The Pennsylvania State University

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ANALYSIS OF THE INTERNATIONAL RESIDENTIAL CODE 2006 LOW RISE WOOD FRAME BUILDING BRACING REQUIREMENTS FOR PENNSYLVANIA

A Thesis in

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by

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ABSTRACT

Buildings must be designed structurally for a fifty year wind speed according to the ASCE 7 Standard. Residential buildings in Pennsylvania currently must be designed for 90 mph winds as shown on the ASCE-7 Standard wind speed map. For this research wind speed data from anemometer stations all over PA and its surrounding states are compared statistically using extreme value distributions. An overall lower wind speed than the Standard's 90mph was found to be statistically accurate. Currently the International Residential Code 2006 Bracing Requirements Table R602.10.1 starts at wind speeds of 100mph or less. The new wind speed found for Pennsylvania is used to redevelop the bracing requirements table to incorporate areas with lower wind speeds than 100mph. The new bracing requirements are found to be stricter than the current code. Further analysis was implemented using an analytical model and a Monte Carlo simulation on two separate residential structures to predict the probability of failure in the walls. It was found that the bracing requirements of the International Residential Code 2006 are inadequate for the state of Pennsylvania.

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Chapter 1 Introduction

Wood frame construction bracing provisions are provided in the 2006 International Residential Code (IRC) [1]. However, there is little documentation of the derivation of these provisions and the technical research behind them [2]. Wall bracing systems such as wood let-in braces, wood structural panels, Portland cement stucco, and other bracing methods are used to provide lateral resistance to a structure. The minimum bracing requirements are listed in the IRC and the table begins with wind speeds at or below 100 mph and seismic categories defined as A and B [1].

The required wind speed used for the design of buildings is that which has a two percent chance of being exceeded. This wind speed is assumed to be the fifty year recurrence interval. The current wind speed map was created using superstations throughout the United States and is not accurate since many superstations contain multiple occurrences of the same wind station.

In areas outside hurricane-prone regions, regional climatic data may be used in lieu of the basic wind speeds given in the ASCE 7 when extreme-value statistical-analysis procedures have been employed in reducing the data and the length of the record, sampling error, averaging time, anemometer height, data quality, and terrain exposure of the anemometer have been taken into account [3].

The state of Pennsylvania is located within a 90 mph wind zone on the ASCE 7 wind speed map [3] yet still must adhere to the bracing requirements listed in the IRC for

100 mph or less. In this research, extreme value statistics and records of wind data are used to predict the fifty year wind speed for the state of Pennsylvania. The ASCE 7 analytical method for wind loads is used to calculate the shear forces felt in braced walls of various house geometries. These results are compared with the bracing requirements of the IRC. Simple analytical models are then used to evaluate the probability of failure of light-frame buildings under random wind loads following an extreme value distribution for the wind in Pennsylvania.

1.1 Problem Statement

This study will determine if a reduced fifty year design wind speed is warranted for the state of Pennsylvania. If the reduced wind speed is feasible through statistical analysis, it will be further determined if the reduced wind speed will comply with the IRC bracing requirements for a typical two story home. Modified bracing requirements will be provided if warranted.

1.2 Objectives

The primary objective of this research is to determine whether a lower wind speed will reduce the bracing requirements provided in the IRC. The secondary objective is to determine whether a lower wind speed is feasible for Pennsylvania. The tertiary objective is to design a new bracing table similar to the IRC bracing table with requirements listed for lower wind speeds.

1.3 Scope

The scope of this research includes using extreme value statistics on recorded wind data for the state of Pennsylvania to develop a fifty year wind speed. Analytical models will then be used to evaluate this wind speed on a one, two and three story home. The probability of failure in each of the walls will be calculated using random multipliers to account for the variability of the structure of the wall, the uncertainty of the stiffness and the openings in the individual walls.

Chapter 2 Background

This section examines topics relevant to this research such as extreme value statistics and the ASCE 7 wind speed map. Topics such as wall bracing, shear walls and analyzing light-frame buildings under lateral loads are also outlined.

2.1 The ASCE 7 wind speed map

The ASCE 7 peak-gust map was adopted in the 1995 ASCE 7 [3] to replace the 1993 ASCE 7 wind map. However, the most current map may not be as accurate as the 1993 version. The new map uses fifty year peak three second gust speeds rather than fastest mile-wind speeds, the wind speed regions were created using "superstations" which contain duplicate wind data sets, and the new speeds do not agree with the speeds contained in the 1993 version [5].

The 1993 map used the fastest mile-wind speeds while the 1995 map uses fifty year peak three second gust speeds. Fifty year peak three second gust speeds are the fastest wind speeds averaged over a three second period. The ratio of fifty year peak three second gust speeds to fastest mile-wind speeds is approximately 1.2 [5]. This means that a fifty year three second gust speed of 90 mph (40 m/s) is 70 mph (31 m/s) as a fastest mile speed. Failure to make use of publicly accessible sets of National Climatic Data Center fastest-mile wind speed data lowers the quality of extreme wind speed estimates. Fastest-mile wind speed data is thought to be more stable than peak gust data [5].

The 1995 wind speed map is based on sets of stations rather than individual stations. This analysis groups individual stations into "superstations". The majority of superstations used to formulate the wind speed map contain stations included in at least two superstations. This duplication of stations statistically weakens the differences of the superstation regions and produces inaccurate results. At least 80% of the total number of superstations contain stations included in at least two superstations. Of the remaining 20%, more than half consist of at most three stations [5].

The major regions of the 1995 wind speed map differ significantly from the 1993 map. In the 90 mph (40 m/s) region of the new wind speed map, the 1993 wind speed map specifies a 70 mph (31 m/s) wind speed region. Adjusting the speed using the 1.2 ratio of peak 3 second gust wind speed to fastest mile wind speed makes it 84 mph (37 m/s). This 1995 wind speed is 15% higher than the 1993 wind speed. In other regions, this conversion shows a decrease in wind speed [5].

2.2 Using extreme value statistics to find the fifty year wind speed

Structures are designed to withstand extreme loads over a lifetime which is strongly influenced by the code requirements for satisfactory behavior. Appropriate design levels for natural processes, such as wind, is very difficult. Extreme wind loading requires decades of reliable wind data to properly design for. Extreme wind events rarely occur, if at all, over a typical period of record in any particular region. The probabilities of wind-induced effects depend on the probability distributions of the extreme wind speeds.

Extreme value theory states that sufficiently large values of independent and identically distributed variates are described by one of three extreme value distributions. The three distributions are the Fréchet distribution, the Gumbel distribution and the reverse Weibull distribution. The Fréchet distribution has an infinite upper tail, the Gumbel distribution a shorter infinite upper tail and the Reverse Weibull distribution has a finite upper tail. The wind loading provisions of the *American National Standard ANSI* A58.1-(1972) were based on the assumption that a Fréchet distribution best fit non-tornado extreme wind speeds. A more extensive study concluded that the Gumbel distribution fit more accurately [6]. The Reverse Weibull is also believed to be a more accurate model because extreme winds are bounded and therefore the distribution should have a finite upper tail [6]. Estimated safety indices for wind-sensitive structures based on the Gumbel distribution have been found to have unrealistically high failure probabilities which are most likely due to the infinite upper tail [6].

The generalized extreme value distribution combines three smaller distributions, the Frechet, the Gumbel and the Reverse Weibull into one. The expression for the generalized extreme value distribution is:

$$y = f(x \mid k, \mu, \sigma) = \frac{1}{\sigma} e^{-(1+k\frac{(x-\mu)}{\sigma})^{-\frac{1}{k}}} (1+k\frac{(x-\mu)}{\sigma})^{-1-\frac{1}{k}} \qquad [2\text{-}1]$$

for $\quad 1 + k\frac{(x-\mu)}{\sigma} > 0$

where:

k	=	the shape parameter (when $k \neq 0$)
x	=	the variate
y	=	the probability density function
σ	=	the scale parameter
μ	=	the location parameter

The cases $k > 0$, $k = 0$, and $k < 0$ correspond to Fréchet (type II extreme value), Gumbel (type I extreme value), and reverse Weibull (type III extreme value) [6]. The generalized extreme value distribution allows you to let the data decide which distribution is appropriate.

The expression for the Gumbel distribution is as follows:

$$F_G(x) = e^{-e^{-\frac{x-\mu_G}{\sigma_G}}} \qquad [2\text{-}2]$$

where:

E(x)	=	the expected value
$F_G(x)$	=	the probability density function
s(x)	=	the standard deviation
σ_G	=	$\frac{6^{\frac{1}{2}}}{\pi} s(x)$
μ_G	=	$E(x) = 0.5772 \frac{6^{\frac{1}{2}}}{\pi} s(x)$

The expression for the Reverse Weibull distribution is as follows:

$$F_W(x) = e^{-\left[\frac{\mu_W - x}{\sigma_W}\right]^{\gamma}}, \; x < \mu_W \qquad [2\text{-}3]$$

where:

E(x)	=	the expected value
$F_W(x)$	=	the probability density function

s(x) = the standard deviation
x = the variate

$$\sigma_W = \frac{s(x)}{\left\{\Gamma\left(1+\frac{2}{\gamma}\right)-\left[\Gamma\left(1+\frac{1}{\gamma}\right)\right]^2\right\}^{\frac{1}{2}}}$$

$$\mu_W = E(x)-\sigma_W\Gamma(1+\frac{1}{\gamma})$$

γ = the tail-length parameter, $-\frac{1}{c}$
Γ = gamma function

Sets of fastest mile wind speeds for winds blowing from any direction can be obtained from the National Climatic Data Center [8]. However, in many stations there are missing years of wind speeds. Groups of stations can be formed using the maximum speed per year out of the group of wind speeds. The data is given as maximum sustained wind speed in knots. Sustained wind speeds are defined as wind speeds averaged over intervals of the order of 1 minute [7]. The knots must be converted into miles per hour. This speed, in mph, must then be converted into the peak 3-s gust speed. The peak 3-s gust is a storm's largest speed averaged over 3 seconds [7]. The approximate mean ratio of the 3-s speed to the hourly (3600-s) sustained wind speed at 10 m above ground in open terrain is 1.52.

Once a set of data has been formed, a histogram can be plotted to determine which distribution governs. The probability density function (PDF) and the cumulative density function (CDF) can then be used to find the percentage of a wind speed being exceeded at a specified value or the value of wind speed which is exceeded by a specific percentage.

Probability of failure is a commonly used term in the area of designing engineering structures. The reason for the use of statistics is to build economically yet safe. The challenge one assumes in conducting a study on the probability of failure is the fact that it is based on the study on unknown information. In many cases there are not nearly enough tests to use for an accurate solution so random variables are used based on what is known in order to compute one. Wind, for instance, is a completely random variable. It can change from day to day over a very wide range. A probability density function describes the relative likelihood that a random variable will assume a particular value.

The data may be plotted as a cumulative distribution function (CDF) which gives the probability that the variable will have a value less than or equal to the selected value. The CDF is the integral of the corresponding probability density function.

2.3 Wall Bracing and the International Residential Code

Residential construction in the state of Pennsylvania is currently designed using a 90 mph fifty year wind speed [3]. The International Residential 2006 Code [1] Table R602.10.1 places a restriction on the type and amount of bracing needed to construct homes based on the wind speed zone that the building will be located.

Table 2- 1: International Residential Code 2006 [1], Table R602.10.1

SEISMIC DESIGN CATEGORY OR WIND SPEED	CONDITION	TYPE OF BRACE	AMOUNT OF BRACING
Category A and B ($S_s \leq 0.35g$ and $S_{ds} \leq 0.33g$) or 100 mph or less	One story Top of two or three story	Methods 1, 2, 3, 4, 5, 6, 7, or 8	Located in accordance with Section R602.10 and at least every 25 feet on center but not less than 16% of braced wall line for Methods 2 through 8.
	First story of two story Second story of three story	Methods 1, 2, 3, 4, 5, 6, 7, or 8	Located in accordance with Section R602.10 and at least every 25 feet on center but not less than 16% of brace wall line for Method 3 or 25% of braced wall line for Methods 2, 4, 5, 6, 7, 8.
	First story of three story	Methods 1, 2, 3, 4, 5, 6, 7, or 8	Located in accordance with Section R602.10 and at least every 35 feet on center but not less than 25% of braced wall line for Method 3 or 35% of braced wall line for Methods 2, 4, 5, 6, 7 ,or 8.

According to Table 2-1, a one story building requires wall bracing at least every 25 feet on center but not less than 16% of the braced wall line. The methods of wall bracing being evaluated in this research are Method 3 for exterior walls and Method 5 for interior walls. Method 3 consists of wood structural panel sheathing with a thickness not less than 5/16 inch (8 mm) for 16-inch (406 mm) stud spacing and not less than 3/8 inch (9 mm) for 24-inch (610 mm) stud spacing [1]. Method 5 consists of gypsum board with minimum ½-inch (13 mm) thickness placed on studs spaced a maximum of 24 inches (610 mm) on center and fastened at 7 inches (178 mm) on center with the size nails specified in Table R602.3(1) for sheathing and Table R 702.3.5 for interior gypsum board in the IRC [1].

2.4 The ASCE 7 Tributary Area Method

The ASCE 7-05 specifies three procedures for determining design wind loads: the simplified procedure, the analytical procedure, and the wind tunnel procedure. The simplified method may be used after obtaining basic wind speeds, importance factors, exposure categories and topographic factors for the building in question.

The basic wind speed is the 3-s peak gust speed at 33 ft (10m) above ground in open terrain. Outside hurricane prone areas, this speed is defined as the 50-year mean recurrence interval (MRI). The 50-year MRI is based on past common practice as applied to allowable stress design [7]. The basic wind speeds are specified in the ASCE 7 wind speed maps [3].

The importance factor is divided into four categories, I through IV, which range from least hazardous to human life in the event of a failure to most hazardous, respectively.

The exposure category must be determined as a function of the nature of the surface. For example, water, open terrain, built-up terrain, wooded areas, etc.

Surface roughness categories are based on measurements by meteorologists and assessments by wind engineers. They are as follows [3]:

Surface roughness B: urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger

Surface roughness C: open terrain with scattered obstructions generally less than 30 ft high, and flat open country, grasslands, and water surfaces in hurricane-prone regions.

Surface roughness D: flat, unobstructed areas, including smooth mudflats, salt flats, and unbroken ice, and water surfaces outside hurricane-prone regions

Exposure categories are as follows: [3]

Exposure B: where surface roughness B prevails in the upwind direction for a distance of at least 2600 ft or 20 times the building height, whichever is greater, except that for buildings with a mean roof height of 30 ft or less, the upwind distance may be reduced to 1500 ft.

Exposure D: where surface roughness D prevails in the upwind direction for at least 5000 ft or 20 times the building height, whichever is greater. Exposure D extends inland from the shoreline for a distance of 660 ft or 20 times the building height, whichever is greater.

Exposure C: where exposures B and D do not apply and is commonly referred to as open terrain exposure

Once these factors are known, the simplified procedure in the ASCE 7 may be used. The equation used in the ASCE 7 [3] to determine wind pressures on a building is:

$$q_z = 0.00256 K_Z K_{ZT} K_d V^2 I \text{ (lb/ft}^2\text{)} \qquad [2\text{-}4]$$

where:

q_z	=	pressure
I	=	importance factor
K_d	=	wind directionality factor
K_Z	=	velocity exposure coefficient
K_{ZT}	=	topographic factor
V	=	velocity

When the wind pressures are determined, the shear forces attributed to each wall may be determined using the tributary area method. Using this method, the wind pressure is distributed over the area of the house it is acting on. The force is divided into each transverse wall which depends on the tributary areas and not on the stiffness of each wall. This method, however, is very rudimentary and the results have little to no value. This method does not consider the randomness of wall construction or the variability of stiffness in each wall.

2.5 Analytical modeling for light-frame buildings

Analytical models may be used to evaluate the expected behavior of a system. Simplified analytical models are needed to obtain a reasonable estimate of statistics needed to describe failure probability [4]. The model must be programmed to allow repeated analyses so complex geometries are restricted.

A wood-frame building can be represented in a model by a series of horizontal diaphragms and vertical shear walls. Forces are distributed into the shear walls by the diaphragms and then transferred into the foundation. Two models which will be used are the rigid-beam model and the rigid-plate model. In both models, the diaphragm is assumed to be rigid and no slip between the walls and the diaphragm is permitted. The walls are represented as linear or nonlinear springs [4].

A Monte Carlo procedure can be developed to simulate random wind speeds and pressures acting on a building, random openings, random stiffness of walls, etc. Each repetition of the program may analyze another scenario in order to find the probability of failure in each wall over a specified number of simulations.

2.5.1 The Rigid-Beam Model

Shear walls are represented by unidirectional springs which support the diaphragm represented by a rigid beam. The forces in the walls are proportional to their stiffness. The walls perpendicular to the beam orientation are included as lateral resisting elements. This model is one dimensional and will overestimate the building's response [4]. This model will be explained in detail in a later chapter and is also explained in the referenced journal paper [4].

2.5.2 The Rigid-Plate Model

A rigid plate represents each floor of the buildings. A plate is allowed to shift and rotate within its plane. The model finds the translation and rotation of the building. This model is two dimensional so the effect of all walls, including transverse walls, is included [4]. If bending stiffness of the walls is known, it may be lumped into the stiffness of the wall. It is, however, considered negligible compared with the in–plane wall stiffness. The forces in the walls of the model are proportional to their stiffness. This model will be explained in detail in a later chapter and is also explained in the referenced journal paper [4].

2.5.3 Modeling Shear Walls

A typical house consists of exterior walls braced using Method 5 of the IRC [1] which is using wood structural panels on one side and interior walls braced using Method

3 of the IRC which is using gypsum board on both sides of the wall. In order to model these walls, actual test data must be used to obtain realistic results.

Figure 2- 1: Illustrates Method 3 – Wood structural panel bracing of the IRC [1]

Eighty wood structural panels were tests using CUREE cyclic load protocol [11]. The eighty walls consisted of wood structural panels varying in thickness from 3/8 in. (1 cm) to 19/32 in. (1.5 cm). The nails spacing also varies along with the type of nails used. Ten of the tests cannot be used as they contain openings or fasteners not specified by the International Residential Code [1]. The rest of the seventy tests proved data to predict the shear resistance of a Method 3 braced wall of the IRC.

A pilot study was done which tested four wood studded gypsum sheathed shear walls [12]. Three of the tests were cyclic tests, while one of the tests was monotonic. The results from these tests provide data for Method 5 braced wall of the IRC.

Figure 2- 2: Illustrates Method 5 – Gypsum board bracing of the IRC [1]

Chapter 3 Wind Speed Procedure

Buildings must be design for the fifty year wind speed which is the wind speed that has a two percent chance of being exceeded [3]. Wind speed data may be downloaded at various stations throughout the United States from the National Climatic Data Center [8].

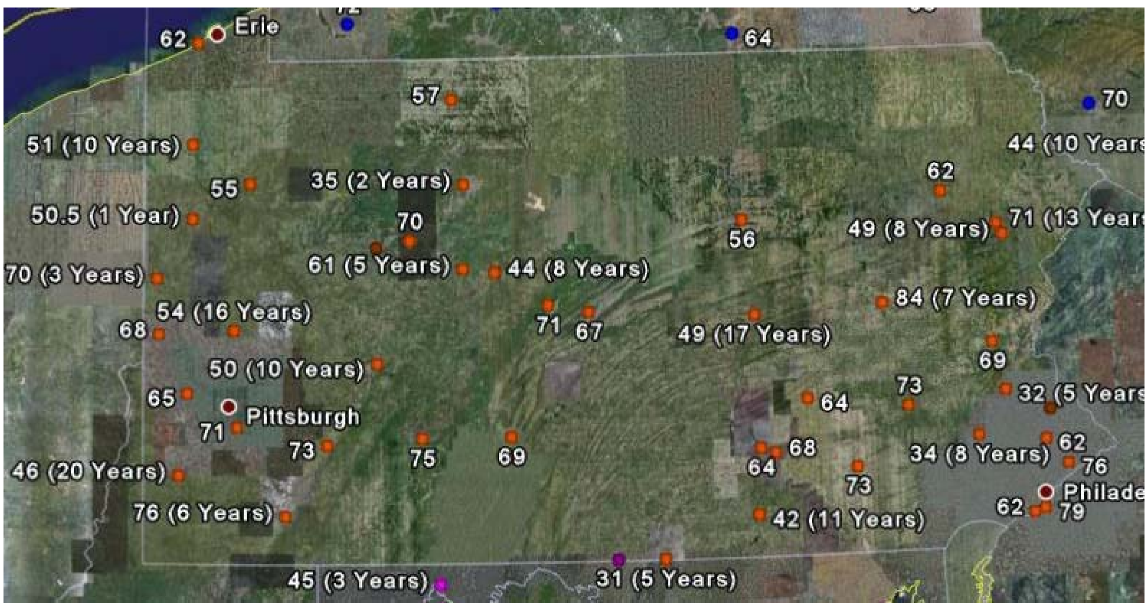

Figure 3- 1: Anemometer Stations in the state of Pennsylvania; wind data collected

A map of all the wind speed stations in Pennsylvania is provided in Figure 3- 1. There are several areas in the state that do not have wind stations. For these areas, stations located in the adjacent states will be used to approximate a wind speed.

The maximum wind speed data must be converted from knots into miles per hour. The wind speed is then converted into the 3-second gust. The peak 3-s gust speed is a storm's largest speed averaged over 3 seconds. For proper calculation of fifty year wind speeds, the annual maximum will be used so as to not have biased data to a particular multiple day storm. Another reason would be to avoid seasonal weather patterns. Therefore, all of the data is converted into the annual maximum wind speeds.

Histograms of the wind data are plotted to determine the fifty year wind speed as shown in Figure 3- 2. This speed is found using the generalized extreme value distribution as shown in Figure 3- 3. The data sets for each station, when plotted as a histogram, all form a Type III Reverse Weibull distribution resulting in a negative value for the shape factor. This distribution forms a finite tail and therefore will not over estimate the wind speed prediction.

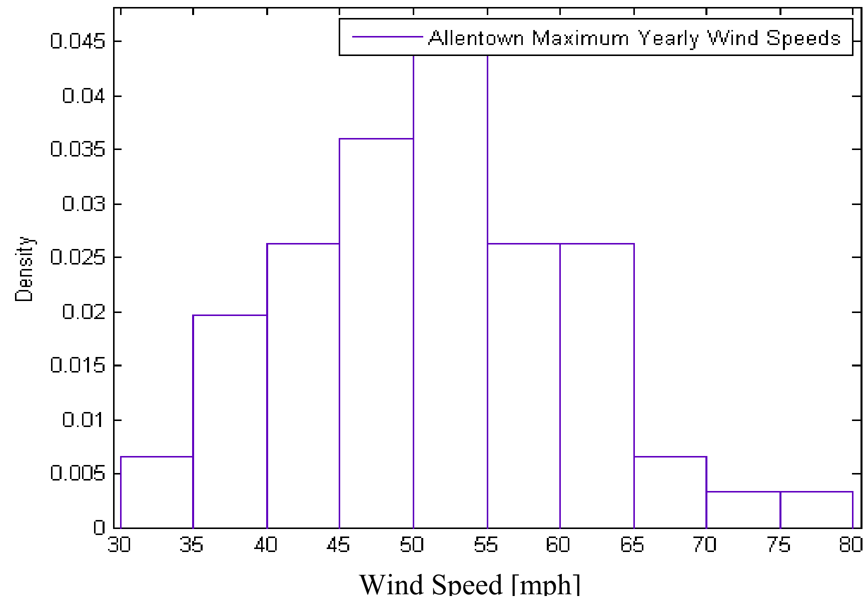

Figure 3- 2: Histogram of Allentown, PA Maximum Yearly Wind Speeds

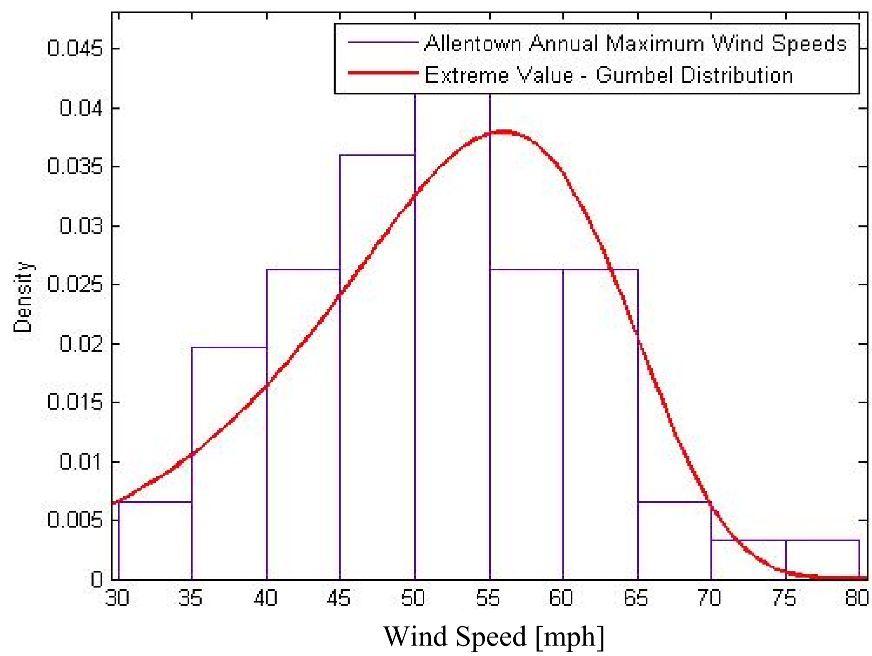

Figure 3- 3: Histogram of Allentown, PA Maximum Yearly Wind Speeds evaluated with the generalized extreme value distribution

Using the generalized extreme value distribution and its cumulative density function (CDF), the 98 percent quantile will be found within a lower and upper bound of 95% confidence. The 98 percent quantile will be equivalent to the speed which has a two percent chance of being exceeded, the fifty year wind speed. A map of Pennsylvania with all of the wind stations and their calculated fifty year wind speeds is shown in Figure 3- 4.

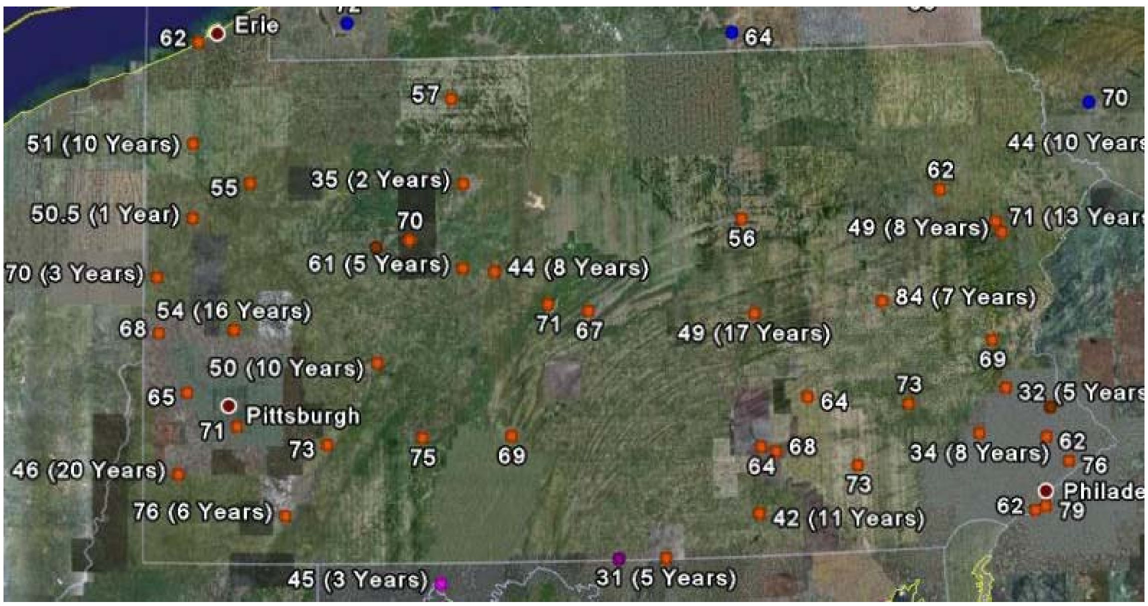

Figure 3- 4: Anemometer stations of Pennsylvania showing the calculated fifty year wind speed at each station

Groups of stations are formed and analyzed for the fifty year wind speed to see if zones can be formed for the state. These "superstations" are formed by taking the maximum speeds per year from multiple stations and creating a histogram. Then the generalized extreme value distribution is fit with the data to determine the fifty year wind speed. In the areas of Pennsylvania where there are not stations close to the border the nearest out of state station is used.

To compare the results from one superstation to another a hypothesis test is conducted. Most hypothesis-testing procedures are based on the assumption that the random samples are selected from a normal distribution [9]. There are multiple tests that can determine whether the data will fit within a normal distribution such as the chi-square goodness of fit test, the Lilliefors test and the Jarque-Bera test. If the data does not fit a normal distribution, such as the extreme value distributions of wind, nonparametric methods must be used to conduct a hypothesis test [9].

A chi-square goodness of fit test performs a chi-square goodness-of-fit test of the default null hypothesis that the data in vector x are a random sample from a normal distribution with mean and variance estimated from x, against the alternative that the data are not normally distributed with the estimated mean and variance [9]. The result h is 1 if the null hypothesis can be rejected at the 5% significance level. The result h is 0 if the null hypothesis cannot be rejected at the 5% significance level. Administering this test on all of the wind superstations created proved that the data does not come from a normal distribution. Nonparametic hypothesis testing must be used.

The Rank-Sum test is used to compare the means of two independent continuous nonnormal data sets [9]. The data sets are presumed to be independent since they include only the annual maximum wind speed. Using the annual maximum wind speed helps to eliminate dependency since the wind speed from a multiple day storm will not be used more than once. This nonparametric test is an alternative to the two-sample t test which tests normal distributions. The null hypothesis H_0 is that μ_1, the mean of one data set, equals μ_2, the mean of another data set, against the alternative that they are not equal.

The Kruskal-Wallis test is a generalization of the rank-sum test to the case of more than two data sets [9]. It is used to test the null hypothesis H_0 that the independent sets of wind speeds are from identical populations.

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Chapter 4 Wind Speed Results

Table 4- 1: Calculated fifty year wind speeds for the state of Pennsylvania

Pennsylvania	Fifty Year Wind Speed, mph (3-s gust)
North	80.5
South	83.8
East	83.4
West	75.9
Entire State	80.5
ASCE 7 Wind Speed Map[3]	90

The first superstation analysis compared the North half of Pennsylvania and the South half of Pennsylvania. Dividing the state into halves by length from top to bottom, the stations in the top half were combined to create the North half of Pennsylvania and the stations in the bottom half were combined to create the South half of Pennsylvania. The Rank-Sum Test was implemented to test the null hypothesis that the mean of each data set is equal. The test accepts the null hypothsis within a 3% significance level. When fitting the generalized extreme value distribution to each superstation, the fifty year wind speeds were calculated as 80.5 mph (129.55 km/h) for the North and 83.8 mph (134.86 km/h) for the South.

The second analysis performed compared the East half of Pennsylvania with the West half of Pennsylvania, dividing the state into two equal lengths from the West to the East. The Rank-Sum Test was implemented to test the null hypothesis that the mean of each data set is equal. The test accepts the null hypothsis within a 5% significance level. The generalized extreme value distribution determined the fifty year wind speed for each superstation to be 83.4 mph (134.22 km/h) for the East and 75.9 mph (122.15 km/h) for the West.

The plotted distributions for the station groups tested may be found in Appendix A. The next analysis performed used the wind speed data from the entire state. This analysis resulted in a fifty year wind speed of 80.5 mph (129.55 km/h).

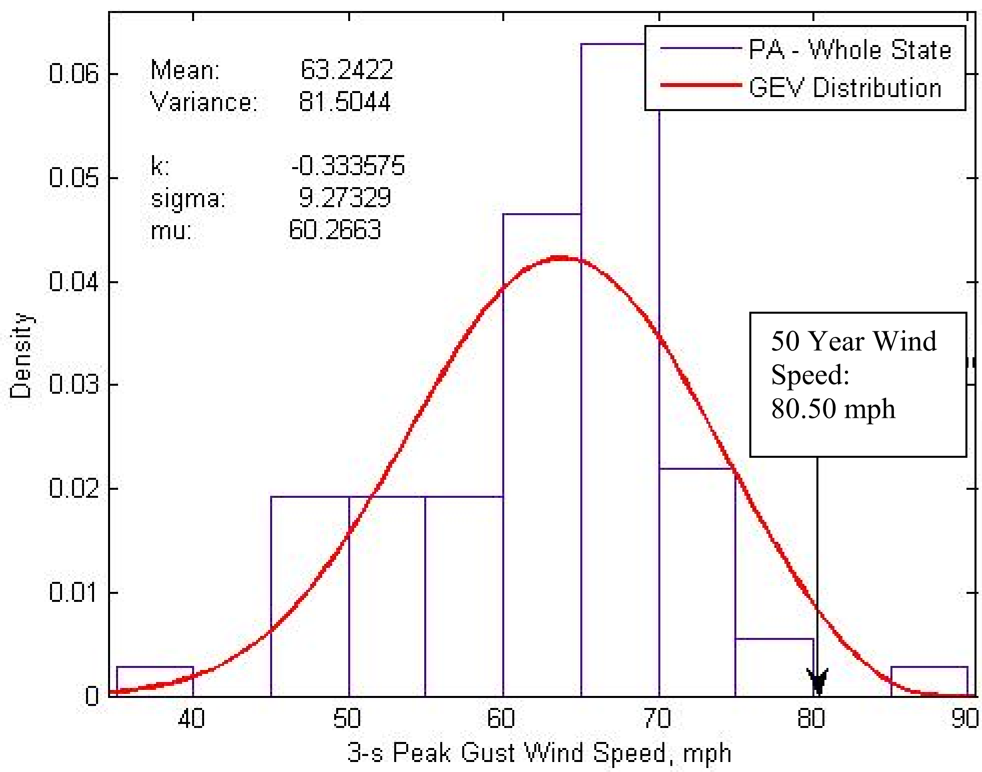

Figure 4- 1: The state of Pennsylvania 3-s Gust Wind Speeds histogram; the negative shape parameter denotes the distribution as the Reverse Weibull distribution

The results from each analysis showed no significant difference between each half. Therefore, the fifty year wind speed for the entire state of Pennsylvania has been determined to be 80 mph (128.75 km/h). This wind speed is 10mph (16.09 km/h) less than the 90 mph (144.84 km/h) prescribed fifty year wind speed given on the ASCE 7 wind speed map [3].

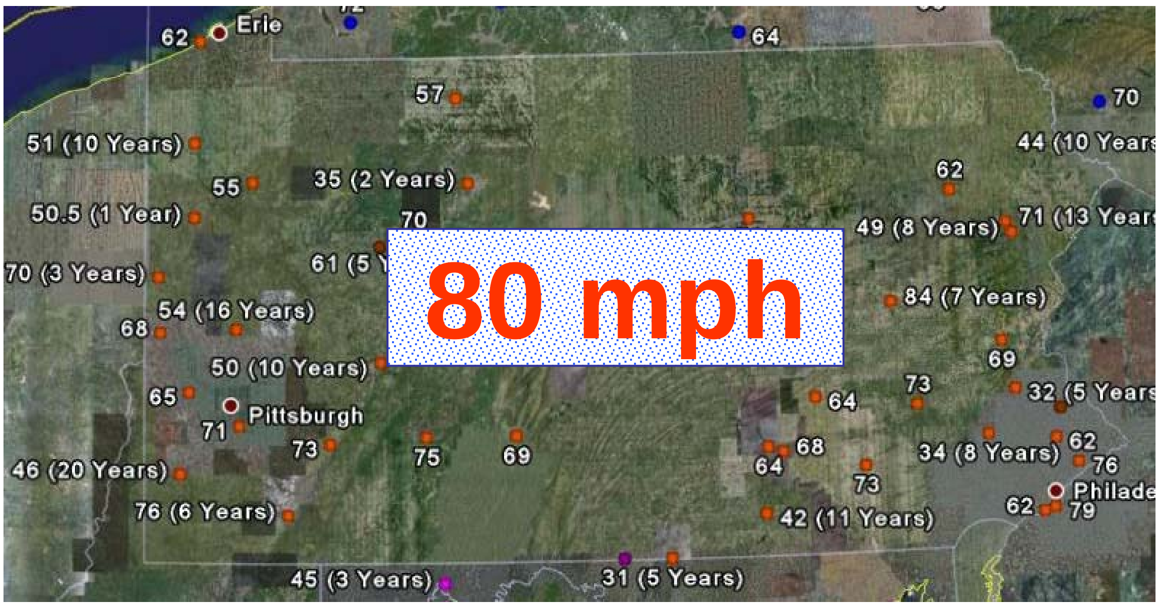

Figure 4- 2: The calculated fifty year wind speed for the state of Pennsylvania

The state of Pennsylvania three second peak gust wind speeds may be described using a Reverse Weibull distribution with parameters: k = -0.333757, sigma = 9.27329 and mu = 60.2663. This distribution may be seen in Figure 4- 3.

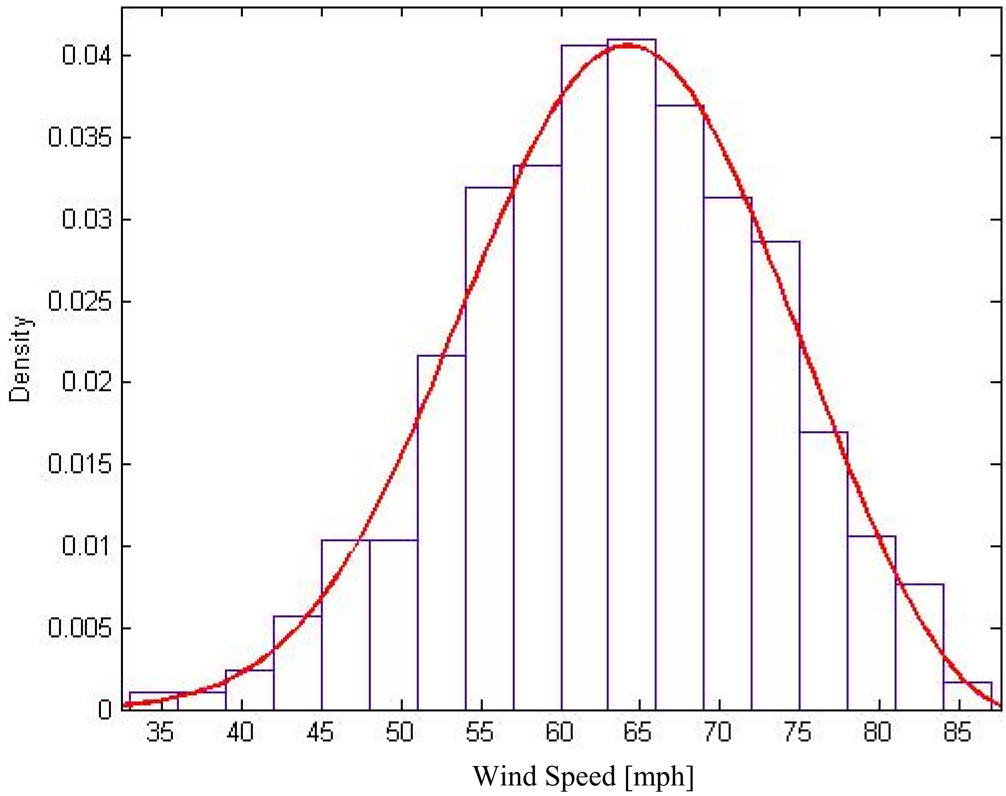

Figure 4- 3: The Reverse Weibull Distribution representing the whole state of Pennsylvania 3-s Peak Gust Wind Speeds

Chapter 5 ASCE 7 Method

The ASCE 7 method for the analytical procedure for wind pressures was used to determine the shear forces in the walls of a typical two story box house in Pennsylvania. The simplified method cannot be used because the lowest wind speed available in the wind pressure tables is 85 mph (136.79 km/h) [3]. The following sections describe the steps used.

5.1 The ASCE 7 Analytical Procedure

The equation the ASCE 7 analytical procedure uses to find the wind pressure is:

$$p = q_h[GC_{pf}) - (GC_{pi})] \text{ (lb/ft}^2\text{) (N/m}^2\text{)} \qquad [5.1]$$

where

GC_{pf} = external pressure coefficient; varies based on wall or roof position and roof slope (Figure 6-10 [3])

GC_{pi} = internal pressure coefficient; +0.18 or -0.18 for enclosed buildings (Figure 6-5 [3])

K_d = the wind directionality factor; 0.85 for buildings (Table 6-4 [3])

K_z = the velocity pressure exposure coefficient; 0.7 for 0-15 ft (0-4.6 m) ground level (Table 6-3 [3])

K_{zt} = the topographic factor; value of 1.0 used for simulations

qh = $0.00256K_zK_{zt}K_dV^2I$ (lb/ft^2)

= $0.613K_zK_{zt}K_dV^2I$ (N/m^2); V in m/s

This formula was used to create a new wind pressure table for the 80mph (128.75 km/h) wind speed which was determined to be the fifty year wind speed in the state of

Pennsylvania. The figure corresponding to the pressures in Table 5- 1 and the full description of the method used may be found in the ASCE 7 [3].

Table 5- 1: ASCE 7 Wind Pressure Table for 80mph winds calculated using Analytical Procedure

Basic Wind Speed (mph)	Roof Angle (degrees)	Load Case	Zones							
			Horizontal Pressures				Vertical Pressures			
			A	B	C	D	E	F	G	H
80	0 to 5	1	10.1	-5.3	6.7	-3.1	-12.2	-6.9	-8.5	-5.4
	10	1	11.4	-4.7	7.6	-2.8	-12.2	-7.4	-8.5	-5.7
	15	1	12.7	-4.2	8.5	-2.4	-12.2	-8.0	-8.5	-6.1
	20	1	14.0	-3.7	9.4	-2.0	-12.2	-8.5	-8.5	-6.4
	25	1	12.7	2.0	9.2	2.1	-5.7	-7.7	-4.1	-6.2
		2								
	30 to 45	1	11.4	7.8	9.1	6.2	0.9	-6.9	0.3	-6.0
		2								

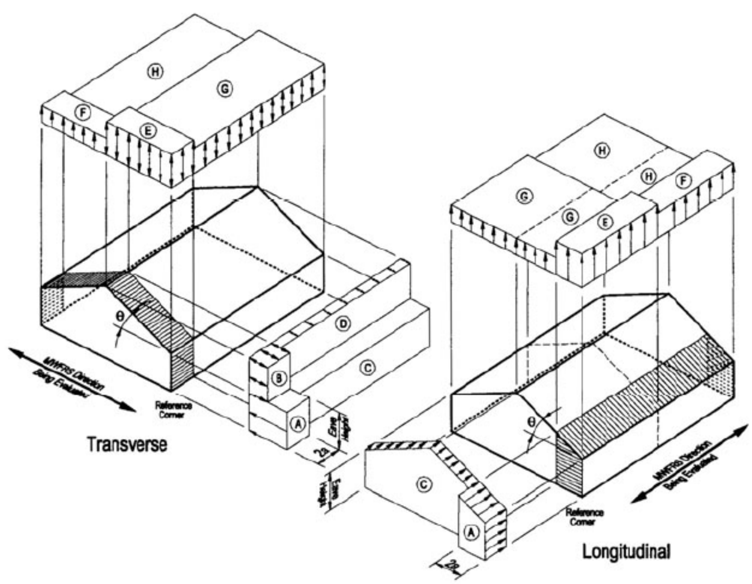

Figure 5- 1: ASCE 7 Figure 6-2 Design Wind Pressures [3]

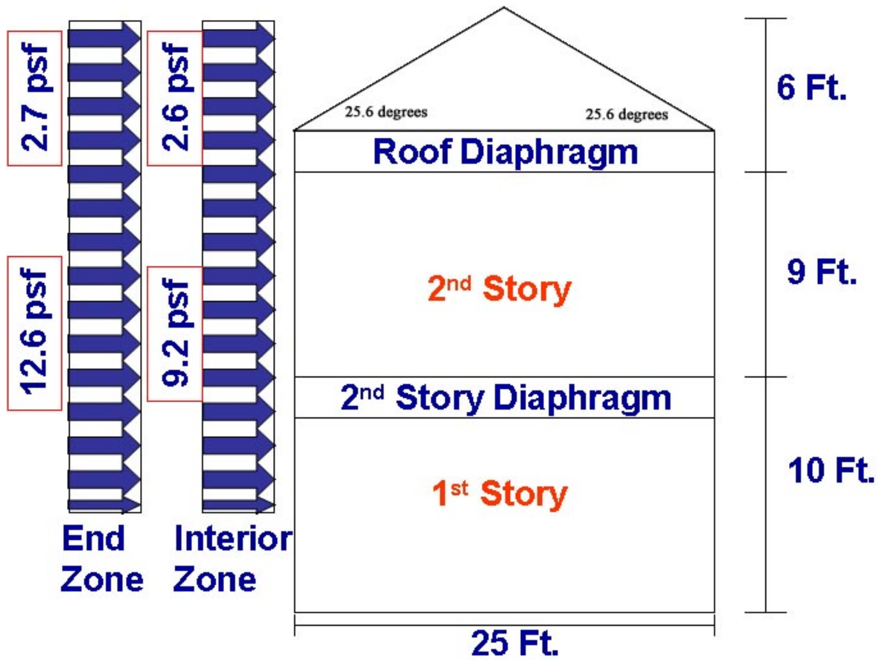

Figure 5- 2: House Geometry with wind pressures used with ASCE 7 method

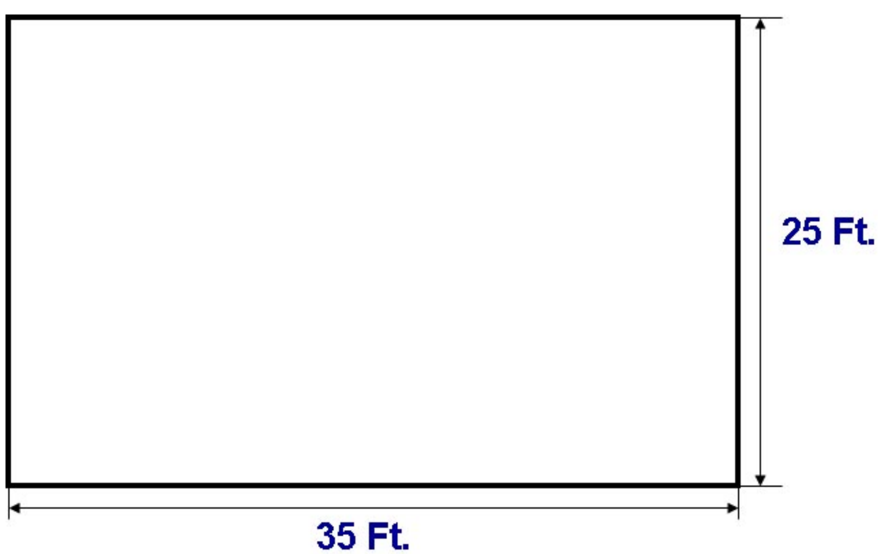

Figure 5- 3: House Dimensions used with ASCE 7 method

The house geometries shown in Figure 5- 2and Figure 5- 3 were used to calculate the shear forces in the walls using the tributary area method. These values were compared to values determined by using seismic values for Pennsylvania to verify that the wind loads governed. For this analysis, the wind is acting only in one direction, the direction of the transverse 25 Ft. (7.62 m) walls. Seismic and wind calculations may be found in Appendix A.

Once the shear forces caused by wine were determined in each wall they are compared with a prescriptive value to determine whether or not they will fail at that load. The APA-Engineered Wood Association has developed a table for various shear walls using specific structural panel thicknesses and nailing [14]. Table 5- 2 is the same table multiplied by a factor of 1.4 which is permitted when using the values for wind analysis per International Building Code and a factor of 0.92 for Spruce Pine-Fir wood.

Table 5- 2: APA Table for allowable shear loads in structural panel shear walls; highlighted boxes are IRC [1] minimum panel thickness and nailing

Spruce Pine - Fir, S.G. = 0.42	Panels Applied Direct to Framing						
Panel Grade	Minimum Nominal Panel Thickness (in.)	Minimum Nail Penetration in Framing (in.)	Nail Size (common or galvanized box)	Nail Spacing at Panel Edges (in.)			
				6	4	3	2
APA STRUCTURAL I grades	5/16	1-1/4	6d	260	390	545	715
	3/8	1-3/8	8d	300	465	645	855
	7/16			330	510	705	940
	15/32			360	555	770	1020
	15/32	1-1/2	10d	435	655	930	1220
APA RATED SHEATHING; APA RATED SIDING and other APA grades except Species Group 5	5/16 or 1/4	1-1/4	6d	230	350	490	630
	3/8			260	385	545	715
	3/8	1-3/8	8d	285	410	575	740
	7/16			310	450	630	820
	15/32			335	490	685	895
	15/32	1-1/2	10d	400	590	840	1080
	19/32			440	655	930	1220

Chapter 6 ASCE 7 Method Results

Table 6- 1: Shear Forces Calculated per 25 Ft. (7.62 m) transverse wall using ASCE 7 Analytical Method

First Floor Shear Force in each wall	3516 lb	141 lb/ft
Second Floor Shear Force in each wall	1838 lb	74 lb/ft

The results for the ASCE 7 method are listed in Table 6- 1. The force per foot may be compared with the APA table in Table 5- 2. The values are well under the limits of the APA table, but in this case the whole 25 feet (7.62 meters) length of each wall was braced. If the minimum requirements of the IRC are used, which states that only 16% of each 25 feet (7.62 meters) of wall length must be braced for a one story house, this leaves each wall with only 4 feet (1.22 meters) of bracing. This is illustrated in Figure 6- 1. The values of shear force per foot of braced wall are changed dramatically. Appendix A includes the calculations to solve for the lateral forces for both wind and seismic loads.

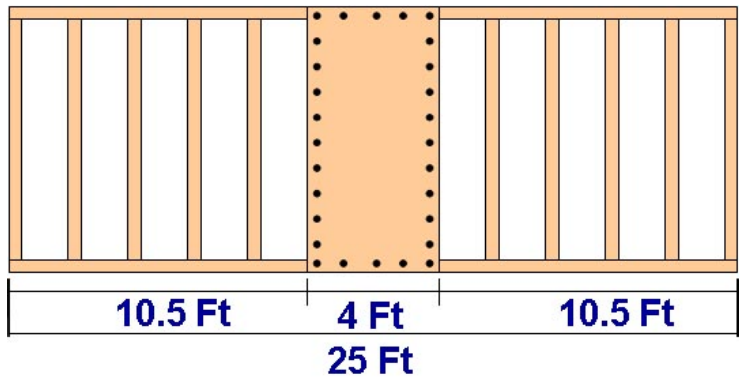

Figure 6- 1: A 25 Foot (7.62 m) wall with 16% braced as a minimum requirement of the IRC; braced panel must be placed in the center of the wall [1]

Table 6- 2: Shear Forces Calculated per 4 Ft. (1.22 m) of braced wall section using ASCE 7 Analytical Method

First Floor Shear Force in each wall	3516 lb	879 lb/ft
Second Floor Shear Force in each wall	1838 lb	460 lb/ft

Comparing these forces per foot of braced wall using the APA table in Table 5- 2, a much higher thickness and nailing is required of the structural panels used for these walls than the minimum required by the IRC. The highlighted sections of Table 5- 2 are the minimum required thickness and nail spacing given in the IRC [1].

Chapter 7 Modeling Procedure

An analytical model study was carried out using a rigid beam model and a rigid plate model, both containing shear walls with nonlinear stiffness. The following sections describe the rigid beam model, the rigid plate model, random variables, and equations that were used. The rigid beam model and the rigid plate model methods have been previously outlined in the cited text [4].

7.1 Rigid Beam Model Description

In this model, the diaphragm of each floor is represented by a rigid beam supported by uni-directional springs. The walls that are perpendicular to the beam are assumed the lateral resisting elements. The model is one dimensional and a schematic of the model is shown in Figure 7- 1. The deflection of any point of the model may be written as

$$\Delta = \lambda x + \gamma \qquad [7.1]$$

where:

x = the point on the wall
Δ = the deformation in the wall
λ = the rotation of the beam
γ = the translation of the beam

The force and moment equilibrium of each diaphragm may then be used to calculate the forces and deflection in the springs representing the perpendicular walls. The stiffness in each spring will be represented by a nonlinear curve and is later discussed in this chapter.

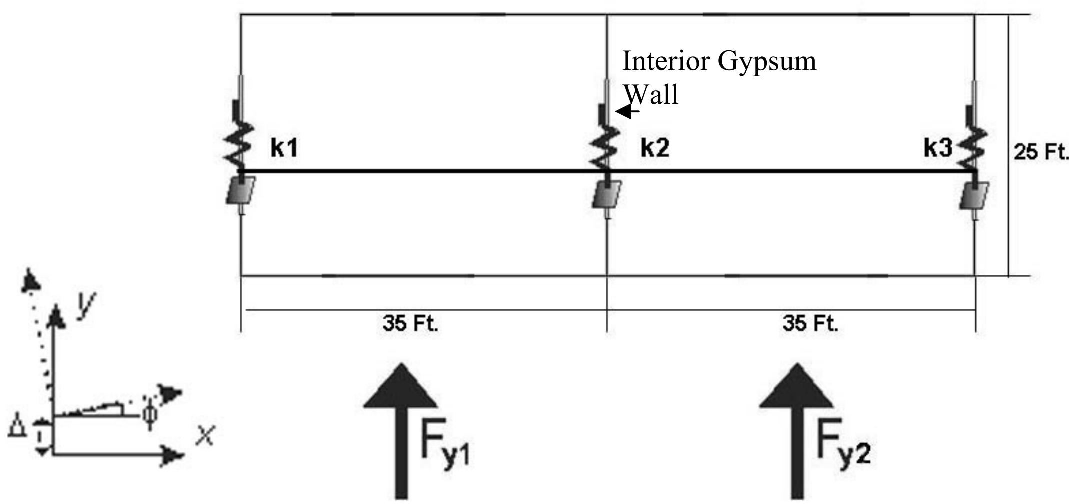

Figure 7- 1: Analytical rigid beam model using International Residential Code Minimum Requirements

The geometry in Figure 7- 1 is set so that exterior and interior walls may be tested. This geometry was not used in the ASCE 7 method approach of Chapter 5 because it would overestimate the shear force in the interior wall. The ASCE 7 method used the tributary area method to calculate lateral loads and is not accurate since the forces in the walls are based on the tributary areas. The reacting forces of the walls are not proportionate to their stiffness.

7.2 Rigid Plate Model Description

Each floor of the building is substituted by a rigid plate. Each plate is allowed to shift and rotate within its plane. The model will produce the translation and rotation of each floor. A set of n points is used with coordinates (x_i , y_i) to define the plate geometry. Each point corresponds to the center of each wall. For this model, the geometry of each floor is assumed to be constant. The bending stiffness of each wall is not included in the model because it is considered to be negligible compared to the in-plant wall stiffness. If it were included, it may be lumped into the shear wall stiffness.

The International Residential Code (IRC) [1] requires that a braced wall line be located at least once every 35 Ft (10.67 m) in a building. In addition, every 25 Ft (7.62 m) of wall must include a minimum percentage of bracing. Each braced wall panel must also be a minimum of 96 inches (1.22 m). These measurements are used with the rigid plate model in order to test the minimum requirements of the IRC.

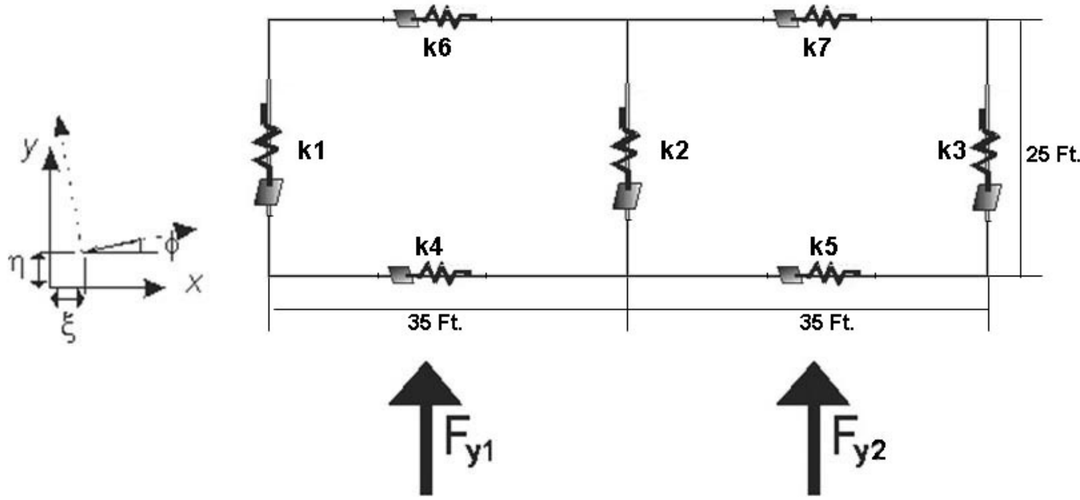

Figure 7- 2: Analytical rigid plate model using International Residential Code Minimum Requirements

Individual walls in the model are represented by a single spring along the x or y axes. The model permits the inclusion of interior walls as bracing elements. Since this model is testing the minimum requirements of the IRC it includes one interior wall so that its stiffness may be tested.

A general expression for the displacement of a point (x_i , y_i) of the floor s can be written as:

$$\delta x_{s,i} = \xi_s + x_i(cos\varphi_s - 1) - y_i \, sin\varphi_s = \xi_s - y_i \, \varphi_s \qquad [7.2]$$

$$\delta y_{s,i} = \eta_s + x_i \, sin\varphi_s + y_i(cos\varphi_s - 1) = \eta_s + x_i\varphi_s \qquad [7.3]$$

where ξ_s, η_s, and φ_s describe the rigid body translations and rotations of the diaphragm s and $\delta x_{s,i}$ and $\delta y_{s,i}$ are deformations of the point I at level s in the direction of x and y.

The corresponding stiffness of each wall may be written as $k_{x,s,i}(\delta x_{s,i})$ and $k_{y,s,i}(\delta y_{s,i})$. Since the stiffness of each wall is a function of the displacement, this produces a set of nonlinear equations. Equilibrium forces in the *x* and *y* directions and a moment equation are used to obtain the unknown rigid body translations and rotations of each floor.

$$\Sigma k_{x,s,i}(\delta_{xs,i} - \delta x_{s-1,i}) - \Sigma k_{x,s+1,i}(\delta x_{s+1,i} - \delta x_{s,i}) - F_{x,s} = 0 \quad [7.4]$$

$$\Sigma k_{y,s,i}(\delta y_{s,i} - \delta y_{s-1,i}) - \Sigma k_{y,s+1,i}(\delta y_{s+1,i} - \delta y_{s,i}) - F_{y,s} = 0 \quad [7.5]$$

$$\Sigma(k_{x,s,i}(\delta x_{s,i} - \delta x_{s-1,i}) - k_{x,s+1,i}(\delta x_{s+1,i} - \delta x_{s,i}))\, y_i - \quad [7.6]$$

$$\Sigma(k_{y,s,i}(\delta y_{s,i} - \delta y_{s-1,i}) - k_{y,s+1,i}(\delta y_{s+1,i} - \delta y_{s,i}))\, x_i -$$

$$F_{x,s}\,\rho_{x,s} - F_{y,s}\,\rho_{y,s} = 0$$

where $\delta x_{s,i}$, $\delta y_{s,i}$ = displacement of a point
$k_{x,s,i}(\delta x_{s,i})$, $k_{y,s,i}(\delta y_{s,i})$ = corresponding stiffness
$F_{x,s}$, $F_{y,s}$ = the external wind forces acting on the system
$\rho_{x,s}$, $\rho_{y,s}$ = coordinates of point where forces are acting

7.3 Wind Pressure

The wind in this analytical model is a random variable for each run of the simulation. The resultant force and its location can be calculated using the following equations:

$$F_{y,s} = \int p(x,z_s)\, dA \quad [7.7]$$

$$\rho_{y,s} = [\int x\, p(x,z_s)\, dA] \;/\; [\int p(x,z_s)\, dA] \quad [7.8]$$

where $p(x,z)$ is the pressure distribution function defined over the area $A(x,z)$, z is the coordinate along the height of the building corresponding to the floor s and x is the coordinate along the length of the beam.

The generalized extreme value distribution was used to represent the wind speed data set for the state of Pennsylvania. These values were obtained from yearly maxima of the peak gust wind speed (mph) measured at all stations throughout the state. The wind speed data sets are available at the National Institute of Standards (NIST) database [8].

The actual wind pressure may be evaluated using the known equation from the ASCE 7 [3]:

$$p = q_h[GC_{pf}) - (GC_{pi})] \text{ (lb/ft}^2\text{) (N/m}^2\text{)} \qquad [7.9]$$

where

GC_{pf} = external pressure coefficient; varies based on wall or roof position and roof slope (Figure 6-10 [3])

GC_{pi} = internal pressure coefficient;
+0.18 or -0.18 for enclosed buildings (Figure 6-5 [3])

K_d = the wind directionality factor; 0.85 for buildings (Table 6-4 [3])

K_z = the velocity pressure exposure coefficient;
0.7 for 0-15 ft (0-4.6 m) ground level (Table 6-3 [3])

K_{zt} = the topographic factor; value of 1.0 used for simulations

qh = $0.00256K_zK_{zt}K_dV^2I$ (lb/ft^2)
= $0.613K_zK_{zt}K_dV^2I$ (N/m^2); V in m/s

The ASCE 7 requires the use of a minimum 10psf (5.75 kPa) pressure for the height of the building if the resulting wind forces using this minimum pressure are greater than that of the calculated pressures [3]. For the purpose of this research, the simulations will be run using the minimum requirement and without using the minimum requirement to compare the results.

Since the actual pressure distribution of the wind over the area is unknown the resultant force where the wind is acting is also unknown. This value will be determined using a normal distribution with mean 1 and standard deviation .05 starting from the center of the wall it is acting on in order to vary the location of the resultant force of the wind along the wall it is acting on [4].

7.4 Random Variables

A Monte Carlo procedure is used with the rigid plate model to determine the probability of failure in each wall. Random variables must be introduced into the model so that a number of simulations may be run.

Experimental data for braced walls of similar construction as Methods 3 and 5 of the IRC [1] must be obtained in order to estimate the response of a building to wind loads with these methods of wall construction. The parameters defining the load-deformation function for the exterior walls are obtained from seventy experimentally tested shear walls [11]. Eighty walls were tested but ten of these walls cannot be used because they include openings and/or staple fasteners. The rest of the seventy shear walls covered a variety of sheathing panel thicknesses, nail sizes and nail spacing. A list of results is given from the shear walls tested includes the ASD design load and displacement and the ultimate load and displacement for each wall [11]. The loads are divided by the length of each wall tested so the load will be in units of lb/ft. The ASD design load follows the provisions in Section 12.8.6 of the ASCE 7 standard for seismic drift capacity [3]. These two points, along with the point of failure for each wall, are the only points known on the load-deformation curve of each wall.

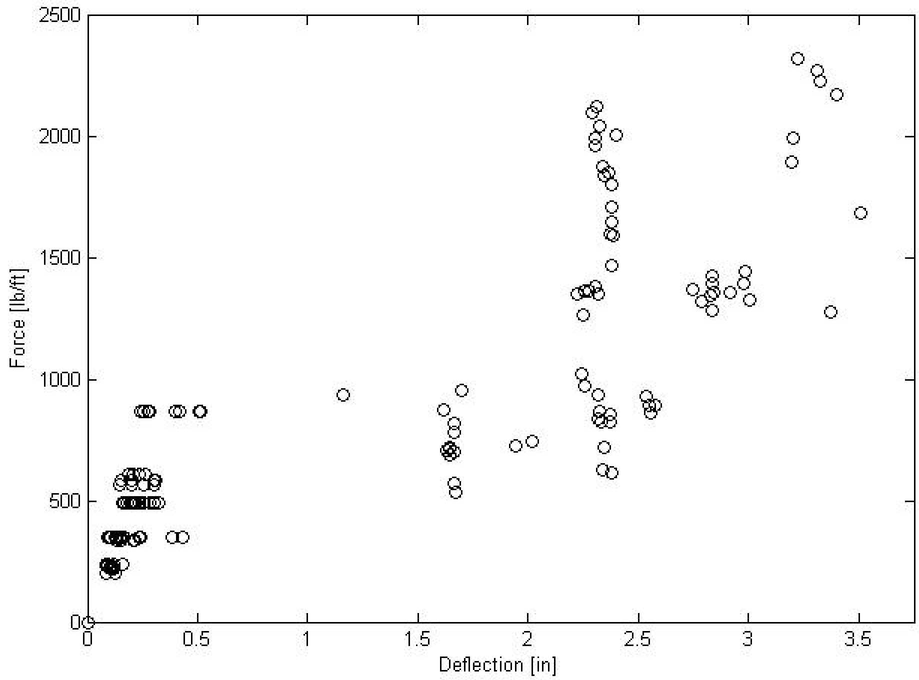

Figure 7- 3: Plot of points given in results table for seventy tested exterior shear walls [11]

The set of points listed for each wall are points that lie on the walls load-deformation curve. These points are plotted in Figure 7- 3. The curve data is not given in the results but is needed in this research since it is testing the response of each wall to wind loading. An example of what the actual load-deformation curve would look like is shown in Figure 7- 4.

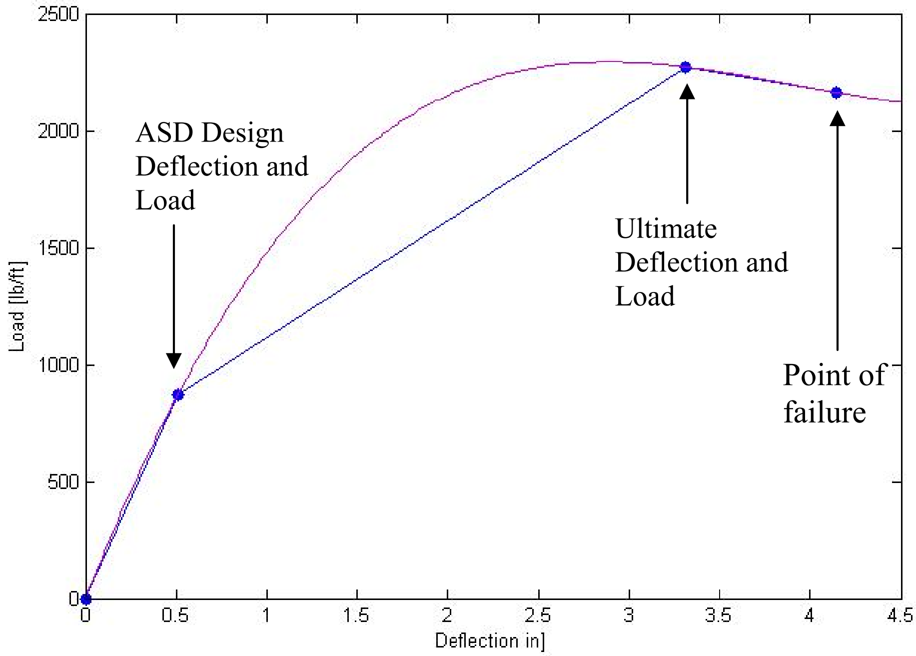

Figure 7- 4: Example piecewise load-deformation curve for residential exterior braced wall

Since the curve data is unknown, it will be reconstructed using a nonlinear least squares regression within 95% confidence intervals of all the data points for all of the walls. The model that the data is fit to is a scaled exponential curve that becomes level as x becomes large.

$$\text{exponential model} = b1\,(1-e^{-b2\,x}) \quad [7.10]$$

where

b1	= Parameter 1
b2	= Parameter 2
x	= Value along x axis
exponential model (y)	= Value along y axis

Only the data before the ultimate point is needed to estimate the response of the wall. Any wall that goes beyond this point has already failed. Failure criteria will be discussed later.

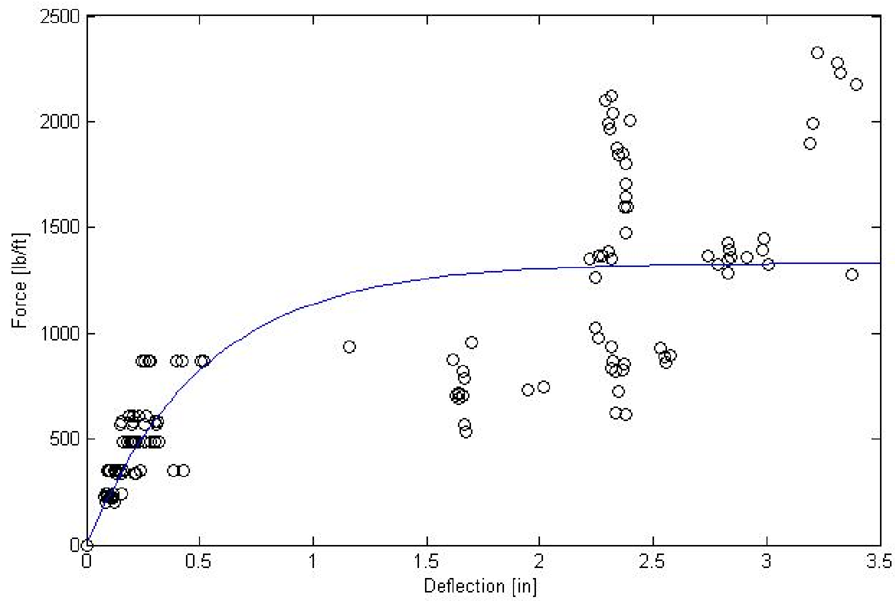

Figure 7- 5: Data from seventy tested exterior walls fit with an exponential curve

The goal of nonlinear regression is to find the values of the variables in the model that make the curve come as close as possible to the points. This is done by minimizing the sum of the squares of the vertical distances of the data points from the curve and is appropriate when you expect that the scatter of points around the curve is Gaussian and unrelated to the Y values of the points.

With many experimental protocols, it is not expected that the experimental scatter will be the same, on average, for all points. Instead, it is expected that the experimental scatter be a constant percentage of the Y value. Weighting the values can help minimize the sum of the square of the relative distances. A measure of goodness-of-fit should weight all the data points equally.

The results of nonlinear regression are meaningful only if the model is correct, the variability around the curve follows an approximate Gaussian distribution, the standard deviation of the variability is the same everywhere and the errors are independent. If the standard deviation is not constant but rather is proportional to the value of Y, the data should be weighted to minimize the sum-of-squares of the relative distances [15].

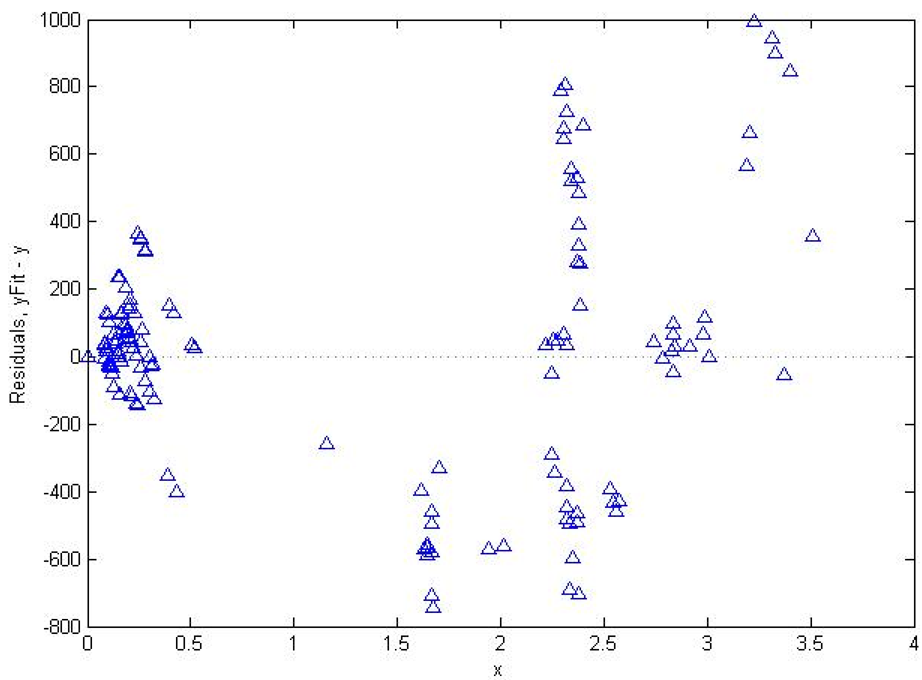

Figure 7- 6: Residual Plot for exponential curve fit in Figure 7- 5

The residual plot in Figure 7- 6 shows that the standard deviation, the variation along the y-axis, is proportional to the value of x, the deflection. This is seen by the data points starting close together for the smaller deflections and increasing outwards for the larger deflections. This can be improved by weighting the data. The data will be weighted by a value of 1/k where k can be estimated as the slope of the variance for the Y values in plotted Figure 7- 6 [15]. The estimated standard deviation in this case describes the average variation for a "standard" observation with a weight.

The most critical area of the load-deformation curve for this research is the area where the deflection is less than ½ inch which is comprised of the ASD points. When the walls pass this deflection they will be beyond the point of failure. The weighted curve is used to provide a more realistic reproduction of the actual load-deformation curve but the area beyond ½ inch has no importance in the experiment.

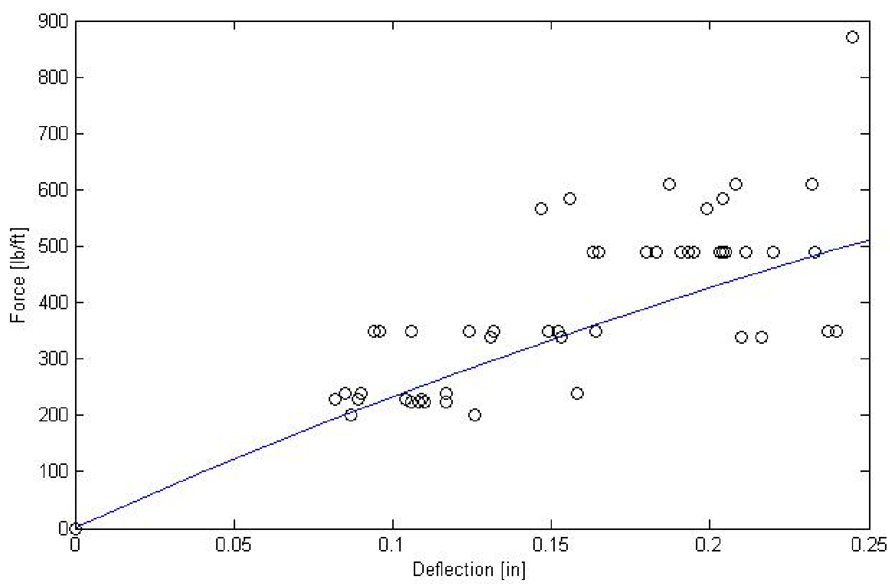

Figure 7- 7: Critical section of load deformation curve for exterior walls

The covariance matrix of the parameters determined for the exponential curve was used to randomly generate the exponential curve parameters within the 95% confidence interval of the weighted curve. These parameters are used to generate a new curve that falls within the 95% confidence interval each time the simulation is run. First, the parameters are estimated for the exponential model. These parameters are most probable values since the model might not exactly fit the data. The 95 % intervals for these parameter values would mean that there is a 95% confidence that the actual parameter values would lie within the range calculated. The 95 % confidence intervals of the predicted values contain 95 % of the actual values of the real distribution.

The interior braced walls consist of gypsum board on both sides. Actual load-deformation curve data is available for these walls [12]. Four walls have been tested constructed using wood studs and gypsum board on both sides. The procedure used to test the walls followed the ASTM E2126 [13]. Since the load curve data is available it is used to form a piecewise linear curve. Since only four walls were tested one generic stiffness function was developed and then scaled by two lognormal distributed random variables x_1 and x_2 with mean 1.0 and variance 0.1. This variance reflects the variance of the walls tested in the paper [12]. The lognormal distribution is used because these values cannot be negative. The first point of the piecewise curve will be set at H/400 where H is the height of the wall. Although there is no prescriptive criterion, H/400 is commonly accepted as a drift limit for wind [5]. This will be used as the failure deflection of the gypsum walls and the exterior structural panel walls. The next point used from the data will be the ultimate load and deflection. An artificial point will also be generated at a load of 5% higher than the ultimate load. This point is used in the case that the deflection goes beyond the ultimate point so that the program will converge.

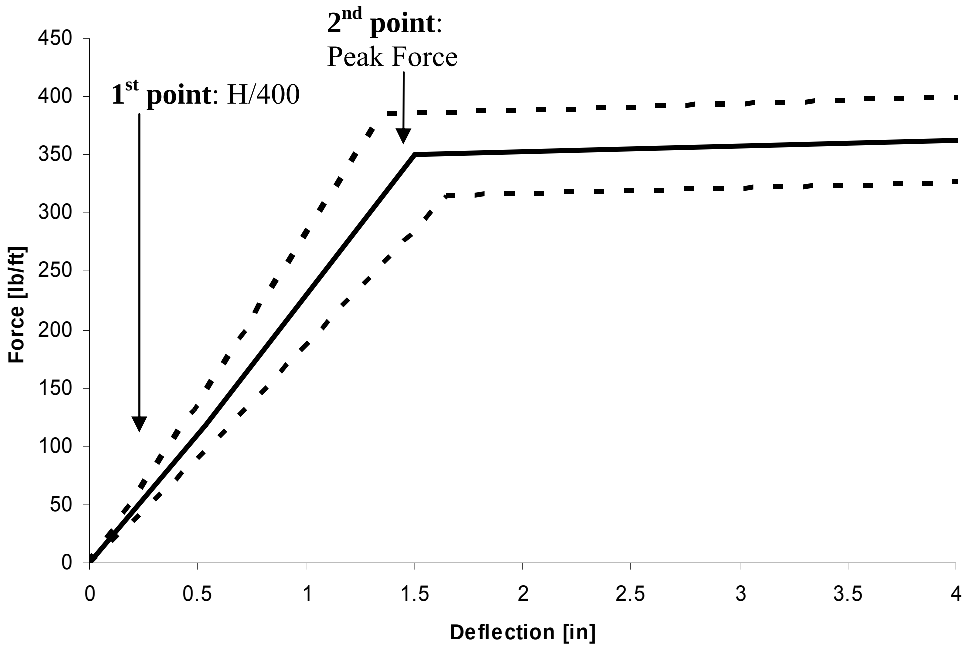

Figure 7- 8: Example of piecewise load-deformation curve for interior gypsum walls

In residential construction, the thickness of the structural panel used in a braced wall and the nailing of the structural panel are different depending on a number of variables. To model the uncertainty of the stiffness function for each wall, the results from the actual tested walls were used to generate dependent random variables of the parameters defining the exponential curve model. Each simulation generates a new stiffness function representing the braced wall construction used in the house in this way. A set of multipliers are also used on the generated stiffness function to represent several random variables. The stiffness of a single wall for a particular run is:

$$k(\delta) = k_{type}\ k_w L\ k_0(\delta) \qquad [7.11]$$

where

$k_0(\delta)$ the generic stiffness function randomly generated using the covariance matrix of the parameters defining the exponential curve model

k_{type} uniformly distributed random coefficients taking the values of: the minimum bracing percentage, 0.3, 0.6, 0.8, and 1.0 to simulate openings in the individual walls and are held fixed for known design or code studies where the amount of bracing is prescribed as a percentage of wall line length; the wall must have a minimum 4ft of bracing [1]

k_w normal random variables with mean 1 and variance 0.15 modeling the variability of the structure of the wall. The value of variance 0.15 reflects the uncertainty in wall construction practice [12]

L the length of the particular wall

The random wall bracing multiplier is arbitrarily selected for each wall and represents a probability of the existence of an opening.

The stiffness function for the interior gypsum walls is generated similarly. Four walls have been tested constructed using wood studs and gypsum board on both sides [12].

$$k(\delta) = k_{type}\ k_w L\ x_1\ k_0(x_2 \delta) \qquad [7.12]$$

where

$k_0(\delta)$ the generic stiffness function [12]

k_{type} uniformly distributed random coefficients taking the values of: the minimum bracing percentage, 0.3, 0.6, 0.8 and 1.0 to simulate openings in the individual walls and are held fixed for known design or code studies where the amount of bracing is prescribed as a percentage of wall line length [4]; the wall must have a minimum 4ft bracing length [1]

k_w normal random variables with mean 1 and variance 0.15 modeling the variability of the structure of the wall. The value of variance 0.15 reflects the uncertainty in wall construction practice [12]

L the length of the particular wall

x_1, x_2 normal random variables with mean 1.0 and variance 0.1 describing the uncertainty of the generic stiffness function. The value of variance 0.1 is based on shear wall tests of identical construction [12] that indicate relatively low variability of stiffness and capacity between shear walls of the same construction

Each simulation draws one random stiffness function for all of the exterior walls in the model and one random stiffness function for all of the interior walls in the model. Therefore, each simulation uses the same thickness and nail spacing for all walls of each type since the stiffness function is drawn from a database of variations.

Chapter 8 Analytical Model Results

Eighteen different Monte Carlo simulations were run 100,000 times each. The following chapter describes the geometries tested and gives a summary of the results. The plate model provides more realistic results since it includes the walls in the opposite direction. Therefore, the results for the plate model only will be given.

8.1 The "IRC House"

In order to test the minimum requirements of the IRC, the geometry used in Figure 8- 1 will be used. The maximum distance between braced wall lines is 35 ft (10.67 m). The minimum bracing requirement is 16% of every 25 ft (7.62 m) braced wall line or a minimum of 4 ft (1.22 m) for a one story house. Therefore, the three walls along the y- axis are set at 25 ft (7.62 m) to test a minimum length of 4 ft (1.22 m) of braced wall. The interior wall is assumed to be constructed using Method 5 of the IRC for gypsum board braced walls. The exterior walls are assumed to be constructed using Method 3 of the IRC for wood structural panel sheathing.

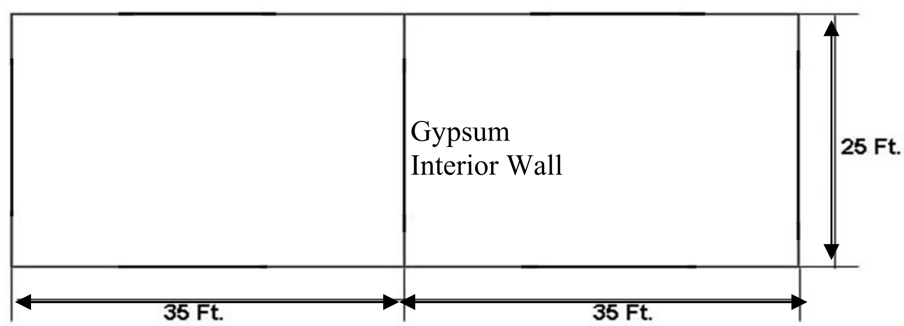

Figure 8- 1: The "IRC House" geometry used to test the minimum requirements

The IRC House was tested using six different scenarios for both the minimum 10 psf (5.75 kPa) pressure requirement and the actual pressures calculated using the ASCE 7 analytical procedure. Table 8- 1 lists the scenarios tested. Random wall openings means that each wall will be multiplied by a random multiplier drawn from a uniform distribution which will affect the length of the wall. The multipliers consist of the minimum bracing required per the IRC bracing table which may vary between 0.16 and 0.25 depending on the number of stories in the house and what floor is being analyzed, 0.30, 0.60, 0.80 and 1.0. If 1.0 was selected it would mean the full length of the wall is braced and there are no openings. If 0.16 was selected it would mean only 16% of the wall was braced and the rest of the wall was open. Fixed wall openings means that all of the walls will be set to the minimum bracing required by the IRC. For a one story house, this means that only 16% of every wall is braced. The rest of each wall is open and does not contribute to the lateral resistance of the wall.

Table 8- 1: Scenarios tested for IRC House

Random Openings in walls		
1 Story	10 psf	ASCE 7 Pressures
2 Story	10 psf	ASCE 7 Pressures
3 Story	10 psf	ASCE 7 Pressures
Fixed Openings in walls: min. bracing used based on # of stories		
1 Story	10 psf	ASCE 7 Pressures
2 Story	10 psf	ASCE 7 Pressures
3 Story	10 psf	ASCE 7 Pressures

The set up for the plate model may be seen in Figure 8- 2. The force in the x direction shown in Figure 8- 2 is a result of the pressures created by the wind blowing on the house in the y direction. This is illustrated in the ASCE 7 [3].

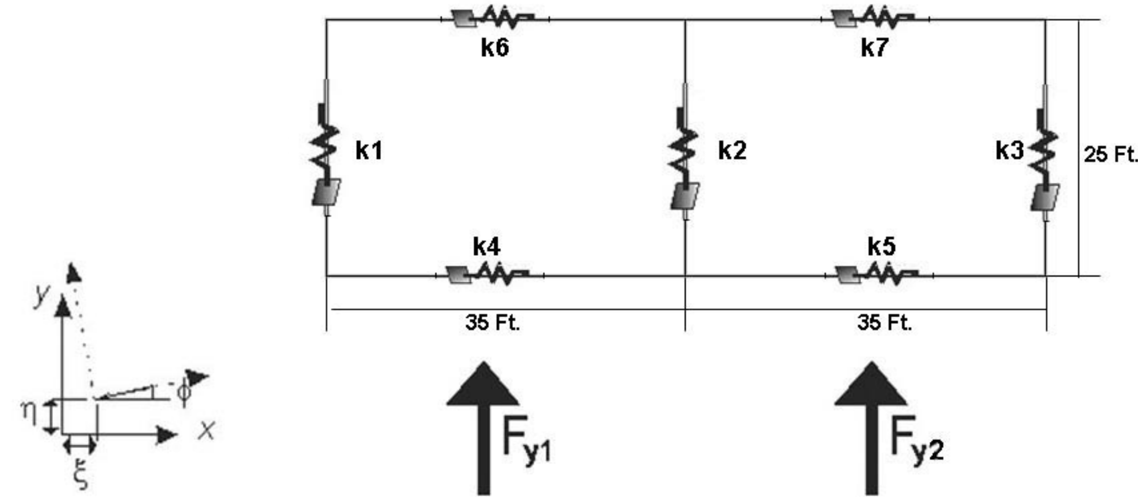

Figure 8- 2: Schematic of the plate model for the IRC house

Detailed results for one simulation will be shown in this chapter. A summary of results from the remaining simulations are given in Appendix C.

The wall openings for the one story IRC house with fixed wall openings are held at the minimum wall bracing requirements of the IRC. The ASCE 7 minimum requirement of 10 psf pressure for the height of the house was not used in this simulation.

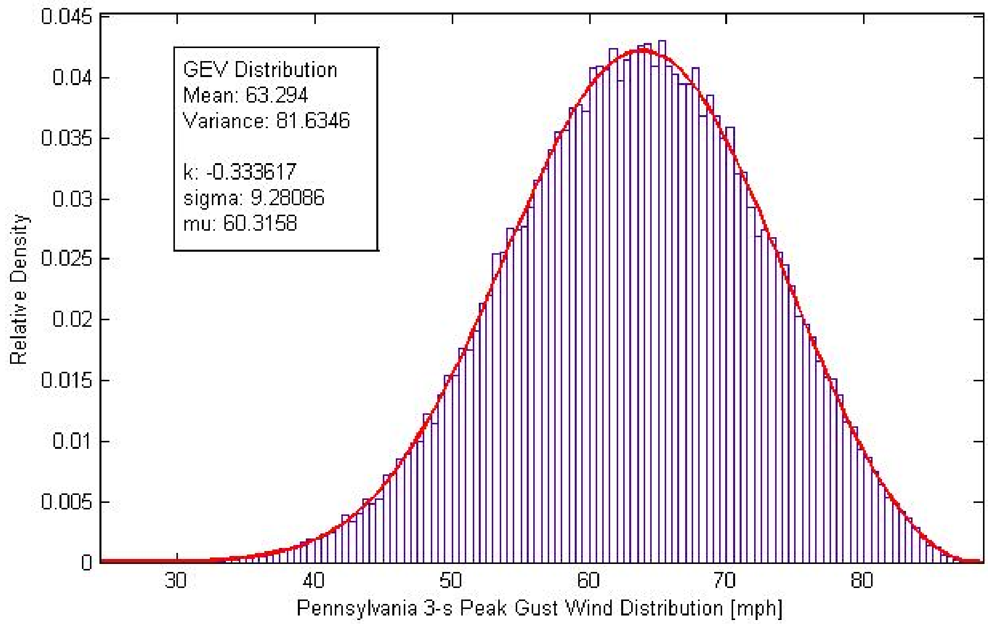

Figure 8- 3: Wind Distribution for one story IRC house with fixed wall openings

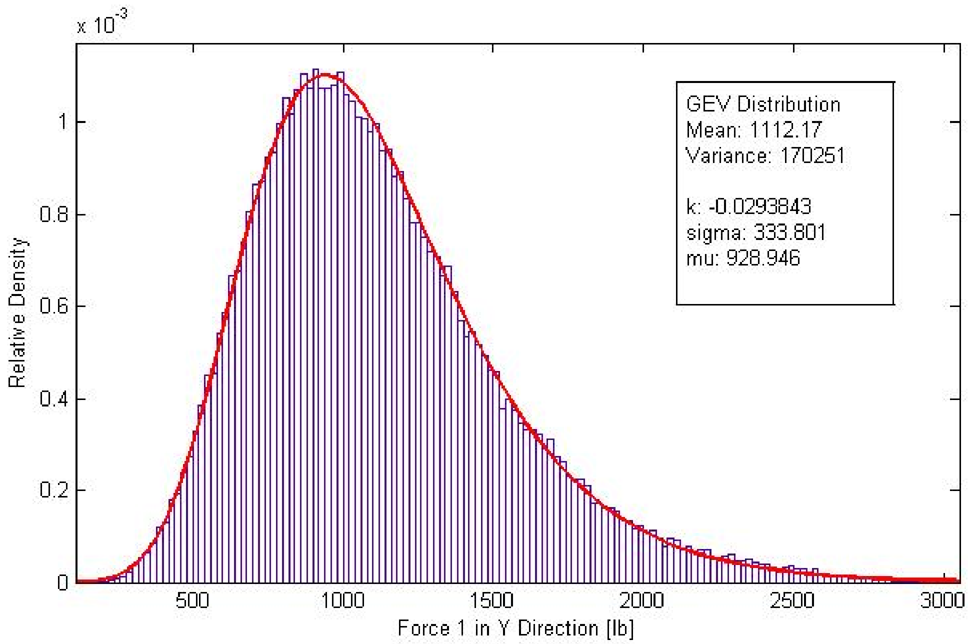

Figure 8- 4: Force 1 in y direction for one story IRC house with fixed wall openings

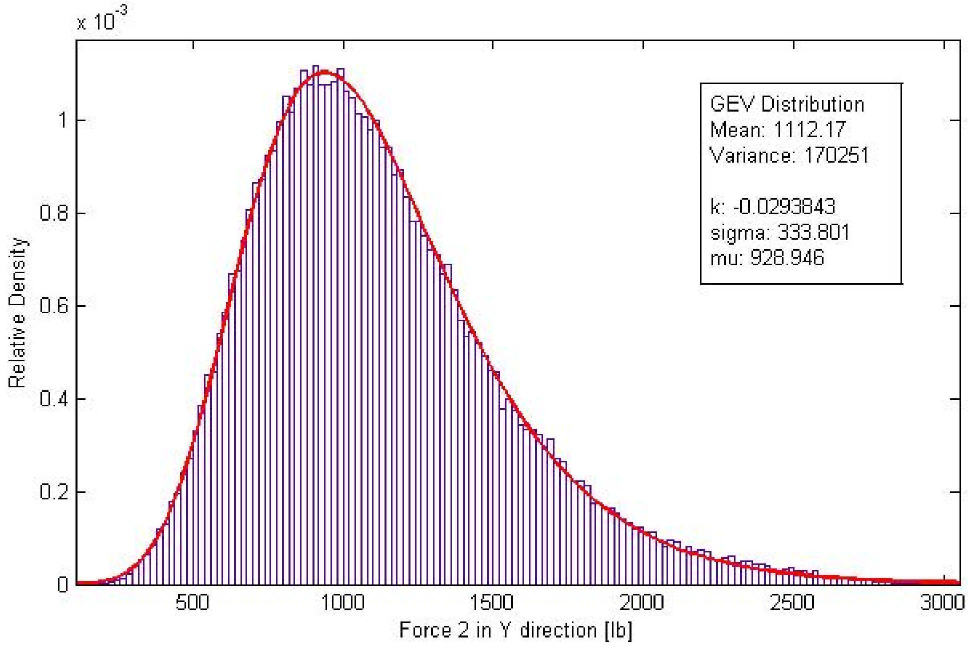

Figure 8- 5: Force 2 in y direction for one story IRC house with fixed wall openings

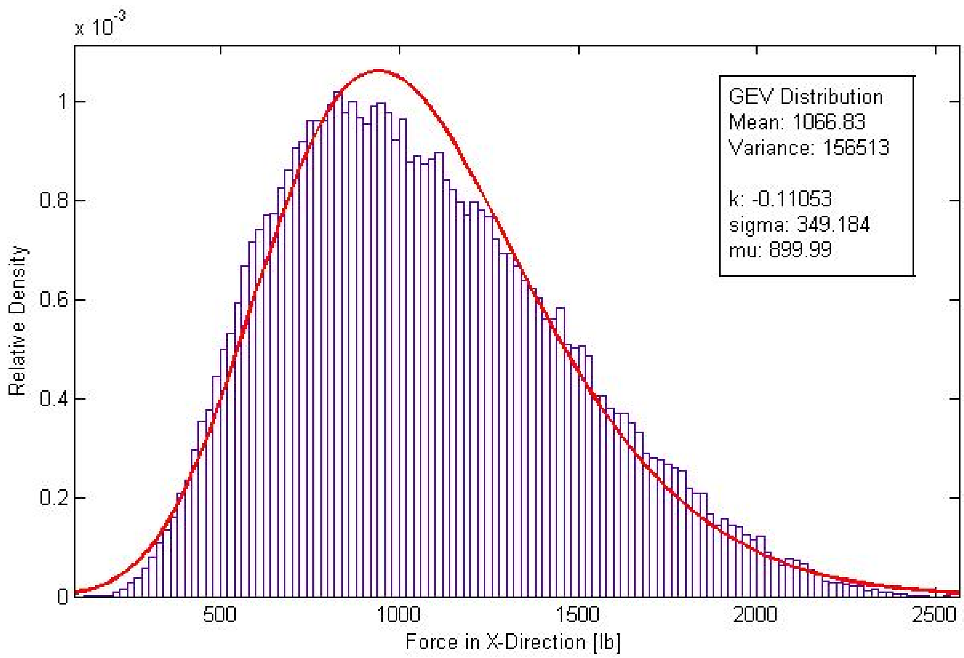

Figure 8- 6: Force in x direction for one story IRC house with fixed wall openings

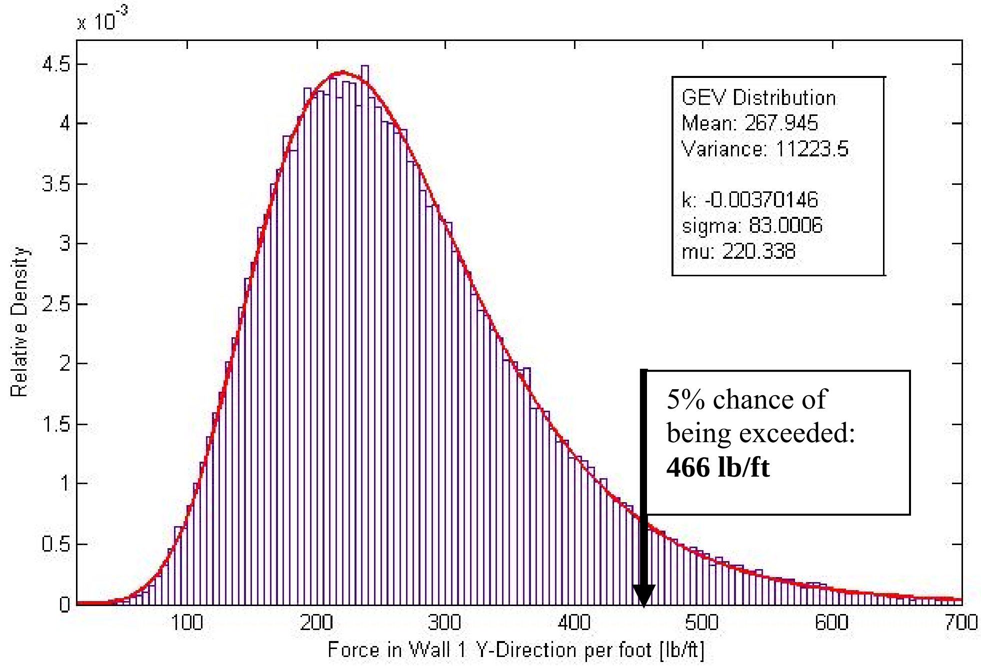

Figure 8- 7: Force in Wall 1 Y-Direction for one story IRC house with fixed wall openings

Figure 8- 7 displays the histogram of the shear force being resisted in the left exterior wall of the house. The mean value is 268 lb/ft. Since each simulation drew a random stiffness out of a database contained multiple structural panel thicknesses and nail spacing, the point at which the shear force has a 5% chance of being exceeded will be the chosen value to design the particular wall for. 5% was arbitrarily chosen as an adequate percentage to design for since a smaller percentage is further evaluating the tail of the distribution and may overestimate the response. This shear force can then be compared to the APA table containing values of shear force for various panel thicknesses and nailing in order to determine the amount required for the house. The maximum shear force calculated this way for each type of wall in each floor of the house should be used to set the minimum requirements based on the APA table.

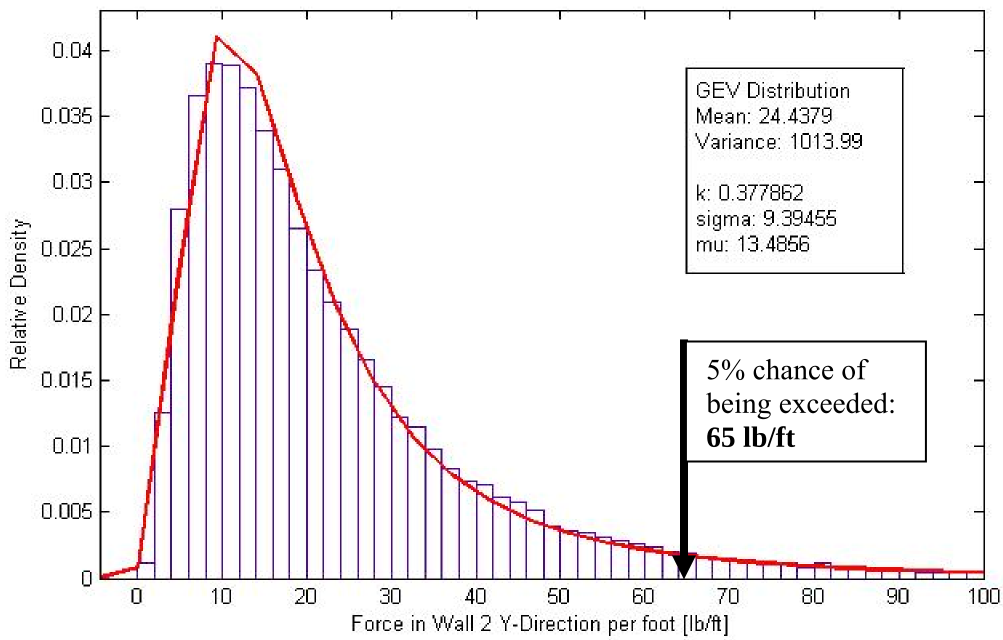

Figure 8- 8: Force in Wall 2 Y-Direction for one story IRC house with fixed wall openings

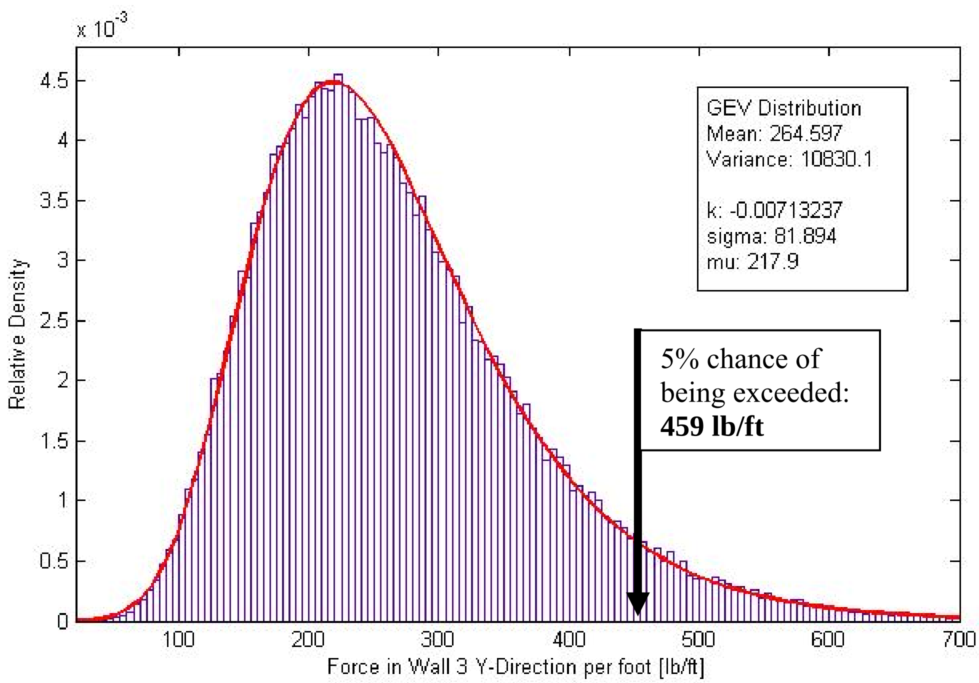

Figure 8- 9: Force in Wall 3 Y-Direction for one story IRC house with fixed wall openings

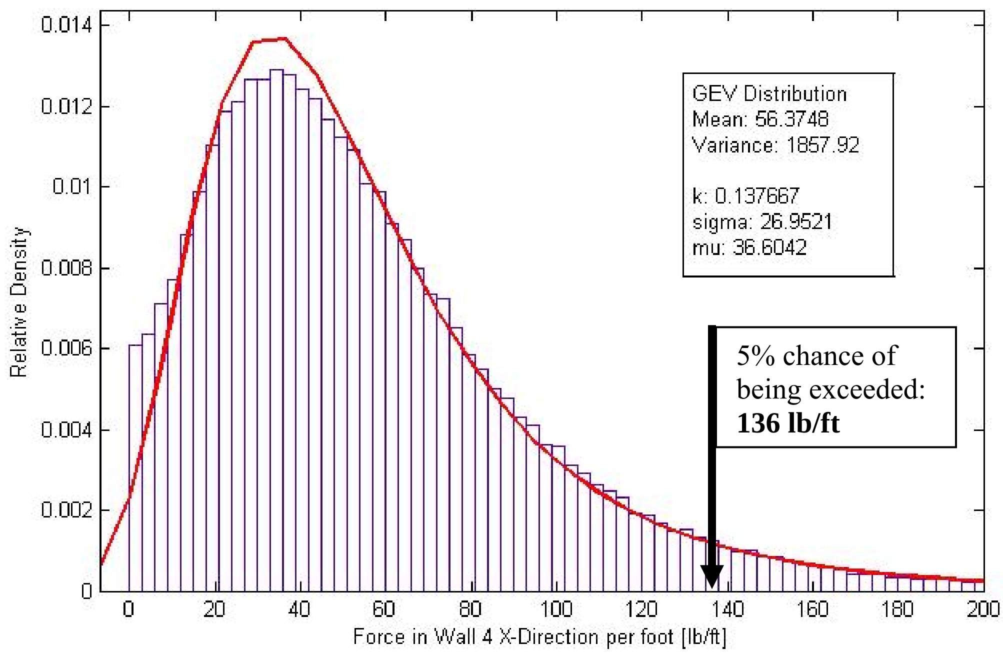

Figure 8- 10: Force in Wall 4 X-Direction for one story IRC house with fixed wall openings

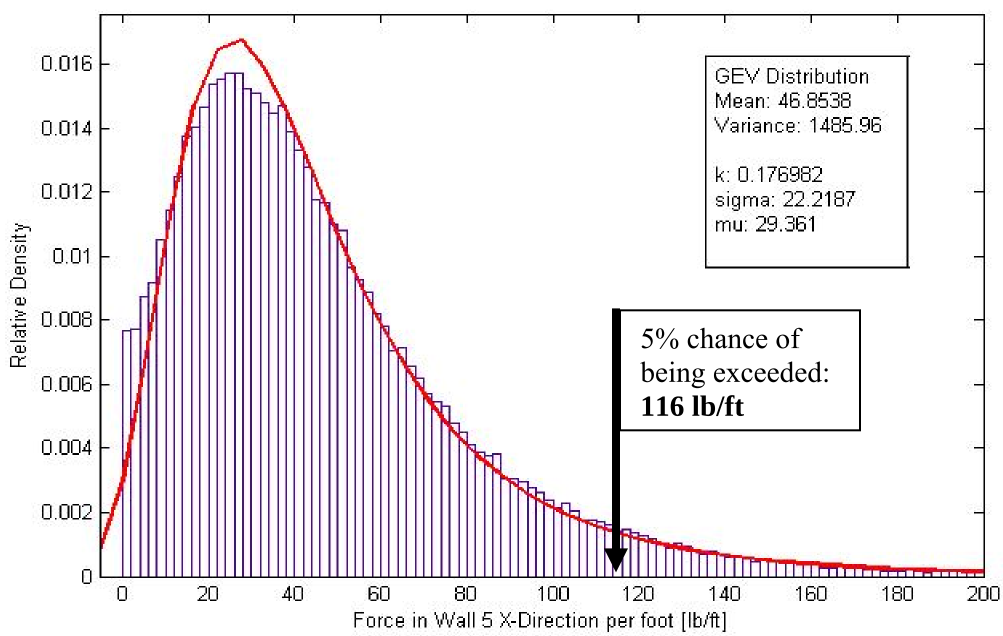

Figure 8- 11: Force in Wall 5 X-Direction for one story IRC house with fixed wall openings

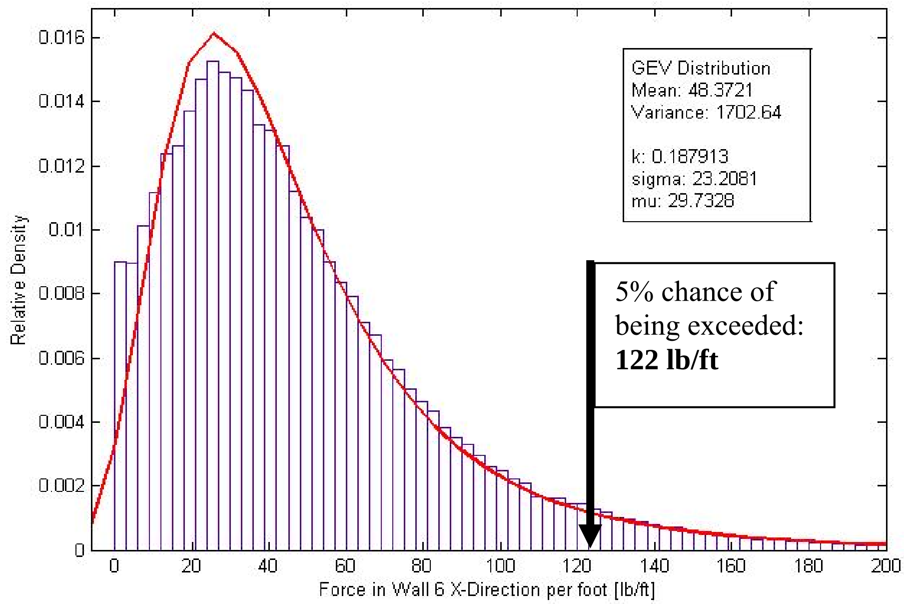

Figure 8- 12: Force in Wall 6 X-Direction for one story IRC house with fixed wall openings

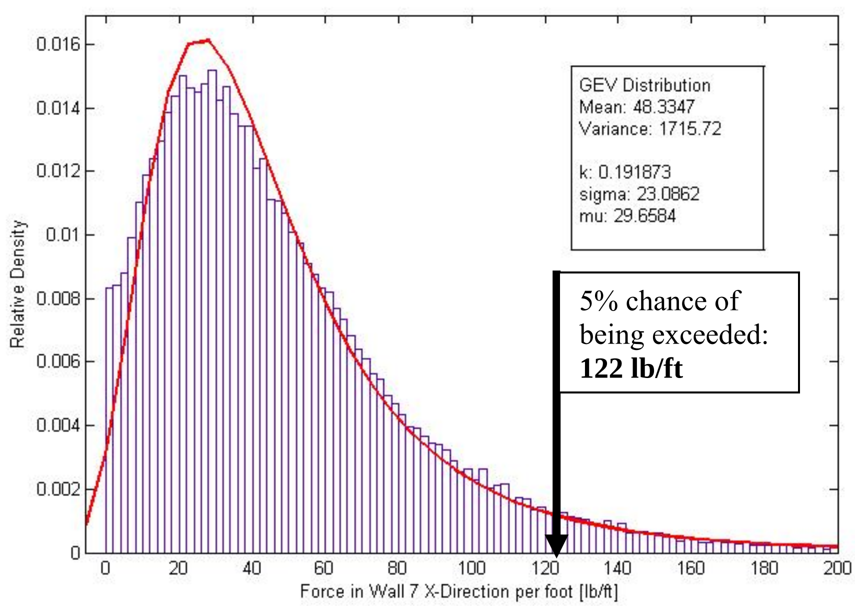

Figure 8- 13: Force in Wall 7 X-Direction for one story IRC house with fixed wall openings

The maximum shear force calculated in Figure 8- 7 through Table 8- 13 is 466lb/ft. According to Table 8- 3 the following minimum thickness and nailing is recommended:

Table 8- 2: Recommendations for exterior braced wall structural panel thickness and nailing

	If only 4 Ft out of 25 Ft Wall Braced
One story Top of two or three story	5/16" – 6d nails spaced 3" at edges
	3/8" – 8d nails spaced 4" at edges
	7/16" – 8d nails spaced 4" at edges
	15/32" – 8d nails spaced 4" at edges

Table 8- 3: Recommended Shear (Pounds per foot) for APA Panel Shear Walls with Framing of Spruce Pine-Fir for Wind Loading

Spruce Pine - Fir, S.G. = 0.42	Panels Applied Direct to Framing						
Panel Grade	Minimum Nominal Panel Thickness (in.)	Minimum Nail Penetration in Framing (in.)	Nail Size (common or galvanized box)	Nail Spacing at Panel Edges (in.) 6	4	3	2
APA STRUCTURAL I grades	5/16	1-1/4	6d	260	390	545	715
	3/8	1-3/8	8d	300	465	645	855
	7/16			330	510	705	940
	15/32			360	555	770	1020
	15/32	1-1/2	10d	435	655	930	1220
APA RATED SHEATHING; APA RATED SIDING and other APA grades except Species Group 5	5/16 or 1/4	1-1/4	6d	230	350	490	630
	3/8			260	385	545	715
	3/8	1-3/8	8d	285	410	575	740
	7/16			310	450	630	820
	15/32			335	490	685	895
	15/32	1-1/2	10d	400	590	840	1080
	19/32			440	655	930	1220

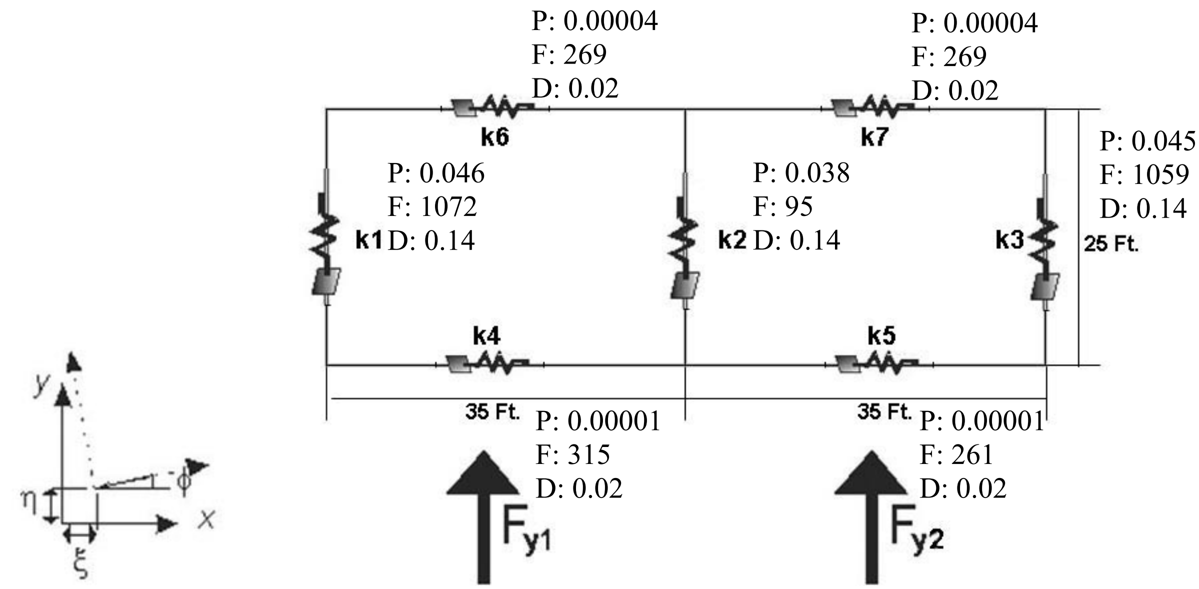

Figure 8- 14: Results for plate model – one story IRC house with fixed wall openings; P: probability of failure, F: force [lb], D: deflection [in]

Table 8- 4 through Table 8- 8 list the probability of failure for each wall in each simulation tested.

Table 8- 4: Probability of failure in walls – one story IRC house with fixed wall openings

	1st Floor	
	Actual Pressures	Min. 10psf
Wall 1	0.04598	0.48871
Wall 2	0.03848	0.50058
Wall 3	0.04532	0.48132
Wall 4	0.00001	0.00005
Wall 5	0.00001	0.00004
Wall 6	0.00004	0.00065
Wall 7	0.00004	0.00065

Table 8- 5: Probability of failure in walls – two story IRC house with fixed wall openings

	1st Floor		2nd Floor	
	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf
Wall 1	0.34578	0.70344	0.03297	0.08651
Wall 2	0.35006	0.72459	0.02205	0.05976
Wall 3	0.34016	0.69401	0.02976	0.03192
Wall 4	0.00340	0.00757	0.00001	0.00102
Wall 5	0.00341	0.00756	0.00001	0.00115
Wall 6	0.00511	0.01222	0.00041	0.01821
Wall 7	0.00510	0.01222	0.00041	0.01820

Table 8- 6: Probability of failure in walls – three story IRC house with fixed wall openings

	1st Floor		2nd Floor		3rd Floor	
	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf
Wall 1	0.74420	1.00000	0.32546	0.72314	0.03287	0.08695
Wall 2	0.76930	1.00000	0.35620	0.75236	0.02356	0.05982
Wall 3	0.74344	0.99000	0.32400	0.68753	0.02986	0.03269
Wall 4	0.01034	0.11000	0.00155	0.00653	0.00001	0.00110
Wall 5	0.01032	0.11000	0.00081	0.00752	0.00001	0.00124
Wall 6	0.01298	0.07000	0.00556	0.01342	0.00042	0.01856
Wall 7	0.01300	0.07000	0.00523	0.01234	0.00043	0.01852

Table 8- 7: Probability of failure in walls – one story IRC house with random wall openings

	1st Floor	
	Actual Pressures	Min. 10psf
Wall 1	0.00147	0.02946
Wall 2	0.00110	0.02092
Wall 3	0.00129	0.02883
Wall 4	0.00000	0.00000
Wall 5	0.00000	0.00000
Wall 6	0.00000	0.00000
Wall 7	0.00000	0.00000

Table 8- 8: Probability of failure in walls – two story IRC house with random wall openings

	1st Floor		2nd Floor	
	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf
Wall 1	0.10396	0.34432	0.00168	0.03244
Wall 2	0.08474	0.34789	0.00101	0.02169
Wall 3	0.10158	0.33794	0.00149	0.02872
Wall 4	0.00029	0.00344	0.00000	0.00002
Wall 5	0.00028	0.00341	0.00000	0.00003
Wall 6	0.00040	0.00447	0.00002	0.00036
Wall 7	0.00040	0.00447	0.00002	0.00036

Table 8- 9: Probability of failure in walls – three story IRC house with random wall openings

	1st Floor		2nd Floor		3rd Floor	
	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf
Wall 1	0.17152	0.46602	0.10452	0.34924	0.00174	0.03568
Wall 2	0.15882	0.51616	0.08622	0.35308	0.00110	0.02202
Wall 3	0.17120	0.46440	0.10558	0.33604	0.00152	0.02874
Wall 4	0.00052	0.00514	0.00052	0.00428	0.00000	0.00000
Wall 5	0.00052	0.00510	0.00052	0.00424	0.00000	0.00000
Wall 6	0.00076	0.00806	0.00084	0.00704	0.00000	0.00024
Wall 7	0.00076	0.00806	0.00084	0.00706	0.00000	0.00024

8.2 A typical L-shaped house

A typical L-shaped house was tested to see how the results compared to the IRC house since most houses typically have more interior walls. This house shape was selected based on the typical US construction identified by the NAHB Research Center [4] and has also been tested as a full scale model in previous research under lateral loads. In this experiment the house was tested using only the random openings method because typically a house will not have only the minimum percentage of each wall braced. If one wall was only 16% braced, most likely the other walls would have more bracing. Table 8- 10 lists the scenarios tested for the L-shaped house.

Table 8- 10: Scenarios tested for the L-shaped house

Random Openings in walls:		
1 Story	10 psf	ASCE 7 Pressures
2 Story	10 psf	ASCE 7 Pressures
3 Story	10 psf	ASCE 7 Pressure

The geometry for the L-shaped housed is shown in [4].

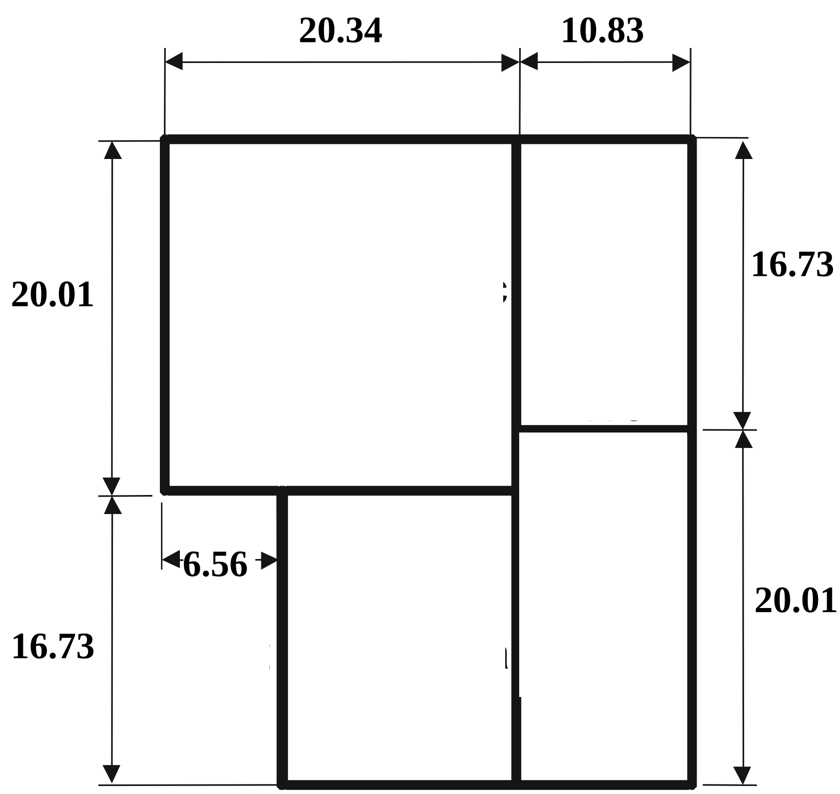

Figure 8- 15: Floor plan of the tested structure (dimensions in ft) for the L-shaped house [4]

The set up for the plate model is shown in [4]. The model was tested using the nonlinear equation solvers with the generic stiffness function to determine the probability of failure in each wall. The failure criterion was set as the H/400 deflection which was explained earlier as the commonly accepted value of drift for wind design.

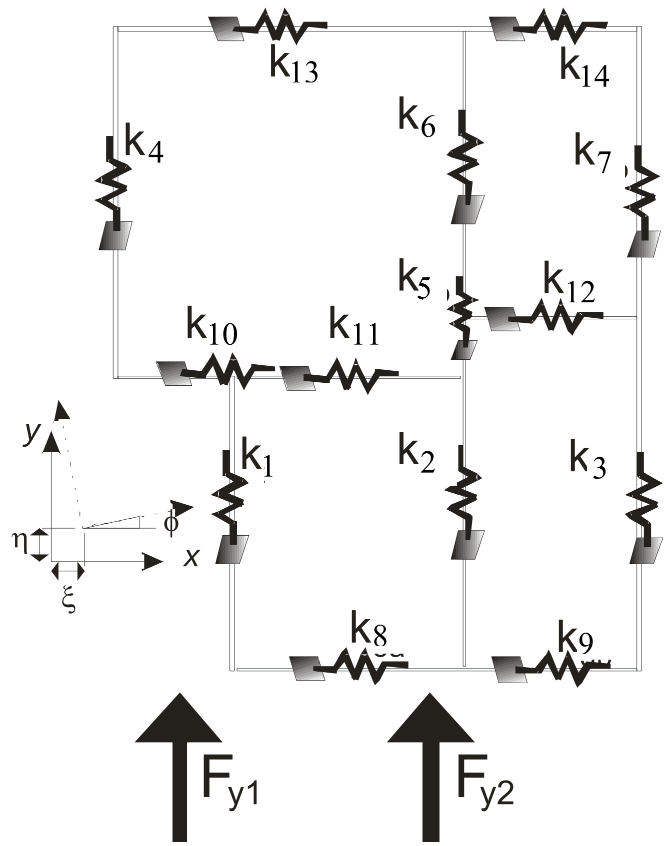

Figure 8- 16: Schematic of the plate model for the L-shaped House [4]

Table 8- 11: Probability of failure in walls – one story L-house with random wall openings

	1st Floor	
	Actual Pressures	Min. 10psf
Wall 1		
Wall 2		
Wall 3		
Wall 4		
Wall 5		
Wall 6		
Wall 7	P→0	P→0
Wall 8		
Wall 9		
Wall 10		
Wall 11		
Wall 12		
Wall 13		
Wall 14		

Table 8- 12: Probability of failure in walls – two story L-house with random wall openings

	1st Floor		2nd Floor	
	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf
Wall 1	0.00249	0.00956	0.00002	0.00013
Wall 2	0.00000	0.00003	0.00000	0.00000
Wall 3	0.00171	0.00710	0.00003	0.00009
Wall 4	0.00279	0.00999	0.00003	0.00018
Wall 5	0.00000	0.00003	0.00000	0.00000
Wall 6	0.00000	0.00003	0.00000	0.00000
Wall 7	0.00171	0.00710	0.00003	0.00009
Wall 8	0.00702	0.02428	0.00016	0.00053
Wall 9	0.00702	0.02428	0.00016	0.00053
Wall 10	0.00842	0.02704	0.00017	0.00049
Wall 11	0.00008	0.00046	0.00000	0.00000
Wall 12	0.00010	0.00044	0.00000	0.00000
Wall 13	0.00892	0.02711	0.00020	0.00059
Wall 14	0.00892	0.02711	0.00020	0.00059

Table 8- 13: Probability of failure in walls – three story L-house with random wall openings

	1st Floor		2nd Floor		3rd Floor	
	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf	Actual Pressures	Min. 10psf
Wall 1	0.00459	0.01857	0.00004	0.00028	0.00001	0.01023
Wall 2	0.00010	0.00007	0.00001	0.00001	0.00000	0.00024
Wall 3	0.00261	0.01325	0.00005	0.00018	0.00002	0.08263
Wall 4	0.00448	0.01854	0.00005	0.00023	0.00002	0.01253
Wall 5	0.00000	0.00005	0.00001	0.00001	0.00000	0.00000
Wall 6	0.00000	0.00005	0.00001	0.00001	0.00000	0.00000
Wall 7	0.00282	0.01357	0.00007	0.00018	0.00002	0.00053
Wall 8	0.01410	0.04523	0.00025	0.00132	0.00008	0.00153
Wall 9	0.01302	0.04896	0.00026	0.00123	0.00001	0.00154
Wall 10	0.01251	0.04521	0.00025	0.00059	0.00006	0.00156
Wall 11	0.00014	0.00082	0.00001	0.00012	0.00001	0.00000
Wall 12	0.00023	0.00086	0.00001	0.00016	0.00001	0.00000
Wall 13	0.01253	0.04523	0.00043	0.00135	0.00015	0.00045
Wall 14	0.01381	0.04756	0.00037	0.00134	0.00016	0.00046

Chapter 9 Conclusions

9.1 Recommendations based on ASCE 7 Analytical Method

The Engineered Wood Associates (APA) developed a table of recommended shear force for APA panel shear walls with framing [14]. This table was compiled using tested shear walls and is for wood types of Douglas-Fir, Larch, or Southern Pine. The table values must be multiplied by an adjustment factor based on specific gravity of the wood if another type of wood is used. Since most house construction in the state of Pennsylvania used Spruce Pine-Fir, the values in the table must be multiplied by an adjustment factor of 1 – (.5 –SG), or 0.92. Per IBC Section 2306.4.1, the allowable shear capacity of the shear wall may also be increased by 40% for wind design [17]. These adjustment factors result in the values of Table 9- 1. Since the APA table is based on experimental tests and is used in practice for the allowable shear force in a wall, it is used in this research to evaluate the simulated shear forces. It is unknown whether The International Residential Code 2006 [1] uses the APA table as a guideline for the bracing table.

Table 9- 1: Recommended Shear (Pounds per foot) for APA Panel Shear Walls with Framing of Spruce Pine-Fir for Wind Loading

Spruce Pine - Fir, S.G. = 0.42			Panels Applied Direct to Framing				
Panel Grade	Minimum Nominal Panel Thickness (in.)	Minimum Nail Penetration in Framing (in.)	Nail Size (common or galvanized box)	Nail Spacing at Panel Edges (in.)			
				6	4	3	2
APA STRUCTURAL I grades	5/16	1-1/4	6d	260	390	545	715
	3/8	1-3/8	8d	300	465	645	855
	7/16			330	510	705	940
	15/32			360	555	770	1020
	15/32	1-1/2	10d	435	655	930	1220
APA RATED SHEATHING; APA RATED SIDING and other APA grades except Species Group 5	5/16 or 1/4	1-1/4	6d	230	350	490	630
	3/8			260	385	545	715
	3/8	1-3/8	8d	285	410	575	740
	7/16			310	450	630	820
	15/32			335	490	685	895
	15/32	1-1/2	10d	400	590	840	1080
	19/32			440	655	930	1220

Using the values in Table 9- 1 and multiplying them by the length of a braced wall segment will give you the design capacity of that wall. Using this table and the shear forces calculated in the ASCE 7 Analytical Method of Chapter 5, a table of guidelines was developed for house construction.

Table 9- 2: Minimum Recommended Structural Panel Wall Bracing and nailing for homes located in 80 mph winds or less

80 mph or less	One story Top of two or three story	**If only 4 Ft out of 25 Ft Wall Braced**
		5/16” – 6d nails spaced 3” at edges
		3/8” – 8d nails spaced 4” at edges
		7/16” – 8d nails spaced 4” at edges
		15/32” – 8d nails spaced 4” at edges
	First story of two story Second story of three story	**If only 4 Ft out of 25 Ft Wall Braced**
		7/16” – 8d nails spaced at 2” at edges
		15/32” – 8d nails spaced 2” at edges
		If only 8 Ft out of 25 Ft Wall Braced
		3/8” – 8d nails spaced 4” at edges
		7/16” – 8d nails spaced 4” at edges
		15/32” – 8d nails spaced 4” at edges
	First story of three story	**If only 4 Ft out of 25 Ft Wall Braced**
		15/32” – 10d nails spaced 2” at edges
		If only 8 Ft out of 25 Ft Wall Braced
		3/8” – 8d nails spaced 3” at edges
		7/16” – 8d nails spaced 3” at edges
		15/32” – 8d nails spaced 3” at edges
		15/32” – 10d nails spaced 4” at edges

a. Wall bracing must be located at least every 25 Ft on center but not less than 16% of braced wall line
b. For walls with more bracing length than the lengths listed here the minimum thickness of Section R602.10 of the IRC [1] may be used
c. All other requirements of the IRC [1] Section R602.10.1 shall apply

9.2 Recommendations based on Monte Carlo simulations

The simulations used a generic stiffness function for the exterior walls based on 70 tested walls. The variation of this stiffness function is dramatic. The tested walls included various thicknesses and nailing. The minimum thickness and nailing used in these tests was 3/8” (0.95 cm) thick with 6d nails spaced 6” (15.2 cm) at edges. The maximum thickness and nailing used in these tests was 19/32” (1.51 cm) thick with 10d nails spaced 2” (5.08 cm) at edges. This covers a variety of thickness and nailings which explains the variation. Running a Monte Carlo simulation at least 100,000 times covers many possible scenarios. The results for the IRC house with walls fixed at the minimum percentage of walls braced shows that this is an unrealistic minimum requirement. The percentage of failure for the one story was 4.6%, two story 34.6% and three story 76.9%. This is when the ASCE 7 pressures are used. When following the ASCE 7 requirement of 10psf (5.75 kPa) pressure over the height of the house, the failure rates are significantly higher.

Since it is extremely unlikely that a house would be constructed with only the minimum percentage of every wall braced, the test was run using random openings in each wall. The percentage of braced wall for each wall was now selected randomly using a uniform distribution with random multipliers. Running the same tests using the random openings the probability of failures reduced significantly. The probability of failure for one story 0.15%, two story 10.4% and three story 17.2%. This still leaves a question about the minimum required bracing because the 10.4% failure for a two story is not acceptable. Using the ASCE 7 minimum 10psf (5.75 kPa) pressure requirement, the probability of failure is again much higher.

It is as likely to construct a box house with one interior wall as it is to construct a house with only the minimum percentage bracing for each wall. Therefore the L-shaped house was tested. The results for the L-shaped house show that a typical house, with more than one interior wall and random openings, has a low probability of failure for each wall in all models. This includes one story, two story and three story models. The openings were set randomly with the IRC required minimum bracing amount for the individual wall, .30, .60, .80 and 1.0 bracing. These results show that it is possible to construct a house with only the minimum percentage bracing on one of the walls, as long as there are enough walls with sufficient bracing that make up the rest of the house.

We recommend using the thickness and nailing provided in Table 9- 3. These conclusions were formulated using the tributary area method in 80 mph winds and confirmed running the Monte Carlo procedure to determine the 95% maximum shear force per wall.

There are some limitations to this research which can be improved upon in future research. The first limitation is the shear wall data being used to simulate the stiffness of the braced walls. Performing experimental tests on specific types of walls to obtain the actual load-deformation curves will greatly improve the reliability of the data. Another option is to use the load-deformation curves of the nails used in each wall to simulate the stiffness of each wall. A second limitation to the research is the acting point of the resultant wind force. Currently it is being randomly drawn from a normal distribution. This may be improved by researching the actual wind distribution along the length of a house. A third limitation is the use of the ASCE 7 wind pressure calculations. The pressure coefficients were developed using wind tunnel experiments and cannot possibly be accurate for every house.

Table 9- 3: Minimum Recommended Structural Panel Wall Bracing and nailing for homes located in 80 mph winds or less

80 mph or less	One story Top of two or three story	**If only 4 Ft out of 25 Ft Wall Braced**
		5/16" – 6d nails spaced 3" at edges
		3/8" – 8d nails spaced 4" at edges
		7/16" – 8d nails spaced 4" at edges
		15/32" – 8d nails spaced 4" at edges
	First story of two story Second story of three story	**If only 4 Ft out of 25 Ft Wall Braced**
		7/16" – 8d nails spaced at 2" at edges
		15/32" – 8d nails spaced 2" at edges
		If only 8 Ft out of 25 Ft Wall Braced
		3/8" – 8d nails spaced 4" at edges
		7/16" – 8d nails spaced 4" at edges
		15/32" – 8d nails spaced 4" at edges
	First story of three story	**If only 4 Ft out of 25 Ft Wall Braced**
		15/32" – 10d nails spaced 2" at edges
		If only 8 Ft out of 25 Ft Wall Braced
		3/8" – 8d nails spaced 3" at edges
		7/16" – 8d nails spaced 3" at edges
		15/32" – 8d nails spaced 3" at edges
		15/32" – 10d nails spaced 4" at edges

a. Wall bracing must be located at least every 25 Ft on center but not less than 16% of braced wall line
b. For walls with more bracing length than the lengths listed here the minimum thickness of Section R602.10 of the IRC [1] may be used
c. All other requirements of the IRC [1] Section R602.10.1 shall apply

References

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[18] Seismic Design Parameters. Version 3.10. USGS Open-File Report 01-437. US Geological Survey, Denver, CO. CD-ROM.

Appendix A Plotted wind distributions for grouped stations in PA

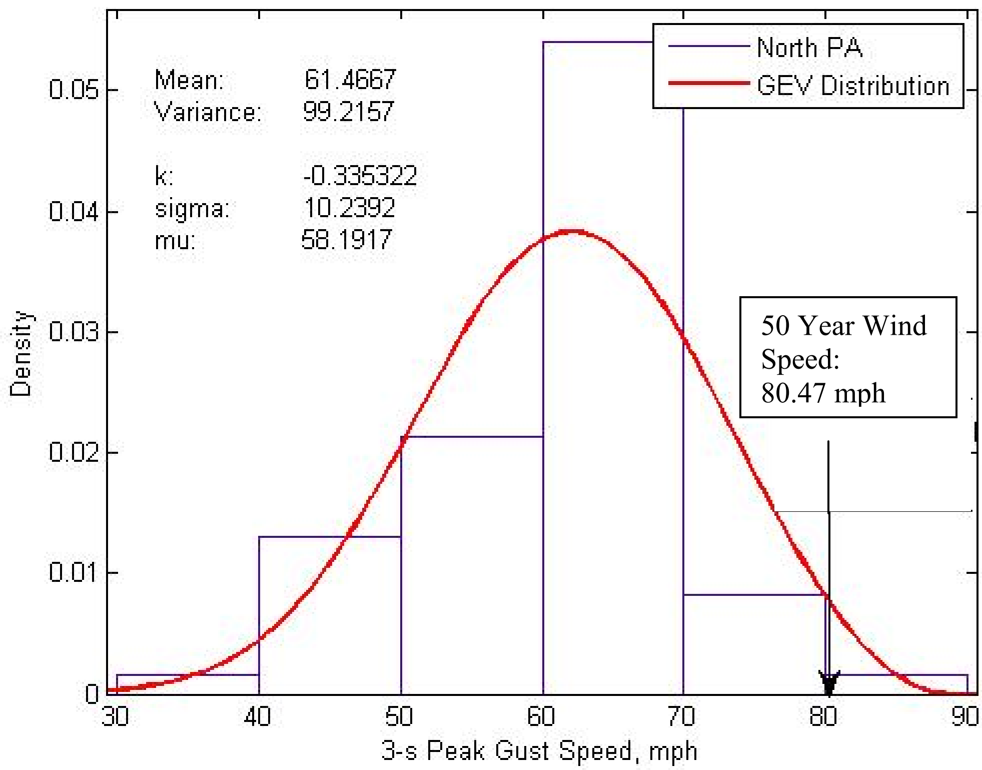


Figure A- 1: The 3-s Peak Gust Speed wind distribution for the North half of Pennsylvania

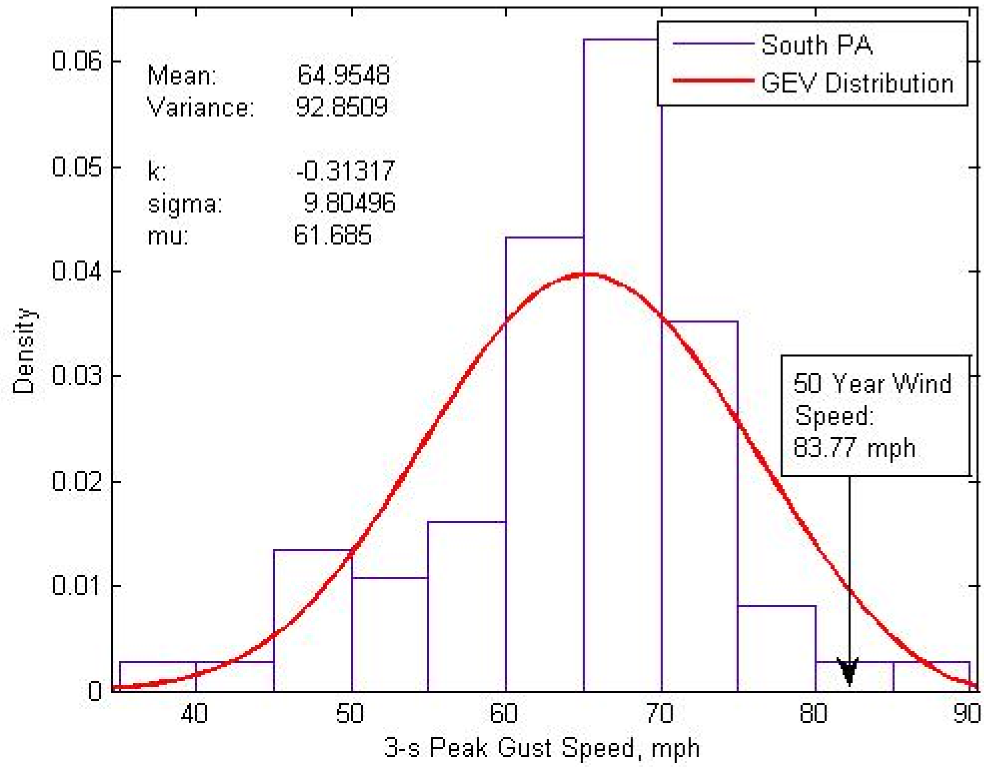


Figure A- 2: The 3-s Peak Gust Speed wind distribution for the South half of Pennsylvania

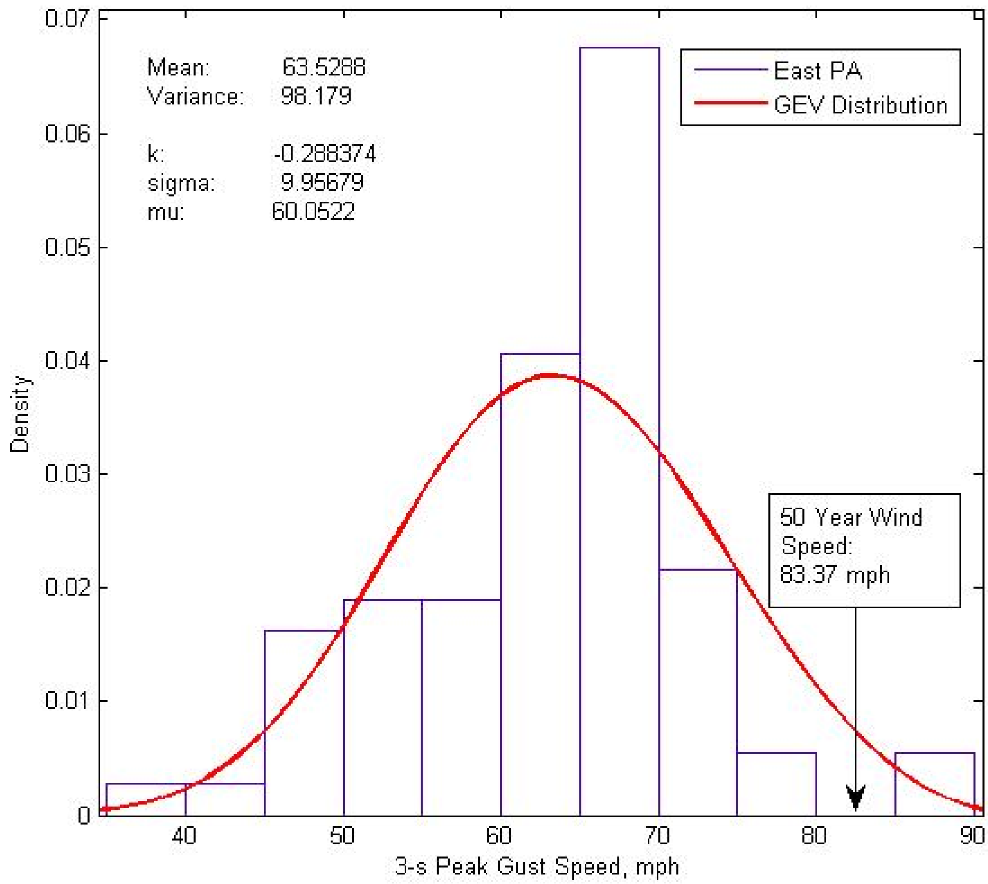


Figure A- 3: The 3-s Peak Gust Speed wind distribution for the East half of Pennsylvania

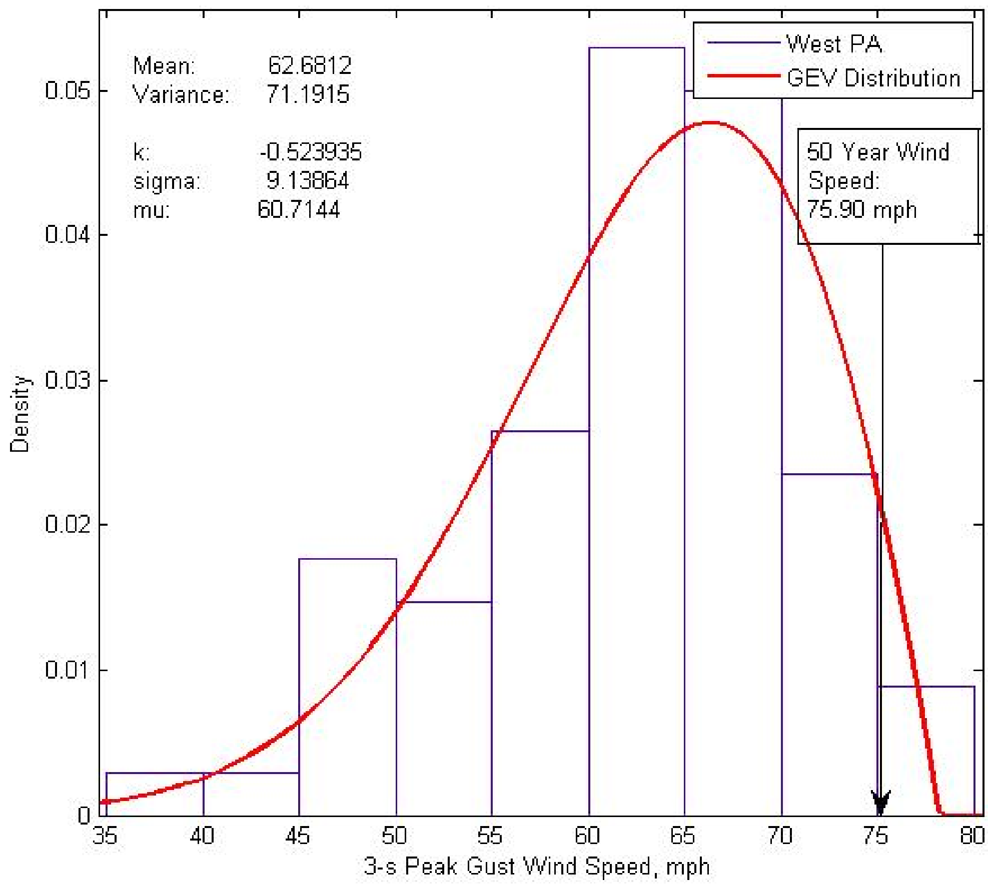


Figure A- 4: The 3-s Peak Gust Speed wind distribution for the West half of Pennsylvania

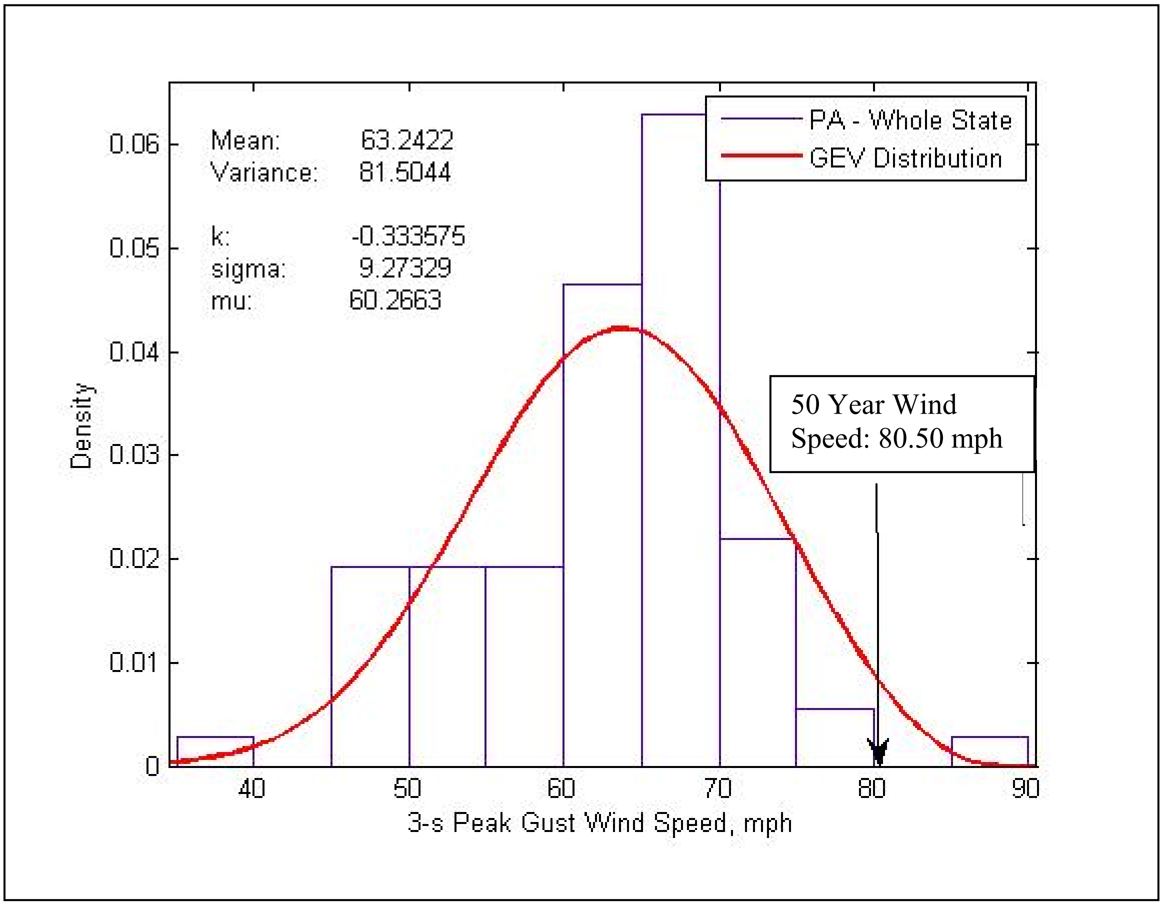


Figure A- 5: The 3-s Peak Gust Speed wind distribution for the whole state of Pennsylvania

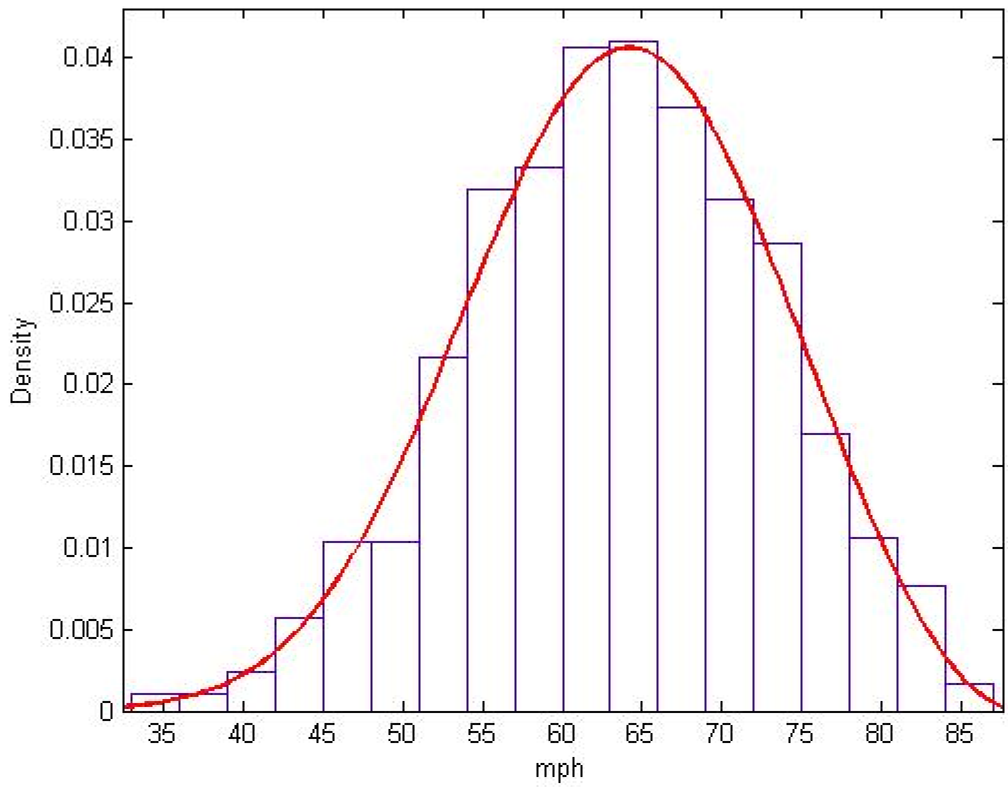


Figure A- 6: The extreme value distribution used in the Monte Carlo simulation for draw random wind speeds in Pennsylvania

Appendix B Calculations for shear forces in tested houses using ASCE 7 Analytical Method

B-1: Wind Calculations

Wind Speed	80	mph	
Exposure	B		
ps = λ kzt I ps30			
λ =	1.0	For 0 to 30 feet	ASCE 7 Fig. 6-2
kzt =	1.0		
I =	1.0		ASCE 7 Table 6-1
kz =	0.70		ASCE 7 Table 6-3
kd =	0.85		ASCE 7 Table 6-4
qh = 0.00256*kz*kzt*kd*V^2*I (lb/ft^2)			ASCE 7, 6.5.10
qh =	9.76	psf	

p = qh[(GCpf)-(Gcpi)] (lb/ft^2)
Zones

Basic Wind Speed (mph)	Roof Angle (degrees)	Load Case	Zones									
			Horizontal Pressures				Vertical Pressures				Overhangs	
			A	B	C	D	E	F	G	H	Ech	Gch
80	0 to 5	1	10.1	-5.3	6.7	-3.1	-12.2	-6.9	-8.5	-5.4		
	10	1	11.4	-4.7	7.6	-2.8	-12.2	-7.4	-8.5	-5.7		
	15	1	12.7	-4.2	8.5	-2.4	-12.2	-8.0	-8.5	-6.1		
	20	1	14.0	-3.7	9.4	-2.0	-12.2	-8.5	-8.5	-6.4		
	25	1	12.7	2.0	9.2	2.1	-5.7	-7.7	-4.1	-6.2		
		2										
	30 to 45	1	11.4	7.8	9.1	6.2	0.9	-6.9	0.3	-6.0		
		2										

Roof Slope	25.6			
First Floor Ht	10		5	ft
Second Floor Ht	9		9	ft
Roof Height	6		6	ft
hmean =	22	ft		
0.4hmean =	8.8	ft		
L =	35	ft		
b =	25	ft		
0.1b =	2.5	ft		
a =	2.5	ft		
2a =	5	ft		

Zone		Asume zero for negative values in calculations
A	12.6	12.6
B	2.7	2.7
C	9.2	9.2
D	2.6	2.6

Load to Roof Diaphragm - Transverse Loading

wend =	A*wall height + B*roof height =	73.0	lb/ft
wint =	C*wall height + D*roof height =	57.0	lb/ft

w = 2074.6 lb

Ra = 1,071.7 lb
Rb = 1,002.9 lb

10psf minimum wind loads

wend = 105 lb/ft
wint = 105 lb/ft

w = 3,675.0 lb

Ra 1837.5 lb
Rb 1837.5 lb

Ra	**1837.5**	**lb**
Rb	**1837.5**	**lb**

Load to Second Floor Diaphragm - Transverse Loading

wend =	A*wall height =	119.5	lb/ft
wint =	C*wall height =	87.4	lb/ft

w =	3220.0	lb
Ra =	**1678.6**	**lb**
Rb =	**1541.4**	**lb**

10psf minimum wind loads

wend =	95	lb/ft
wint =	95	lb/ft
w =	3325	lb
Ra	**1662.5**	**lb**
Rb	**1662.5**	**lb**

Ra	**1678.6**	**lb**
Rb	**1662.5**	**lb**

First Floor Shear Force
3516.1 lb
Second Floor Shear Force
1837.5 lb

B-2: Seismic force calculations

$Ta = C_t h^x$

S_S =	0.169	g	CD: Seismic Design Parameters Version 3.10 State College Zip Code	
S_1 =	0.059	g	16801	
Site Class =	D			
F_a =	1.6		ASCE 7 - Table 11.4-1	
$S_{MS} = S_S \times F_a$ =	0.270	g		ASCE 7 Eq. 11.4-1
$S_{DS} = 2/3 \times S_{MS}$ =	0.180	g		ASCE 7 Eq. 11.4-3
F_v =	2.4		ASCE 7 - Table 11.4-2	
$S_{M1} = S_1 X F_v$ =	0.1416	g		ASCE 7 Eq. 11.4-2
$S_{D1} = 2/3 \times S_{M1}$ =	0.094	g		ASCE 7 Eq. 11.4-4
$T_S = S_{D1}/S_{DS}$ =	0.52	sec		ASCE 7 Section 11.4.5

S_{DS} will define the seismic design forces because S_{D1} is smaller.

Seismic Base Shear

$V = C_s W$ = ASCE 7 Eq. 12.8-1

$C_s = S_{DS} / (R/I)$ = 0.026 g ASCE 7 Eq. 12.8-2 (Cannot be less than 0.01g)

R =	7	ASCE 7 Table 12.2-1
I =	1	ASCE 7 Section 11.5.1 (Occupancy Category II)

Tributary Roof Dead Loads

Weight of 1-ft-wide strip tributary to roof:

Roof dead load D =	(15psf)(25ft) =	375	lb/ft
<u>Wall dead load D (2 longitudinal walls) =</u>	<u>2(12psf)(9/2) =</u>	<u>108</u>	
Dead load D of 1-ft strip at roof =		483	lb/ft

Wr = ∑W1 = 16.905 k

Dead load D of 2 end walls = 2(12psf)(25)(9/2) = 2.7 k

Total dead load D tributary to roof = 19.6 k

Tributary Second-Floor Dead Loads
Weight of 1-ft wide strip tributary to second floor:

Second floor dead load D =	(6psf)(25ft) =	150	lb/ft
Partition Load =	(12psf)(25ft) =	300	
Wall dead load D (2 longitudinal walls) =	2(12psf)(9/2 + 10/2) =	228	
Dead load D of 1-ft strip at second floor =		678	lb/ft

W2 = ∑W1 = 23.73 k

Dead load D of 2 end walls = 2(12psf)(25)(9/2 + 10/2) = 5.7 k

Total dead load D tributary to second floor = 29.43 k

Fx Story (Shearwall) Force Table - R = 7

1	2	3	4	5	6	7	
Story	Height hx	Weight wx	wxhx	Story force Fx = .0019hxwx	Fx Coef.	Story shear Vx	
R	19	19.6	372.4	0.71	0.0360	0.71	k
2	10	29.43	294.3	0.56	0.0189	1.26	k
1	0						
Sum		49.03	666.7				

V = 1.26 k

V / ∑wxhx = 0.0019

Uniform Forces to Diaphragms Using Fx Story Coefficients

wur = .0360(483) = 17.37999 lb/ft

Rur = wurL/2 = 304.1 lb

Load from Second Floor Diaphragm

wu2 = .0189(678) = 12.8404 lb/ft

Ru2 = wu2L/2 = 224.7 lb

The wind load diaphragm reactions are

Rr	1837.5	lb
R2	1678.6	lb

The seismic Fpx diaphragm reactions are

Rur	304.1	lb
Ru2	224.7	lb

Wall shear Vu2r = 1/2(story shear Vu2r) = 353 lb

Appendix C Results for IRC house simulations

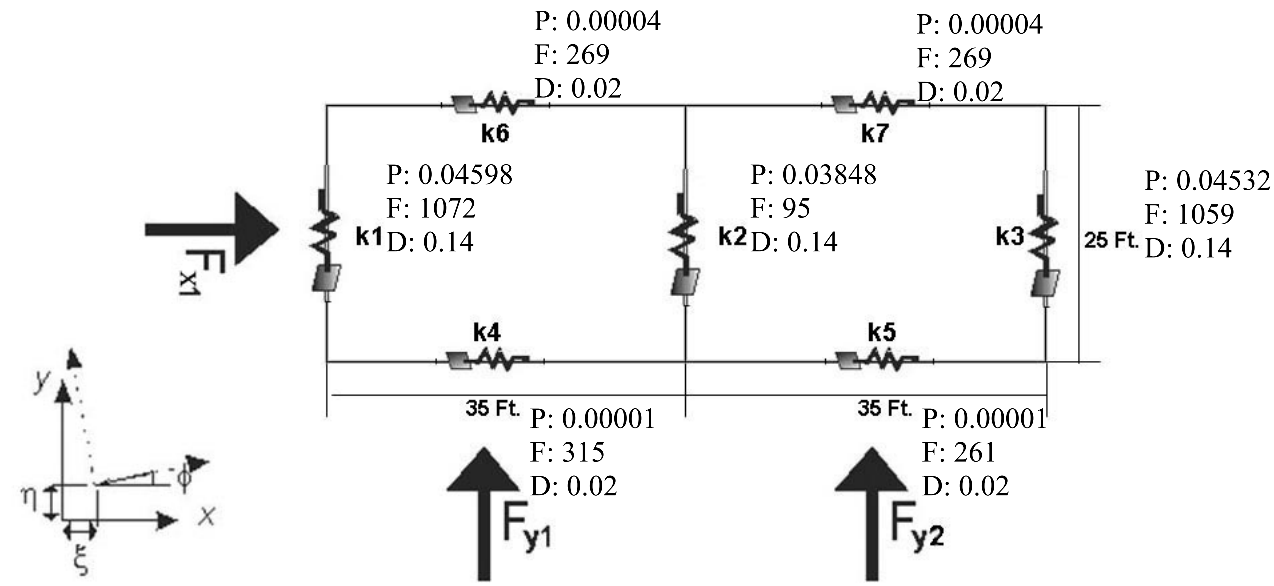


Figure C- 1: Results for plate model – one story IRC house with fixed wall openings and actual ASCE 7 pressures used; P: probability of failure, F: force [lb], D: deflection [in]

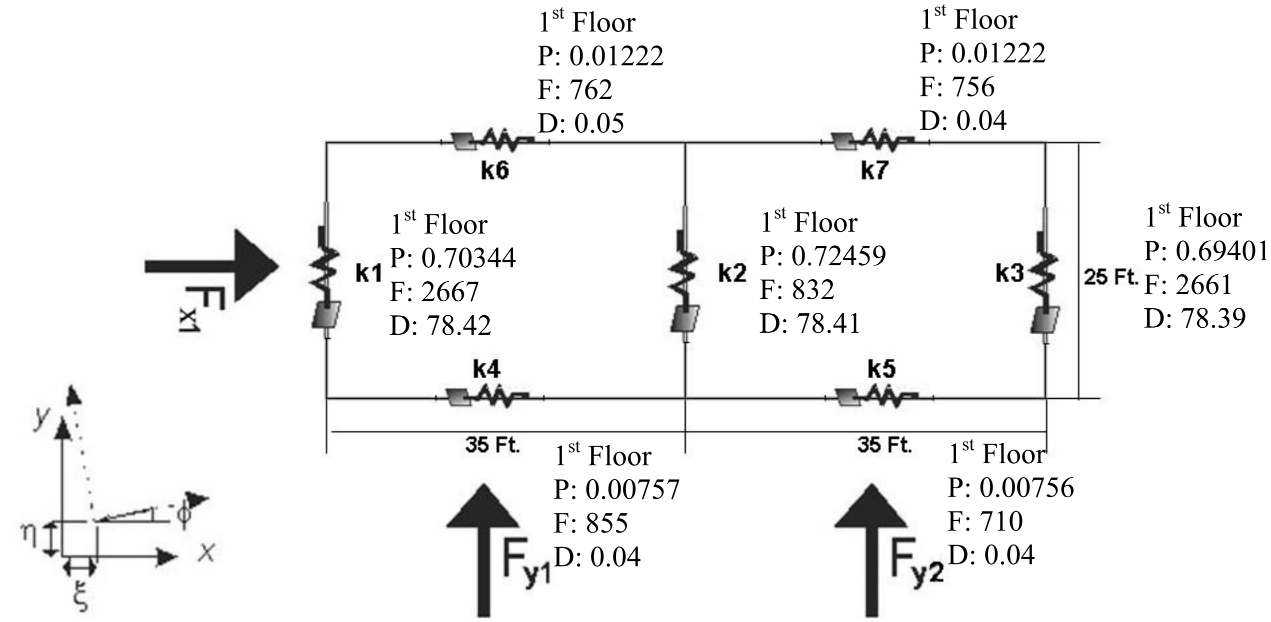


Figure C- 2: Results for plate model – two story IRC house with fixed wall openings and actual ASCE 7 pressures used; P: probability of failure, F: force [lb], D: deflection [in]

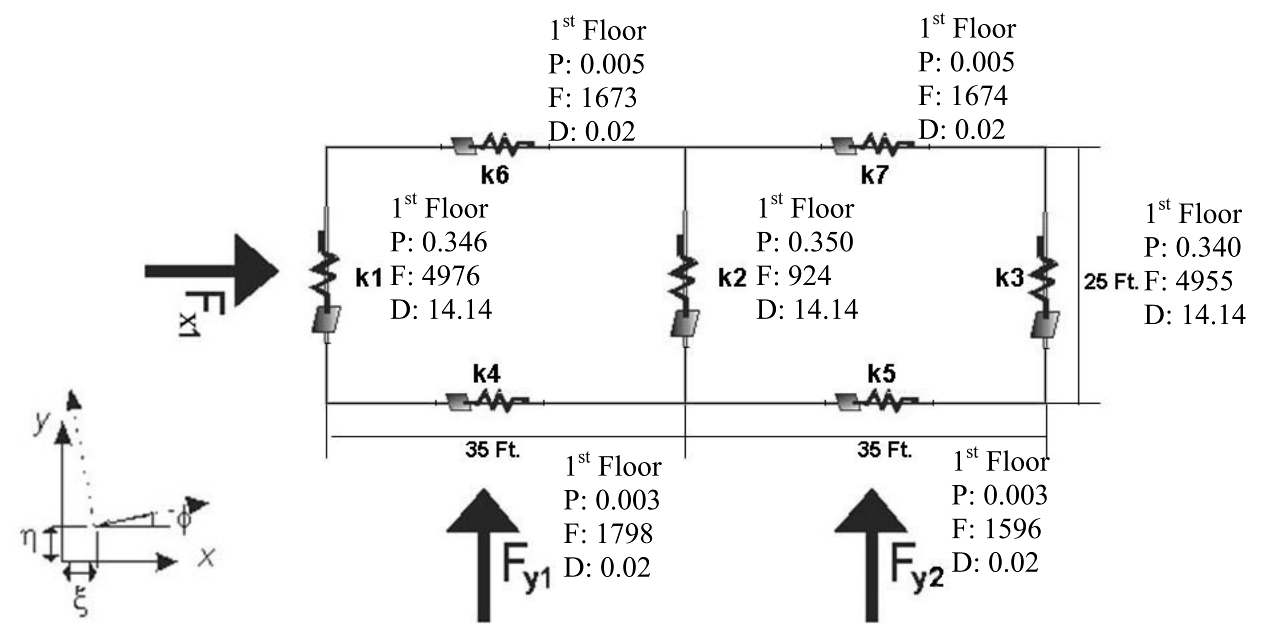


Figure C- 3: Results for plate model – two story IRC house with fixed wall openings and minimum 10psf pressure used; P: probability of failure, F: force [lb], D: deflection [in]

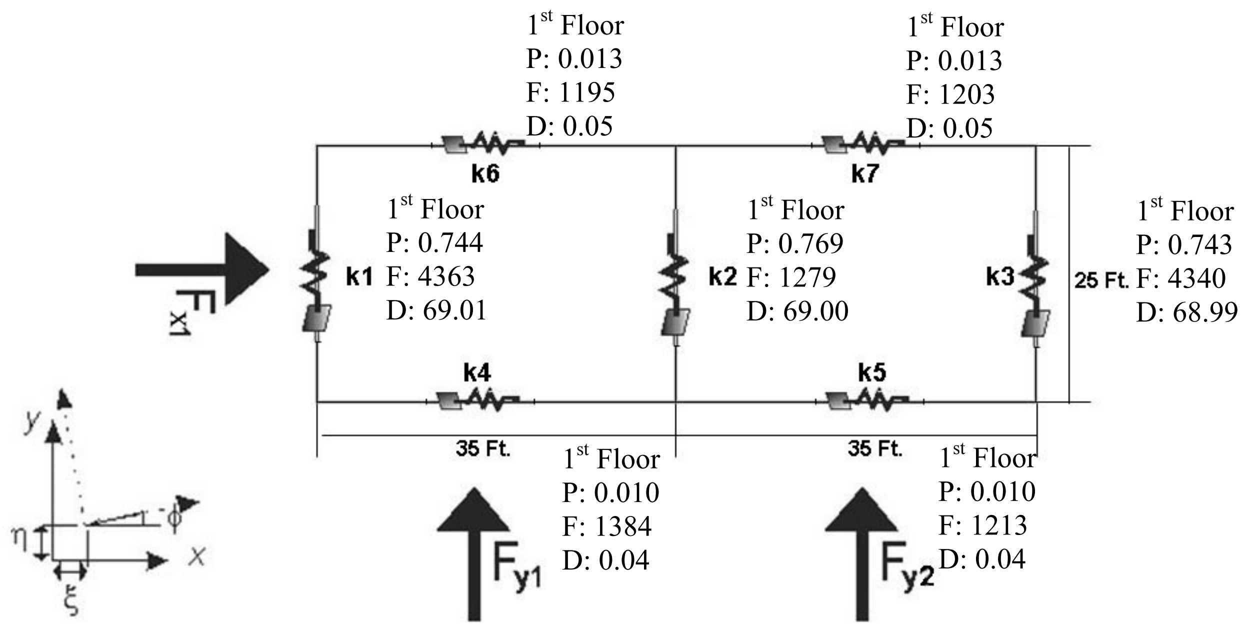


Figure C- 4: Results for plate model – three story IRC house with fixed wall openings and actual ASCE 7 pressures used; P: probability of failure, F: force [lb], D: deflection [in]

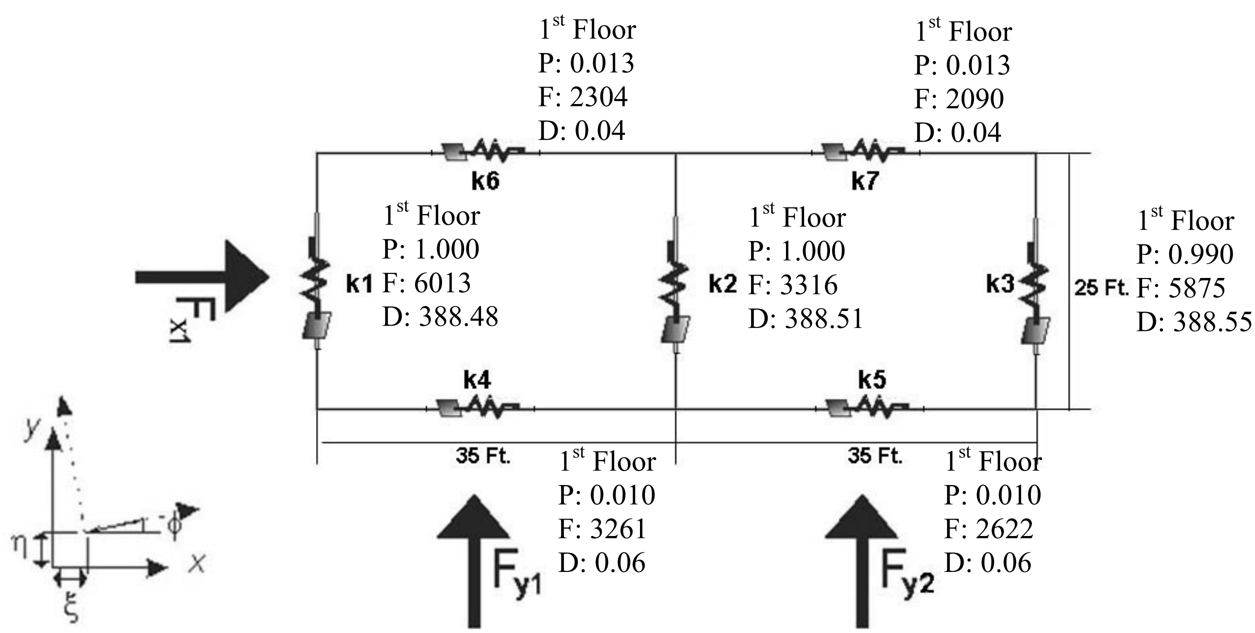


Figure C- 5: Results for plate model – three story IRC house with fixed wall openings and minimum 10psf pressures used; P: probability of failure, F: force [lb], D: deflection [in]

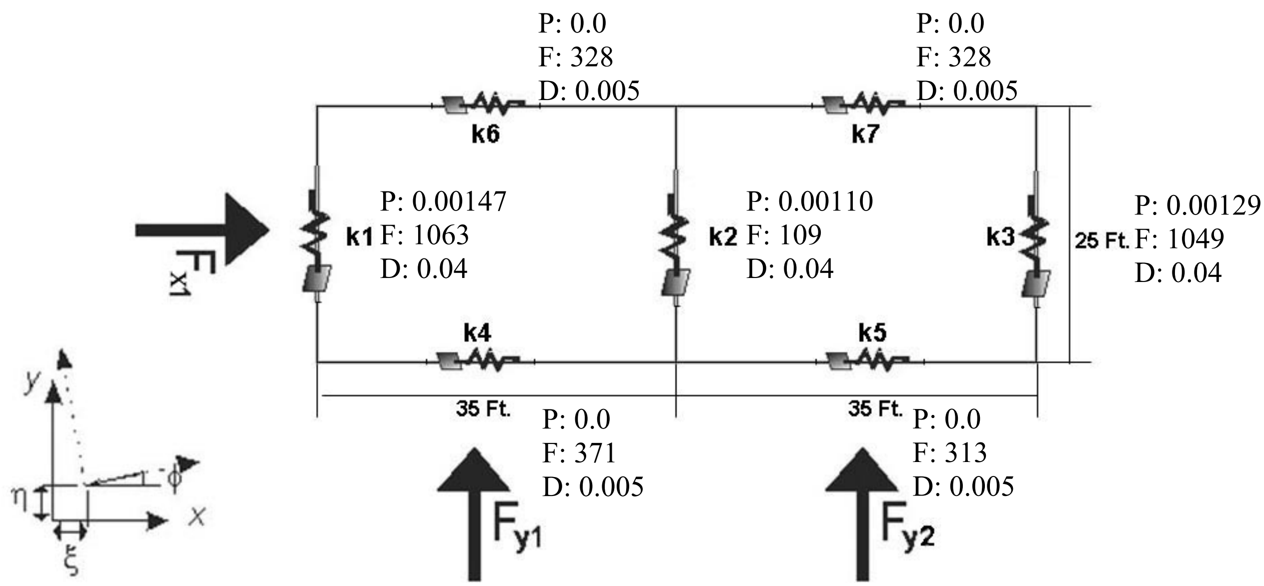


Figure C- 6: Results for plate model – one story IRC house with random wall openings and actual ASCE 7 pressured used; P: probability of failure, F: force [lb], D: deflection [in]

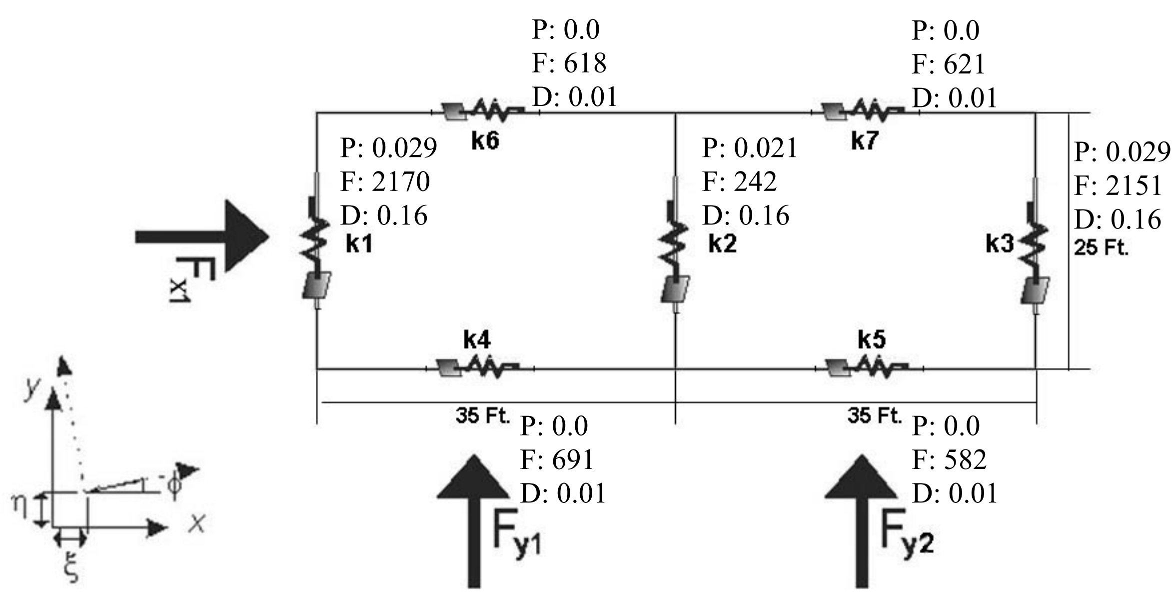


Figure C- 7: Results for plate model – one story IRC house with random wall openings and minimum 10psf pressure used; P: probability of failure, F: force [lb], D: deflection [in]

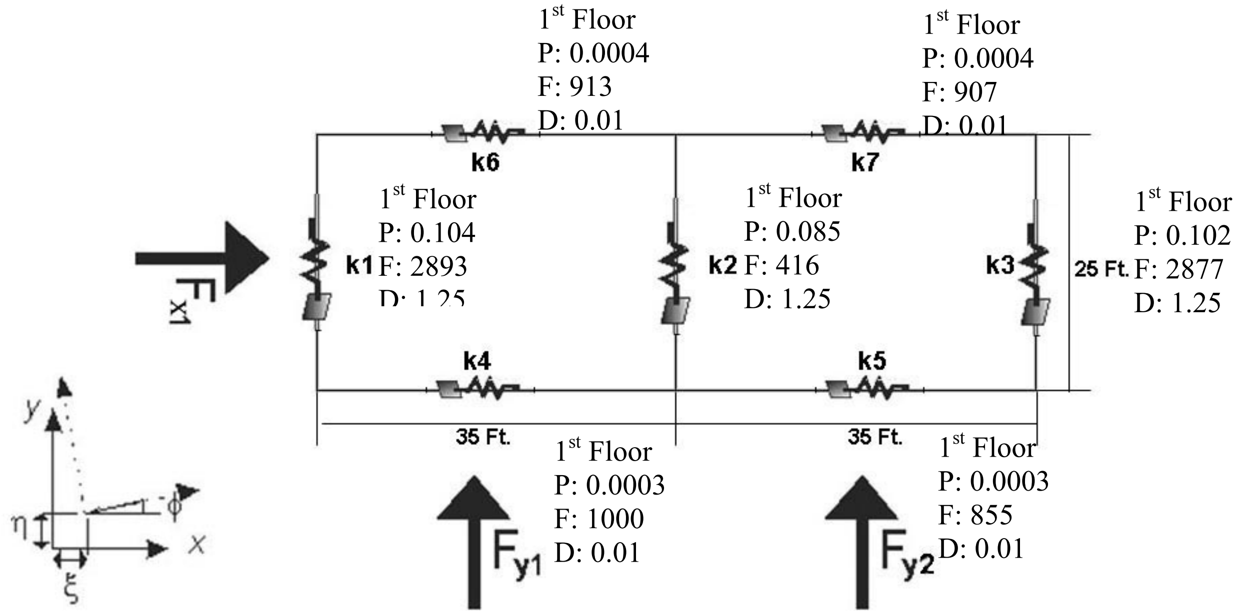


Figure C- 8: Results for plate model – two story IRC house with random wall openings and actual ASCE 7 pressures used; P: probability of failure, F: force [lb], D: deflection [in]

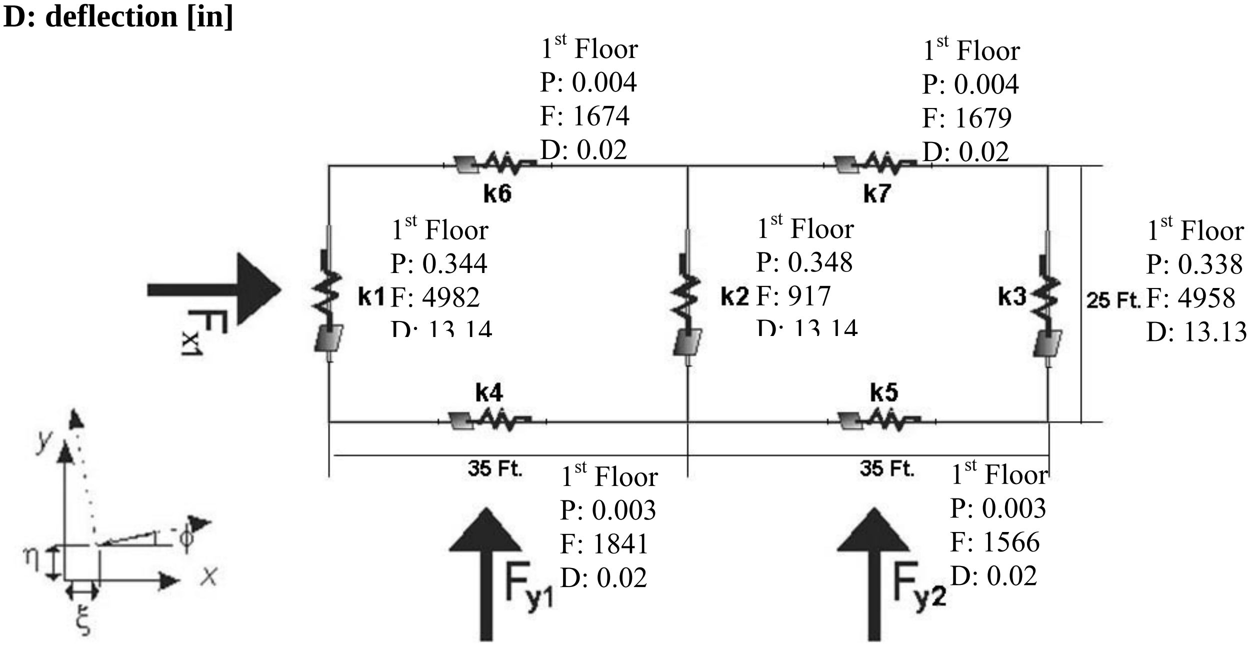


Figure C- 9: Results for plate model – two story IRC house with random wall openings and minimum 10psf pressures used; P: probability of failure, F: force [lb], D: deflection [in]

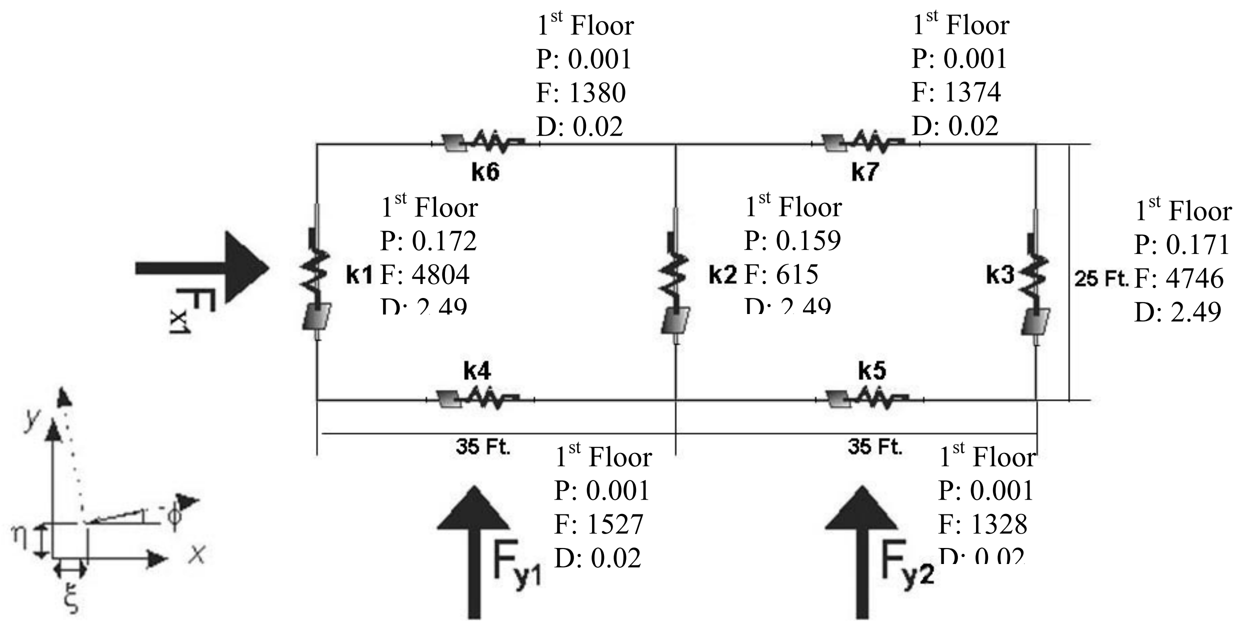


Figure C- 10: Results for plate model – three story IRC house with random wall openings and actual ASCE 7 pressures used; P: probability of failure, F: force [lb], D: deflection [in]

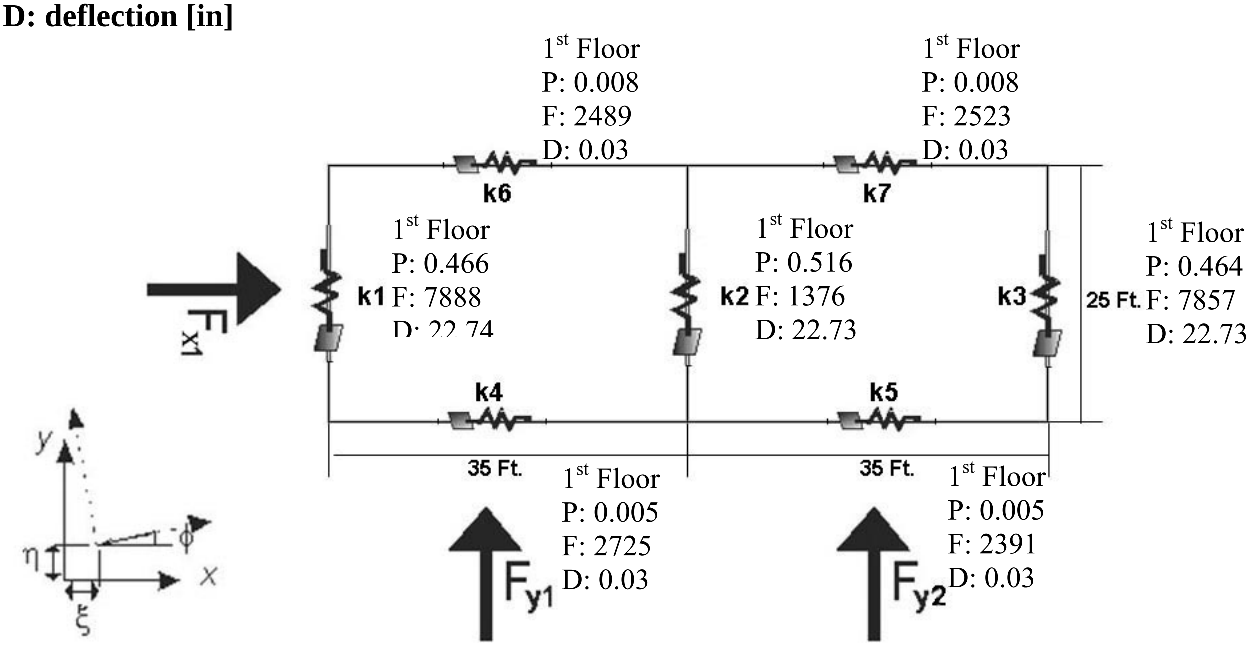


Figure C- 11: Results for plate model – three story IRC house with random wall openings and minimum 10 psf pressures used; P: probability of failure, F: force [lb], D: deflection [in]

Appendix D Matlab Programs

D-1: Main Program

```
function nonlinx2 = nonlinx2(X,Y)


nsamples = X; %number of times program will run
nlevs = Y; %number of levels of house

nnod = csvread('input.csv',0,0,[0,0,0,0]); % input number of nodes
nodes = csvread('input.csv', 1, 0, [1,0,11,1]); % input node values

% Plot the geometry of the house
X = [nodes(1,1);nodes(2,1)];
Y = [nodes(1,2);nodes(2,2)];
plot(X,Y)
hold on
X2 = [nodes(2,1);nodes(3,1)];
Y2 = [nodes(2,2);nodes(3,2)];
plot(X2,Y2)
X3 = [nodes(1,1);nodes(4,1)];
Y3 = [nodes(1,2);nodes(4,2)];
plot(X3,Y3)
X4 = [nodes(4,1);nodes(5,1)];
Y4 = [nodes(4,2);nodes(5,2)];
plot(X4,Y4)
X5 = [nodes(5,1);nodes(6,1)];
Y5 = [nodes(5,2);nodes(6,2)];
plot(X5,Y5)
X6 = [nodes(2,1);nodes(5,1)];
Y6 = [nodes(2,2);nodes(5,2)];
plot(X6,Y6)
X7 = [nodes(3,1);nodes(6,1)];
Y7 = [nodes(3,2);nodes(6,2)];
plot(X7,Y7)
hold off


NX = csvread('input.csv', 12, 0, [12,0,12,0]); % # of walls in the X
direction
WALLSX = csvread('input.csv', 13, 0, [13,0,19,5]); % [X coordinate, Y
coordinate, wall stiffness, wall length]
NY = csvread('input.csv', 20, 0, [20,0,20,0]); % # of walls in the Y
direction
WALLSY = csvread('input.csv', 21, 0, [21,0,27,5]); % [X coordinate, Y
coordinate, wall stiffness, wall length]
```

```
nwalltypes = csvread('input.csv', 28, 0, [28,0,28,0]); % # of wall
types based on openings in walls
walltypes = csvread('input.csv', 29, 0, [29,0,29+(nwalltypes-1),0]); %
wall types [percentage of actual braced wall]
walltypes2 = [0.25;0.6;0.8;1.0];
walltypes3 = [0.35;0.6;0.8;1.0];


wallmu = csvread('input.csv', 34, 0, [34,0,34,0]); % input variation in
stiffness due to construction practice parameters
wallsigma = csvread('input.csv', 34, 1, [34,1,34,1]); % input variation
in stiffness due to construction practice parameters

p1 = csvread('input.csv', 45, 0, [45,0,45,0]); % parameters for Extreme
Value distribution to find wind speed
p2 = csvread('input.csv', 45, 1, [45,1,45,1]); % parameters for Extreme
Value distribution
p3 = csvread('input.csv', 45, 2, [45,2,45,2]); % parameters for Extreme
Value distribution

rhomu = csvread('input.csv', 46, 0, [46,0,46,0]); % input distribution
parameters for varying resulting point of wind
rhosigma = csvread('input.csv', 46, 1, [46,1,46,1]); % input
distribution parameters for varying resulting point of wind

height = csvread('input.csv',54,0,[54,0,54,0]);
Min = csvread('input.csv',60,0,[60,0,60,0]);

SigmaDep = [8556.8 -511.3;-511.3 32.0];
mu = [1007.1 39.6];
ZDep = mvnrnd(mu, SigmaDep, 100000);



for t = 1:nsamples

    stopBar= progressbar(t/nsamples,0);

if (stopBar) break; end


    randn('state', sum(100*clock)); % Randomize seed used in random
functions with clock

NFX = csvread('input.csv', 35, 0, [35,0,35,0]); % # of forces in the X
direction
FX = 0; % Set forces in X direction = to 0
FX = csvread('input.csv', 36, 0, [36,0,37,2]); %Width of X forces for
1st and 2nd floors
RX = 0; % Set point where forces are acting = to 0
RX = csvread('input.csv', 38, 0, [38,0,39,2]); % Point where X
direction forces are acting for 1st and 2nd floors
```

```
XX = csvread('input.csv',52,0,[52,0,52,0]);

NFY = csvread('input.csv', 40, 0, [40,0,40,0]); % # of forces in the Y
direction
FY = 0; % Set forces in Y direction = to 0
FY = csvread('input.csv', 41, 0, [41,0,42,2]); %Width of Y forces for
1st and 2nd floors
RY = 0; % Set point where forces are acting = to 0
RY = csvread('input.csv', 43, 0, [43,0,44,2]); % Point where Y
direction forces are acting for 1st and 2nd floors
YY = csvread('input.csv',53,0,[53,0,53,0]);


w1 = 0; %Set multiplier = to 0
w2 = 0; %Set multiplier = to 0
for i = 1:NX
    for s = 1:nlevs
        w2 = 0;
    w1(i,s) = random('logn',wallmu,wallsigma); %pick random multiplier
for variation in construction practice
    if(WALLSX(i,6) > 0)
        if (nlevs == 1)
        w2(i,1) = .16;
        elseif (nlevs == 2)
            if (WALLSX(i,5) == 1)
                w2(i,1) = .16;
            elseif (WALLSX(i,5) == 2)
                if (s == 1)
                w2(i,1) = .25;
                elseif (s == 2)
                    w2(i,1) = .16;
                end
            end
        elseif (nlevs == 3)
            if (WALLSX(i,5) == 1)
                if (s == 1)
                    w2(i,1) = .25;
                elseif (s == 2)
                    w2(i,1) = .16;
                elseif (s == 3)
                    w2(i,1) = .16;
                end
            elseif (WALLSX(i,5) == 2)
                if (s == 1)
                    w2(i,1) = .35;
                elseif (s == 2)
                    w2(i,1) = .25;
                elseif (s == 3)
                    w2(i,1) = .16;
                end
            end
        end
    else
    if (nlevs == 1)
```

```
    w2 = randsample(walltypes,NX,true); %Randomize wall openings from
uniform distribution
        elseif (nlevs == 2)
            if (WALLSX(i,5) == 1)
                w2 = randsample(walltypes,NX,true);
            elseif (WALLSX(i,5) == 2)
                if (s == 1)
                    w2 = randsample(walltypes2,NX,true);
                elseif (s == 2)
                        w2 = randsample(walltypes,NX,true);
                end
            end
        elseif (nlevs == 3)
            if (WALLSX(i,5) == 1)
                if (s == 1)
                    w2 = randsample(walltypes2,NX,true);
                elseif (s == 2)
                    w2 = randsample(walltypes,NX,true);
                elseif (s == 3)
                    w2 = randsample(walltypes,NX,true);
                end
            elseif (WALLSX(i,5) == 2)
                if (s == 1)
                    w2 = randsample(walltypes3,NX,true);
                elseif (s == 2)
                    w2 = randsample(walltypes2,NX,true);
                elseif (s == 3)
                    w2 = randsample(walltypes,NX,true);
                end
            end
        end
    end
    KX(i,s) = WALLSX(i,3)*w1(i,s); % Multiply variables with actual
wall stiffness in X direction
    KX(i,s) = KX(i,s).*w2(i,1);
    if (s == 1)
    openingsx1(t,i) = w2(i,1); % Create vector to save % of braced wall
for each wall in x direction on first floor
    elseif (s == 2)
        openingsx2(t,i) = w2(i,1); % Create vector to save % of braced
wall for each wall in x direction on second floor
        else
            openingsx3(t,i) = w2(i,1);
    end
    end
end

for j = 1:NX
      Lengthx1(t,j) = WALLSX(j,4)*openingsx1(t,j); % Compute and save
actual length of wall minus openings
      if(nlevs > 1)
      Lengthx2(t,j) = WALLSX(j,4)*openingsx2(t,j); % Compute and save
actual length of wall minus openings
      end
      if(nlevs > 2)
```

```
            Lengthx3(t,j) = WALLSX(j,4)*openingsx3(t,j);
        end
end


for i = 1:NX
    KXall1(t,i) = KX(i,1); % Create vector of wall stiffness
multipliers for all x direction walls on first floor
    if(nlevs > 1)
    KXall2(t,i) = KX(i,2); % Create vector of wall stiffness
multipliers for all x direction walls on second floor
    end
    if(nlevs > 2)
        KXall3(t,i) = KX(i,3);
    end
end

w1 = 0; % Set multiplier = to 0
w2 = 0; % Set multiplier = to 0

for i = 1:NY
    for s = 1:nlevs
        w2 = 0;
    w1(i,s) = random('logn',wallmu,wallsigma); %pick random multiplier
for variation in construction practice
    if(WALLSY(i,6) > 0)
        if (nlevs == 1)
        w2(i,1) = .16;
        elseif (nlevs == 2)
            if (WALLSY(i,5) == 1)
                w2(i,1) = .16;
            elseif (WALLSY(i,5) == 2)
                if (s == 1)
                w2(i,1) = .25;
                elseif (s == 2)
                    w2(i,1) = .16;
                end
            end
        elseif (nlevs == 3)
            if (WALLSY(i,5) == 1)
                if (s == 1)
                    w2(i,1) = .25;
                elseif (s == 2)
                    w2(i,1) = .16;
                elseif (s == 3)
                    w2(i,1) = .16;
                end
            elseif (WALLSY(i,5) == 2)
                if (s == 1)
                    w2(i,1) = .35;
                elseif (s == 2)
                    w2(i,1) = .25;
                elseif (s == 3)
                    w2(i,1) = .16;
```

```
                end
            end
        end
    else
        if (nlevs == 1)
    w2 = randsample(walltypes,NY,true); %Randomize wall openings from
uniform distribution
        elseif (nlevs == 2)

            if (WALLSY(i,5) == 1)
                w2 = randsample(walltypes,NY,true);
            elseif (WALLSY(i,5) == 2)
                if (s == 1)
                    w2 = randsample(walltypes2,NY,true);
                elseif (s == 2)
                        w2 = randsample(walltypes,NY,true);
                end
            end
        elseif (nlevs == 3)

            if (WALLSY(i,5) == 1)
                if (s == 1)
                    w2 = randsample(walltypes2,NY,true);
                elseif (s == 2)
                    w2 = randsample(walltypes,NY,true);
                elseif (s == 3)
                    w2 = randsample(walltypes,NY,true);
                end
            elseif (WALLSY(i,5) == 2)
                if (s == 1)
                    w2 = randsample(walltypes3,NY,true);
                elseif (s == 2)
                    w2 = randsample(walltypes2,NY,true);
                elseif (s == 3)
                    w2 = randsample(walltypes,NY,true);
                end
            end
        end
    end
    KY(i,s) = WALLSY(i,3)*w1(i,s); % Multiply variables with actual
wall stiffness in Y direction
    KY(i,s) = KY(i,s).*w2(i,1);
    if (s == 1)
    openingsy1(t,i) = w2(i,1); % Create vector to save % of braced wall
for each wall in y direction on first floor
    elseif (s == 2)
        openingsy2(t,i) = w2(i,1); % Create vector to save % of braced
wall for each wall in y direction on second floor
    else
        openingsy3(t,i) = w2(i,1);
    end
    end
end
```

```
for j = 1:NY
      Lengthy1(t,j) = WALLSY(j,4)*openingsy1(t,j); % Compute and save
actual length of wall minus openings
      if (nlevs > 1)
      Lengthy2(t,j) = WALLSY(j,4)*openingsy2(t,j); % Compute and save
actual length of wall minus openings
      end
      if (nlevs > 2)
          Lengthy3(t,j) = WALLSY(j,4)*openingsy3(t,j);
      end
end


for i = 1:NY
    KYall1(t,i) = KY(i,1); % Create vector of wall stiffness
multipliers for all y direction walls on first floor
    if (nlevs > 1)
    KYall2(t,i) = KY(i,2); % Create vector of wall stiffness
multipliers for all y direction walls on second floor
    end
    if (nlevs > 2)
        KYall3(t,i) = KY(i,3);
    end
end

if (XX > 0)
w1 = 0; % Set multiplier = to 0
w2 = 0; % Set multiplier = to 0
for i = 1:NFX
    w1(i,1) = random('gev',p1,p2,p3); % Randomize wind velocity using
generalized extreme value distribution
    qhx(i,1) = (2.4243*10^-
3)*0.75*0.85*1.0*1.0*0.5*(1.46666667*abs(w1(i,1)))^2; % Formula used
for wall pressure
end
for i = 1:NFX
windx(t,i) = abs(w1(i,1)); % Create vector of all generated wind speeds
in x direction on first floor
qhx(t,i) = qhx(i,1); % Create vector of all resultant forces calculated
in x direction on first floor
end
else
    for i = 1:NFX
    qhx(i,1) = 0;
    end
end

Cp = [0.40, -0.69,  -0.37,  -0.29,  -0.45,  -0.45,  0.61,   -1.07,  -
0.53,  -0.43;
    0.44,   -0.69,  -0.41,  -0.34,  -0.45,  -0.45,  0.67,   -1.07,  -
0.58,  -0.50;
    0.49,   -0.69,  -0.44,  -0.38,  -0.45,  -0.45,  0.74,   -1.07,  -
0.64,  -0.57;
```

```
    0.53,   -0.69,  -0.48,  -0.43,  -0.45,  -0.45,  0.80,   -1.07,  -
0.69,  -0.64;
    0.55,   -0.24,  -0.46,  -0.40,  -0.45,  -0.45,  0.75,   -0.40,  -
0.61,  -0.56;
    0.56,   0.21,   -0.43,  -0.37,  -0.45,  -0.45,  0.69,   0.27,   -
0.53,  -0.48];

roofslopes = [1;2;3;4;5;6];
roofangles = [5;10;15;20;25;30];

slope = randsample(roofslopes,1,true);



    for k = 1:10
Cpx1(1,k) = max(qhx(1,1)*(Cp(slope,k)-.18),qhx(1,1)*(Cp(slope,k)+.18));
if (NFX == 2)
    Cpx2(1,k) = max(qhx(2,1)*(Cp(slope,k)-
.18),qhx(2,1)*(Cp(slope,k)+.18));
end
    end

    GCpfx1(1,1) = Cpx1(1,7) - Cpx1(1,10);
    GCpfx1(1,2) = Cpx1(1,8) - Cpx1(1,9);
    GCpfx1(1,3) = Cpx1(1,1) - Cpx1(1,4);
    GCpfx1(1,4) = Cpx1(1,2) - Cpx1(1,3);
    GCpfx1(1,5) = Cpx1(1,8);
    GCpfx1(1,6) = Cpx1(1,9);
    GCpfx1(1,7) = Cpx1(1,2);
    GCpfx1(1,8) = Cpx1(1,3);
    if (NFX == 2)
    GCpfx2(1,1) = Cpx2(1,7) - Cpx2(1,10);
    GCpfx2(1,2) = Cpx2(1,8) - Cpx2(1,9);
    GCpfx2(1,3) = Cpx2(1,1) - Cpx2(1,4);
    GCpfx2(1,4) = Cpx2(1,2) - Cpx2(1,3);
    GCpfx2(1,5) = Cpx2(1,8);
    GCpfx2(1,6) = Cpx2(1,9);
    GCpfx2(1,7) = Cpx2(1,2);
    GCpfx2(1,8) = Cpx2(1,3);
    end

    roofheight = tand(roofangles(slope,1))*.5*WALLSY(1,4);
    a =
max(min(.1*min(WALLSX(1,4),WALLSY(1,4)),.4*roofheight),.04*min(WALLSX(1
,4),WALLSY(1,4)));
    a = max(a,3);

if (YY > 0)
w1 = 0; % Set multiplier = to 0
w2 = 0; % Set multiplier = to 0
for i = 1:NFY
    w1(i,1) = random('gev',p1,p2,p3); % Randomize wind velocity using
generalized extreme value distribution
```

```
    qhy(i,1) = (2.4243*10^-
3)*0.75*0.85*1.0*1.0*0.5*(1.46666667*abs(w1(i,1)))^2; % Formula used
for wall pressure
end
for i = 1:NFY
windy(t,i) = abs(w1(i,1)); % Create vector of all generated wind speeds
in x direction on first floor
qhyall(t,i) = qhy(i,1); % Create vector of all resultant forces
calculated in x direction on first floor
end
else
    for i = 1:NFY
    qhy(i,1) = 0;
    end
end

for k = 1:10
Cpy1(1,k) = max(qhy(1,1)*(Cp(slope,k)-.18),qhy(1,1)*(Cp(slope,k)+.18));
if (NFY == 2)
    Cpy2(1,k) = max(qhy(2,1)*(Cp(slope,k)-
.18),qhy(2,1)*(Cp(slope,k)+.18));
end
    end

    GCpf1(1,1) = Cpy1(1,7) - Cpy1(1,10) + GCpfx1(1,1);
    GCpf1(1,2) = Cpy1(1,8) - Cpy1(1,9)+ GCpfx1(1,2);
    GCpf1(1,3) = Cpy1(1,1) - Cpy1(1,4)+ GCpfx1(1,3);
    GCpf1(1,4) = Cpy1(1,2) - Cpy1(1,3)+ GCpfx1(1,4);
    GCpf1(1,5) = Cpy1(1,8)+ GCpfx1(1,5);
    GCpf1(1,6) = Cpy1(1,9)+ GCpfx1(1,6);
    GCpf1(1,7) = Cpy1(1,2)+ GCpfx1(1,7);
    GCpf1(1,8) = Cpy1(1,3)+ GCpfx1(1,8);
    if (NFY == 2)
    GCpf2(1,1) = Cpy2(1,7) - Cpy2(1,10);
    GCpf2(1,2) = Cpy2(1,8) - Cpy2(1,9);
    GCpf2(1,3) = Cpy2(1,1) - Cpy2(1,4);
    GCpf2(1,4) = Cpy2(1,2) - Cpy2(1,3);
    GCpf2(1,5) = Cpy2(1,8);
    GCpf2(1,6) = Cpy2(1,9);
    GCpf2(1,7) = Cpy2(1,2);
    GCpf2(1,8) = Cpy2(1,3);
    end
    if (NFX == 2)
    GCpf2(1,1) = GCpf2(1,1) + GCpfx2(1,1);
    GCpf2(1,2) = GCpf2(1,2) + GCpfx2(1,2);
    GCpf2(1,3) = GCpf2(1,3) + GCpfx2(1,3);
    GCpf2(1,4) = GCpf2(1,4) + GCpfx2(1,4);
    GCpf2(1,5) = GCpf2(1,5) + GCpfx2(1,5);
    GCpf2(1,6) = GCpf2(1,6) + GCpfx2(1,6);
    GCpf2(1,7) = GCpf2(1,7) + GCpfx2(1,7);
    GCpf2(1,8) = GCpf2(1,8) + GCpfx2(1,8);
    end
```

```
    for k = 1:8
        if (GCpf1(1,k) < 0)
            GCpf1(1,k) = 0;
        end
        if (NFY == 2)
            if (GCpf2(1,k) < 0)
                GCpf2(1,k) = 0;
            end
        end
    end
    for k = 1:8
GCpf1all(t,k) = GCpf1(1,k);
if (NFY == 2)
GCpf2all(t,k) = GCpf2(1,k);
end
    end
    for i = 1:NFX
        if (nlevs == 1)
        FXp(i,1) = (FX(i,1)-2*a)*GCpf1(1,3)*.5*height+(FX(i,1)-
2*a)*GCpf1(1,3)*roofheight*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,
1)*roofheight*.5;
        elseif (nlevs == 2)
            FXp(i,1) = (FX(i,1)-2*a)*GCpf1(1,3)*.5*height+(FX(i,1)-
2*a)*GCpf1(1,3)*height*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,1)*h
eight*.5;
            FXp(i,2) = (FX(i,1)-2*a)*GCpf1(1,3)*.5*height+(FX(i,1)-
2*a)*GCpf1(1,3)*roofheight*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,
1)*roofheight*.5;
        else
            FXp(i,1) = (FX(i,1)-2*a)*GCpf1(1,3)*.5*height+(FX(i,1)-
2*a)*GCpf1(1,3)*height*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,1)*h
eight*.5;
            FXp(i,2) = (FX(i,1)-2*a)*GCpf1(1,3)*.5*height+(FX(i,1)-
2*a)*GCpf1(1,3)*height*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,1)*h
eight*.5;
            FXp(i,3) = (FX(i,1)-2*a)*GCpf1(1,3)*.5*height+(FX(i,1)-
2*a)*GCpf1(1,3)*roofheight*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,
1)*roofheight*.5;
        end
    end

    for i = 1:NFX
        if (nlevs == 1)
        FXm(i,1) = (FX(i,1)-2*a)*10*.5*height+(FX(i,1)-
2*a)*10*roofheight*.5+(2*a)*10*.5*height+(2*a)*10*roofheight*.5;
        elseif (nlevs == 2)
            FXm(i,1) = (FX(i,1)-2*a)*10*.5*height+(FX(i,1)-
2*a)*10*height*.5+(2*a)*10*.5*height+(2*a)*10*height*.5;
            FXm(i,2) = (FX(i,1)-2*a)*10*.5*height+(FX(i,1)-
2*a)*10*roofheight*.5+(2*a)*10*.5*height+(2*a)*10*roofheight*.5;
        else
            FXm(i,1) = (FX(i,1)-2*a)*10*.5*height+(FX(i,1)-
2*a)*10*height*.5+(2*a)*10*.5*height+(2*a)*10*height*.5;
            FXm(i,2) = (FX(i,1)-2*a)*10*.5*height+(FX(i,1)-
2*a)*10*height*.5+(2*a)*10*.5*height+(2*a)*10*height*.5;
```

```
            FXm(i,3) = (FX(i,1)-2*a)*10*.5*height+(FX(i,1)-
2*a)*10*roofheight*.5+(2*a)*10*.5*height+(2*a)*10*roofheight*.5;
        end
    end

    for i = 1:NFX
        for j = 1:nlevs
        FXmsum = sum(FXm(i,j));
        FXpsum = sum(FXp(i,j));
        end
    end
   if (Min == 1)
    for i = 1:NFX
        for j = 1:nlevs
    if (FXmsum < FXpsum)
        FX(i,j) = FXp(i,j);
    else
        FX(i,j) = FXm(i,j);
    end
        end
    end
   elseif (Min == 0)
       for i = 1:NFX
           for j = 1:nlevs
               FX(i,j) = FXp(i,j);
           end
       end
   end


for i = 1:NFX
    Forcexall1(t,i) = FX(i,1); % Create vector of wall stiffness
multipliers for all y direction walls on first floor
    if (nlevs > 1)
    Forcexall2(t,i) = FX(i,2); % Create vector of wall stiffness
multipliers for all y direction walls on second floor
    end
    if (nlevs > 2)
    Forcexall3(t,i) = FX(i,3);
    end
end


for i = 1:NFX
    for s = 1:nlevs
    w2(i,s) = random('norm',rhomu,rhosigma); % Randomize multiplier for
point where forces are acting
    RX(i,s) = w2(i,s)*RX(i,s); % Multiply point where forces are acting
by its multiplier
    end
end
```

```
    for i = 1:NFY
        if (nlevs == 1)
        FYp(i,1) = (FY(i,1)-2*a)*GCpf1(1,3)*.5*height+(FY(i,1)-
2*a)*GCpf1(1,4)*roofheight*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,
2)*roofheight*.5;
        elseif (nlevs == 2)
            FYp(i,1) = (FY(i,1)-2*a)*GCpf1(1,3)*.5*height+(FY(i,1)-
2*a)*GCpf1(1,3)*height*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,1)*h
eight*.5;
            FYp(i,2) = (FY(i,1)-2*a)*GCpf1(1,3)*.5*height+(FY(i,1)-
2*a)*GCpf1(1,4)*roofheight*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,
2)*roofheight*.5;
        else
            FYp(i,1) = (FY(i,1)-2*a)*GCpf1(1,3)*.5*height+(FY(i,1)-
2*a)*GCpf1(1,3)*height*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,1)*h
eight*.5;
            FYp(i,2) = (FY(i,1)-2*a)*GCpf1(1,3)*.5*height+(FY(i,1)-
2*a)*GCpf1(1,3)*height*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,1)*h
eight*.5;
            FYp(i,3) = (FY(i,1)-2*a)*GCpf1(1,3)*.5*height+(FY(i,1)-
2*a)*GCpf1(1,4)*roofheight*.5+(2*a)*GCpf1(1,1)*.5*height+(2*a)*GCpf1(1,
2)*roofheight*.5;
        end
    end

   for i = 1:NFY
        if (nlevs == 1)
        FYm(i,1) = (FY(i,1)-2*a)*10*.5*height+(FY(i,1)-
2*a)*10*roofheight*.5+(2*a)*10*.5*height+(2*a)*10*roofheight*.5;
        elseif (nlevs == 2)
            FYm(i,1) = (FY(i,1)-2*a)*10*.5*height+(FY(i,1)-
2*a)*10*height*.5+(2*a)*10*.5*height+(2*a)*10*height*.5;
            FYm(i,2) = (FY(i,1)-2*a)*10*.5*height+(FY(i,1)-
2*a)*10*roofheight*.5+(2*a)*10*.5*height+(2*a)*10*roofheight*.5;
        else
            FYm(i,1) = (FY(i,1)-2*a)*10*.5*height+(FY(i,1)-
2*a)*10*height*.5+(2*a)*10*.5*height+(2*a)*10*height*.5;
            FYm(i,2) = (FY(i,1)-2*a)*10*.5*height+(FY(i,1)-
2*a)*10*height*.5+(2*a)*10*.5*height+(2*a)*10*height*.5;
            FYm(i,3) = (FY(i,1)-2*a)*10*.5*height+(FY(i,1)-
2*a)*10*roofheight*.5+(2*a)*10*.5*height+(2*a)*10*roofheight*.5;
        end
   end

   for i = 1:NFY
        for j = 1:nlevs
        FYmsum = sum(FYm(i,j));
        FYpsum = sum(FYp(i,j));
        end
   end

    if (Min == 1)
    for i = 1:NFY
        for j = 1:nlevs
```

```
    if (FYmsum < FYpsum)
        FY(i,j) = FYp(i,j);
    else
        FY(i,j) = FYm(i,j);
    end
        end
    end
    elseif (Min == 0)
        for i = 1:NFY
            for j = 1:nlevs
                FY(i,j) = FYp(i,j);
            end
        end
    end


for i = 1:NFY
    Forceyall1(t,i) = FY(i,1); % Create vector of wall stiffness
multipliers for all y direction walls on first floor
    if (nlevs > 1)
    Forceyall2(t,i) = FY(i,2); % Create vector of wall stiffness
multipliers for all y direction walls on second floor
    end
    if (nlevs > 2)
    Forceyall3(t,i) = FY(i,3);
    end
end

for i = 1:NFY
    for s = 1:nlevs
    w2(i,s) = random('norm',rhomu,rhosigma); % Randomize multiplier for
point where forces are acting
    RY(i,s) = w2(i,s)*RY(i,s); % Multiply point where forces are acting
by its multiplier
    end
end

for i = 1:NFY
    RY1(t,i) = RY(i,1); % Create vector of all randomized points where
forces are acting on first floor
    if (nlevs > 1)
    RY2(t,i) = RY(i,2); % Create vector of all randomized points where
forces are acting on second floor
    end
    if (nlevs > 2)
        RY3(t,i) = RY(i,3);
    end
end
```

```
NP2 = csvread('input.csv', 55, 0, [55,0,55,0]); % # of points on
stiffness plot
XP2 = 0; % Set X coordinates = to 0
XP2 = csvread('input.csv', 56, 0, [56,0,58,0]); % X coordinates
YP2 = 0; % Set Y coordinates = to 0
YP2 = csvread('input.csv', 56, 1, [56,1,58,1]); % Y coordinates

ppmu2 = csvread('input.csv', 59, 0, [59,0,59,0]); % input parameters to
randomize stiffness plot
ppsigma2 = csvread('input.csv', 59, 1, [59,1,59,1]); % input parameters
to randomize stiffness plot

w1 = 0; % Set multiplier = to 0
w2 = 0; % Set multiplier = to 0;


for i = 1:(NP2-1)
    w1(i,1) = random('logn',ppmu2,ppsigma2);
    XP2(i,1) = XP2(i,1)*w1(i,1);
    w2(i,1) = random('logn',ppmu2,ppsigma2);
    YP2(i,1) = YP2(i,1)*w2(i,1);
end

YP2(3,1) = 1.05*YP2(2,1);

for i = 1:NP2
    YP2all(t,i) = YP2(i,1); %Create vector of all Y axis points
generated on each run
    XP2all(t,i) = XP2(i,1); %Create vector of all X axis points
generated on each run
end

%Run nonlinear solver
[x,fval,fxall,dxall,fyall,dyall] =
nonlinear(NX,NY,WALLSX,WALLSY,KX,KY,nlevs,FX,FY,RX,RY,ZDep(t,1),ZDep(t,
2),XP2,YP2,NFX,NFY);



[x,fval,fxallb,dxallb,fyallb,dyallb] =
nonlinearbeam(NX,NY,WALLSX,WALLSY,KX,KY,nlevs,FX,FY,RX,RY,ZDep(t,1),ZDe
p(t,2),XP2,YP2,NFX,NFY,XX,YY);



%Create vectors for all forces and displacements calculated in walls on
each run
for i = 1:NY
    Fyall1(t,i) = abs(fyall(i,1));
    end
    for i = 1:NX
    Fxall1(t,i) = abs(fxall(i,1));
```

```
    end
for i = 1:NY
    dyall1(t,i) = dyall(i,1);
    end
    for i = 1:NX
    dxall1(t,i) = dxall(i,1);
    end
if (nlevs > 1)
    for i = 1:NY
    Fyall2(t,i) = abs(fyall(i,2));
    end
    for i = 1:NX
    Fxall2(t,i) = abs(fxall(i,2));
    end
for i = 1:NY
    dyall2(t,i) = dyall(i,2);
    end
    for i = 1:NX
    dxall2(t,i) = dxall(i,2);
    end
end
if (nlevs > 2)
 for i = 1:NY
    Fyall3(t,i) = abs(fyall(i,3));
    end
    for i = 1:NX
    Fxall3(t,i) = abs(fxall(i,3));
    end
for i = 1:NY
    dyall3(t,i) = dyall(i,3);
    end
    for i = 1:NX
    dxall3(t,i) = dxall(i,3);
    end
end

for i = 1:NY
    Fyall1b(t,i) = abs(fyallb(i,1));
    end
    for i = 1:NX
    Fxall1b(t,i) = abs(fxallb(i,1));
    end
for i = 1:NY
    dyall1b(t,i) = dyallb(i,1);
    end
    for i = 1:NX
    dxall1b(t,i) = dxallb(i,1);
    end
if (nlevs > 1)
    for i = 1:NY
    Fyall2b(t,i) = abs(fyallb(i,2));
    end
    for i = 1:NX
    Fxall2b(t,i) = abs(fxallb(i,2));
    end
```

```
for i = 1:NY
    dyall2b(t,i) = dyallb(i,2);
    end
    for i = 1:NX
    dxall2b(t,i) = dxallb(i,2);
    end
end
if (nlevs > 2)
    for i = 1:NY
    Fyall3b(t,i) = abs(fyallb(i,3));
    end
    for i = 1:NX
    Fxall3b(t,i) = abs(fxallb(i,3));
    end
for i = 1:NY
    dyall3b(t,i) = dyallb(i,3);
    end
    for i = 1:NX
    dxall3b(t,i) = dxallb(i,3);
    end
end


end %End main loop


%Calculate the force per length each wall is under
for t = 1:nsamples
    for i = 1:NY
        Stiffy1(t,i) = Fyall1(t,i)/Lengthy1(t,i);
        if (nlevs > 1)
        Stiffy2(t,i) = Fyall2(t,i)/Lengthy2(t,i);
        end
        if (nlevs > 2)
        Stiffy3(t,i) = Fyall3(t,i)/Lengthy3(t,i);
        end
    end
    for i = 1:NX
        Stiffx1(t,i) = Fxall1(t,i)/Lengthx1(t,i);
        if (nlevs > 1)
        Stiffx2(t,i) = Fxall2(t,i)/Lengthx2(t,i);
        end
        if (nlevs > 2)
        Stiffx3(t,i) = Fxall3(t,i)/Lengthx3(t,i);
        end
    end
end




% Calculate the average of all forces in each wall
Fyavg1 = sum(Fyall1,1)/nsamples;
Fxavg1 = sum(Fxall1,1)/nsamples;
```

```
dyavg1 = sum(dyall1,1)/nsamples;
dxavg1 = sum(dxall1,1)/nsamples;
if (nlevs > 1)
Fyavg2 = sum(Fyall2,1)/nsamples;
Fxavg2 = sum(Fxall2,1)/nsamples;
dyavg2 = sum(dyall2,1)/nsamples;
dxavg2 = sum(dxall2,1)/nsamples;
end
if (nlevs > 2)
Fyavg3 = sum(Fyall3,1)/nsamples;
Fxavg3 = sum(Fxall3,1)/nsamples;
dyavg3 = sum(dyall3,1)/nsamples;
dxavg3 = sum(dxall3,1)/nsamples;
end
Fyavg1b = sum(Fyall1b,1)/nsamples;
Fxavg1b = sum(Fxall1b,1)/nsamples;
dyavg1b = sum(dyall1b,1)/nsamples;
dxavg1b = sum(dxall1b,1)/nsamples;
if (nlevs >1)
Fyavg2b = sum(Fyall2b,1)/nsamples;
Fxavg2b = sum(Fxall2b,1)/nsamples;
dyavg2b = sum(dyall2b,1)/nsamples;
dxavg2b = sum(dxall2b,1)/nsamples;
end
if (nlevs >2)
Fyavg3b = sum(Fyall3b,1)/nsamples;
Fxavg3b = sum(Fxall3b,1)/nsamples;
dyavg3b = sum(dyall3b,1)/nsamples;
dxavg3b = sum(dxall3b,1)/nsamples;
end
% Calculate the min and max of all forces in each wall
for i = 1:NX
FxMax1(1,i) = max(Fxall1(:,i));
FxMin1(1,i) = min(Fxall1(:,i));
end
for i = 1:NX
FxMax1b(1,i) = max(Fxall1b(:,i));
FxMin1b(1,i) = min(Fxall1b(:,i));
end
% Calculate the min and max of all forces in each wall
for i = 1:NY
FyMin1(1,i) = min(Fyall1(:,i));
FyMax1(1,i) = max(Fyall1(:,i));
end
for i = 1:NY
FyMin1b(1,i) = min(Fyall1b(:,i));
FyMax1b(1,i) = max(Fyall1b(:,i));
end
% Calculate the probability of failure in the y direction walls on the
% first floor
for t = 1:nsamples
for i = 1:NY
    if(WALLSY(i,5) == 1)
if(abs(dyall1(t,i)) > height/400)
    py1(t,i) = 1;
```

```
else
    py1(t,i) = 0;
end
    elseif (WALLSY(i,5) == 2)
       if(abs(dyall1(t,i)) > height/400)
    py1(t,i) = 1;
else
    py1(t,i) = 0;
       end
    end
end
end
for t = 1:nsamples
for i = 1:NY
    if(WALLSY(i,5) == 1)
if(abs(dyall1b(t,i)) > height/400)
    py1b(t,i) = 1;
else
    py1b(t,i) = 0;
end
elseif (WALLSY(i,5) == 2)
    if(abs(dyall1b(t,i)) > height/400)
    py1b(t,i) = 1;
else
    py1b(t,i) = 0;
    end
    end
end
end
% Calculate the probability of failure in the x direction walls on the
% first floor
 for t = 1:nsamples
for i = 1:NX
    if(WALLSX(i,5) == 1)
if(abs(dxall1(t,i)) > height/400)
    px1(t,i) = 1;
else
    px1(t,i) = 0;
end
    elseif(WALLSX(i,5) == 2)
      if(abs(dxall1(t,i)) > height/400)
    px1(t,i) = 1;
else
    px1(t,i) = 0;
      end
    end
end
 end
 for t = 1:nsamples
for i = 1:NX
    if(WALLSX(i,5) == 1)
if(abs(dxall1b(t,i)) > height/400)
    px1b(t,i) = 1;
else
    px1b(t,i) = 0;
```

```
end
    elseif(WALLSX(i,5) == 2)
      if(abs(dxall1b(t,i)) > height/400)
    px1b(t,i) = 1;
else
    px1b(t,i) = 0;
      end
    end
end
 end

fy1 = zeros(NY,1);
fx1 = zeros(NX,1);
fy1b = zeros(NY,1);
fx1b = zeros(NX,1);
for i = 1:NY
    for j = 1:nsamples
fy1(i,1) = fy1(i,1) + py1(j,i);
    end
    pfy1(i,1) = fy1(i,1)/nsamples;
end
for i = 1:NX
    for j = 1:nsamples
fx1(i,1) = fx1(i,1) + px1(j,i);
    end
    pfx1(i,1) = fx1(i,1)/nsamples;
end
for i = 1:NY
    for j = 1:nsamples
fy1b(i,1) = fy1b(i,1) + py1b(j,i);
    end
    pfy1b(i,1) = fy1b(i,1)/nsamples;
end
for i = 1:NX
    for j = 1:nsamples
fx1b(i,1) = fx1b(i,1) + px1b(j,i);
    end
    pfx1b(i,1) = fx1b(i,1)/nsamples;
end

% Calculate the min and max force in each wall
if (nlevs > 1)
for i = 1:NX
FxMax2(1,i) = max(Fxall2(:,i));
FxMin2(1,i) = min(Fxall2(:,i));
end

for i = 1:NY
FyMin2(1,i) = min(Fyall2(:,i));
FyMax2(1,i) = max(Fyall2(:,i));
end
for i = 1:NX
FxMax2b(1,i) = max(Fxall2b(:,i));
FxMin2b(1,i) = min(Fxall2b(:,i));
```

```
end

for i = 1:NY
FyMin2b(1,i) = min(Fyall2b(:,i));
FyMax2b(1,i) = max(Fyall2b(:,i));
end
% Calculate the probability of failure in each wall
for t = 1:nsamples
for i = 1:NY
    if(WALLSY(i,5) == 1)
if(abs(dyall2(t,i)) > height/400)
    py2(t,i) = 1;
else
    py2(t,i) = 0;
end
    elseif(WALLSY(i,5) == 2)
      if(abs(dyall2(t,i)) > height/400)
    py2(t,i) = 1;
else
    py2(t,i) = 0;
      end
    end
end
end
for t = 1:nsamples
for i = 1:NY
    if(WALLSY(i,5) == 1)
if(abs(dyall2b(t,i)) > height/400)
    py2b(t,i) = 1;
else
    py2b(t,i) = 0;
end
    elseif(WALLSY(i,5) == 2)
        if(abs(dyall2b(t,i)) > height/400)
    py2b(t,i) = 1;
else
    py2b(t,i) = 0;
        end
    end
end
end

 for t = 1:nsamples
for i = 1:NX
    if(WALLSX(i,5) == 1)
if(abs(dxall2(t,i)) > height/400)
    px2(t,i) = 1;
else
    px2(t,i) = 0;
end
    elseif(WALLSX(i,5) == 2)
       if(abs(dxall2(t,i)) > height/400)
    px2(t,i) = 1;
else
```

```
    px2(t,i) = 0;
       end
    end
end
 end
 for t = 1:nsamples
for i = 1:NX
    if(WALLSX(i,5) == 1)
if(abs(dxall2b(t,i)) > height/400)
    px2b(t,i) = 1;
else
    px2b(t,i) = 0;
end
    elseif(WALLSX(i,5) == 2)
       if(abs(dxall2b(t,i)) > height/400)
    px2b(t,i) = 1;
else
    px2b(t,i) = 0;
       end
    end
end
 end

fy2 = zeros(NY,1);
fx2 = zeros(NX,1);
fy2b = zeros(NY,1);
fx2b = zeros(NX,1);
for i = 1:NY
    for j = 1:nsamples
fy2(i,1) = fy2(i,1) + py2(j,i);
    end
    pfy2(i,1) = fy2(i,1)/nsamples;
end
for i = 1:NX
    for j = 1:nsamples
fx2(i,1) = fx2(i,1) + px2(j,i);
    end
    pfx2(i,1) = fx2(i,1)/nsamples;
end

for i = 1:NY
    for j = 1:nsamples
fy2b(i,1) = fy2b(i,1) + py2b(j,i);
    end
    pfy2b(i,1) = fy2b(i,1)/nsamples;
end
for i = 1:NX
    for j = 1:nsamples
fx2b(i,1) = fx2b(i,1) + px2b(j,i);
    end
    pfx2b(i,1) = fx2b(i,1)/nsamples;
end
end
```

```
if (nlevs > 2)
for i = 1:NX
FxMax3(1,i) = max(Fxall3(:,i));
FxMin3(1,i) = min(Fxall3(:,i));
end

for i = 1:NY
FyMin3(1,i) = min(Fyall3(:,i));
FyMax3(1,i) = max(Fyall3(:,i));
end
for i = 1:NX
FxMax3b(1,i) = max(Fxall3b(:,i));
FxMin3b(1,i) = min(Fxall3b(:,i));
end

for i = 1:NY
FyMin3b(1,i) = min(Fyall3b(:,i));
FyMax3b(1,i) = max(Fyall3b(:,i));
end
% Calculate the probability of failure in each wall
for t = 1:nsamples
for i = 1:NY
    if(WALLSY(i,5) == 1)
if(abs(dyall3(t,i)) > height/400)
    py3(t,i) = 1;
else
    py3(t,i) = 0;
end
    elseif(WALLSY(i,5) == 2)
      if(abs(dyall3(t,i)) > height/400)
    py3(t,i) = 1;
else
    py3(t,i) = 0;
      end
    end
end
end
for t = 1:nsamples
for i = 1:NY
    if(WALLSY(i,5) == 1)
if(abs(dyall3b(t,i)) > height/400)
    py3b(t,i) = 1;
else
    py3b(t,i) = 0;
end
    elseif(WALLSY(i,5) == 2)
      if(abs(dyall3b(t,i)) > height/400)
    py3b(t,i) = 1;
else
    py3b(t,i) = 0;
      end
    end
end
end
```

```
 for t = 1:nsamples
for i = 1:NX
    if(WALLSX(i,5) == 1)
if(abs(dxall3(t,i)) > height/400)
    px3(t,i) = 1;
else
    px3(t,i) = 0;
end
    elseif(WALLSX(i,5) ==2)
      if(abs(dxall3(t,i)) > height/400)
    px3(t,i) = 1;
else
    px3(t,i) = 0;
end
    end
end
 end
 for t = 1:nsamples
for i = 1:NX
    if(WALLSX(i,5) == 1)
if(abs(dxall3b(t,i)) > height/400)
    px3b(t,i) = 1;
else
    px3b(t,i) = 0;
end
    elseif(WALLSX(i,5) == 2)
      if(abs(dxall3b(t,i)) > height/400)
    px3b(t,i) = 1;
else
    px3b(t,i) = 0;
      end
    end
end
 end

fy3 = zeros(NY,1);
fx3 = zeros(NX,1);
fy3b = zeros(NY,1);
fx3b = zeros(NX,1);
for i = 1:NY
    for j = 1:nsamples
fy3(i,1) = fy3(i,1) + py3(j,i);
    end
    pfy3(i,1) = fy3(i,1)/nsamples;
end
for i = 1:NX
    for j = 1:nsamples
fx3(i,1) = fx3(i,1) + px3(j,i);
    end
    pfx3(i,1) = fx3(i,1)/nsamples;
end

for i = 1:NY
```

```
    for j = 1:nsamples
fy3b(i,1) = fy3b(i,1) + py3b(j,i);
    end
    pfy3b(i,1) = fy3b(i,1)/nsamples;
end
for i = 1:NX
    for j = 1:nsamples
fx3b(i,1) = fx3b(i,1) + px3b(j,i);
    end
    pfx3b(i,1) = fx3b(i,1)/nsamples;
end
end
% Output matrices


csvwrite('Fyall1.csv',Fyall1)
csvwrite('Fxall1.csv',Fxall1)
csvwrite('dyall1.csv',dyall1)
csvwrite('dxall1.csv',dxall1)
csvwrite('KYall1.csv',KYall1)
csvwrite('KXall1.csv',KXall1)
csvwrite('openingsy1.csv',openingsy1)
csvwrite('openingsx1.csv',openingsx1)
csvwrite('Lengthx1.csv',Lengthx1)
csvwrite('Lengthy1.csv',Lengthy1)
csvwrite('Forceyall1.csv',Forceyall1)
csvwrite('Forcexall1.csv',Forcexall1)

if (nlevs > 1)
csvwrite('KYall2.csv',KYall2)
csvwrite('KXall2.csv',KXall2)
csvwrite('Fyall2.csv',Fyall2)
csvwrite('Fxall2.csv',Fxall2)
csvwrite('dyall2.csv',dyall2)
csvwrite('dxall2.csv',dxall2)
csvwrite('openingsy2.csv',openingsy2)
csvwrite('openingsx2.csv',openingsx2)
csvwrite('Lengthx2.csv',Lengthx2)
csvwrite('Lengthy2.csv',Lengthy2)
csvwrite('Forceyall2.csv',Forceyall2)
csvwrite('Forcexall2.csv',Forcexall2)
end

if (nlevs > 2)
csvwrite('KYall3.csv',KYall3)
csvwrite('KXall3.csv',KXall3)
csvwrite('Fyall3.csv',Fyall3)
csvwrite('Fxall3.csv',Fxall3)
csvwrite('dyall3.csv',dyall3)
csvwrite('dxall3.csv',dxall3)
csvwrite('openingsy3.csv',openingsy3)
csvwrite('openingsx3.csv',openingsx3)
csvwrite('Lengthx3.csv',Lengthx3)
csvwrite('Lengthy3.csv',Lengthy3)
```

```
csvwrite('Forceyall3.csv',Forceyall3)
csvwrite('Forcexall3.csv',Forcexall3)
end

if (YY > 0)
csvwrite('windy.csv',windy)
end
if (XX > 0)
csvwrite('windx.csv',windx)
end

csvwrite('GCpf1all.csv',GCpf1all)


csvwrite('YP2all.csv',YP2all)
csvwrite('XP2all.csv',XP2all)
if (NFY >0)
csvwrite('RY1.csv',RY1)
end



% Write results to output file named "results.txt"
fid = fopen('results.txt', 'wt');

fprintf(fid,'Probability of failure of the individual walls. \n');
fprintf(fid,'Story \t Wall \t\t Plate Model \n');
for i = 1:NY
fprintf(fid,'1 \t\t WY \t\t %1.5f \n', pfy1(i,1));
end
for i = 1:NX
fprintf(fid,'1 \t\t WX \t\t %1.5f \n', pfx1(i,1));
end
if (nlevs > 1)
    for i = 1:NY
fprintf(fid,'2 \t\t WY \t\t %1.5f \n', pfy2(i,1));
    end
    for i = 1:NX
fprintf(fid,'2 \t\t WX \t\t %1.5f \n', pfx2(i,1));
    end
end
if (nlevs > 2)
    for i = 1:NY
fprintf(fid,'3 \t\t WY \t\t %1.5f \n', pfy3(i,1));
    end
    for i = 1:NX
fprintf(fid,'3 \t\t WX \t\t %1.5f \n', pfx3(i,1));
    end
end

fprintf(fid,'Shear forces in walls, lb \n');
fprintf(fid,'Story \t Wall \t\t Min \t\t\t Max \t\t\t Mean \n');
for i = 1:NY
```

```
fprintf(fid,'1 \t\t WY \t %2.5f \t\t %2.5f \t\t %2.5f \n', FyMin1(1,i),
FyMax1(1,i), Fyavg1(1,i));
end
for i = 1:NX
fprintf(fid,'1 \t\t WX \t %2.5f \t\t %2.5f \t\t %2.5f \n', FxMin1(1,i),
FxMax1(1,i), Fxavg1(1,i));
end
if (nlevs >1)
    for i = 1:NY
fprintf(fid,'2 \t\t WY \t %2.5f \t\t %2.5f \t\t %2.5f \n', FyMin2(1,i),
FyMax2(1,i), Fyavg2(1,i));
    end
    for i = 1:NX
fprintf(fid,'2 \t\t WX \t %2.5f \t\t %2.5f \t\t %2.5f \n', FxMin2(1,i),
FxMax2(1,i), Fxavg2(1,i));
    end
end
if (nlevs >2)
    for i = 1:NY
fprintf(fid,'3 \t\t WY \t %2.5f \t\t %2.5f \t\t %2.5f \n', FyMin3(1,i),
FyMax3(1,i), Fyavg3(1,i));
    end
    for i = 1:NX
fprintf(fid,'3 \t\t WX \t %2.5f \t\t %2.5f \t\t %2.5f \n', FxMin3(1,i),
FxMax3(1,i), Fxavg3(1,i));
    end
end

fprintf(fid,'Displacements in walls, in \n');
fprintf(fid,'Story \t Wall \t\t Mean \n');
for i = 1:NY
fprintf(fid,'1 \t\t WY \t\t %2.5f \n', dyavg1(1,i)*12);
end
for i = 1:NX
fprintf(fid,'1 \t\t WX \t\t %2.5f \n', dxavg1(1,i)*12);
end
if (nlevs >1)
    for i = 1:NY
fprintf(fid,'2 \t\t WY \t\t %2.5f \n', dyavg2(1,i)*12);
    end
for i = 1:NX
fprintf(fid,'2 \t\t WX \t\t %2.5f \n', dxavg2(1,i)*12);
end
end
if (nlevs >2)
    for i = 1:NY
fprintf(fid,'3 \t\t WY \t\t %2.5f \n', dyavg3(1,i)*12);
    end
    for i = 1:NX
fprintf(fid,'3 \t\t WX \t\t %2.5f \n', dxavg3(1,i)*12);
    end
end

fclose(fid);
```

```
% Write results to output file named "resultsbeam.txt"
fid = fopen('resultsbeam.txt', 'wt');

fprintf(fid,'Probability of failure of the individual walls. \n');
fprintf(fid,'Story \t Wall \t\t Beam Model \n');
for i = 1:NY
fprintf(fid,'1 \t\t WY \t\t %1.5f \n', pfy1b(i,1));
end
for i = 1:NX
fprintf(fid,'1 \t\t WX \t\t %1.5f \n', pfx1b(i,1));
end
if (nlevs >1)
    for i = 1:NY
fprintf(fid,'2 \t\t WY \t\t %1.5f \n', pfy2b(i,1));
    end
    for i = 1:NX
fprintf(fid,'2 \t\t WX \t\t %1.5f \n', pfx2b(i,1));
    end
end
if (nlevs >2)
    for i = 1:NY
fprintf(fid,'3 \t\t WY \t\t %1.5f \n', pfy3b(i,1));
    end
    for i = 1:NX
fprintf(fid,'3 \t\t WX \t\t %1.5f \n', pfx3b(i,1));
    end
end

fprintf(fid,'Shear forces in walls, lb \n');
fprintf(fid,'Story \t Wall \t\t Min \t\t\t Max \t\t\t Mean \n');
for i = 1:NY
fprintf(fid,'1 \t\t WY \t %2.5f \t\t %2.5f \t\t %2.5f \n',
FyMin1b(1,i), FyMax1b(1,i), Fyavg1b(1,i));
end
for i = 1:NX
fprintf(fid,'1 \t\t WX \t %2.5f \t\t %2.5f \t\t %2.5f \n',
FxMin1b(1,i), FxMax1b(1,i), Fxavg1b(1,i));
end
if (nlevs >1)
    for i = 1:NY
fprintf(fid,'2 \t\t WY \t %2.5f \t\t %2.5f \t\t %2.5f \n',
FyMin2b(1,i), FyMax2b(1,i), Fyavg2b(1,i));
    end
    for i = 1:NX
fprintf(fid,'2 \t\t WX \t %2.5f \t\t %2.5f \t\t %2.5f \n',
FxMin2b(1,i), FxMax2b(1,i), Fxavg2b(1,i));
    end
end
if (nlevs >2)
    for i = 1:NY
fprintf(fid,'3 \t\t WY \t %2.5f \t\t %2.5f \t\t %2.5f \n',
FyMin3b(1,i), FyMax3b(1,i), Fyavg3b(1,i));
    end
```

```
    for i = 1:NX
fprintf(fid,'3 \t\t WX \t %2.5f \t\t %2.5f \t\t %2.5f \n',
FxMin3b(1,i), FxMax3b(1,i), Fxavg3b(1,i));
    end
end

fprintf(fid,'Displacements in walls, in \n');
fprintf(fid,'Story \t Wall \t\t Mean \n');
for i = 1:NY
fprintf(fid,'1 \t\t WY \t\t %2.5f \n', dyavg1b(1,i)*12);
end
for i = 1:NX
fprintf(fid,'1 \t\t WX \t\t %2.5f \n', dxavg1b(1,i)*12);
end
if (nlevs >1)
    for i = 1:NY
fprintf(fid,'2 \t\t WY \t\t %2.5f \n', dyavg2b(1,i)*12);
    end
    for i = 1:NX
fprintf(fid,'2 \t\t WX \t\t %2.5f \n', dxavg2b(1,i)*12);
    end
end
if (nlevs >2)
    for i = 1:NY
fprintf(fid,'3 \t\t WY \t\t %2.5f \n', dyavg3b(1,i)*12);
    end
    for i = 1:NX
fprintf(fid,'3 \t\t WX \t\t %2.5f \n', dxavg3b(1,i)*12);
    end
end

fclose(fid);
```

D-2: Deflection in X Direction Subfunction

```
function [DX] = DX(xi,phi,R,S)

DX = xi + (R*(cosd(phi)-1)-S*sind(phi));
```

D-3: Deflection in Y Direction Subfunction

```
function [DY] = DY(eta,phi,R,S)

DY = eta + R*sind(phi) + S*(cosd(phi)-1);
```

D-4: Generic Stiffness Plot Subfunctions

```
function KS = KS(X,XP,YP)


for i = 1
    xs(i,1) = XP(i,1);
    fs(i,1) = YP(i,1);
    ys(i,1) = fs(i,1)/xs(i,1);
end

for i = 2:3
    xs(i,1) = XP(i,1);
    fs(i,1) = YP(i,1);
    ys(i,1) = (fs(i,1)-fs(i-1,1))/(xs(i,1)-xs(i-1,1));
end

if (X < xs(1,1))
    KS = X * ys(1,1);
elseif (X < xs(2,1))
        KS = fs(1,1)+ys(2,1)*(X - xs(1,1));
    else
        KS = fs(2,1)+ys(3,1)*(X - xs(2,1));
end


function [y] = KS(b1,b2,x)



y = b1*(1-exp(-b2*x));
```

D-5: Nonlinear Equations for Plate Model Subfunction

```
function [x,fval,fxall,dxall,fyall,dyall] =
nonlinear(NX,NY,WALLSX,WALLSY,KX,KY,nlevs,FX,FY,RX,RY,ZDep1,ZDep2,XP2,Y
P2,NFX,NFY)

for i = 1:nlevs*3
xstart(i,1) = .001; % starting guess vector for nonlinear solver
end
fun = @nonlinearplate;
options =
optimset('Display','off','MaxIter',500,'MaxFunEvals',500,'TolFun',1e-
8);
[x,fval,exitflag,output] = fsolve(fun,xstart,options);
```

```
function [F] = nonlinearplate(X)
F = zeros(nlevs*3,1); % Set variables equal to 0

for i = 1:NX
    eqx = 0;
    eqm = 0;
    R = WALLSX(i,1); % Set wall location in in x direction
    S = WALLSX(i,2); % Set wall location in y direction
   for j = nlevs-1:-1:0
   eqxm1 = eqx; % Set floor below force to previous force found
   eqmm1 = eqm; % Set floor below force to previous force found
   k = KX(i,j+1); % Set stiffness multipliers
   dx0 = DX(X(3*j+1),X(3*j+3),R,S); % Deflection in walls in x
direction
   dy0 = DY(X(3*j+2),X(3*j+3),R,S); % Deflection in walls in y
direction
   if (j > 0)
  dxm1 = DX(X(3*(j-1)+1),X(3*(j-1)+3),R,S); % Deflection in walls in x
direction on floor below
   dym1 = DY(X(3*(j-1)+2),X(3*(j-1)+3),R,S); % Deflection in walls in y
direction on floor below
   else
   dxm1 = 0; % Floor below force if evaluating first floor
       dym1 = 0; % Floor below force if evaluating first floor
   end
   if (WALLSX(i,5) == 1)
   eqx = (WALLSX(i,4) * k * KSExp( ZDep1,ZDep2,(dx0 - dxm1))); % Find
force/length value on stiffness plot and multiply by stiffness
multipliers and length of wall
   % using deflections and multiply by stiffness multiplier
   elseif (WALLSX(i,5) == 2)
       eqx = (WALLSX(i,4) * k * KS( (dx0 - dxm1),XP2,YP2));
   end
   fxall(i,j+1) = eqx; % Create vector of wall forces
   dxall(i,j+1) = (dx0 - dxm1); % Create vector of wall deflections
   eqm = -(S - dym1) * eqx; % Moment equation
   F(3*j+1) = F(3*j+1) + eqx - eqxm1; % Add forces from each wall
together subtracting forces from below
   F(3*j+3) = F(3*j+3) + eqm - eqmm1; % Moment equation
   end
end
for i = 1:NY
    eqy = 0;
    eqm = 0;
    R = WALLSY(i,1); % Set wall location in in x direction
    S = WALLSY(i,2); % Set wall location in in y direction
   for j = nlevs-1:-1:0
   eqym1 = eqy; % Set floor below force to previous force found
   eqmm1 = eqm; % Set floor below force to previous force found
   k = KY(i,j+1); % Set stiffness multipliers
   dx0 = DX(X(3*j+1),X(3*j+3),R,S); % Deflection in walls in x
direction
```

```
   dy0 = DY(X(3*j+2),X(3*j+3),R,S); % Deflection in walls in y
direction
   if (j > 0)
   dxm1 = DX(X(3*(j-1)+1),X(3*(j-1)+3),R,S); % Deflection in walls in x
direction on floor below
   dym1 = DY(X(3*(j-1)+2),X(3*(j-1)+3),R,S); % Deflection in walls in y
direction on floor below
   else
   dxm1 = 0; % Floor below force if evaluating first floor
       dym1 = 0; % Floor below force if evaluating first floor
   end
   if (WALLSY(i,5) == 1)
   eqy = (WALLSY(i,4) * k * KSExp( ZDep1,ZDep2,(dy0 - dym1))); % Find
force/length value on stiffness plot
   elseif (WALLSY(i,5) == 2)
       eqy = (WALLSY(i,4) * k * KS( (dy0 - dym1),XP2,YP2));
   end
   fyall(i,j+1) = eqy; % Create vector of wall forces
   dyall(i,j+1) = (dy0-dym1); % Create vector of wall deflections
   eqm = (R - dxm1) * eqy; % Moment equation
   F(3*j+2) = F(3*j+2) + eqy - eqym1; % Add forces from each wall
together subtracting forces from below
   F(3*j+3) = F(3*j+3) + eqm - eqmm1; % Moment equation
   end
end

for j = 1:nlevs
    for i = 1:NFX
        F(3*(j-1)+1)=F(3*(j-1)+1)-FX(i,j); % right hand side of
equation - wind force
        F(3*(j-1)+3)=F(3*(j-1)+3)+FX(i,j)*RX(i,j); % right hand side of
moment equation - wind force * point
    end
    for i = 1:NFY
        F(3*(j-1)+2)=F(3*(j-1)+2)-FY(i,j); % right hand side of
equation - wind force
        F(3*(j-1)+3)=F(3*(j-1)+3)-FY(i,j)*RY(i,j); % right hand side of
moment equation - wind force * point
    end
end


end

end
```

D-6: Nonlinear Equations for Beam Model Subfunction

```
function [x,fval,fxallb,dxallb,fyallb,dyallb] =
nonlinearbeam(NX,NY,WALLSX,WALLSY,KX,KY,nlevs,FX,FY,RX,RY,ZDep1,ZDep2,X
P2,YP2,NFX,NFY,XX,YY)
```

```
for i = 1:nlevs*2
xstart(i,1) = .1; % starting guess vector for nonlinear solver
end
fun = @nonlinearsolver;
options =
optimset('Display','off','MaxIter',1000,'MaxFunEvals',1000,'TolFun',1e-
4);
[x,fval,exitflag,output] = fsolve(fun,xstart,options);



function [F] = nonlinearsolver(X)
F = zeros(nlevs*2,1); % Set variables equal to 0

if  (XX > 0)
    R = WALLSX(1,2);

for i = 1:NX
    eqx = 0;
    eqm = 0;
   for j = nlevs-1:-1:0
   S = WALLSX(i,1);
   eqxm1 = eqx; % Set floor below force to previous force found
   eqmm1 = eqm; % Set floor below force to previous force found
   k = KX(i,j+1); % Set stiffness multipliers
   dx = X(2*j+1)+X(2*j+2)*S; % Deflection in walls in x direction
   if (j > 0)
  dxm1 = X(2*(j-1)+1)+X(2*(j-1)+2)*S; % Deflection in walls in x
direction on floor below
   else
   dxm1 = 0; % Floor below force if evaluating first floor
   end
   if (WALLSX(i,5) == 1)
   eqx = (WALLSX(i,4) * k * KSExp( ZDep1,ZDep2,(dx - dxm1))); % Find
force/length value on stiffness plot and multiply by stiffness
multipliers and length of wall
   % using deflections and multiply by stiffness multiplier
   elseif (WALLSX(i,5) == 2)
       eqx = (WALLSX(i,4) * k * KS( (dx - dxm1),XP2,YP2));
   end
   fxallb(i,j+1) = eqx; % Create vector of wall forces
   dxallb(i,j+1) = (dx - dxm1); % Create vector of wall deflections
   for t = 1:NY
   fyallb(t,j+1) = 0;
   dyallb(t,j+1) = 0;
   end
   if (WALLSX(i,5) == 1)
   eqm = (WALLSX(i,4) * k * KSExp( ZDep1,ZDep2,(dx - dxm1)) *S); %
Moment equation
   elseif (WALLSX(i,5) == 2)
       eqm = (WALLSX(i,4) * k * KS( (dx - dxm1),XP2,YP2) *S);
   end
```

```
   F(2*j+1) = F(2*j+1) + eqx - eqxm1; % Add forces from each wall
together subtracting forces from below
   F(2*j+2) = F(2*j+2) + eqm - eqmm1; % Moment equation
   end
end
end
if (YY > 0)
        S = WALLSY(1,1);
for i = 1:NY
    eqy = 0;
    eqm = 0;
   for j = nlevs-1:-1:0
   eqym1 = eqy; % Set floor below force to previous force found
   eqmm1 = eqm; % Set floor below force to previous force found
   k = KY(i,j+1); % Set stiffness multipliers
   R = WALLSY(i,1);
   dy = X(2*j+1)+X(2*j+2)*R; % Deflection in walls in y direction
   if (j > 0)
   dym1 = X(2*(j-1)+1)+X(2*(j-1)+2)*R; % Deflection in walls in y
direction on floor below
   else
   dym1 = 0; % Floor below force if evaluating first floor
   end
   if (WALLSY(i,5) == 1)
   eqy = (WALLSY(i,4) * k * KSExp( ZDep1,ZDep2,(dy - dym1))); % Find
force/length value on stiffness plot
   elseif (WALLSY(i,5) == 2)
       eqy = (WALLSY(i,4) * k * KS( (dy - dym1),XP2,YP2));
   end
   fyallb(i,j+1) = eqy; % Create vector of wall forces
   dyallb(i,j+1) = (dy-dym1); % Create vector of wall deflections
   for t = 1:NX
   fxallb(t,j+1) = 0;
   dxallb(t,j+1) = 0;
   end
   if (WALLSY(i,5) == 1)
   eqm = (WALLSY(i,4) * k * KSExp( ZDep1,ZDep2,(dy - dym1)) * R); %
Moment equation
   elseif (WALLSY(i,5) == 2)
       eqm = (WALLSY(i,4) * k * KS( (dy - dym1),XP2,YP2) * R);
   end
   F(2*j+1) = F(2*j+1) + eqy - eqym1; % Add forces from each wall
together subtracting forces from below
   F(2*j+2) = F(2*j+2) + eqm - eqmm1; % Moment equation
   end
end
end

for j = 0:nlevs-1
    if (XX > 0)
    for i = 1:NFX
        F(2*j+1)=F(2*j+1)-FX(i,j+1); % right hand side of equation -
wind force
        F(2*j+2)=F(2*j+2)+FX(i,j+1)*RX(i,j+1); % right hand side of
moment equation - wind force * point
```

```
    end
    end
    if (YY > 0)
    for i = 1:NFY
        F(2*j+1)=F(2*j+1)-FY(i,j+1); % right hand side of equation - 
wind force
        F(2*j+2)=F(2*j+2)-FY(i,j+1)*RY(i,j+1); % right hand side of 
moment equation - wind force * point
    end
    end
end


end

end
```

D-7 Input

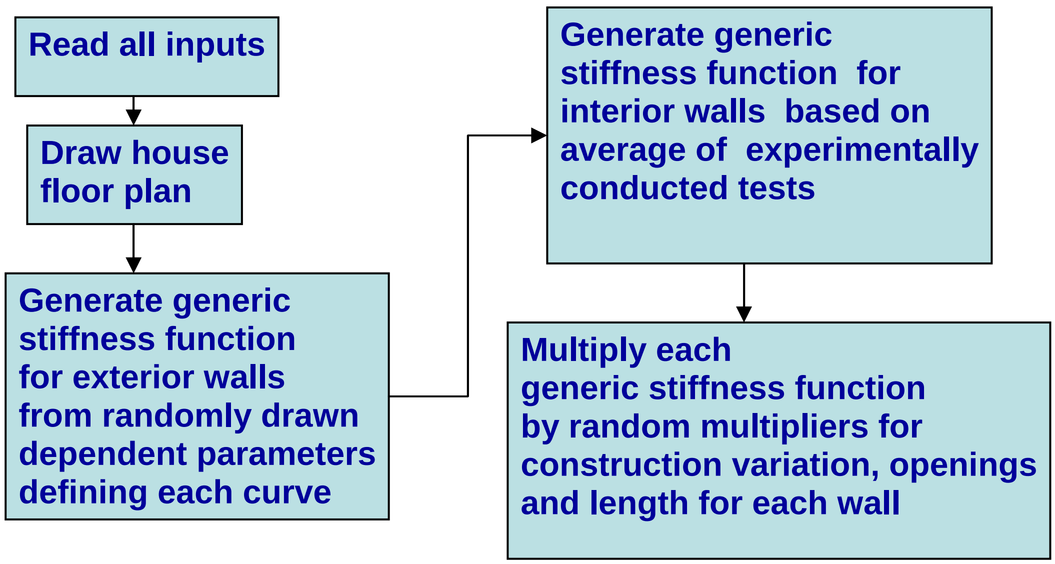
# of Nodes	6	
Node 1	0	0
Node 2	35	0
Node 3	70	0
Node 4	0	25
Node 5	35	25
Node 6	70	25
Node 7	0	0
Node 8	0	0
Node 9	0	0
Node 10	0	0
Node 11	0	0
# of Walls in X Direction	4	

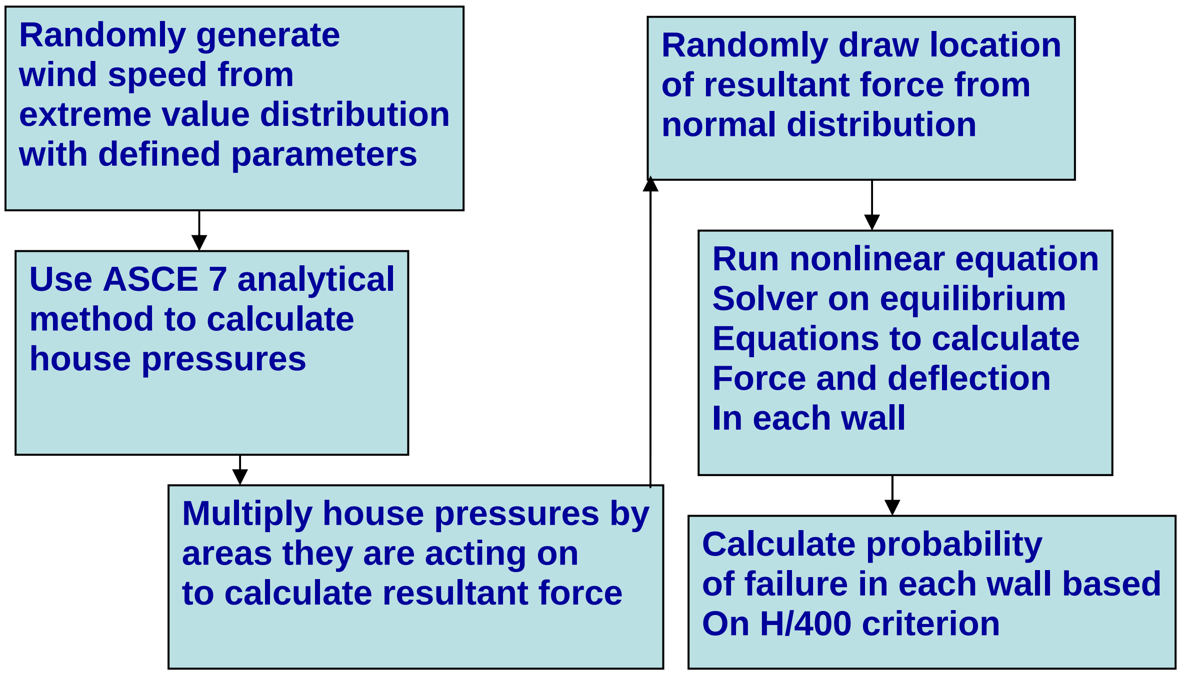
	X Location	Y Location	Length of Wall	“1” Exterior “2” Interior	“1” Use Fixed Minimum Bracing “0” Use random bracing
Wall 4	17.5	0	35	1	1
Wall 5	52.5	0	35	1	1
Wall 6	17.5	25	35	1	1
Wall 7	52.5	25	35	1	1
# of Walls in Y Direction	3				
Wall 1	0	12.5	25	1	1
Wall 2	35	12.5	25	2	1
Wall 3	70	12.5	25	1	1
# of Wall Percentages	5				
% 1	1				
% 2	0.8				

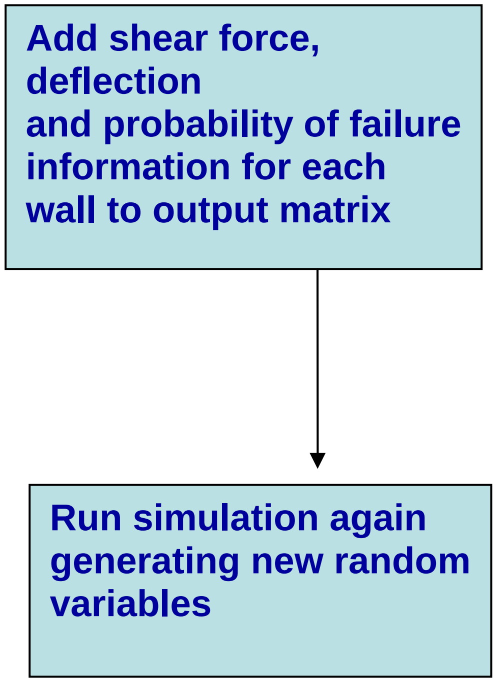
% 3	0.6		
% 4	0.3		
% 5	0.16		
Lognormal distribution parameters for wall construction variation multipliers	-0.0699	0.3738	
# of wind forces in X direction	1		
	First Floor	Second Floor	Third Floor
Wind force 1	25	0	0
Location 1	12.5	0	0
# of wind forces in Y dirction	2		
Wind force 1	35	0	0
Wind force 2	35	0	0
Location 1	17.5	0	0
Location 2	52.5	0	0
Wind Distribution Parameters	-0.33376	9.27329	60.2663
Deflection for last point on exterior wall load-deformation curve	5		
Height of Floors	9		
# of Points on load-deformation curve for interior walls	3		
Point 1	0.044417	100	
Point 2	0.125	350	
Point 3	5	367.5	
Lognormal distribution parameters to vary load deformation curve for interior walls	-0.0477	0.3087	
Toggle “0” to use actual	0		

ASCE 7
pressures,
“1” to use
minimum
10psf
pressure

Appendix E Matlab Flowchart




Randomly generate wind speed from extreme value distribution with defined parameters
Use ASCE 7 analytical method to calculate house pressures
Multiply house pressures by areas they are acting on to calculate resultant force
Randomly draw location of resultant force from normal distribution
Run nonlinear equation Solver on equilibrium Equations to calculate Force and deflection In each wall
Calculate probability of failure in each wall based On H/400 criterion


Add shear force, deflection
and probability of failure information for each wall to output matrix
Run simulation again generating new random variables