THE RELATIVE SAFETY OF BUILDINGS IN A HURRICANE HAZARD

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ABSTRACT

The structural feasibility of vertical evacuation using multistory structures in a hurricane is analyzed. The risks of death or injury associated with several mitigative options are discussed and methods for calculating or estimating the associated risks are presented. Criteria for feasibility determination are presented and applied to the identified mitigative options. The methodology is applied to determine the feasibility of vertical evacuation at a specific location, and for a given class of structures using data currently available.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

THE RELATIVE SAFETY OF BUILDINGS IN A HURRICANE HAZARD

1.0 INTRODUCTION

The Atlantic and Gulf coasts of the United States are highly vulnerable to hurricanes. Traditionally, if a hurricane was impendent at some coastal location, the inhabitants moved inland to higher ground (i.e., evacuated horizontally) to reduce the risk of injury or death. Recently, both the Florida coast in particular, and Gulf coast, in general, have experienced a marked increase in population. Simultaneously, the barrier islands along the coast have been transformed from relatively uninhabited locations into densely populated residential and resort areas. Given the present transportation network in many areas of the Gulf and Atlantic coasts and the state-of-the-art in predicting the trajectory and the time of landfall of hurricanes, it may be impossible for the entire population-at-risk to safely evacuate horizontally in the face of an impending disaster. Therefore, under some conditions, it may be feasible to seek some form of alternate protection from hurricanes to mitigate the disaster.

Depending upon its location, a structure exposed to a hurricane is subjected to extreme wind loadings and various levels of flooding, scour, surge, and battering with debris. At one extreme, in a low-elevation coastal zone, the wind velocity is highest, flooding is highly likely, and water could be moving at a significant speed, thereby inducing additional loadings on the structure. In addition, the flowing water may transport large floating objects which can induce significant damage if such objects were to impact an existing structure. The flowing water also increases the likelihood of scour around foundations thereby rendering the building even more susceptible to the existing environmental forces.

At the other extreme, structures located well inland or outside the "V Zone" of the Federal Insurance Administration Flood Maps are subject mainly to wind loading (25). If such edifices can structurally withstand the aerodynamic forces of the hurricane and the performance of the utilities can be maintained, then, if there are no legal, political, and sociological barriers to using the buildings as a shelter, it is conceivable that a part or all of the population-at-risk in a community may seek refuge in such structures (i.e., evacuate vertically).

In recent years, many studies have focused on the general objective of increasing the resistance of buildings to hurricane and high winds (2, 3, 4, 5, 7, 8, 11, 12, 19, 22, 23). Many studies have also focused on methods of assessing the accumulated damage sustained by existing structures (5, 6, 9, 13, 14, 16, 26). However, few works have been published on the structural feasibility of using existing multistory buildings for shelter during a hurricane (10, 21). The subject matter is relatively new and many unexamined questions remain outstanding. For example, leaving aside for the moment such important considerations as the legal, sociological, economic, and psychological aspects of the problem, is vertical evacuation structurally feasible? In fact, even before the question of feasibility is discussed, is there an existing methodology to evaluate the structural feasibility of vertical evacuation. Furthermore, suppose that vertical evacuation proves to be structurally feasible, at least in principle, then what specific techniques and methodologies can be utilized to assesss routinely the "evacuation worthiness" of a specific structure? In a related situation, if such a methodology exists and a structure is deemed structurally unsatisfactory for vertical evacuation, then, according to the evaluation scheme, are the costs and technology necessary to render the building suitable for vertical evacuation within reasonable bounds? Finally, if all of these structurally related difficulties were surmounted, how might the appropriate agency conduct an investigation to determine the vertical evacuation capacity of the certified buildings in a given community, city, or region?

In the present research effort an attempt is made to investigate the overall feasibility of using multistory structures as hurricane evacuation shelters in coastal areas. The total research program focuses not only on the structural feasibility of the concept, but also on the accompanying social, economic, legal, and political aspects. This paper analyzes the structural feasibility of vertical evacuation using available data on the performance of structures in a hurricane. The risks of death or injury associated with several mitigative options are discussed and methods for calculating or estimating the associated risks are presented. Furthermore, criteria for feasibility determination are presented and applied to the identified mitigative options. Finally, the methodology is applied to determine the feasibility of vertical evacuation at a specific location for a given class of structures using data currently available.

2.0 STRUCTURAL RISK ASSESSMENT

2.1 Potential Structures for Vertical Evacuation

The most general class of structures to be considered here for vertical evacuation are those structures which are more than two stories high and are fully engineered. The height requirement is based on the observation that even if the building were located in a high surge zone the probability of the height of storm surge being greater than 20 feet is negligible. The requirement that the buildings be fully engineered (i.e., buildings which have received specific, individualized design attention from professional architects and engineers), is motivated by the findings of several studies on wind damage due to extreme wind; namely, fully engineered buildings sustain significantly less damage than partially engineered structures or structures that received no detailed engineering attention (15). To investigate the feasibility of vertical evacuation for a specific type of structure the general class of building defined above may be further subdivided into a set of more restrictive categories; for example, "four-to-seven-story" concrete buildings, "eight-to-fifteen-story" steel structures, or "greater-than-fifteen-story" steel buildings. Depending upon the availability of historical damage data and the required degree of specificity the classificatory system can be made even more detailed.

2.2 Approach to Feasibility Determination

On being notified that a major hurricane is impending and assuming that vertical evacuation is an option, an individual may decide either to remain at home, seek refuge in a traditional shelter, evacuate horizontally, or evacuate vertically. On the other hand, if in some given location civil defense authorities know that the warning time for the hurricane is insufficient for the entire population-at-risk to evacuate horizontally in a safe manner, or given the event that during the course of horizontal evacuation, crucial transportation arteries cease to function satisfactorily thereby preventing any further horizontal evacuation, the authorities may advise the population-at-risk either to return to their homes, to seek refuge in a traditional shelter, or to evacuate vertically. Whereas, on the one hand the individual may be inclined to select the alternative that he conceives to minimize the risk of injury and death to himself or his family; on the other hand the state and local authorities are concerned with minimizing the risks to the entire population-at-risk. Note that risk, as used in the context of this paper, is defined to be the likelihood that an individual may be injured or killed.

Central to both the governmental and the individual decision process is the concept of risk. In fact, if the risk of injury or death associated with each of the above four alternatives can be computed and compared, such comparison may provide a rational basis for evaluating the structural feasibility of vertical evacuation. For example, in a given hurricane, if the magnitude of the risk of death or injury to an individual who has evacuated vertically is less than the magnitude of the risk associated with all the other competing alternatives, then vertical evacuation in that building may be considered structurally feasible. The problem of determining the structural feasibility of vertical evacuation can, therefore, be viewed as one of finding the relative risks associated with vertical shelters and the competing alternatives. A more detailed explanation of the computations of the risk experienced by an individual who has selected, or who was directed to use, any of the above alternatives is presented below.

2.3 Risks Associated with Using Structures for Shelter

The risks to an individual who has inhabited a given structure during a hurricane may be computed once the severity and probability of the occurrence of the hurricane are known, a damage probability matrix (DPM) of the structure is defined, and the incident losses as a function of damage to the structure are defined. Empirical damage probability matrices of a given class of buildings can be developed from the historical performance of that class of buildings. Statistics of hurricane occurrence and severity can be obtained from meteorological data. Incident losses can be estimated from existing actuarial data.

One approach to develop a damage probability matrix for a structure exposed to a hurricane hazard is to utilize the procedure suggested by Whitman (26) for developing analogous damage probability matrices for buildings subjected to earthquakes. Whitman, et al. (26), for example, expressed damage probabilities as a percentage based on the level of damage sustained by a sample of 370 comparable buildings. They then defined four progressive damage states as follows:

State 1. Undamaged or minor damage to nonstructural parts.

State 2. Lightly to moderately damaged: Parapets fallen; cracked or shattered walls capable of being repaired; substantial amount of cracked or fallen plaster; glass breakage; minor amounts of fallen masonry; some damage to mechanical and piping systems.

State 3. Seriously damaged: Frame cracked or locally distressed; walls cracked or collapsed in upper stories; floors cracked; considerable damage to ceilings, partitions, finishes, windows, and mechanical and electrical systems.

State 4. Essentially a total loss: Building either collapsed or in dangerous condition; repairs are not economically feasible.

Motivated by Whitman's work (26, 27, 28), both Hart (9), and Lee and Collins (13) used damage probability matrices to compute the risk to United States structures subjected to wind hazards. Table 1 shows the typical form of a damage probability matrix for hurricanes of varying intensities. Each column of the matrix represents a different level of damage. The i, j^{th} element of the matrix gives the probability that a building will experience damage state i, if a hurricane of intensity j occurs.

Here it is assumed that the elements of a DPM for a specific building type and corresponding to a hurricane of specific intensity can be estimated from a post-hurricane inspection of a sample of buildings in a desired category (e.g. four-to-eight-story concrete buildings) or by analysis. Furthermore, if one assumes that the level of damage sustained by a fully engineered building (as defined above) in one location is similar to the level of damage sustained by a similar fully

Damage State (i)	Hurricane Intensities (MPH) (j)						
	73.0- 87.5 (2)	87.5- 112.5 (3)	112.5- 137.5 (4)	137.5- 175 (5)	175- 225 (6)	225- 275 (7)	275- 325 (8)
1. None, Minor							
2. Slight, Minor							
3. Serious				ij			
4. Total							
Mean Damage Ratios							

Table 1. Form of Damage Probability Matrix for Hypothetical Building Subjected to the Range of Hurricane Intensities

engineered building at a different location when the latter structure is subjected to a similar loading environment, then the damage probability matrix for a sample of buildings subjected to storms of a given intensity in one location is similar for the same class of buildings in the location of interest. Consequently, in principle damage probability matrices can be constructed from data obtained from structures at several locations. For the feasibility determination discussed here DPM's must be generated for residential units, potential vertical evacuation shelters, and traditional evacuation shelters.

With the damage probability matrices defined as above for the range of expected hurricane intensities, the next step is to define the necessary incident losses (costs or fatalities) that would permit the computation of risks in terms of causalities or costs. Note that incident losses include the effects of hurricanes beyond damage to the building.

cane intensities considered, respectively. Also, let P represent the NxR damage probability matrix. If the elements of the incident losses (deaths or injuries) are collected into a matrix L, given by

$$L = (l_1, l_2, \ldots, l_N) \tag{1}$$

where l_i is the fraction of dead or injured if damage state i occurs, and the occurance rates (number of hurricanes per year in a specific range and at a specific location) are collected into a matrix A such that

$$A = (A_1, A_2, \ldots, A_R) \tag{2}$$

where A_j is the occurrence rate for hurricane of intensity j, then the expected annual life loss or injury per person exposed, d_v, may be given by the equation:

$$d_v = LPA^T \tag{3}$$

where the superscript 'T' represents the transpose of the matrix.

Note that Equation (3) considers all hurricanes in the range 1-N. The expected life loss or injury per person exposed, d_{vj}, to a specific hurricane of intensity j may be given by the equation

$$d_{vj} = LP_jA_j \tag{4}$$

where P_j is the j^{th} column of the DPM for the structure under consideration. A schematic outlining the proposed logic for risk determination is shown in Figure 1.

These effects include, but are not limited to, injuries sustained and lives lost. Estimates of the fraction of the total inhabitants dead and the fraction injured as a function of the damage states during an earthquake is shown in Table 2. If one accepts the results of Whitman (26) and assumes that the magnitude of dead or injured in a building is only a function of the level of damage sustained by that building and the type of building, then the incident losses proposed by Whitman can also be used for hurricanes. Such an approach is presently justified since no comparative data base currently exists for hurricanes.

Damage State	Fraction[1] Dead	Fraction[1] Injured
None (O)	0	0
Light (L)	0	0
Moderate (M)	0	1/100
Heavy (H)	1/400	1/50
Total (T)	1/100	1/10
Collapse (C)[2]	1/5	1

Table 2. Incident Losses as a Function of Damage Level

[1]The fraction of the total occupants that are present, on the average, in a building at any time. (Passersby may also be killed and injured by falling objects or by collapse. These are also calculated in the fractions.)

[2]The collapse may be partial rather than total.

Having defined the damage probability matrix and the appropriate incident losses, the annual risk to an individual when using a specific class of structures at a specific location may be determined as follows. Let N and R be the number of damage states and number of hurri-

Figure 1. Schematic of Proposed Logic for Risk Determination

3.0 THE RELATIVE SAFETY OF BUILDINGS IN A HURRICANE

3.1 Example Problem

A study of the Galveston County area in Texas estimates that evacuation times as long as 26 hours are needed while the maximum hurricane warning time is approximately 11 hours (17). The Weather Service reports that a hurricane is rapidly approaching the region. Based on an analysis of the situation, emergency management personnel conclude that horizontal evacuation should not be recommended.

Since the individual will not evacuate horizontally, he or she has the options of remaining at home (assumed to be a one-family residence), seeking refuge in a traditional shelter (such as those provided by the Red Cross), or evacuating vertically. Thus the problem here is to evaluate the structural feasibility of vertical evacuation, assuming the above scenarios, and using the methodology developed in the previous sections. The feasibility of opting for vertical evacuation will be examined for the following hypothetical hurricane ranges:

a) Category 1 or 2 Hurricanes (74-110 miles per hour),

b) Category 3 or 4 Hurricanes (111-155 miles per hour),

c) Category 5 Hurricanes (155-325 miles per hour), and

d) All Hurricanes.

3.2 Occurrence and Severity of Hurricanes

As stated in the last section, the location of interest here is the Galveston, Texas, area. The occurrence and severity of storms at that location can be determined by utilizing the Frechet distribution (24). The Frechet cumulative probability distribution function $F_V(V)$ expresses the probability that a wind speed V will exceed a given wind speed V_m and is given by the equation:

$$F_V(V_m) = \exp\left[- (V_m/s)^{-g}\right] \qquad (5)$$

in which V is any arbitrary wind speed, V_m is a preselected wind speed, s the standard deviation of the distribution, and g is the tail length parameter for the distribution. The corresponding return period of the windspeed, V_m, is the inverse of the probability. Data for extreme wind speed distributions and their associated return periods have been provided by Thom (24). To define the distribution in Equation (5) for a specific location the following procedure suggested by Hart (9) was used to obtain the statistical parameters s and g. The parameters were evaluated using the wind speeds associated with the 10 and 50 year return periods. Applying Equation (5) for the two periods one obtains:

$$F_{10} = 1/10 = \exp\left[-(V_{10}/s)^{-g}\right] \qquad (6)$$

and

$$F_{50} = 1/50 = \exp\left[-(V_{50}/s)^{-g}\right] \qquad (7)$$

where V_{10} and V_{50} are the wind speeds associated with return periods of 10 and 50 years, respectively, for the Houston/Galveston area. From the data provided by Thom (24), V_{10} and V_{50} were estimated to be 65 and 90 miles per hour, respectively, for the Houston/Galveston area. With two equations and two unknowns, Equations (6) and (7) were solved simultaneously to yield the parameters s and g.

Once the Frechet distribution for the specific location is determined, the return time associated with the hurricane in any speed range can be obtained. The ranges for the hurricane speeds used in this example are shown in Table 1. Using the calibrated Frechet distribution (s = 38.518 and g = -1.62867), the probability of occurrence (P_{UL}) of a hurricane in the range of speeds V_L to V_U, where subscripts U and L refer to the upper and lower values of the range, respectively, is given by:

$$P_{UL} = F_V(V_U) - F_V(V_L) \qquad (8).$$

These results are summarized in Table 3 for the ranges of windspeeds selected.

Range of Hurricanes (mph)	Hurricane Class* (Approximate)	Strike Probability
73 - 87	1	3.809×10^{-2}
87 - 112	2	2.023×10^{-2}
112 - 137	3	3.192×10^{-3}
137 - 175	4	3.99×10^{-4}
175 - 225	5	9.56×10^{-7}
225 - 275	5	2.78×10^{-8}
275 - 325	5	3.33×10^{-11}

Table 3. Strike Probabilities of Hurricane in Ranges of Interest (Galveston, Texas)

*Saffir-Simpson (20)

3.3 Definition of Building Types

The buildings of interest in this example are residential units, low-rise institutional structures likely to be used by such groups as the Red Cross, and multistory buildings (the most likely candidates for vertical evacuation). Normally residential buildings will fall into the one-to-three story wood or masonry structures. The structures to be used by the sheltering groups may be taken as being equivalent to one-to-three story structures, and the strongest structural candidates for vertical evacuation are the fully engineered structures of four-or-more stories. Note that some tall buildings may not be suitable for vertical evacuation because of discomfort due to excessive motion during the course of a storm, although the structure may be capable of safely resisting the aerodynamic loading.

3.4 Damage Probability Matrices for the Selected Structures

Hart (9) has provided damage probability matrices based on expert opinion for ten structural types subjected to hurricanes of varying intensities which included, "a one-to-three story wood frame residential", "one- to-three story concrete or masonry wall residential", "one-to-three story wood frame commercial and/or industrial", "one-to-three story metal commercial/industrial", and "four-or-more story structures". The remaining categories included damage probability matrices for mobile homes and damage probability matrices for window damage. In the present example we will take the damage probability matrices of 1) "one-to-three story wooden frame residential" to represent the typical residential unit, 2) "one-to-three story concrete or masonry wall commercial and industrial" to represent the most likely shelter selected by the Red Cross, and 3) the "four-or-more story structure" to represent the choice for vertical evacuation. In the present exercise questions of motion discomfort are ignored. This aspect can be addressed in future studies in which structural candidates for vertical evacuation are categorized more precisely. The damage probability matrices for the three types of structures are shown in Tables 4 to 6. The reader should keep in mind that these results represent the consensus of wind engineering experts and only provide best informed guesses regarding the actual behavior of buildings. The damage states appearing in the tables should be interpreted as follows:

None: No damage.

Light: Minor ceiling tile or partition cracking; possible damage due to missiles.

Moderate: Many partitions cracked or ceiling tiles fallen down; a few structural members appear to be stressed beyond yield level.

Heavy: Significant number of structural members with structural damage, or damage to a structural system; roof having major damage or blown off.

Very Severe: Major damage; structure standing but will probably be taken down; no structural system collapse.

Collapse: Structure does not remain standing.

3.5 Risk Computation for Each Building Type

Assume that the incident losses are independent of the building type and are only a function of the damage level.* Also let the incident

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*Empirical data (28) suggests that the fraction of occupants killed or injured maybe a function of the materials of construction and the

Damage State	Hurricane Intensity (Wind Speed - MPH) 75	100	125	150	200	250	300
None	.668	.356	.197	.113	.089	.064	.000
Light	.269	.266	.148	.063	.028	.039	.000
Moderate	.049	.224	.239	.106	.049	.014	.013
Heavy	.010	.130	.239	.314	.086	.021	.013
Very Severe	.003	.016	.155	.255	.407	.119	.078
Collapse	.001	.008	.021	.150	.340	.744	.898

(Hart, 1976)

Table 4. Damage Probability Matrix for 1-3 Story Wood Frame Residential Structures

Damage State	Hurricane Intensity (Wind Speed - MPH) 75	100	125	150	200	250	300
None	.903	.567	.440	.191	.103	.071	.000
Light	.080	.183	.141	.156	.062	.027	.013
Moderate	.011	.178	.178	.164	.152	.044	.026
Heavy	.003	.048	.097	.275	.242	.159	.144
Very Severe	.001	.012	.120	.104	.237	.258	.100
Collapse	.001	.012	.024	.109	.203	.440	.717

(Hart, 1976)

Table 5. Damage Probability Matrix for 1-3 Story Concrete or Masonry Commercial or Industrial Structures

losses for the fraction injured L_i be given by(1):

$$L_i = (0, 0, 0.01, 0.02, 0.1, 1.0) \quad (9)$$

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weight density of the structure.

Damage State	Hurricane Intensity (Wind Speed - MPH)						
	75	100	125	150	200	250	300
None	.950	.811	.439	.239	.151	.089	.006
Light	.048	.169	.356	.224	.084	.078	.039
Moderate	.002	.019	.188	.344	.291	.156	.172
Heavy	.000	.001	.018	.180	.280	.261	.211
Very Severe	.000	.000	.000	.012	.132	.198	.247
Collapse	.000	.000	.000	.000	.063	.219	.326

(Hart, 1976)

Table 6. Damage Probability Matrix for 4 or More Story Structures

and the incident losses for the fraction dead L_d by:

$$L_d = (0, 0, 0, 0.0025, 0.01, 0.2) \quad (10).$$

From Table 3, the strike probability of hurricanes in the range of interest are given by:

$$A = (3.809X10^{-2}, 2.023X10^{-2}, 3.192X10^{-3}, 3.996X10^{-4}, 9.564X10^{-7}, 2.775X10^{-8}, 3.331X10^{-11}) \quad (11).$$

Substituting the values of matrices L_d and A along with the appropriate values of the damage probability matrices (Tables 4 to 6) into Equations (2) and (3), the annual risks of death for various wind ranges may be computed. A typical set of results for the expected fatalities using the values of matrix L_d and the damage probability matrices are shown in Table 7. Similarly, by combining the values of matrix L_i with the appropriate values of the damage probability matrices, the expected injuries for the same wind ranges may be computed. These results are summarized in Table 8.

Shelter Type	Hurricane Intensity (Wind Speed - MPH)					
	80	100	125	150	200	250
Residential[a]	$.255 \times 10^{-3}$	$.209 \times 10^{-2}$	$.635 \times 10^{-2}$	$.333 \times 10^{-1}$	$.723 \times 10^{-1}$	.150
Traditional Shelter[b]	$.218 \times 10^{-3}$	$.264 \times 10^{-2}$	$.624 \times 10^{-2}$	$.235 \times 10^{-1}$	$.436 \times 10^{-1}$	$.910 \times 10^{-1}$
Multistory[c]	.000	$.250 \times 10^{-5}$	$.450 \times 10^{-4}$	$.570 \times 10^{-3}$	$.146 \times 10^{-1}$	$.434 \times 10^{-1}$

Table 7. Expected Fatalities as a Function of Shelter Type

[a]*Based on the damage probability matrix for a 1-3 story wood frame structure.*

[b]*Based on the damage probability matrix for a 1-3 story concrete or masonry Commercial or Industrial Building.*

[c]*Based on the damage probability matrix for buildings greater than four stories.*

Shelter Type	Hurricane Intensity (Wind Speed - MPH)					
	80	100	125	150	200	250
Residential[a]	$.119 \times 10^{-2}$	$.144 \times 10^{-1}$	$.437 \times 10^{-1}$	.183	.383	.756
Traditional Shelter[b]	$.127 \times 10^{-2}$	$.159 \times 10^{-1}$	$.397 \times 10^{-1}$	.127	.233	.469
Multistory[c]	$.200 \times 10^{-4}$	$.210 \times 10^{-3}$	$.224 \times 10^{-2}$	$.824 \times 10^{-2}$	$.847 \times 10^{-1}$	.246

Table 8. Expected Injuries as a Function of Shelter Type

[a]*Based on the damage probability matrix for a 1-3 story wood frame structure.*

[b]*Based on the damage probability matrix for a 1-3 story concrete or masonry Commercial or Industrial Building.*

[c]*Based on the damage probability matrix for buildings greater than four stories.*

3.6 Feasibility Analysis

So far we have estimated the mean risk of injury and the mean risk of death to which an individual is subjected if he, or she, elects to evacuate vertically, seek a traditional shelter, or remain at home. In this section the feasibility of vertical evacuation will be established by using the following procedure: 1) utility (payoff) matrices which summarize the risk of injury or death associated with a given option and hurricane of a given intensity are constructed, 2) an appropriate objective criterion is stated, and 3) the alternatives are evaluated for a variety of hurricane ranges.

The results presented in Tables 7 and 8 may be interpreted as payoff matrices for mean injuries and mean deaths. If we let u_{ij} be the mean injury or fatality associated with shelter option i and a hurricane of intensity j, one appropriate objective function is:

$$E_i = \sum_{j=L}^{k} u_{ij} P(V_j)$$

where E_i is the expected value of the annual loss for hurricanes of speeds between, and including, V_L and V_k, and $P(V_j)$ is the probability of occurrence of a hurricane of windspeed V_j. Note that the probabilities, $P(V_j)$ ($j = 1, \ldots, 7$), are given in Table 3. The most feasible option will be the one for which E_i ($i = 1, 2, 3$) is a minimum, i.e., the option that produces the minimum risks in terms of injury or death.

The values of the annual losses for all options are presented in Tables 9 and 10 for four cases: 1) a Category 1 or Category 2 hurricane ($74 < V < 110$ mph), 2) a Category 3 or Category 4 hurricane (111

Options	Traditional Shelters	Staying Home	Vertical Evacuation
	Category 1 or 2 Hurricanes		
Injured	3.701×10^{-4}	3.672×10^{-4}	5.011×10^{-6}
Dead	6.172×10^{-5}	5.200×10^{-5}	5.059×10^{-8}
	Category 3 or 4 Hurricanes		
Injured	1.775×10^{-4}	2.126×10^{-4}	1.044×10^{-5}
Dead	2.931×10^{-5}	3.358×10^{-5}	3.714×10^{-7}
	Category 5 Hurricanes		
Injured	2.224×10^{-6}	3.683×10^{-6}	8.166×10^{-7}
Dead	4.194×10^{-7}	6.954×10^{-7}	1.409×10^{-7}
	All Hurricanes		
Injured	5.498×10^{-4}	5.835×10^{-4}	1.627×10^{-5}
Dead	9.145×10^{-5}	8.628×10^{-5}	5.629×10^{-7}

Table 9. Expected Annual Losses per Person Exposed As A Function of Option and Hurricane Range - Galveston, Texas

$< V < 155$ mph), 3) a Category 5 hurricane ($155 < V < 300$ mph), and 4) all hurricanes ($74 < V < 300$ mph). For Category 1 or Category 2 hurricanes the risk of death when using a traditional shelter or staying at home is three orders of magnitude greater than the risks associated with vertical evacuation. Therefore, vertical evacuation is the best strategy. For Category 3 or Category 4 hurricanes the risk of death for traditional shelters and staying at home are one order of magnitude greater than the risks associated with vertical evacuation. Therefore, vertical evacuation is the best strategy. For Category 5 hurricanes the risk of death for all shelters are of the same order of magnitude.

Options	Traditional Shelters	Staying Home	Vertical Evacuation
	Category 1 or 2 Hurricanes		
Injured	73.9	73.3	1
Dead	1220.0	1027.9	1
	Category 3 or 4 Hurricanes		
Injured	17.0	20.4	1
Dead	78.9	90.4	1
	Category 5 Hurricanes		
Injured	2.7	4.5	1
Dead	3.0	4.9	1
	All Hurricanes		
Injured	33.8	35.9	1
Dead	162.5	153.3	1

Table 10. Normalized Expected Annual Losses per Person Exposed Relative to the Vertical Evacuation Option - Galveston, Texas

Differences in risk levels between the alternatives are minimal, although the risks associated with vertical evacuation are slightly smaller. Finally, if all hurricanes are taken together the risks of death for the shelters are two orders of magnitude greater than those of vertical evacuation. Therefore, the best strategy is always vertical evacuation. Thus we conclude, on the basis of these results, that vertical evacuation is feasible under the following conditions:

1. The shelter is used for a Category 1 or Category 2 hurricane, and

2. The shelter is used for a Category 3 or a Category 4 hurricane.

4.0 SUMMARY AND CONCLUSIONS

A method for evaluating the structural feasibility of vertical evacuation (seeking refuge in specifically designated multistory structures during a hurricane) based on the expected performance of various building types has been proposed. A method of estimating the risk of injury or death to an individual in a given shelter has been presented. The method considers the location and severity of the hurricane, the historical resistance of the class of structures, and the vulnerability of the population-at-risk. A decision rule utilizing the expected risks has also been used.

The methodology was applied to the case of evaluating the feasibility of vertical evacuation in the Galveston, Texas, area. Risks of injury and death were computed for the options of vertical evacuation, staying at home, using traditional shelters, and no horizontal evacuation. Risk computations were based on meteorological, structural, and actuarial data presented in the literature. The criterion for the feasibility of vertical evacuation was defined as follows: If the risks associated with vertical evacuation are smaller than the risks associated with the most competitive alternative, the risks associated with vertical evacuation are acceptable. Using this criterion and the expected value rule, vertical evacuation appears structurally feasible for the following conditions:

1. The shelter is used for a Category 1 or Category 2 hurricane.
2. The shelter is used for a Category 3 or a Category 4 hurricane.

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