364	lb

overturning moment	**1346922**	**lb-ft**	**just uplift moment**	**1122552**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	745	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	20300	lb		

Moments (Roof Only)

roof to plate connections	750960	lb-ft	
roof dead load	365400	lb-ft	
resisting moment	**1116360**	**lb-ft**	**ROOF FAILURE**

Roof Overturning with Metal Connections (H8 x2)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**206**	**mph**				
horizontal 0-30ft	93.0	psf	3346	plf	50196	lb
uplift	80.8	psf	2908	plf	104684	lb

overturning moment	**2260783**	**lb-ft**	**just uplift moment**	**1884314**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	1490	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	20300	lb		

Moments (Roof Only)

roof to plate connections	1501920	lb-ft	
roof dead load	365400	lb-ft	
resisting moment	**1867320**	**lb-ft**	**ROOF FAILURE**

Roof Overturning with Metal Connections (H10A)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**185**	**mph**				
horizontal 0-30ft	75.0	psf	2699	plf	40489	lb
uplift	65.1	psf	2345	plf	84428	lb

overturning moment	**1823366**	**lb-ft**		**just uplift moment**	**1519698**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	1140	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	20300	lb		

Moments (Roof Only)

roof to plate connections	1149120	lb-ft	
roof dead load	365400	lb-ft	
resisting moment	**1514520**	**lb-ft**	**ROOF FAILURE**

House Overturning without Brick Veneer and Nailed Connections

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**142**	**mph**				
horizontal 0-30ft	44.2	psf	1591	plf	23867	lb
uplift	38.4	psf	1382	plf	49742	lb

overturning moment	**1074358**	**lb-ft**	**just uplift moment**	**895352**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	86	lb		
metal connection	0	lb	metal connections	0
sheathing capacity	1210	lb	sheathing connections	9
dead load	32900	lb		

Moments (House)

wall connections	86688	lb-ft	
sheathing connections	392040	lb-ft	
house dead load	592200	lb-ft	
resisting moment	**1070928**	**lb-ft**	**HOUSE FAILURE**

House Overturning without Brick Veneer and Metal Connections (LTTI31)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**149**	**mph**				
horizontal 0-30ft	48.7	psf	1752	plf	26275	lb
uplift	42.3	psf	1521	plf	54766	lb

overturning moment	**1182860**	**lb-ft**	**just uplift moment**	**985796**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	86	lb		
metal connection	1350	lb	metal connections	2
sheathing capacity	1210	lb	sheathing connections	9
dead load	32900	lb		

Moments (House)

wall connections	183888	lb-ft	
sheathing connections	392040	lb-ft	
house dead load	592200	lb-ft	
resisting moment	**1168128**	**lb-ft**	**HOUSE FAILURE**

House Overturning without Brick Veneer and Metal Connections (HTT5)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**162**	**mph**				
horizontal 0-30ft	57.5	psf	2070	plf	31054	lb
uplift	50.0	psf	1798	plf	64740	lb

overturning moment	**1398220**	**lb-ft**	**just uplift moment**	**1165312**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	86	lb		
metal connection	4350	lb	metal connections	2
sheathing capacity	1210	lb	sheathing connections	9
dead load	32900	lb		

Moments (House)

wall connections	399888	lb-ft	
sheathing connections	392040	lb-ft	
house dead load	592200	lb-ft	
resisting moment	**1384128**	**lb-ft**	**HOUSE FAILURE**

House Overturning with Brick Veneer and Nailed Connections

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**186**	**mph**				
horizontal 0-30ft	75.8	psf	2729	plf	40928	lb
uplift	65.9	psf	2371	plf	85343	lb

overturning moment	**1843129**	**lb-ft**	**just uplift moment**	**1536173**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	86	lb		
metal connection	0	lb	metal connections	0
sheathing capacity	1210	lb	sheathing connections	9
dead load	75600	lb		

Moments (House)

wall connections	86688	lb-ft	
sheathing connections	392040	lb-ft	
house dead load	1360800	lb-ft	
resisting moment	**1839528**	**lb-ft**	**HOUSE FAILURE**

House Overturning with Brick Veneer and Metal Connections (LTTI31)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**191**	**mph**				
horizontal 0-30ft	79.9	psf	2877	plf	43156	lb
uplift	69.4	psf	2500	plf	89993	lb

overturning moment	**1943546**	**lb-ft**	**just uplift moment**	**1619876**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	86	lb		
metal connection	1350	lb	metal connections	2
sheathing capacity	1210	lb	sheathing connections	9
dead load	75600	lb		

Moments (House)

wall connections	183888	lb-ft	
sheathing connections	392040	lb-ft	
house dead load	1360800	lb-ft	
resisting moment	**1936728**	**lb-ft**	**HOUSE FAILURE**

House Overturning with Brick Veneer and Metal Connections (HTT5)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**202**	**mph**				
horizontal 0-30ft	89.4	psf	3218	plf	48267	lb
uplift	77.7	psf	2796	plf	100658	lb

overturning moment	**2173842**	**lb-ft**	**just uplift moment**	**1811843**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	86	lb		
metal connection	4350	lb	metal connections	2
sheathing capacity	1210	lb	sheathing connections	9
dead load	75600	lb		

Moments (House)

wall connections	399888	lb-ft	
sheathing connections	392040	lb-ft	
house dead load	1360800	lb-ft	
resisting moment	**2152728**	**lb-ft**	**HOUSE FAILURE**

House Overturning w/o Veneer Only Metal Connections (SSP Connector)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**139**	**mph**				
horizontal 0-30ft	42.4	psf	1525	plf	22871	lb
uplift	36.8	psf	1324	plf	47662	lb

overturning moment	**1029455**	**lb-ft**

just uplift moment	**857923**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	420	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	32900	lb		

Moments (House)

wall connections	423360	lb-ft	
sheathing connections	0	lb-ft	
house dead load	592200	lb-ft	
resisting moment	**1015560**	**lb-ft**	HOUSE FAILURE

House Overturning w/ Veneer Only Metal Connections (SSP Connector)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**184**	**mph**				
horizontal 0-30ft	74.2	psf	2670	plf	40053	lb
uplift	64.4	psf	2320	plf	83517	lb

overturning moment	**1803709**	**lb-ft**	**just uplift moment**	**1503313**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	420	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	75600	lb		

Moments (House)

wall connections	423360	lb-ft	
sheathing connections	0	lb-ft	
house dead load	1360800	lb-ft	
resisting moment	**1784160**	**lb-ft**	HOUSE FAILURE

House Overturning w/o Veneer Only Metal Connections (PA51 Connector)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**223**	**mph**				
horizontal 0-30ft	108.9	psf	3921	plf	58818	lb
uplift	94.7	psf	3408	plf	122676	lb

overturning moment	**2649309**	**lb-ft**	**just uplift moment**	**2208175**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	2025	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	32900	lb		

Moments (House)

wall connections	2041200	lb-ft	
sheathing connections	0	lb-ft	
house dead load	592200	lb-ft	
resisting moment	**2633400**	**lb-ft**	HOUSE FAILURE

House Overturning w/ Veneer Only Metal Connections (PA51 Connector)

House Dimensions

length	36	ft			
width	36	ft	perimeter	144	sq ft
height	9	ft			
roof height	6	ft	total	15	ft

Wind Loads

Wind Speed	**253**	**mph**				
horizontal 0-30ft	140.2	psf	5047	plf	75700	lb
uplift	121.8	psf	4386	plf	157907	lb

overturning moment	**3410082**	**lb-ft**	**just uplift moment**	**2842328**	**lb-ft**

Connections

Spacing	1.333	ft		
# of connections	28			
wood connection capacity	0	lb		
metal connection	2025	lb	metal connections	28
sheathing capacity	0	lb	sheathing connections	0
dead load	75600	lb		

Moments (House)

wall connections	2041200	lb-ft	
sheathing connections	0	lb-ft	
house dead load	1360800	lb-ft	
resisting moment	**3402000**	**lb-ft**	**HOUSE FAILURE**

VITA

Alexander Kennedy Morrison

Candidate for the Degree of

Master of Science

Thesis: ANALYSIS OF LOAD PATHS IN RESIDENTIAL HOUSES

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Bachelor of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2011.

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