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THE STRUCTURAL FEASIBILITY OF VERTICAL EVACUATION

by

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ABSTRACT

A structural risk assessment of the concept of vertical evacuation is performed. The identification, quantification, and assessment of the risk associated with using a structure as a shelter in a hurricane environment is described. The most recent scientific and engineering evidence to establish the safety of the occupants in structures subjected to hurricane forces is assembled and evaluated. The method of Fault-Tree Analysis is utilized to comprehensively identify the sources of risk to the occupant of the structure. Sources of risk include those resulting from frame failure, foundation failure, cladding failure, roof failure, and partition failure. Analytical techniques from Structural Reliability Theory and existing statistical data (mostly available in the literature) are utilized to estimate the risk associated with using a given structure in a particular hurricane. Finally, by applying feasibility criteria based on least-risk and cost, specific scenarios are evaluated to determine the conditions under which the concept of vertical evacuation is structurally feasible.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

APPENDIX Page

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

FIGURE Page

CHAPTER I

INTRODUCTION

Depending upon its location, a structure exposed to a hurricane will be subjected to extreme wind loadings and various levels of flooding, scouring, surging, and battering by water and airborne debris. At one environmental extreme in a low elevation coastal setting, the wind velocity is highest, flooding is highly probable, and wind-driven water could be moving at significant speeds. The flowing water transports large floating objects which can induce significant damage if they should collide with an existing structure. The flowing water also increases the likelihood of scour around foundations which then renders the building even more susceptible to other environmental forces. At the other environmental extreme, structures located outside high velocity zones, as defined by the Federal Insurance Administration as Zone V of their Flood Insurance Maps (Federal Emergency Management Agency, 1984), are subject to less severe winds and flooding.

Vertical evacuation is the proposed use of deliberately selected, multi-story buildings to serve as human shelters during a hurricane. The motivation for the technical feasibility of vertical evacuation has its basis in the historically superior performance of engineered structures in a wind hazard (Davenport, 1972; Hart, 1976; Minor and Mehta, 1979; Kareem, 1985). In the United States, for example, no multi-story structure that was designed by professional architects and engineers and subjected primarily to hurricane or tornadoic generated wind forces has been observed to collapse. Although severe roof and cladding damage has been observed in some of these structures, the collapse of the frame or the foundation has not been observed. On the other hand, small residential buildings and low-rise structures - e.g., shopping centers, schools, and industrial buildings - are frequently decimated by tornadoic or hurricane winds. These observations support the hypothesis that if a structure is subjected primarily to a wind hazard, is multi-storied (two or more stories high), and has been designed and constructed under the guidance of building professionals (i.e., registered architects and engineers) then occupants of that structure have a better chance of survival when compared to occupants in small residential buildings and low-rise structures subjected to the same hazard.

In recent years, many studies have focused on the general objective of increasing the resistance of buildings to hurricanes and high winds (Davenport, 1972; Hix, 1976; Tryggvason et al., 1976; Heine, 1978; Beason and Morgan, 1984; Minor, 1985). Many studies have also focused on methods of assessing the accumulated damage sustained by existing structures (Culver et al., 1975; Liu and Yao, 1978; Yao, 1979). However, few works, if any, have focused specifically on the structural feasibility of using existing multi-story buildings for shelter during a hurricane.

At the beginning of this study, in the fall of 1983, many questions pertaining to the structural feasibility of vertical evacuation were unanswered. For example, leaving aside such complications as legal, sociological, economic, and psychological aspects, we asked ourselves: is vertical evacuation feasible? In fact, even before we tackled the question of feasibility, *per se*, we needed to know if there existed a methodology to evaluate the feasibility of vertical evacuation. Furthermore, given that vertical evacuation may prove to be feasible, at least in some areas, what specific techniques and methodologies might be utilized to assess the "evacuation worthiness" of a specific structure? In a related situation, if such a methodology existed and a structure was deemed unsatisfactory for vertical evacuation: were the costs and technology necessary to render the building suitable for vertical evacuation within reasonable bounds? Finally, if all of the above difficulties were surmounted, how might the appropriate agency conduct an investigation to determine the vertical evacuation capacity of the buildings in a given community, city or region?

The basic objective of the structural portion of this project was to provide some answers to these questions. At the outset of the project we hoped to achieve the following five objectives: 1) to establish the feasibility of using existing structures for vertical evacuation, 2) to develop a consistent methodology for classifying structures according to their suitability for vertical evacuation, 3) to estimate costs associated with strengthening (upgrading) existing buildings, 4) to develop a methodology which estimates the evacuation capacity of a given area, and 5) to develop preliminary structural design guidelines for future vertical evacuation shelters.

This report summarizes our findings with regards to the structural portion of the study. The remainder of the report is organized into three chapters. The first chapter establishes our philosophical approach to establishing the structural feasibility of vertical evacuation. We feel that the risk assessment approach is rational and interdisciplinary. In the second chapter we develop a methodology for evaluating specific structures by integrating existing techniques from the fields of risk analysis and structural mechanics. Fault-Tree Analysis and Structural Reliability Theory are combined to express the performance of a structure in terms of the safety it provides to the occupants of the structure. In the final chapter, we demonstrate how the proposed risk assessment techniques will be used to evaluate the feasibility of vertical evacuation. In that chapter potential shelters on Galveston Island are first identified. Next, representative structures from the collection of potential structures are analyzed using the risk assessment procedure. Finally, the structural feasibility of vertical evacuation is evaluated by examining two plausible scenarios involving a hurricane approaching the island.

CHAPTER II

OVERVIEW OF STRUCTURAL ASSESSMENT APPROACH

Whatever may be the reasons for invoking vertical evacuation, the selected structures must protect the inhabitants for the duration of the hurricane - from less than twenty-four hours to as much as several days depending upon the trajectory of the hurricane. During this critical period the structure must continually resist multi-directional hurricane-force winds of a range of magnitudes. In addition, the structure may be impacted by air-borne missiles or water-borne debris, and it may also be buffeted by hydrodynamic forces. Therefore, any structure selected as a vertical evacuation shelter must either be designed to meet certain predetermined safety requirements or it must be rigorously shown that the option of vertical shelters exposes the inhabitants to the least risks after all other mitigative alternatives are evaluated.

Although the structural specifications for a vertical shelter may appear obvious (i.e., will this building safely withstand a given hurricane), when one examines more closely the question of structural safety, especially in the context of vertical evacuation, the perception of exactly what these safety requirements should be, and how they may be evaluated for a given structure, quickly becomes blurred. Many individuals involved in the safety decision process, including some structural engineers, naively believe that if a structure was designed and built according to an accepted code of practice, then the structure is unconditionally safe. Or, if a structure has been inspected and the result of the inspection indicated that the prescriptions of the governing code were satisfied, the structure again is considered safe.

Recent developments in structural mechanics have shown that there is no rational explanation of the degree of absolute safety provided by structures designed using traditional working stress design and ultimate strength methods (Freudenthal, et al., 1966; ASCE, 1972). In response to these and subsequent findings, the modern trend has been to take into consideration the random nature of the loads to which structures are subjected and the variations in the material properties of the structural constituents. In other words, the loads impacting a structure and the resistance of that structure are considered to be random variables. The safety margin provided by the structure is the amount by which the random resistance of the structure exceeds the random load applied to the structure. Failure is said to occur when the safety margin is less than, or equal to, zero. The relative safety of a structure is now expressed in terms of a probability of failure. The smaller the probability of failure, the safer the structure.

One advantage of this more modern approach is the realization that safety is a relative concept. But the perennial question - 'how safe is safe?' - remains unanswered (Derby and Keeney, 1981; Burton and Pushchak, 1984). One school of thought defines safety in terms of levels of acceptable risks (Lowrance, 1976). Thus what is safe depends upon what levels of risk an individual is willing to take on a voluntary basis or the levels of acceptable risk that a governmental agency may set (Starr, 1969). The latter risk level established by the authority is sometimes referred to as the involuntary risk. In both cases, the individual or the governmental decision will depend upon the extent to which alternatives are available. Thus the voluntary or the involuntary safety levels for vertical evacuation may depend upon specific scenarios and competing alternatives.

Realizing that a determination of the acceptable safety levels depends upon what options are available in a particular situation, the technical information provided by an engineer or a scientist is simply not sufficient to engender a rational and balanced decision. Accordingly, technical contributions from the engineer must interface with such other aspects of the study as the social, political, psychological, legal, and economic (Petak and Atkisson, 1982; Salmon, 1984). It is an appreciation for the interdisciplinary, and hopefully transdisciplinary, environment of the current problem that provides background for the structural approach presented here.

The purpose of this chapter is to examine the issue of the structural feasibility of vertical evacuation in a more interdisciplinary context than the restricted case of whether or not a specific building satisfies a given building code. The objective here is to provide decision-makers with relevant information that would lead to a determination of the feasibility of vertical evacuation in a given community subjected to a given set of environmental conditions and sheltering conditions. First, recent methods of evaluating buildings in a wind hazard will be reviewed. This review will then be followed by a description of a hypothetical decision-making environment in which the fate of vertical evacuation as a feasible option will be decided. In this section, several scenarios that a community may experience will also be described on the basis of a comparison of the current structural approaches to building evaluation and the decision-making environment. The next such section discusses the nature of the structural information that decision-makers may need as input into the decision matrix. The chapter then concludes with a discussion on how this body of information may be obtained using state-of-the-art techniques in structural mechanics and system safety technology.

Some Recent Methods of Structural Assessment in a Wind Hazard

Over the past two decades, several attempts to evaluate the structural performance of existing buildings have been published (Hart, 1976; Yao, 1979). A major work by Culver, et al., (1975) presented methods to evaluate structures subjected to earthquakes, hurricanes, and tornadoes. In that work three methods of analysis, each distinguished by the complexity of the structure or its intended use, were proposed. In the first method, the Field Evaluation Method, buildings were evaluated qualitatively on the basis of their structural characteristics, structural configuration, and the observed degree of deterioration. The intent was to provide a rapid, inexpensive means of identifying hazardous or potentially hazardous structures.

In the second method, the Approximate Analytical Evaluation Method, buildings were evaluated on the basis of the behavior of anticipated critical structural members. Using information from design and construction documents, as well as anticipated loads on the structure provided by codes, an elastic-static structural analysis was performed to identify the critical structural members.

The third method, the Detailed Analytical Evaluation Method, computed the damage level in the structure subjected to the wind hazard. Damage was related to the story ductility (i.e., calculated interstory drift of the i^{th} story divided by a user specified interstory drift to yield). A versatile computer program was provided with the report. To use the Detailed Analytical Method requires specific information about the structural properties and geometry of the building and the loading on the structure. The authors intended the procedure to be used for complex or critical structures such as hospitals and communication centers.

One stated purpose of the three methods for evaluating existing buildings was to determine the risk to life safety under natural hazard conditions. The authors claim that while the safety of the building occupants cannot be evaluated directly, the safety of the occupants can be related to the structural performance and the resulting damage to the building. Without further discussion on how building damage may be quantitatively related to occupant safety, the remainder of the report dwelled on evaluation of damage. Although the authors did not specify an acceptable level of damage, they pointed out that such a specification varied with the usage and function of the structure. They recommended that the interpretation of the level of damage predicted by the proposed methods 'as they relate to life and property loss' be exercised by the user.

Hasselman et al., (1980) developed a computer program to assist building and safety officials in calculating the damage potential of multi-story buildings exposed to earthquake, severe wind, and tornado forces. The assumption in this work, as in the Culver study, is that the potential safety of the occupants is related to the damage. Building interstory drift was again taken as the indicator of damage. The determination of damageability characteristics of the building components was based on expert opinion and a limited amount of data. The final damage to the structure was reported as a percentage of replacement cost on a floor-by-floor basis. Obviously the city official in making any safety decision must take the responsibility of relating building damage level to occupant safety.

Recently Mehta et al., (1981) proposed a procedure for predicting wind damage to buildings. Two procedures, one subjective and the other analytical, were used to evaluate potential windstorm damage to existing buildings. In the subjective approach an on-site survey of the building is performed to establish structural details. The resulting damage to the structure is inferred by using damage experience from similar structures. In the analytical approach a structural analysis is performed based on a knowledge of the prevailing aerodynamic forces and the strength of the building components used in the structure. Results of the analysis provided a scenario of the sequence of damage to the structure as a function of windspeed. The authors also claim that by using a wind-hazard probability model and the results of the deterministic structural analysis, the probability of damage sequence can be determined.

More recently Spangler and Jones (1984) were among the first to address the specific problem of structural certification of potential hurricane shelters for vertical evacuation (i.e., the use of deliberately-selected, multi-story structures as shelters). The authors proposed the following procedure to evaluate a structure: 1) identify potential shelters, 2) collect relevant information on the structure, 3) physically inspect the structure, 4) physically inspect the surrounding terrain, 5) analyze the collected information, and 6) rate the safety of the building. The safety of the structure was based either on a subjective opinion or a static structural analysis of the building. The resistance of the structure was expressed in terms of the magnitude of the hurricane (expressed in terms of the Saffir-Simpson scale) that the structure could 'safely' withstand. The decision that a structure could withstand a hurricane of a given magnitude was based on the allowable stress and stability criteria defined by existing building codes.

Decision Environment for the Feasibility of Vertical Evacuation

The field of risk analysis is comprised of three parts (Burton and Pushchak, 1984): 1) the identification of the risk, 2) the measure or estimation of the risk, and 3) the evaluation of the risk. It is now generally agreed that the field of risk analysis extends beyond the boundaries of science and engineering and indeed includes the social process of judging safety or determining the acceptability of risk (Starr, 1969). While rather complete risk analyses have been carried out for a number of industries and certain problematic situations (e.g., siting of hazardous wastes) (Burton and Pushchak, 1984), no such analysis has yet been applied to ascertain the structural feasibility of vertical evacuation.

As far as assessing risks for which no precedence exists, vertical evacuation may be considered to belong to the class of new technologies such as nuclear power stations, toxic dumping sites or automotive air bags. As such, many of the difficulties and controversies encountered in the decision process leading to the acceptance of a given technology are expected to be repeated for vertical evacuation along with the nuances peculiar to vertical evacuation. For example, many questions will develop out of fear of the risks from using vertical evacuation. Can these risks be calculated using current state-of-the-art structural theory? Even if the risk is calculable or estimable: will experts agree on the validity of the results? Conversely, if vertical evacuation were to be employed: what are the benefits (lives saved) of such an option and do these benefits outweigh the risks (e.g., fatalities and cost to upgrade)?

Since no generally accepted structural standards exist which attempt to certify a structure for use as a vertical evacuation shelter (even the emergency conditions under which vertical evacuation may be deemed necessary are undefined), the structural feasiblity of vertical evacuation will have to be determined on the basis of some form of risk-benefit analysis. That is, the safety of structures must be determined on the basis of an acceptable level of risk. What level of risk is socially acceptable to the individual or the governing body will depend upon the extent to which the benefits outweigh the risks for a given scenario. Since the balance of risks and benefits is a function of the scenario and its location, levels of acceptable risks for vertical evacuation will vary with the location, the scenario, and the options available (Derby and Keeney, 1981).

The possible scenarios and options will depend upon the characteristics of a given community: what may happen in a coastal community on the mainland adjacent to ample exit routes may be totally different from the situation on a barrier island with limited egress. Consequently, the following example scenarios and options, that are probable in a coastal community threatened by a hurricane, are presented.

Scenario I: "Horizontal evacuation plans exist and have been successfully executed many times in the past. Contingency plans also exist for some level of vertical evacuation. A hurricane in impending and the order is given to evacuate. The amount of time available for evacuation is considered 'safe'. Under what conditions may vertical evacuation be considered the better option?"

Several communities have developed contingency plans for evacuation in the face of an impendent hurricane. The major variables influencing the risks of evacuation are the number of people to be evacuated, outflow rate characteristics of the evacuation arteries, the time the evacuation order is given relative to the estimated time to landfall of the hurricane, the instantaneous meteorological and climatic conditions, the public response to instructions from the authorities, the efficiency of the communications, and the time of day (Bastien et al., 1985).

If the contingency arrangements are executed as planned, there is, theoretically, no need for vertical evacuation. However, from a risk assessment perspective, if it is shown that the risk (e.g., the expected number of fatalities) involved in the horizontal evacuation under these ideal circumstances is greater than the corresponding number of injuries or fatalities if vertical evacuation were used, then vertical evacuation may be a feasible option even for this case.

Scenario II: "Horizontal evacuation plans exist for the community but they have never been tested. The community has no experience upon which to predict how the populous or the transportation system will function. Contingency plans also exist for vertical evacuation. A hurricane is impending and the order is given to evacuate. The time allocated to effect the evacuation is considered 'safe'. Under what conditions may vertical evacuation be considered the better option?"

In an operation as complicated as evacuating perhaps hundreds of thousands of people, it would be considered miraculous if all events went as planned. Too many uncertainties are involved in such an operation and too many undefined synapses exist at which mishaps may occur. For example, there are uncertainties in predicting the trajectory of the hurricane, uncertainties in knowing the number of people who would heed the call to evacuate, and uncertainties in predicting the effectiveness of escape routes. Furthermore, in the event of accidents, there is uncertainty in the response of clearing crews - hours may pass before the flow of traffic resumes. To complicate the resolution of such problems, a hurricane may be in the vicinity. High winds and rain are expected to flood coastal highways and reduce vehicular traffic flow. The entire system (which consists of the impending hurricane, the evacuation plans, the response to the evacuation recommendation, and the performance of the transportation network) is riddled with uncertainty.

Given the many events, and combination of events, that may lead to the malfunctioning of the evacuation plans, it is reasonable to expect that a significant percentage of the population can be stranded, and, therefore, exposed to the full fury of the hurricane hazard. If evacuation plans are examined and scenarios involving potential malfunctioning modelled, it may then be possible to estimate, however crudely, the percentage of stranded evacuees. Further estimates then can be made of the probable number of injuries and fatalities associated with a given scenario. On the other hand, assuming that a vertical evacuation option is selected and the number of stranded residents were sheltered in appropriate structures, a second set of calculations can be made to determine the probable magnitude of injuries and fatalities. Furthermore, assuming that no other options are available, vertical evacuation is structurally feasible so long as its use results in a net saving of lives.

Scenario III: "Despite previous orders to evacuate many inhabitants remain exposed to the hazard. The hurricane will strike imminently. Contingency plans for vertical evacuation exist. How should these stranded citizens be sheltered?"

In many coastal regions a certain percentage of residents will refuse to evacuate, deciding instead to ride out the storm at home. Although the reasons for such refractory behavior are beyond the scope of this inquiry, these people may not be taking advantage of the best shelter available. The question is: Where should these people be advised to seek shelter? Under such conditions the remaining residents may have at least three choices: 1) stay at home, 2) seek out a traditional Red Cross-type shelter, or 3) use a designated vertical evacuation shelter. If a risk analysis of the options shows that the use of vertical evacuation shelters would result in the least lives lost and the greatest number of lives saved, vertical evacuation is structurally feasible in this scenario.

Scenario IV: "A hurricane is approaching a barrier island. Two days prior to this event, the causeway connecting the island to the mainland became dysfunctional. Contingency plans for vertical evacuation exist. Is vertical the best option in this case?"

In several situations - for example, the case in which a barrier island is connected to the mainland only by water transportation or in which the only escape route is inoperative - horizontal evacuation may not be an option and consequently the island inhabitants must find the best shelter on the island. The choices to the potential sheltered population or to the authorities in this situation are similar to the previous scenario in that residents may seek refuge in their homes, a traditional shelter, or a designated vertical evacuation shelter. It thus seems reasonable that the inhabitants should seek the shelters that subject them to the least-risk and provide the maximum benefit to the community: that is, the option which indicates the least cost in lives and the greatest number of lives saved.

Structural Information Required by Decision-Makers

Based on the scenarios in which vertical evacuation is a potential option, it appears that none of the above approaches (Culver et al., 1975; Hasselman et al., 1980; Mehta et al., 1981; Spangler and Jones, 1984) proposed to evaluate the performance of a structure in a wind hazard can be used in their present form. All of these structural assessment methods fail to account quantitatively for the consequences (i.e., injuries or fatalities) resulting from the damage. Furthermore, none of the methods systematically account for the uncertainties in the forces to which the structure will be subjected, the uncertainties in the strength characteristics of the structural elements, or the uncertainty in the method of analysis used to determine the structural response. Moreover, the manner in which the results are presented (namely in terms of expected damage, damage sequence, or the degree to which a particular code is satisfied) makes it difficult to rationally establish the relative safety of different buildings and difficult to compare the safety of a building to the risks involved in horizontal evacuation.

In the process of evaluating the feasibility of vertical evacuation as a general concept, decision-makers must know in the most precise terms and, using the best information available, understand the nature of the risks and benefits that may be associated with the structural aspects of vertical evacuation. These technical predictions, in the form of risk magnitudes, may then be combined with and played against a variety of equally important political, economic, psychological, legal, and ethical issues to produce a balanced and equitable decision. Since the bottom line of the operation is to maximize the saving of lives and to minimize injuries, the performance of a given structure should be expressed in terms directly related to these measures. Although the problem of predicting injuries or fatalities as a function of damage to a structure has been conspicuously avoided in the great majority of structural safety assessment procedures, in order to evaluate the feasibility of a concept such as vertical evacuation, such predictions, nevertheless, must be made. Assuming that such measures of risk are used, then it would be possible not only to compare the protection offered by two different types of structures but also to compare the relative safety of two different alternatives (e.g., vertical evacuation and horizontal evacuation). Therefore, we propose that the risks be measured in basic units of fatalities and injuries and the benefits be measured in terms of lives saved and injuries prevented.

Approach to Obtaining the Desired Information

Fortunately, several investigators have pioneered studies that attempt to estimate the risks of fatalities (or other costs) associated with utilizing a given structure subjected to a variety of hazards (Whitman et al., 1975; Lee and Collins, 1977; Gorman and Moses, 1979; Whitman et al., 1980; Whitman et al., 1980). In an extensive research program at the Massachusetts Institute of Technology Whitman et al., (1975) developed a method, entitled "Seismic Design Decision Analysis" (SDDA), aimed at selecting the optimal level of seismic resistance for an individual structure or group of structures. The objective of the research effort was to develop an explicit procedure for balancing costs and risks. The method considered the cost of providing increased seismic resistance, the structural damage that may occur during future earthquakes, and the social consequences of such damage. Although the method was illustrated for buildings subjected only to earthquakes, conceptually there is no reason why the method cannot be extended to arbitrary structures subjected to arbitrary hazards (including hurricanes) provided the information needed to perform a structural analysis is available.

Lee and Collins (1977) also presented a general risk assessment methodology for structures. The objective of the method was to minimize the risk, i.e., the chance of loss of life or personal injury, or of economic loss from damage to facilities, resulting from the occurrence of the hazard. The hazards considered were fire, earthquake, wind, and flood. The methodology systematically combined the following elements: 1) a quantitative description of the hazard (for example the magnitude of a hurricane and the associated return period); 2) a description of the assets exposed to the hazard; 3) a description of the current state of the structure, i.e., its vulnerability; 4) a relationship - theoretical or empirical - that can relate the hazard level to the expected damage; and, 5) a risk equation. The risk equation allows the computation of an average annual loss or the risk of the mission failure.

While the original motivation of Lee and Collins' methodology was to permit the selection of different funding levels to meet budgetary restrictions and to optimize the level of protection from the stated disaster, conceptually their approach is identical to that used by Whitman et al., (1975) and likewise can be extended to evaluate the risks associated with using vertical shelters. In both cases, many parts of the general model are based on existing empirical models and data are readily available in the technical literature. However, the parts of the model which attempt to predict the damage to the structure and to estimate the losses given a specific level of damage are not as well founded.

Three outstanding and persistent problems in the general areas of damage prediction and loss prediction follow. The first problem centers around quantitatively defining various damage states. In the Whitman et al., (1975) approach, the structure may sustain damage ranging from light, which may manifest itself as no more than a few hairline cracks - as in the case of a reinforced concrete structure - to total collapse of the structure. Between the extremes are a series of damage states - moderate, severe, and total. The problem is to quantitatively distinguish between the various damage states, particularly adjacent states, and to relate these states to commonly agreed upon structural indicators such as stiffness degradation (partial or total).

The second problem involves relating damage to injuries and fatalities. If a structure is damaged, if only to a minor degree, it is possible that an injury or a fatality may result from that damage. For example, excessive interstory drift may cause cracking in a ceiling which, in turn, may cause material to be dislodged. And, even though the main structural frame has sustained no damage a potential casualty resulting from the dislodged ceiling material may range from a minor injury to a fatality. Given the innumerable ways such accidents may occur, it could be quite difficult to predict or collect data representing such a range of events. Fortunately, both areas are being researched (Anagnostopoulos and Whitman, 1977; Scholl et al., 1982).

A third problem is to rationally incorporate into the analysis the damage sustained by the nonstructural portions of the structure - the doors and windows, exterior cladding, roof, and internal partitions - and the consequences of the damage on the safety of the occupant. Although, for example, the cladding does not receive the same degree of engineering attention as does the frame or the foundation, in a hurricane environment the consequences of cladding failure (collapse) may be equally as devastating to the building occupant as the consequences of the failure (collapse) of the structural frame.

The three difficulties mentioned may be circumvented in the following way. First, assume that if a structure is subjected to hurricane-force winds, then, although the structure may sustain any of the damage states listed by Whitman et al., (1975) the fatalities resulting from the eventuality of any **non-collapse** damage states are insignificant compared to the proportion of fatalities resulting from **collapse.** Thus, if the damage condition corresponds to an unambiguous failure state such as collapse, then there is no need to distinguish between qualitative damage states. Accordingly, critical structural states corresponding to, for example, the collapse of the major structural frame, collapse of the exterior walls, or collapse of the roof become the target of analysis.

The risks of collapse of structural subsystems can be determined using the methods of structural reliability (ASCE, 1972). Structural reliability theory is concerned with the rational treatment of uncertainties (i.e., uncertainties in loads, material properties, and theories of structural behavior) in structural engineering, and with the methods of assessing the safety and serviceability of structures (Thoft-Christensen and Baker, 1982). It is a subject which has grown rapidly during the last decade and it has evolved from being a topic for purely academic research to a set of well-developed methodologies with an increasing range of applications.

The second difficulty - the problem associated with the complexity of incorporating injuries in the analysis - may be circumvented by taking as the measure of risk the number of fatalities resulting from the collapse. To compute the number of fatalities, one must know the probability of the joint event that the structure, or one of its subsystems, collapses and an occupant is killed. Such a probability can be estimated using 1) the probability of collapse of the subsystem as developed in the last paragraph using reliability theory and, 2) the probability of being killed, given that the structure has collapsed. The latter probability will depend upon the nature of the construction and the specific details of the structure. Empirical estimates of such probabilities can be based on data developed for various classes of structures.

Finally, the information on the failure (collapse) characteristics of various subsystems of the building and the consequences of such failures can be integrated into a single analysis by using the techniques from Fault-Tree Analysis (Hammer, 1980). The method generates a diagram (called a fault tree) which is a model of the event relationships for the system under study. This method has been used in such diverse applications as the risk analysis of nuclear power plants (Rasmussen, 1974), the safety analysis of piping systems (Abes et al., 1985), and the reliability analysis of construction field instrumentation (Kuroda and Miki, 1985). Fault-Tree Analysis can also provide a rational, conceptual, framework to evaluate the safety of occupants in a structure exposed to a wind hazard. In the next chapter, such a model will be developed for a typical hurricane shelter.

CHAPTER III

A METHOD TO EVALUATE OCCUPANT SAFETY

In the last chapter we found that in most of the traditional approaches aimed at evaluating the safety of existing buildings, the protection offered by the structure was evaluated on the basis of either the level of damage sustained by the structure, or the extent to which a structure satisfied a particular building code. For the same loading environment one of two structures is considered safer if 1) the factors of safety of its elements are larger, or 2) the predicted damage sustained by the structure is smaller. In all cases, the evaluatory criteria for structural safety is tied to the structure. However, such criteria may not guarantee the safety of the occupants of the structure. For example, an occupant may be injured or killed as the result of a falling ceiling or a collapsing partition. Furthermore, factors of safety for structural elements or probabilities of failure of a structural frame may not have the same interpretation for different structures. It is conceivable, for example, that two different structures (say a ductile steel structure and a brittle masonry structure) having identical failure probabilities, or experiencing the same magnitude of damage, may result in different levels of injury or death to occupants.

Since in a vertical shelter the potential for injury resulting from nonstructural causes may be equal to, or greater than, that resulting from structural failure, it is fitting to propose a method of structural evaluation which focuses directly on the safety of the occupant, and which simultaneously accounts for the structural and the nonstructural failure characteristics of the structure.

This chapter presents a methodology to evaluate the protection provided by a structure from the perspective of an occupant of the building. The method of Fault-Tree Analysis is reviewed. Using results from the existing theory, a fault-tree model of a typical vertical evacuation shelter is developed. The model is analyzed to provide basic modes of failure and expressions for the probability of a fatality. Finally, a numerical example is presented to illustrate the methodology.

Fault-Tree Model of a Vertical Evacuation Shelter

Overview

Fault-Tree Analysis can provide a rational and a conceptual framework to evaluate the safety of occupants in a structure exposed to a hurricane. The Fault-Tree Analysis process starts with a defined 'undesired' event (i.e., the top event) then proceeds by induction to develop a set of contributory events which can cause the top event. The process is continued for each of the contributory events until the resulting contributory events become basic events (i.e., events for which statistical information is readily available or can be developed by analysis). The method generates a diagram (called a fault tree) which is a model of the event relationships for the system (Barlow and Lambert, 1975). A description and definition of the symbols used in developing the model and a description of a typical fault-tree are provided in Figures 3.1 and 3.2. This method has been

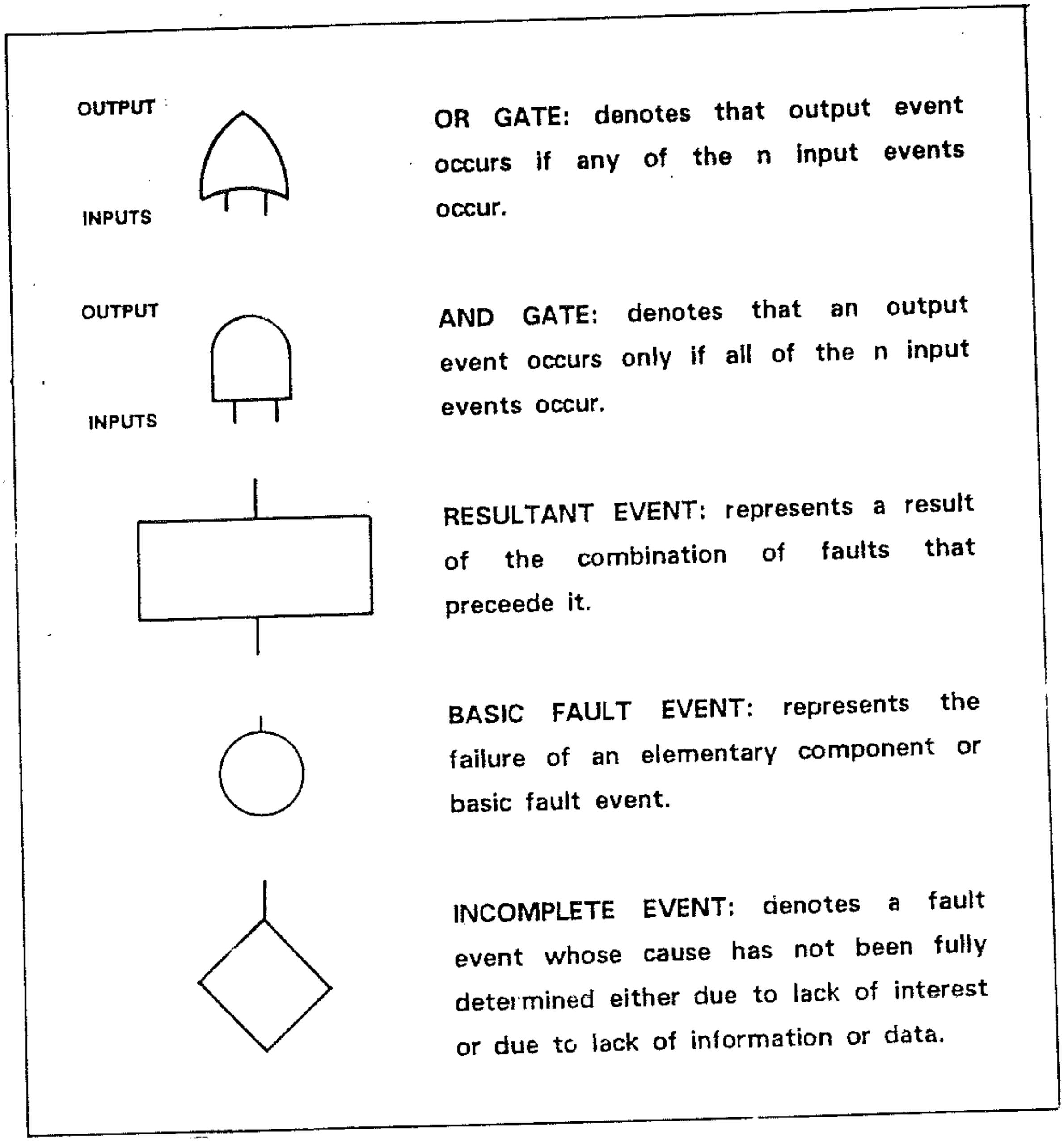


Figure 3.1. Definition of the Symbols

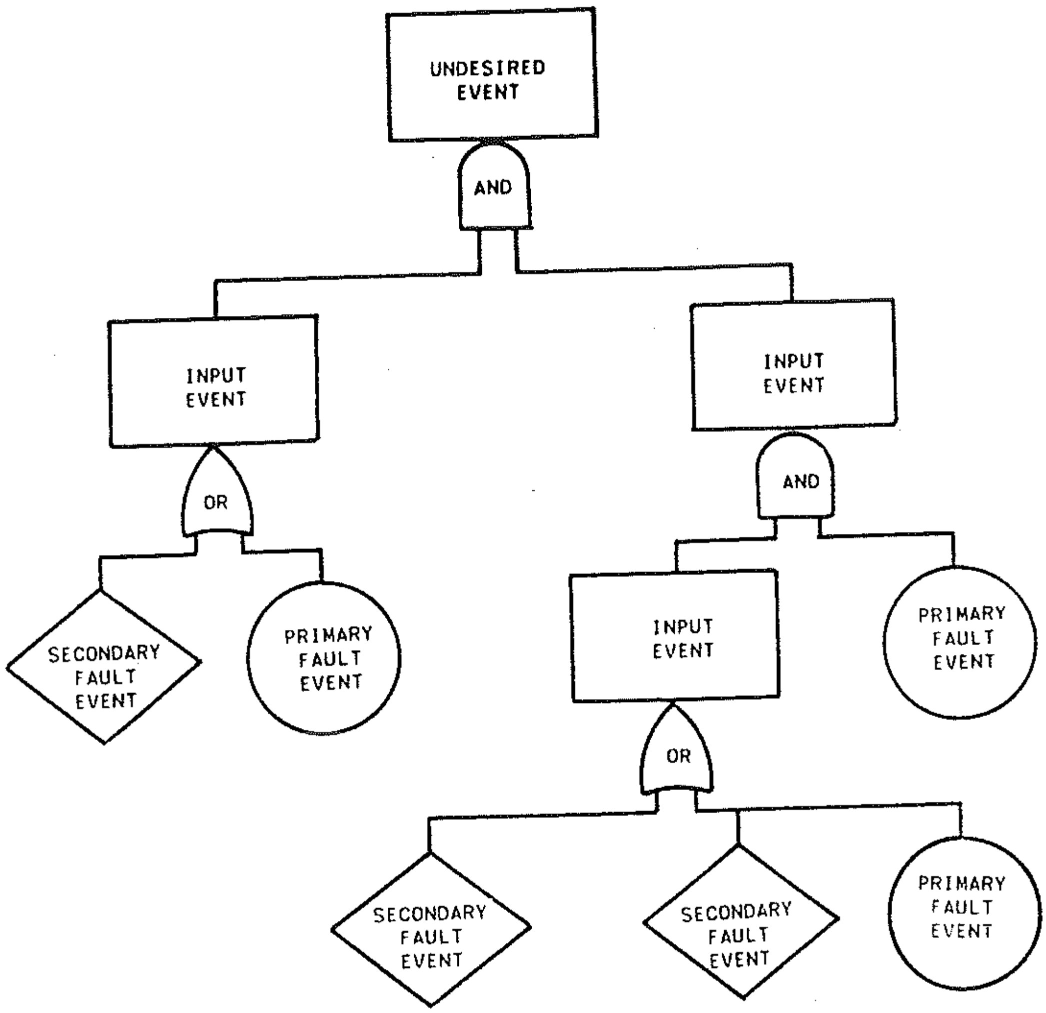


Figure 3.2. Typical Fault Tree

used in such diverse applications as nuclear power plants (Rasmussen, 1974; Cummings, 1975), the safety analysis of piping systems (Abes et al., 1985) and the reliability analysis of construction field instrumentation (Kuroda and Miki, 1985).

Definition of the Undesired Event

The system of interest in this study is any potential vertical evacuation shelter. The structural and nonstructural elements of the building include a foundation, a structural framing system to transfer the loads to the foundation, exterior walls or cladding, openings in the exterior walls (doors and windows), a roof, internal partitions and floors among others, e.g., the mechanical system. In addition, each structure may or may not have been designed according to some building code and has accumulated a unique damage history.

In this study the undesired event is a fatality or an injury which occurs during the course of the hurricane. However, since exactly what constitutes an injury may be difficult to define, the top event will be limited to potential human fatalities.

Development of the Fault-Tree Model for a Vertical Shelter

Figure 3.3 depicts a typical stage in the development of the fault-tree model for a general building structure. According to Figure 3.3, if a fatality occurs, then the occupant has been killed by 1) crushing by structural parts or missile impact, 2) drowning, 3) fire, or 4) electrocution. It is assumed that the fatality occurs while the individual is within the confines of the structure. In

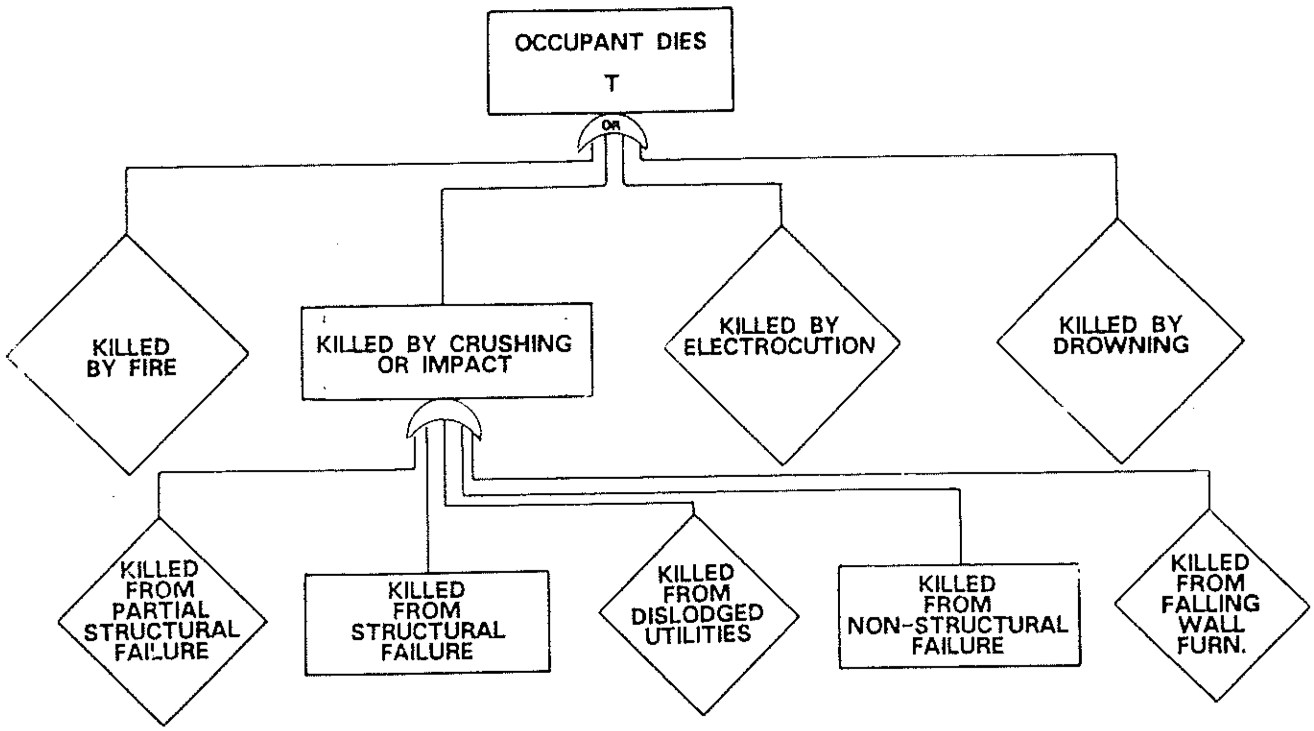


Figure 3.3. Typical Step in Fault-Tree Generation

this study death by fire, death by electrocution, and death by flooding are not developed further. They are enclosed in diamond boxes, since it is assumed that death resulting from structural or nonstructural failure will be the most likely in a hurricane environment.

This inductive procedure is continued until the tree is resolved into basic events denoted by the circles. Statistical information describing these events either exists or can be developed analytically. The remainder of the fault tree, developed by continuing the process initiated in Figure 3.3, is shown in Figure 3.4. Note that sixteen basic events (X_1-X_{16}) have been identified and defined in Table 3.1.

The fault tree presented in Figure 3.4 represents a comprehensive model that relates the basic fault events to occupant safety. The model contains several attributes. First, this model of occupant safety is general (i.e., the same formulation can be applied to many structural types with little or no modification). Second, the model is highly integrative (i.e., it pulls together the occurrence of structural as well as nonstructural failures). As will be shown later, it also allows a smooth interface between existing methods of safety evaluation, such as reliability analysis (e.g., water forces, wind-borne debris), and occupant safety. The model also integrates the occurrence of other hazards that may simultaneously occur during a hurricane. Third, the model is comprehensive. Assuming that data are available, the relative importance of each hazard type may be determined. Put another way, the model clearly states what informa-

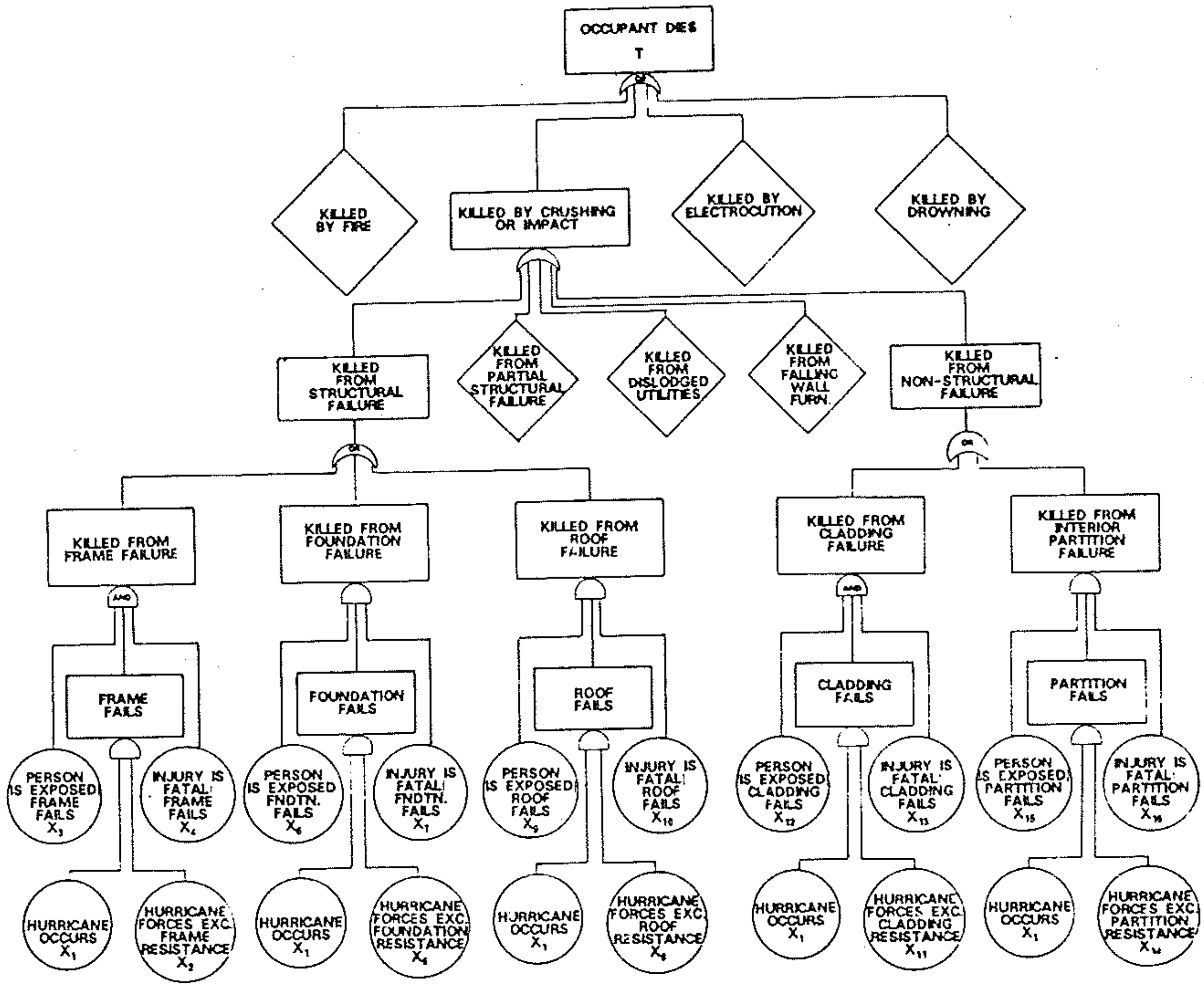


Figure 3.4. Fault-Tree Model of a Vertical Shelter

Table 3.1. Definition of Basic Events

Event	Description of Event
$T \equiv$	Occupant Dies
$X_1 \equiv$	Hurricane Occurs
$X_2 \equiv$	Hurricane Forces Exceed Frame Resistance
$X_3 \equiv$	Person is Exposed|Frame Fails
$X_4 \equiv$	Injury is Fatal|Frame Fails
$X_5 \equiv$	Hurricane Forces Exceed Foundation Resistance
$X_6 \equiv$	Person is Exposed|Foundation Fails
$X_7 \equiv$	Injury is Fatal|Foundation Fails
$X_8 \equiv$	Hurricane Forces Exceed Roof Resistance
$X_9 \equiv$	Person is Exposed|Roof Fails
$X_{10} \equiv$	Injury is Fatal|Roof Fails
$X_{11} \equiv$	Hurricane Forces Exceed Cladding Resistance
$X_{12} \equiv$	Person is Exposed|Cladding Fails
$X_{13} \equiv$	Injury is Fatal|Cladding Fails
$X_{14} \equiv$	Hurricane Forces Exceed Interior Partition Resistance
$X_{15} \equiv$	Person is Exposed|Partition Fails
$X_{16} \equiv$	Injury is Fatal|Partition Fails

tion is needed to perform an analysis of occupant safety.

Qualitative Analysis of the Shelter Model

An important purpose of a fault-tree model is to determine when the occurrence of basic events can cause the occurrence of the top event. This condition can be investigated by determining what are called the "minimum cut sets" of the tree (Barlow and Lambert, 1975). Minimum cut sets may be thought of as basic modes of system failure. It is also important to note that minimum cut sets are invariant to properties of the basic events themselves; the cut sets depend only upon the topology of the fault tree. Once the minimal cut sets for a tree have been determined, the fault tree can be represented in a nonredundant fashion (i.e., no basic events are repeated) by the union of all the minimal cut sets of the system. The minimal cut sets for this system are shown in Table 3.2.

Quantitative Analysis of the Shelter Model

The objective of a quantitative analysis is to determine the probability of occurrence of the top event. From fault-tree theory, the probability that a system fails equals the probability that one or more of the system's minimal cut sets fail. Note that if the minimal cut sets contain common events (for example, the occurrence of the hurricane), then the probability of the occurrence of the top event cannot be obtained by a direct combination of the output from the various gates of the tree. The common events can be eliminated by using certain identities from set theory. The result of these manip-

Table 3.2. Minimal Cut Sets

Set No.	Elements of Set
1	[x_1, x_2, x_3, x_4]
2	[x_1, x_5, x_6, x_7]
3	[x_1, x_8, x_9, x_{10}]
4	[x_1, x_{11}, x_{12}, x_{13}]
5	[x_1, x_{14}, x_{15}, x_{16}]

ulations is a nonredundant fault tree.

The probability of the top event in a fault tree is obtained by utilizing the Boolean algebra properties of the AND and OR gates. If S_1, $S_2, \ldots, S_n$ are the input events to an AND gate, the output event, S_o, is given by:

$$S_o = S_1 \cap S_2 \cap S_3 \cap \ldots \cap S_n \quad (3.1)$$

where the symbol $\cap$ represents the intersection of the events. If the same events are inputs to an OR gate, the output event Y_o is given by:

$$Y_o = S_1 \cup S_2 \cup S_3 \cup \ldots \cup S_n \quad (3.2)$$

where the symbol $\cup$ represents the union of the events.

To obtain the AND and OR gate top event probability, the following formulae are used in conjunction with the laws of probability. For an AND gate with n statistically independent inputs, S_1, ..., S_n, the top event probability is given by:

$$P(S_1 \cap S_2 \cap \ldots \cap S_n) = P(S_1)P(S_2) \ldots P(S_n) \quad (3.3)$$

The probability of occurrence of an output event for an OR gate is obtained using the addition law of probability. For example, for an OR gate with two statistically independent inputs, Y_1 and Y_2, the top event probability is given by:

$$P(Y_1 \cup Y_2) = P(Y_1) + P(Y_2) - P(Y_1) * P(Y_2) \quad (3.4)$$

Using the definitions of the basic events defined in Table 3.1, the following new events are defined:

$$Y_1 = X_2 \cap X_3 \cap X_4 \qquad Y_2 = X_5 \cap X_6 \cap X_7$$

$$Y_3 = X_8 \cap X_9 \cap X_{10} \qquad Y_4 = X_{11} \cap X_{12} \cap X_{13} \quad (3.5)$$

$$Y_5 = X_{14} \cap X_{15} \cap X_{16}$$

Then the top event "T" is given by:

$$T = (X_1 \cap Y_1) \cup (X_1 \cap Y_2) \cup (X_1 \cap Y_3) \cup (X_1 \cap Y_4) \cup (X_1 \cap Y_5) \quad (3.6)$$

Using the distributive law, the repeated event X_1 can be eliminated to give:

$$T = X_1 \cap (Y_1 \cup Y_2 \cup Y_3 \cup Y_4 \cup Y_5) \quad (3.7)$$

The above equation can be used to construct the nonredundant fault tree shown in Figure 3.5. In addition, the probability of the top event is now given by:

$$P(T) = P(X_1)[P(Y_1) + P(Y_2) + P(Y_3) + P(Y_4) + P(Y_5) + \ldots] \quad (3.8)$$

in which,

$$P(Y_1) = P(X_2)P(X_3)P(X_4) \qquad P(Y_2) = P(X_5)P(X_6)P(X_7)$$
$$P(Y_3) = P(X_8)P(X_9)P(X_{10}) \qquad P(Y_4) = P(X_{11})P(X_{12})P(X_{13}) \quad (3.9)$$
$$P(Y_5) = P(X_{14})P(X_{15})P(X_{16})$$

The engineering effort is now focused on determining the probabilities of occurrences of the basic events, and using Equation (3.8) to estimate the probability of occurrence of the top event.

Risk Models for Vertical Shelters

If N is the number of people sheltered in the structure, the risk associated with using the structure, E[N] (the expected number of fatalities), may then be estimated using the equation:

$$E[N] = P[T]N \quad (3.10)$$

where P[T] is given in Equation (3.8). Some investigators, however, find the definition of risk in Equation (3.10) to be lacking in some respects. For example, if for two alternative options, a and b, $P[T]_a N_a = P[T]_b N_b$ where $P[T]_a >> P[T]_b$ how does one decide between

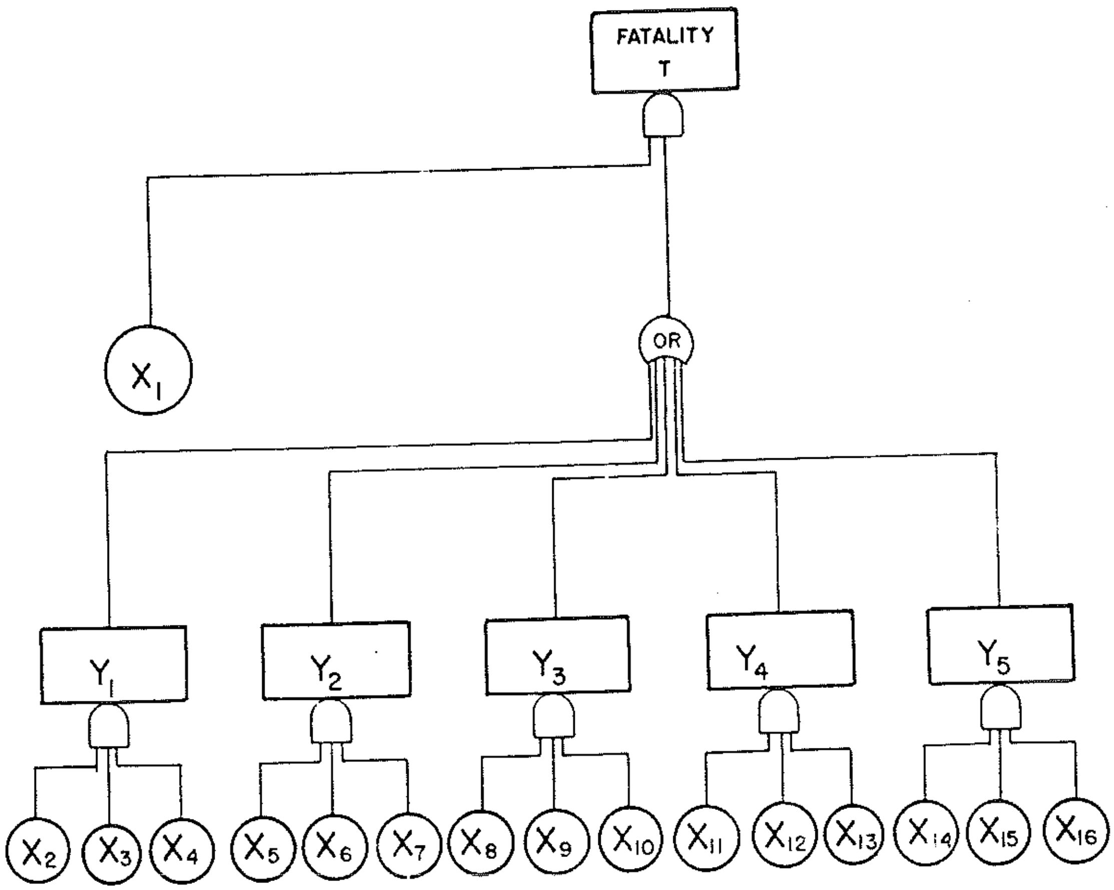


Figure 3.5. Nonredundant Fault Tree

them on the basis of expected risk? One way to overcome this limitation is to represent risk via so-called risk curves (Kaplan and Garrick, 1981) or 'risk profiles' (Fiksel and Rosenfield, 1982). The risk curve, denoted by R(x), is the complement of the probability distribution function of the annual losses and is defined to be:

$$R(x) = P[\text{annual losses exceed } x] \tag{3.11}$$

where x is some realization of the random variable X. Closely associated with the risk curve above is the "conditional risk profile" which for a specific hazard E is defined to be:

$$R(x|E) = P[\text{losses exceed } x \text{ given that event } E \text{ occurred}] \tag{3.12}$$

Risk curves may be generated as follows. First a list of N scenarios, each with its likelihood of occurrence and the consequence of that scenario, is generated. Each line in the list is sometimes referred to as a triplet: e.g., the i^{th} line will consist of the triplet (s_i, p_i, x_i) - where s_i is a scenario identification, p_i is the probability of the scenario, and x_i is the consequence of the scenario (Kaplan and Garrick, 1981). Second, if the triplets are arranged as in Table 3.3 with the consequences ordered according to the rule $x_1 < x_2 < \ldots < x_n$, the cumulative probability, P_i, in the fourth column, can be determined by summing the p_i terms from the bottom. Third, the family of points (x_i, P_i) are now plotted to give a staircase function. The smoothed curve through this staircase function is the risk curve R(x). A typical set of risk curves are shown in Figure 3.6. Note that the expectation of the consequence E[X] may be given by:

$$E[X] = \int_{-\infty}^{\infty} x[d\{1-R(x)\}/dx]dx \tag{3.13}$$

Table 3.3. Construction of Risk Curves

Scenario (1)	Consequence (2)	Occurrence (3)	Cumulative Probability (4)
1	X_1	p_1	$P_1 = \sum_{k=1}^{N} p_k$
2	X_2	p_2	$P_2 = \sum_{k=2}^{N} p_k$
.	.	.	.
.	.	.	.
i	X_i	p_i	$P_i = \sum_{k=i}^{N} p_k$
.	.	.	.
.	.	.	.
N	X_n	p_n	$P_N = p_n$

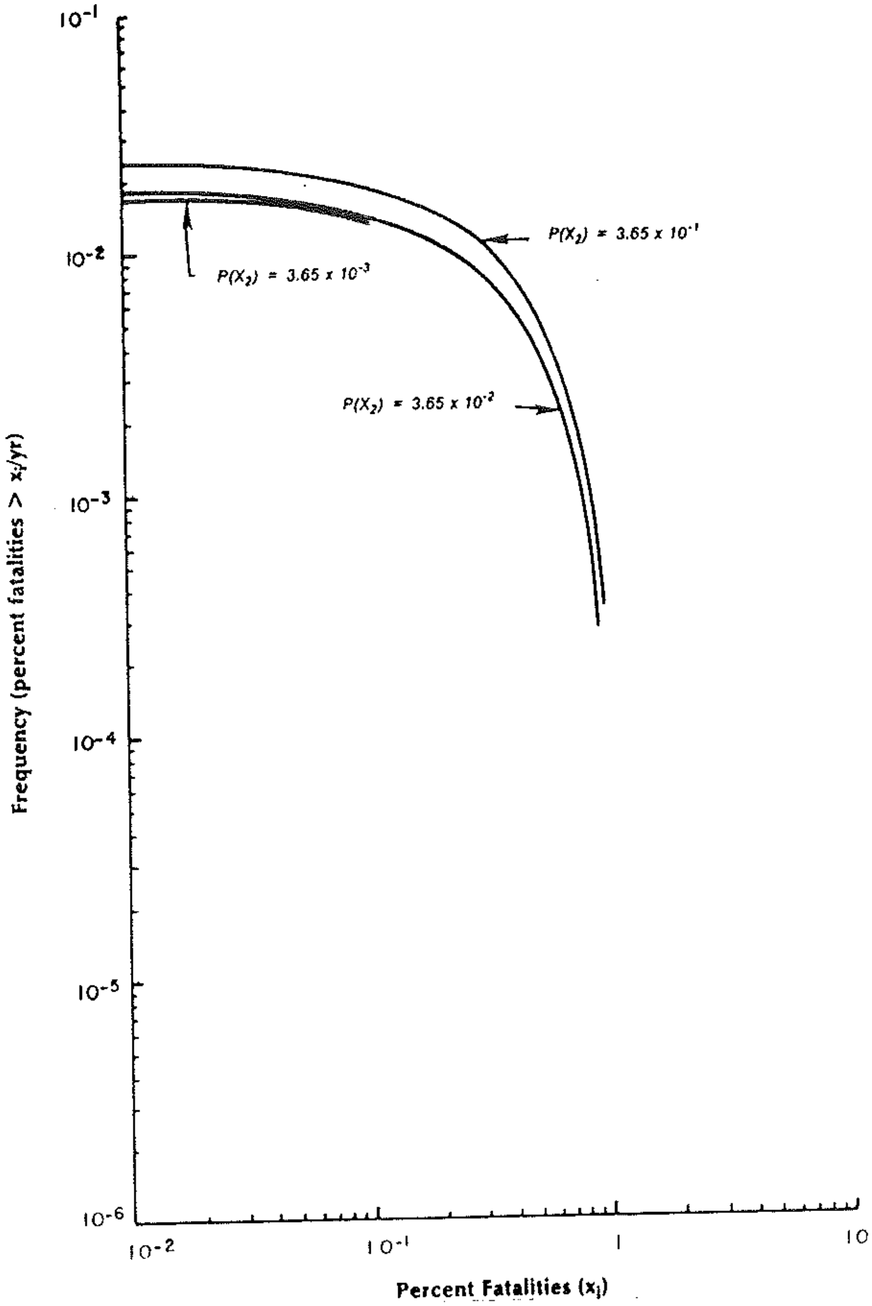


Figure 3.6. Typical Risk Curves with Probability of Frame Failure as a Parameter

which can be shown to be the area under the curve (Rowe, 1977). Similarly the variance of the losses may be computed from

$$Var[X] = \int_{-\infty}^{\infty}(x - E[x])^2[d\{1 - R(x)\}/dx]dx \qquad (3.14)$$

If we define the random variable X to be the fraction of the building inhabitants to be killed and the event E to be a hurricane of some predetermined intensity, then the fault-tree model may be used to generate risk curves by making the substitutions shown in Table 3.4. For each hurricane the realization of the random variable X, x_i, will take on values between zero and one. Assuming that data are available to determine the probability of the basic events, the risk curve is determined from the collection of points (x_i, $P[(X > x_i)|\text{Hurricane Occurs}]$).

Probability Assignment for Basic Events

The events needed for input into the present model may be classified into four categories: statistics describing the hurricane (X_1), statistics describing the reliability of the building components (X_2, X_5, X_8, X_{11}, X_{14}), statistics describing the exposure (X_3, X_6, X_9, X_{12}, X_{15}), and statistics describing the consequences resulting from the failure of the building components (X_4, X_7, X_{10}, X_{13}, X_{16}).

In evaluating potential shelters it will be assumed that the structure receives the full force of the given hurricane. Thus $P[X_1] = 1$.

The conditional failure probabilities of the building components $P(X_2)$, $P(X_5)$, $P(X_8)$, $P(X_{11})$, $P(X_{14})$ (i.e., for the frame, foundation, roof, cladding (including doors and windows), and partitions, respec-

Table 3.4. Definition of Events

Old Event	New Description of Event
T	$(X > x_i)$ | Hurricane Occurs
X_4	$(X > x_i)$ | Frame Fails and Hurricane Occurs
X_7	$(X > x_i)$ | Foundation Fails and Hurricane Occurs
X_{10}	$(X > x_i)$ | Roof Fails and Hurricane Occurs
X_{13}	$(X > x_i)$ | Cladding Fails and Hurricane Occurs
X_{16}	$(X > x_i)$ | Partitions Fail and Hurricane Occurs

tively) will be developed using established techniques from the field of structural reliability. In summary, a structural reliability analyses proceeds as follows (Thoft-Christensen and Baker, 1982):

1. Limit state functions g_i (also known as failure modes) for the structure are developed and expressed in the form

$$Z_i = g_i(Y_1, Y_2, \ldots, Y_n) \tag{3.15}$$

   where the random variables $Y_1, Y_2, \ldots, Y_n$ represent the loads or resistances for the structure and i represents the i^{th} failure mode.

2. Using specifically developed techniques, probabilities are assigned to the event $Z_i \leq 0$ which defines the failure of the structure in the i^{th} mode, i.e.,

$$P_{fi} = P[Z_i \leq 0] \tag{3.16}$$

3. From a knowledge of the failure behavior of the individual modes, the failure probability of the entire system is estimated.

Each building may be analyzed in the following manner: 1) on the basis of a review of the plans, specifications, and the governing building codes used in designing the structure in question, limit state functions can be written for probable failure modes; 2) again, using information provided by plans and specifications in conjunction with additional information gained from a field inspection of the structure, appropriate resistance variables can be assigned to the limit state functions in (1); 3) on the basis of an analysis of the hurricane loads on the structure, numerical values can be assigned to the loading variables in the limit state function; and 4) using techniques from structural reliability failure probabilities can be computed for each failure mode and for the system formed by the collection of the failure modes. The result will be, for each building subsystem, a single number describing the probability of failure.

Since the structures considered are to be used as storm shelters, people will be exposed if failure of any of the subsystems occurs. Thus, we may set:

$$P[X_3] = P[X_6] = P[X_9] = P[X_{12}] = P[X_{15}] = 1 \qquad (3.17)$$

Note that these numbers may vary depending on the exact location of the sheltered population.

Whereas analytical techniques exist which permit the calculation of failure probabilities for structures, we know of no comparable set of techniques that would permit us to estimate the consequences of failure in terms of fatalities or injuries. Therefore, until such techniques are available, we must resort to empirical means. Although fatalities resulting from structural and nonstructural failures due to wind hazard are known to occur, we know of no systematic study which has generated a data base relating, say, the occurrence of structural damage to fatalities as a function of building materials, building geometry, and damage state. One of the few organized collection of such data relating damage to fatalities has been provided for fatalities occurring during earthquakes (Whitman et al., 1980). If we assume that the relationship between damage and fatalities is independent of the force system that caused the damage, then we may use the earthquake generated damage-fatality data to predict fatalities in a hurricane. A summary of fatality statistics for various classes of structures damaged at various levels is presented in Table 3.5 (Anagnostopoulos and Whitman, 1977; Whitman et al., 1980). Until better data are made available we will be conservative and

Table 3.5. Mean Values and Standard Deviation for Fatalities as Fraction of Total Occupants

Damage State	Wood	Masonry		Reinf. Conc; Steel	
		Residential	Commercial	≤ 5 stories	> 5 stories
Moderate	0.0001[a] (0.0013)[b]	0.0015 (0.0013)	0.0005 (0.0028)	0.00012 (0.0011)	0.00012 (0.0011)
Heavy	0.001 (0.0057)	0.002 (0.0079)	0.0045 (0.016)	0.0016 (0.0071)	0.0016 (0.0071)
Total	0.008 (0.024)	0.018 (0.038)	0.0245 (0.048)	0.021 (0.041)	0.024 (0.043)
Collapse	0.07 (0.23)	0.2 (0.25)	0.4 (0.41)	0.4 (0.41)	0.6 (0.44)

[a]Mean fraction of fatalities.
[b]Standard deviation.

assume that if any of the designated protective subsystems fails (i.e., roof, cladding, frame or foundation), the consequences of failure corresponding to frame collapse will result.

Risk Assessment of A Typical Shelter

We now demonstrate in detail the risk evaluation of a typical shelter. An actual structure located on the Gulf Coast will be analyzed. The analysis procedure consists of the following steps: 1) a description of the sources of information, 2) a description of the structure and the surrounding terrain, 3) a description of the analysis procedure, 4) a definition of failure of the building subsystems, 5) a determination of resistance and loading statistics, and 6) the risk analysis.

Data defining the structure were obtained from three sources: 1) construction plans and specifications for the building; 2) the Standard Building Code, the AISC Specifications for Design, Fabrication and Erection of Structural Steel for Buildings, and American Concrete Institute Building Code Requirements for Reinforced Concrete (ACI 318); and 3) a visual inspection of the structure and the surrounding terrain.

Description of Structure

The structure, located on the Gulf Coast, doubles as a retirement home and health-care facility. The waterfront structure, built in 1964-1965, consists of a seven-story main structure and a two-story health-care facility. Each floor in the main structure covers an area of 13,000 square feet while the health-care facility covers an area of approximately 6,500 square feet per floor. The height of the first story is 12.0 feet above ground level. The height of each succeeding floor is 9.67 feet.

Figure 3.7 shows a typical floor plan and elevation of the structure. The foundation consists of footings supported on piles (three or four per column, with a resistance of 45 tons per pile). The lateral load resisting system consists of moment-resisting reinforced concrete frame. The cladding is comprised of masonry walls and windows using 7/32-inch heavy sheet glass. In the main structure, west, southeast (short), southeast (long), and northeast elevations have 384, 18, 245, and 0 windows, respectively. The two-story part of the building has 60 and 28 windows on the southeast (long) and northeast sides, respectively. The floors and the roof are of monolithic-type reinforced concrete construction. Roofing consists of built-up asphalt and gravel.

Steps in the Evaluation Procedure

The key steps of the evaluation procedure were as follows: 1) failure functions for structural units (cladding elements, doors, windows, roof elements, etc.) were defined (to contain the complexity of the analysis, where possible linear failure functions were selected); 2) loading statistics (derived from the hurricane) and resistance statistics (derived from the materials and the design specifications) were determined for the unit; 3) approximate failure probabilities for the units were defined using Mean Value Methods

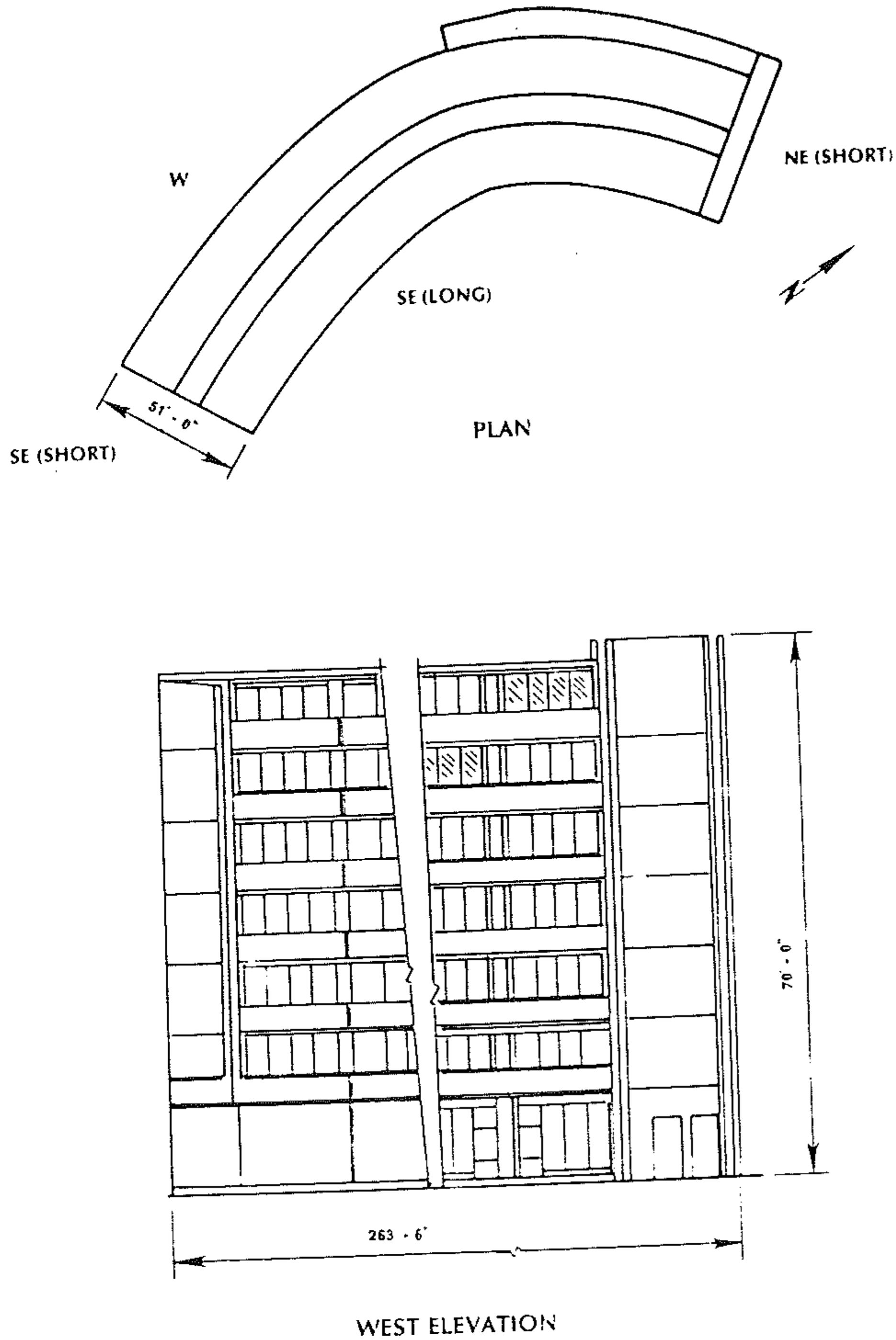


Figure 3.7. Plan and Elevation of Existing Example Structure

from Structural Reliability Theory; 4) failure scenarios for the building system were synthesized using Fault-Tree Analysis; 5) failure probabilities for the building system were computed; 6) risks of fatalities were computed using Equation (3.8); 7) modifications were made to upgrade the structure to resist a Category 3 hurricane; and 8) new risks of fatalities and costs to upgrade the structure were computed.

Frame and Foundation Failure

On the basis of historical observation, the chances that the frame or foundation of a professionally engineered structure will fail in a Category 1, 2, or 3 hurricane is quite small. In fact, no such failures have been documented for structures subjected primarily to wind. If a structure is subjected to wind and water, the cladding will usually fail first, thus relieving the load on the frame. If the foundation is well constructed (e.g., on piles), failure by scouring can also be ruled out. Therefore, in this study, if the structure was professionally engineered, and the foundation was designed to resist scouring, frame and foundation failures were ignored.

Furthermore, if the above restrictions are in effect, in Category 3 - 5 hurricanes, the chances of roof and cladding failures are many times greater than the chances of frame failure or foundation failure. Thus, if the consequences of roof and cladding failure are of the same order of magnitude as the consequences of frame and foundation failure, the risks of frame and foundation failure are small compared to the risks associated with roof and cladding failure.

Therefore, frame failure may be neglected in the risk analysis for Categories 3 - 5.

Roofing Failure

The roofing system is modelled as a two element series system consisting of the roof beams and the roof deck. Failure of the roof system occurs if a major structural unit supporting the deck (e.g., beam/joist) fails or if more than five percent of the deck area fails. To determine deck failure, the roof decking was divided into equal panel sizes and the failure probability of one panel determined. Failure characteristics of the deck system were estimated by assuming that the failure of each panel was independent and that the failure characteristics of the system could be modelled by a binomial distribution. The probability of failure of one panel was equated with the probability of a "success" in the binomial sense.

Cladding Failure

Cladding failure occurs if the cladding system provides no protection from the external hazard. Operationally, failure of the cladding system occurs if more than 40% of the cladding area on each wall on opposite sides of the building is lost. The building cladding area was divided into equal panel sizes and the reliability of one panel determined. Using the binomial distribution, as above, the failure probability of each side was determined. Assumed panel sizes for the roof and cladding systems were based on engineering judgment. Factors considered included type of construction material, spacing of cladding supports, and spacing of decking supports.

Hurricane Forces

Hurricane categories were identified by the Saffir-Simpson Scale (Simpson and Riehl, 1981). The mean and variance of the windspeed for each hurricane category were estimated assuming a uniform probability density function. For example if V_a and V_b are the lower and upper values of windspeed for a given category, the mean speed is $(V_a + V_b)/2$ and the variance is $(V_b - V_a)^2/12$.

Wind pressure acting on the structural frame was determined by increasing the basic wind pressure $[P = 0.00256V^2(H/30)^{2/7}]$ by a shape factor of 1.3 (C_D = 1.3). To model the hurricane wind field, the wind pressure acting on the building above a height of 30 feet was assumed constant. From ground level to a height of 30 feet wind pressure was assumed to vary linearly. Statistics for the windspeed and lateral pressures resulting from the five hurricane categories are listed in Table 3.6.

Wind pressures acting on the roof, cladding, and openings were determined by increasing the basic wind pressure by a shape factor of 1.5 (C_D = 1.5). The statistics describing the representative uplift pressures on the roof are listed in Table 3.7.

Water force calculations were based on procedures provided in *Shore Protection Planning and Design* (Coastal Engineering Research Center, 1966). Results of a SLOSH analysis for the site indicated that for the given site surge depths were zero for Hurricane Categories 1 and 2, and 7.7 feet, 12.3 feet, and 14.2 feet for Hurricane Catego-

Table 3.6. Hurricane Categories and Their Resulting Loading on the Structures

Hurricane Category (i)	Parameters			
	Windspeed V_i (MPH)		Wind Pressure P_i (psf)	
	mean	variance	mean	variance
1	84.5	36.75	23.76	9.52
2	103.0	16.33	35.31	15.02
3	120.5	30.08	48.32	29.80
4	143.0	48.00	68.05	60.81
5	165.5	30.08	91.15	95.26

Table 3.7. Hurricane Uplift Pressures[a] (psf)

Hurricane Category	Mean	COV
1	29.25	0.17
2	43.45	0.13
3	59.47	0.16
4	83.76	0.13
5	112.19	0.12

[a] $P = 0.00256 C_D V^2$, $\mu_{C_D} = -1.5$, $COV[C_D] = 0.1$

ries 3, 4, and 5, respectively.

Resistance Variables

The nominal design resistances (R_{design}) for the various structural elements were assumed to be the allowable loads listed on the construction drawings. If information regarding the design resistance was not available, it was estimated from the applicable building code. Mean resistances for cladding and roof elements were estimated as follows (see Appendix B):

$$\bar{R} = R_{design}/(1 - \beta(COV[R])) \tag{3.18}$$

where β is the reliability index associated with the design and COV[R] is the coefficient of variation associated with the parameters under study. Note that β may be estimated from the observed failure rate, P_f, of the various elements using the equation:

$$-\beta = \Phi^{-1}(P_f) \tag{3.19}$$

where Φ is the standard normal distribution. Values of β used in this study are listed in Table 3.8. Resistance statistics (mean and variance) were also estimated based on the values given in Table 3.9.

Risk Analysis

Using these definitions of failure for the various building components and the guidelines for defining the loading and resistance statistics, failure probabilities were computed for frame failure, foundation failure, cladding failure, and roof failure. Detailed failure functions and statistical parameters for the loading and resistance variables can be found elsewhere (Stubbs, 1987). In addition, since

Table 3.8. Reliability Indices Assumed in Study

Building Component	P_f	β
Roof elements	0.001	3.093
Wall unit	0.01	2.331
Window or door unit	0.01	2.331

Table 3.9. Additional Resistance Statistics Used in Study

Component	$\bar{R}^a/R_n$	COV	Assumed Distribution	Source
Cold formed steel members	1.17	0.17	Normal	A58.1[b]
Masonry	1.05	0.10	Normal	Engineering judgment
Reinforced concrete	1.22	0.16	Normal	A58.1[b]

[a] $\bar{R}$ = Mean resistance.
R_n = Nominal resistance.
[b] See (Ellingwood et al., 1980; ANSI, 1982).

stairwell space in the structure under consideration was limited, the exposure probabilities were set at a maximum, i.e., unity, as defined in Equation (3.17). These input values are summarized in Table 3.10, for the existing structure, and Table 3.11, for the structure upgraded to resist a Category 3 hurricane. Note that the hypothetical upgrading in this case included only modifications to the cladding and roof. Note also, in Table 3.11, that the weak link in the building system is the roof (Event X_8) which exhibits a relatively significant failure probability ($4.9X10^{-2}$) for a Category 3 hurricane.

The probabilities associated with the consequences of failure are listed in Table 3.12. These numbers have been extrapolated from the damage-death statistics for a similar structure (reinforced concrete structure, greater than five stories) subjected to earthquakes. Because the failure of either the roof, cladding, frame or foundation exposes the occupant directly to the hurricane environment, the consequences of these types of failures were set equal to the consequences of failure of the structure in an earthquake. How these assumptions may be refined is a subject of future research. The results of the analyses are shown in Tables 3.13 and 3.14. Tables 3.13 and 3.14 represent the output of the risk model, Equation (3.8).

Table 3.10. Risk Model Data Input for Existing Example Structure

Basic Event	Basic Event Probabilities — Hurricane Category 1	2	3	4	5
X_1	1.00	1.00	1.00	1.00	1.00
X_2	*	*	*	*	*
X_3	1.00	1.00	1.00	1.00	1.00
X_5	*	*	*	*	*
X_6	1.00	1.00	1.00	1.00	1.00
X_8	*	$1.41X10^{-5}$	$4.90X10^{-2}$	$9.99X10^{-1}$	1.00
X_9	1.00	1.00	1.00	1.00	1.00
X_{11}	*	*	*	1.00	1.00
X_{12}	1.00	1.00	1.00	1.00	1.00
X_{14}	*	*	*	*	*
X_{15}	1.00	1.00	1.00	1.00	1.00

*Less than 10^{-7} or failure ignored.

Table 3.11. Risk Model Data Input for Upgraded Example Structure

Basic Event	Basic Event Probabilities — Hurricane Category 1	2	3	4	5
X_1	1.00	1.00	1.00	1.00	1.00
X_2	*	*	*	*	*
X_3	1.00	1.00	1.00	1.00	1.00
X_5	*	*	*	*	*
X_6	1.00	1.00	1.00	1.00	1.00
X_8	*	*	*	$2.58X10^{-3}$	1.00
X_9	1.00	1.00	1.00	1.00	1.00
X_{11}	*	*	*	*	1.00
X_{12}	1.00	1.00	1.00	1.00	1.00
X_{14}	*	*	*	*	*
X_{15}	1.00	1.00	1.00	1.00	1.00

*Less than 10^{-7} or failure ignored.

Table 3.12. Risk Model Fatality Input for Example Structure

Basic Event	Description of Basic Event	Mean	Standard Deviation	Distribution
X_4	Fraction x killed| frame fails	0.60	0.44	Lognormal
X_7	Fraction x killed| foundation fails	0.60	0.44	Lognormal
X_{10}	Fraction x killed| roof fails	0.60	0.44	Lognormal
X_{13}	Fraction x killed| cladding fails	0.60	0.41	Lognormal
X_{16}	Fraction x killed| partition fails	0.02	0.04	Lognormal

Table 3.13. Risk of Using Example Structure in Various Hurricanes

Hurricane Category	Expected Fraction of Fatalities	Standard Deviation of Expected Fatalities
1	*	*
2	3.86×10^{-6}	1.48×10^{-3}
3	1.34×10^{-2}	8.64×10^{-2}
4	4.22×10^{-1}	3.05×10^{-1}
5	4.22×10^{-1}	3.05×10^{-1}

*Probability of failure < 10^{-7}.

Table 3.14. Risk of Using Upgraded Example Structure in Various Hurricanes

Hurricane Category	Expected Fraction of Fatalities	Standard Deviation of Expected Fatalities
1	*	*
2	*	*
3	*	*
4	7.05×10^{-4}	2.00×10^{-2}
5	4.22×10^{-1}	3.05×10^{-1}

*Probability of failure < 10^{-7}.

CHAPTER IV

APPLICATION TO GALVESTON

Introduction

In the event of a hurricane, shelters are made available to desiring residents. Traditionally, the capacity of these shelters, i.e., the number of people that can be sheltered, is based on the space requirement per person. Shelter capacity is estimated by dividing the total space available in a building by the space requirement per person. Therefore, the shelter capacity is only a function of the total space available and the space requirement per person.

In an earlier part of this study, we have argued that the expected number of fatalities in a given structure subjected to a given hurricane depends on the number of occupants in the structure, the range of mitigative options available, the characteristics of the structure, and the physical characteristics of the hurricane. Since the traditional method of determining shelter capacity ignores any quantitative consideration of risk, the method fails to provide a rational basis for selection of vertical shelters.

As an alternative to the traditional method of assigning shelters or determining shelter capacity, the following methodology is proposed: 1) potential shelters are identified; 2) relevant statistical characteristics of the shelters and hurricane are determined; 3) the risk (expressed in terms of expected fatalities) associated with using the shelter is estimated; 4) hurricane-related scenarios describing the situations under which the shelters may be utilized are defined; 5) all mitigative options are defined; 6) all structures belonging to a given sheltering option are identified and the risks of using such shelters as a group is estimated; 7) the risks associated with all other options are also computed; and 8) on the basis of a comparison of the risks associated with the various options, the structural feasibility of a given type of sheltering option is evaluated.

Identification of Potential Shelters

Objectives

In this section, we attempt to complete the first and second steps in the proposed methodology. The remaining steps will be presented in the subsections entitled "The Risk Analysis of Potential Shelters" and "The Evaluation of Scenarios". The first objective of this study is to estimate the number, and summarize the physical characteristics of, buildings that may be available for use as potential vertical shelters in Galveston, Texas. In the survey, information is to be collected on the building ownership (public/private), its footprint area (i.e., the area enclosed by the first floor), the number of floors in the building, the governing building code, the estimated age of the building, the structural materials, and the framing concept used. The second objective of the study is to develop classificatory criteria for the potential vertical shelters and assign each structure to an appropriate category. This categorization will simplify future risk computations for the vertical evacuation option for the city as a whole.

Methodology

The following methodology was developed to estimate the number of potential vertical shelters. First, criteria were established to identify potential structures and to collect the appropriate building data needed for further analysis. Areas of the city containing these buildings were then identified. Next, these areas were physically surveyed, the potential buildings were identified, and the buildings were classified by structural type and ownership. Finally, a standard building was defined for each structural type and the number of these buildings within the city was estimated.

Criteria for Selecting Potential Shelters

Criteria were established to identify potential shelters and to collect the data required to categorize those structures. The criteria used here to identify potential shelters are as follows:

1. The building must provide dry space in the event that the region is flooded;
2. The building must not be located in the high velocity zone;
3. Single family residences (including duplexes) are excluded as potential shelters;
4. Buildings which show signs of neglect or disrepair (in the opinion of the inspecting engineer) are to be excluded as potential shelters; and
5. Buildings which appear not to have received attention from professional architects and engineers are to be excluded as potential shelters.

The height requirement for potential shelters (Criterion 1) can be determined from storm surge data. Figure 4.1 shows the potential storm surge penetration for Galveston Island for hurricanes of intensities of 74 to over 155 mph (Ruch, 1981). Note that, except for the northeastern portion of the island protected by the seawall, the

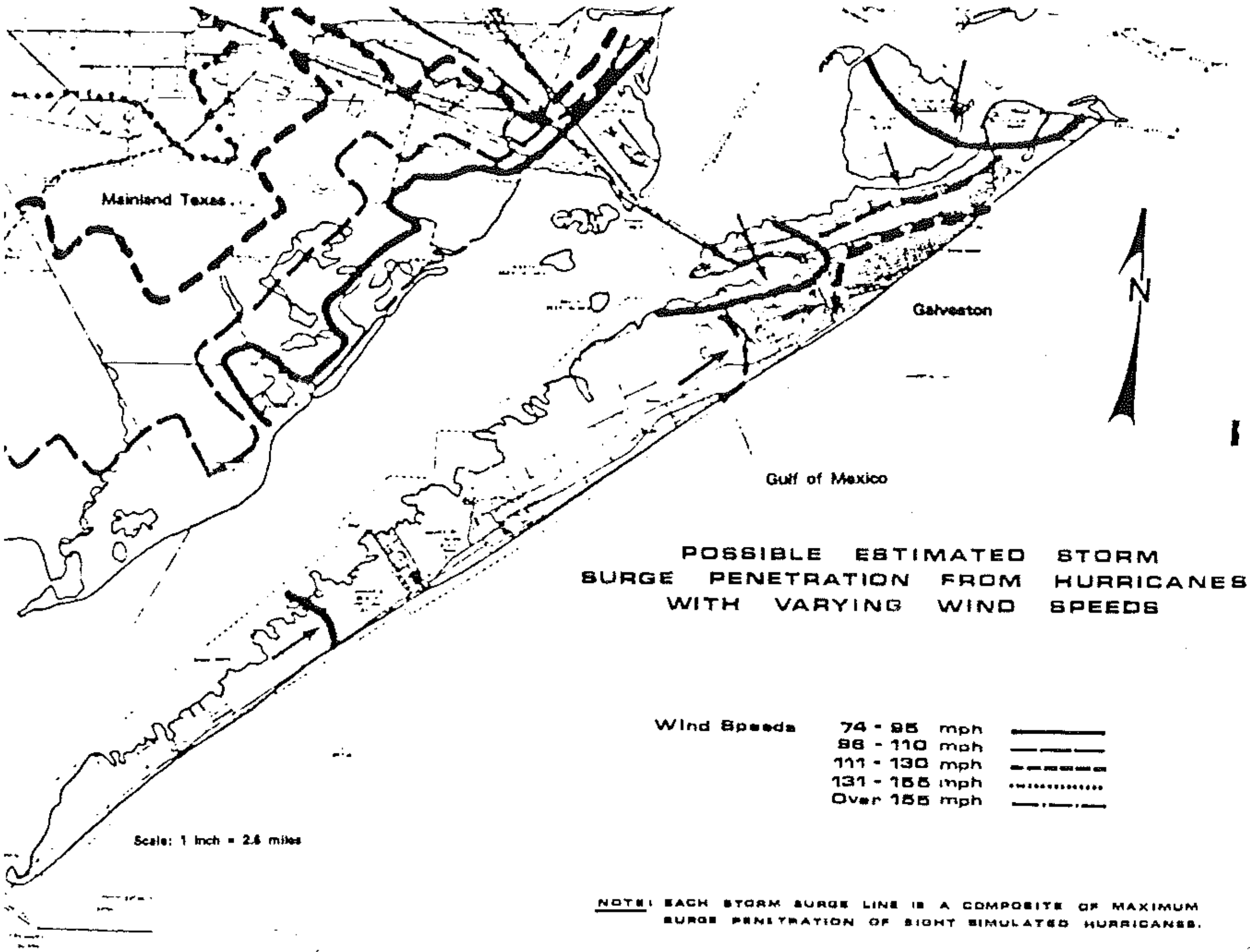


Figure 4.1. Potential Surge Penetration for Hurricanes

(Ruch, 1981)

remainder of the island will be flooded in the event that a Category 2 storm occurs. The maximum estimated surge height within the non-high velocity zone is 2.0 feet. For a hurricane of Category 4 or greater, the entire island will be flooded. The maximum estimated surge height, which occurs during a Category 4 storm twenty miles left of Galveston, is 10.8 feet above ground level (Ruch, 1983). Therefore, to provide dry space, the structure must be at least two stories high.

Figure 4.2 shows the limits of the V-zone for the Island (Federal Emergency Management Agency, 1984). As shown in the figure, the V-zone penetrates all of the island west of the airport and Galveston Bay. Therefore, only structures within the area east of the airport and north of Seawall Boulevard need be considered.

After applying the remaining criteria to the entire city, four areas were delineated which contained potential shelters. These areas included the Central Business District (CBD), the Seawall/beachfront area, the University of Texas Medical Branch, and a collection of schools. Each of these areas was then field-surveyed to identify potential shelters and collect the needed data.

The Building Survey

In addition to identifying potential shelters, data were also needed to summarize the physical characteristics of the buildings. For each building, the following data were collected in a field survey:

1. The building address,

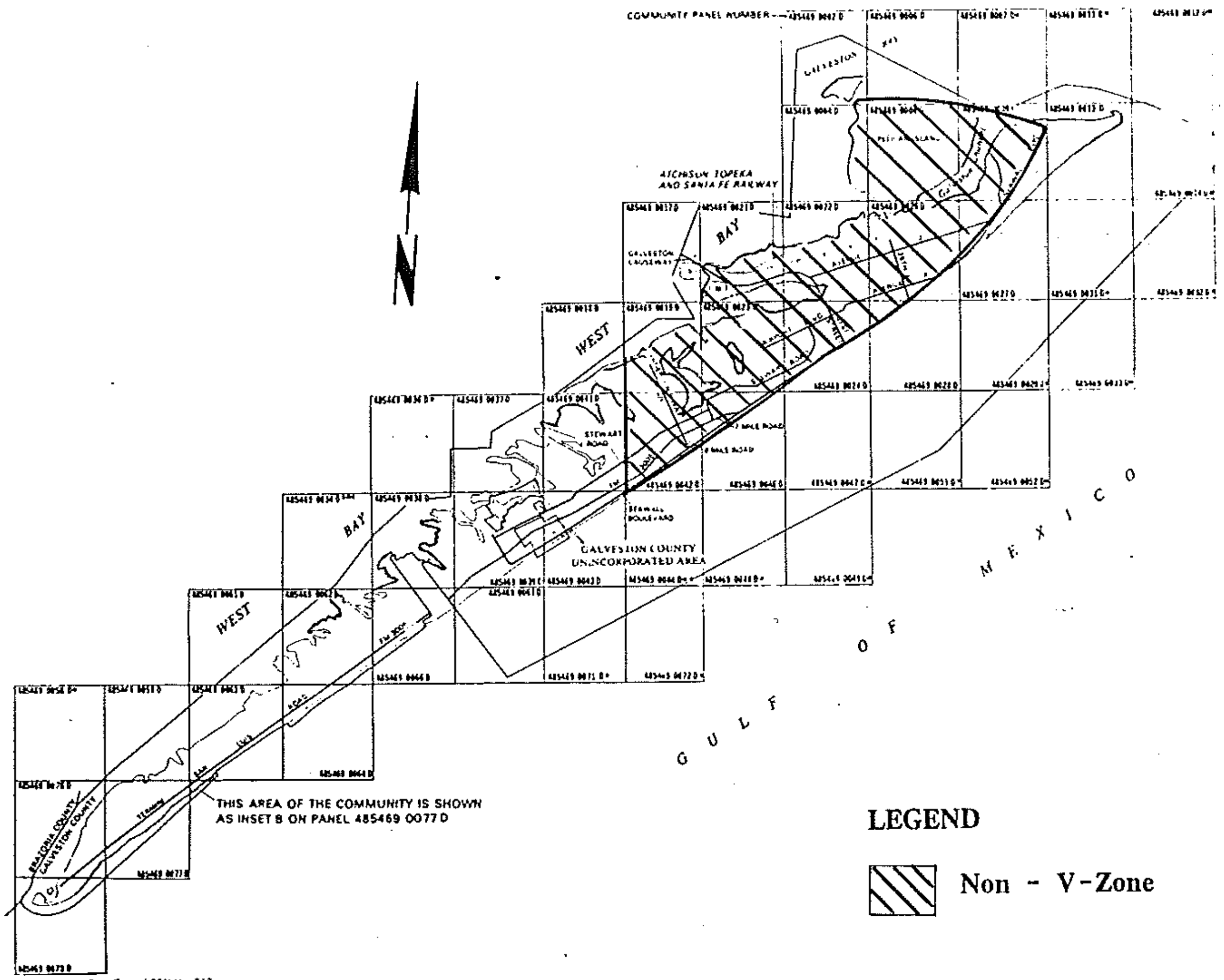


Figure 4.2. Limits of V-Zone for Galveston
(Federal Emergency Management Agency, 1984)

2. The building ownership (public/private),
3. The building footprint,
4. The number of stories in the building,
5. The governing building code,
6. The estimated age of the building,
7. The structural framing system used for the building, and
8. The major structural materials used for the building.

How this information was gathered for each of the four city areas is described below.

The Public Schools

The schools within the city were the first group of buildings to be surveyed for potential shelters. Due to the relatively small number of schools, which happened to be located in the residential portion of the city, all schools were surveyed. A total of twenty buildings were identified, but only six met the criteria for potential shelters. The latter buildings were all of reinforced concrete/masonry construction and were two stories high. Footprints of these buildings ranged from approximately 12,000 square feet to 126,000 square feet. All six buildings were either recently constructed (within the last decade) or renovated. This information is presented in Table 4.1.

The University of Texas Medical Branch

The University of Texas Medical Branch was the second group of buildings in Galveston to be surveyed. Using existing maps of the campus, a list of buildings was first compiled. Next, a field survey was performed to see which of the buildings could possibly function as shelters. If a building was deemed suitable as a shelter, then

Table 4.1. Galveston Schools That Are Potential Vertical Shelters

Bldg. No.	Footprint Area (SF)	No. of Stories	Ownership	Structural Frame Material
1	126,000	2	Public	RC[a]/masonry
2	69,300	2	Public	RC/masonry
3	60,800	2	Public	RC/masonry
4	41,000	2	Private	RC/masonry
5	12,600	2	Private	RC/masonry
6	38,000	2	Public	RC/masonry

[a]RC = Reinforced Concrete.

the appropriate building data were collected.

The data for buildings on the University of Texas Medical Branch campus are summarized in Table 4.2. Of the 56 buildings on the campus, 34 met the criteria as potential shelters. All structures appeared to be reinforced concrete/masonry construction. The majority of these buildings were new, with a few older renovated structures. Heights of these buildings ranged from two to ten stories. Their functions included administration, academic, hospital/medical care and residential. Footprint areas ranged from a low of 4,500 square feet to a maximum of 41,000 square feet.

The Central Business District

The buildings in the Central Business District formed the third group of buildings to be surveyed. Since so many buildings were present in the CBD, the building characteristics for the area were estimated from a sample population. According to the Comprehensive Plan Report for the City of Galveston (Springer, 1973) the CBD is defined as the area bounded by the wharves, Avenue K, 19th Street, and 26th Street. This area encompasses a total of 69 blocks. To construct the sample, each block was assigned a number between 1 and 69. A random number table was used to produce a random ordering of the blocks. Each block, in the order selected, was then surveyed. The potential shelters in that block were identified and the needed data collected. The sampling was halted when the average footprint/building and average number of floors/building converged. Of the 69 blocks in the CBD, 24 were surveyed.

Table 4.2. University of Texas Buildings That Are Potential Shelters[a]

Bldg. No.	Footprint Area (SF)	No. of Stories	Use
1	4,500	2	Office
2	15,000	5	Office
3	11,200	5	Academic
4	41,100	4	Academic
5	27,200	7	Hospital
6	37,400	2	Hospital
7	13,500	4	Academic
8	6,400	2	Academic
9	6,400	2	Academic
10	34,900	6	Hospital
11	6,400	2	Academic
12	23,400	6	Academic
13	12,200	4	Academic
14	22,400	5	Hospital
15	38,400	9	Hospital
16	30,900	10	Hospital
17	21,200	4	Hospital
18	31,500	6	Hospital
19	19,500	3	Academic
20	10,000	4	Academic
21	19,200	6	Academic
22	13,500	4	Academic
23	8,500	5	Academic
24	21,300	3	Library
25	6,400	2	Dorm
26	5,600	2	Dorm
27	5,600	9	Hospital
28	12,500	3	Academic
29	10,000	5	Hospital
30	20,600	5	Office
31	15,600	3	Hospital
32	13,100	2	Academic
33	6,400	2	Dorm
34	6,400	2	Dorm

[a]All buildings are of reinforced concrete/masonry and are publicly owned.

Compared to the schools and the campus buildings, the CBD yielded a more varied assortment of building types and functions. As is typical for a business district the majority of the structures functioned as retail or commercial establishments; however, some residential buildings (i.e., apartments and hotels) were present. While a sizable number of the buildings surveyed in the CBD were built at the turn of the century, they appeared to be in good structural condition as a result of renovations. The sample of the CBD produced buildings as high as 11 stories, and footprints ranging from less than 3,000 square feet to slightly over 27,000 square feet. Also, a combination of steel framed and reinforced concrete/masonry structures were identified. The data for this category are summarized in Table 4.3.

The Seawall Area

Finally, the Seawall/beachfront area was surveyed for potential shelters. This area included those blocks along Seawall Boulevard beginning at 1st Street and continuing to 103rd Street. While not all numbered streets physically extend to Seawall Boulevard, their intersection with Seawall Boulevard was estimated. Initially, the Seawall area was inspected for city blocks which did not contain suitable structures. These blocks were eliminated from the survey. The remaining blocks were numbered consecutively, then randomly ordered for the field survey. The Seawall area was then surveyed for potential buildings in a manner similar to that used for the CBD. The sampling was stopped when the average footprint/building and number of floors/building converged. Seventy-five blocks along the Sea-

Table 4.3. Potential Vertical Shelters in the Central Business District

Bldg. No.	Footprint Area (SF)	No. of Stories	Ownership	Structural Frame Material	Use
1	4,300	2	Private	RC[a]/CMU[b]	Retail
2	8,400	2	Private	RC/CMU	Commercial
3	2,800	2	Private	CMU	Apartment
4	10,300	8	Private	RC	Commercial
5	9,800	3	Private	RC	Retail
6	9,800	2	Private	RC/CMU	Retail
7	7,800	3	Private	RC	Retail
8	20,000	4	Public	RC	Library
9	7,500	2	Private	RC	Commercial
10	13,100	5	Public	Steel	Office
11	9,400	2	Public	RC	Office
12	3,200	2	Private	CMU	Retail
13	2,800	2	Public	CMU	Commercial
14	4,700	4	Private	RC	Commercial
15	25,000	2	Private	RC	Commercial
16	5,000	2	Private	RC	Commercial
17	25,000	3	Private	Steel	Commercial
18	3,700	2	Private	CMU	Apartment
19	15,600	3	Private	RC	Commercial
20	9,000	10	Private	RC	Residential
21	18,200	6	Private	RC	Commercial
22	7,500	3	Private	RC	Office
23	8,500	2	Private	Steel	Office

Table 4.3. (Continued)

Bldg. No.	Footprint Area (SF)	No. of Stories	Ownership	Structural Frame Material	Use
24	5,300	2	Private	Steel	Office
25	12,700	2	Private	RC	Retail
26	23,900	2	Private	RC	Retail
27	7,000	3	Private	RC	Retail
28	3,500	3	Private	RC	Office
29	4,100	3	Private	RC	Office
30	9,400	2	Private	Steel	Commercial
31	8,400	3	Private	RC	Retail
32	22,500	2	Private	RC	Retail
33	24,100	4	Private	RC	Commercial
34	27,500	3	Private	RC	Retail
35	4,300	4	Private	RC	Retail
36	4,300	3	Private	RC	Retail
37	16,200	3	Private	RC	Commercial
38	11,300	3	Private	RC	Commercial
39	4,200	11	Private	RC	Commercial
40	4,200	5	Private	RC	Commercial
41	10,000	2	Private	RC	Office
42	4,200	2	Private	RC	Office
43	5,000	2	Private	RC	Commercial
44	5,000	2	Private	RC	Commercial
45	5,000	2	Private	RC	Commercial

[a]RC = Reinforced Concrete.
[b]CMU = Concrete Masonry Unit.

wall contained potential shelters, and of these, a total of 40 were sampled.

Buildings in this area were built primarily for recreational or residential use (i.e., hotels or condominiums) and ranged in heights from two to 12 stories. Footprints of these structures ranged from 3,000 to 53,000 square feet. Along the seawall, framing systems used were found to be either rigid steel frame or concrete frame, with the exception of some low level condominiums which were wooden frame structures. Those buildings constructed of steel and precast, post-tensioned concrete were counted as steel framed structures. Data for the sample of buildings on the seawall are summarized in Table 4.4.

Classification of Potential Shelters by Structural Type

Within each of these four geographical areas, the buildings were classified according to the structural framing and number of stories. From the data collected, six structural types were identified. The six structural types are defined in Table 4.5.

Recall that Tables 4.3 and 4.4 contained information only on the sample used for the CBD or the Seawall. For these two cases, the total number of buildings, in terms of the structural type defined in Table 4.5, were estimated using the equation:

$$B_{ti} = (N_b/n)B_i \qquad (4.1)$$

where: N_b = the number of blocks in the total population area; n = the number of blocks in the sample; B_i = the number of buildings in the sample for structural Type i; and B_{ti} = the estimated number of buildings in the population for structural Type i. The estimated

Table 4.4. Potential Vertical Shelters on the Seawall/Beachfront

Bldg. No.	Footprint Area (SF)	No. of Stories	Ownership	Structural Frame Material	Use
1	10,200	3	Private	CMU[a]	Residential
2	3,400	3	Private	CMU	Residential
3	6,600	4	Private	RC[b]	Commercial
4	24,400	5	Private	RC	Commercial
5	15,600	3	Private	Steel	Residential
6	12,600	11	Private	RC	Residential
7	12,500	5	Private	RC	Commercial
8	2,800	2	Private	RC	Commercial
9	8,400	2	Private	Wood	Commercial
10	11,300	2	Private	CMU	Residential
11	14,100	4	Private	RC	Residential
12	6,600	2	Private	CMU	Residential
13	6,600	2	Private	CMU	Residential
14	6,600	2	Private	CMU	Residential
15	6,750	2	Private	RC	Residential
16	53,100	2	Private	Wood	Residential
17	5,000	3	Private	CMU	Residential
18	5,000	3	Private	CMU	Residential
19	5,000	3	Private	CMU	Residential
20	5,000	3	Private	CMU	Residential
21	5,000	3	Private	CMU	Residential
22	5,000	3	Private	CMU	Residential
23	5,000	3	Private	CMU	Residential
24	9,000	8	Private	Steel	Residential

Table 4.4. (Continued)

Bldg. No.	Footprint Area (SF)	No. of Stories	Ownership	Structural Frame Material	Use
25	23,400	4	Private	Wood	Residential
26	23,400	4	Private	Wood	Residential
27	23,400	4	Private	Wood	Residential
28	23,400	4	Private	Wood	Residential
29	15,600	2	Private	Wood	Residential
30	10,000	12	Private	RC	Residential
31	34,000	3	Private	CMU	Residential
32	34,000	3	Private	CMU	Residential
33	28,100	4	Private	Wood	Residential
34	28,100	4	Private	Wood	Residential
35	9,400	2	Private	Wood	Residential
36	9,400	2	Private	Wood	Residential
37	9,400	2	Private	Wood	Residential
38	9,400	2	Private	Wood	Residential
39	9,300	6	Private	RC	Residential
40	22,500	4	Private	Wood	Residential
41	22,500	4	Private	Wood	Residential
42	22,500	4	Private	Wood	Residential
43	22,500	4	Private	Wood	Residential
44	22,500	4	Private	Wood	Residential
45	22,500	4	Private	Wood	Residential
46	22,500	4	Private	Wood	Residential
47	22,500	4	Private	Wood	Residential

[a]CMU = Concrete Masonry Unit.
[b]RC = Reinforced Concrete.

Table 4.5. Structural Categories for Potential Vertical Shelters

Structural Type	Description of Framing
A	Reinforced Concrete Frame, 2 stories
B	Reinforced Concrete Frame, 3-5 stories
C	Reinforced Concrete Frame, greater than 5 stories
D	Steel Frame, 2 stories
E	Steel Frame, greater than 2 stories
F	Wooden Frame, 2-4 stories

number of buildings in the CBD and the Seawall/beachfront areas are summarized in Table 4.6. The distribution of buildings, by structural type and location, is summarized in Table 4.7.

Further details on each structural type are provided in Tables 4.8 and 4.9. Note that, although the average height of the buildings belonging to one structural type varies little from area to area, the corresponding variation in the footprint of the same type is quite large. For example, the average footprint for a Type A school is more than eight times the area of an average Type A structure on the seawall.

Classification of Potential Shelters by Ownership

The potential shelters identified were next classified by ownership; that is, public or private. Fortunately, each structure fell into one of the above categories. The majority of the schools and the buildings of the University of Texas Medical Branch were public property. The potential shelters within the CBD, with the exception of a few governmental buildings, were privately owned. The buildings in the Seawall/beachfront area were also privately owned. The potential shelter areas for private and public structures are summarized in Table 4.10 as a function of the structural type.

Definition of Standard Buildings

A standard building may be defined as a building which belongs to one of the six structural types and whose height and footprint are related to the average values of the buildings in that category. For

Table 4.6. Estimate of the Number of Potential Shelters in the CBD and Seawall

Structural Type	CBD[a] No. of Bldg. Sampled	CBD[a] Est. No. of Bldg.	Seawall[b] No. of Bldg. Sampled	Seawall[b] Est. No. of Bldg.
A	19	55	6	11
B	17	49	13	24
C	4	12	3	6
D	3	9	0	0
E	2	6	2	4
F	0	0	21	39

[a] $N_b/n = 2.9$
[b] $N_b/n = 1.9$

Table 4.7. Estimate of the Number of Potential Shelters By Location and Structural Type

Structural Type	Building Estimate CBD	Seawall	UT[a]	Schools	Total
A	55	11	10	6	82
B	49	24	16	-	89
C	12	6	8	-	26
D	9	-	-	-	9
E	6	4	-	-	10
F	-	39	-	-	39

[a] University of Texas Medical Branch.

Table 4.8. Average Footprint per Building By Structural Type

Structural Type	Average Footprint per Building (SF) CBD	Seawall	UT[a]	Schools	Population Average[b]
A	9,000	7,000	9,900	57,900	12,400
B	10,600	8,200	16,500	-	11,000
C	9,900	10,600	25,800	-	15,000
D	7,700	-	-	-	7,700
E	19,000	12,300	-	-	16,300
F	-	21,200	-	-	21,200

[a]University of Texas Medical Branch.
[b]Weighted Average.

Table 4.9. Average Number of Floors per Building By Structural Type

Structural Type	Average Number of Floors CBD	Seawall	UT[a]	Schools	Population Average[b]
A	2.0	2.0	2.0	2.0	2.0
B	3.4	3.5	4.1	-	3.6
C	8.8	4.8	7.9	-	7.6
D	2.0	-	-	-	2.0
E	4.0	5.0	-	-	4.4
F	-	3.0	-	-	3.0

[a]University of Texas Medical Branch.
[b]Weighted Average.

Table 4.10. Total Area as a Function of Ownership

Structural Type	Total Area (SF)		Total Area (SF)
	Public	Private	
A	893,000	1,144,000	2,037,000
B	1,015,000	2,455,000	3,470,000
C	1,983,000	1,351,000	3,334,000
D	-	108,000	108,000
E	-	678,000	678,000
F	-	2,480,000	2,480,000
Totals	3,891,000	8,216,000	12,107,000

example, the standard Type A building will contain the weighted average of the footprint (12,250 square feet) and the average number of stories (2) for all to the Type A buildings in the sample. The properties of the six standard buildings are summarized in Table 4.11. Note that the last columns in Tables 4.10 and 4.11 are quite close.

Risk Evaluation of Potential Shelters

This section summarizes the results of a structural risk analysis of the six generic building types that were identified as potential vertical shelters. First, the "model" building for each category is described. Second, the method used to evaluate the candidate structures is summarized. Finally, the results of the risk analysis for the six building types are presented.

Selection of Standard Buildings for Analysis

To estimate the probable behavior of each class of buildings, we selected structures with the geometric and material characteristics closest to the structural types listed in Tables 4.5 to 4.11. Plans and specifications of the selected structures were obtained from the City of Galveston. A description of the representative structures used in the study follows.

Table 4.11. Properties of the Six Standard Buildings

Structural Type	No. of Bldg.	Weighted Average: Footprint Area (SF)	Weighted Average: No. of Floors	Total Area (SF)
A	85	12,000	2.0	2,040,000
B	79	11,000	4.0	3,476,000
C	32	15,000	7.0	3,360,000
D	7	8,000	2.0	112,000
E	9	16,000	5.0	720,000
F	39	21,000	3.0	2,457,000

Standard Type A Building

The building is located on the northern side of Galveston Island and functions as a dormitory. Figure 4.3 shows a typical plan and two elevations of the structure. Built in 1983, the building covers a floor plan area of approximately 7,000 square feet and is two stories high. The height of both stories is 10 feet and the first floor is 2.5 feet above ground level. This building was assumed to be designed in accordance with the 1982 Standard Building Code.

A total of seven, two-story, reinforced concrete buildings are clustered around the building in question. One hundred feet to the south of this building is a multi-story parking garage.

The foundation consists of 6 X 6 feet spread footings supporting an 8-inch thick grade beam on the building perimeter and 7 X 7 feet footings supporting 1.0 X 1.5 feet floor beams which span the interior area. Loads are transmitted to the foundation by 1 foot square concrete columns. The lateral load resisting system consists of a monolithically poured, moment-resisting frame. The roofing consists of a lightweight aggregate fill covered with two inches of insulation and a built-up roof. Wall A faces north and is a hollow tile infill wall covered with face brick. The remaining three walls are similar in construction. Walls A and B each consist of 20 cladding units, each with dimensions approximately 14 X 10 feet, while Walls C and D consist of six units each.

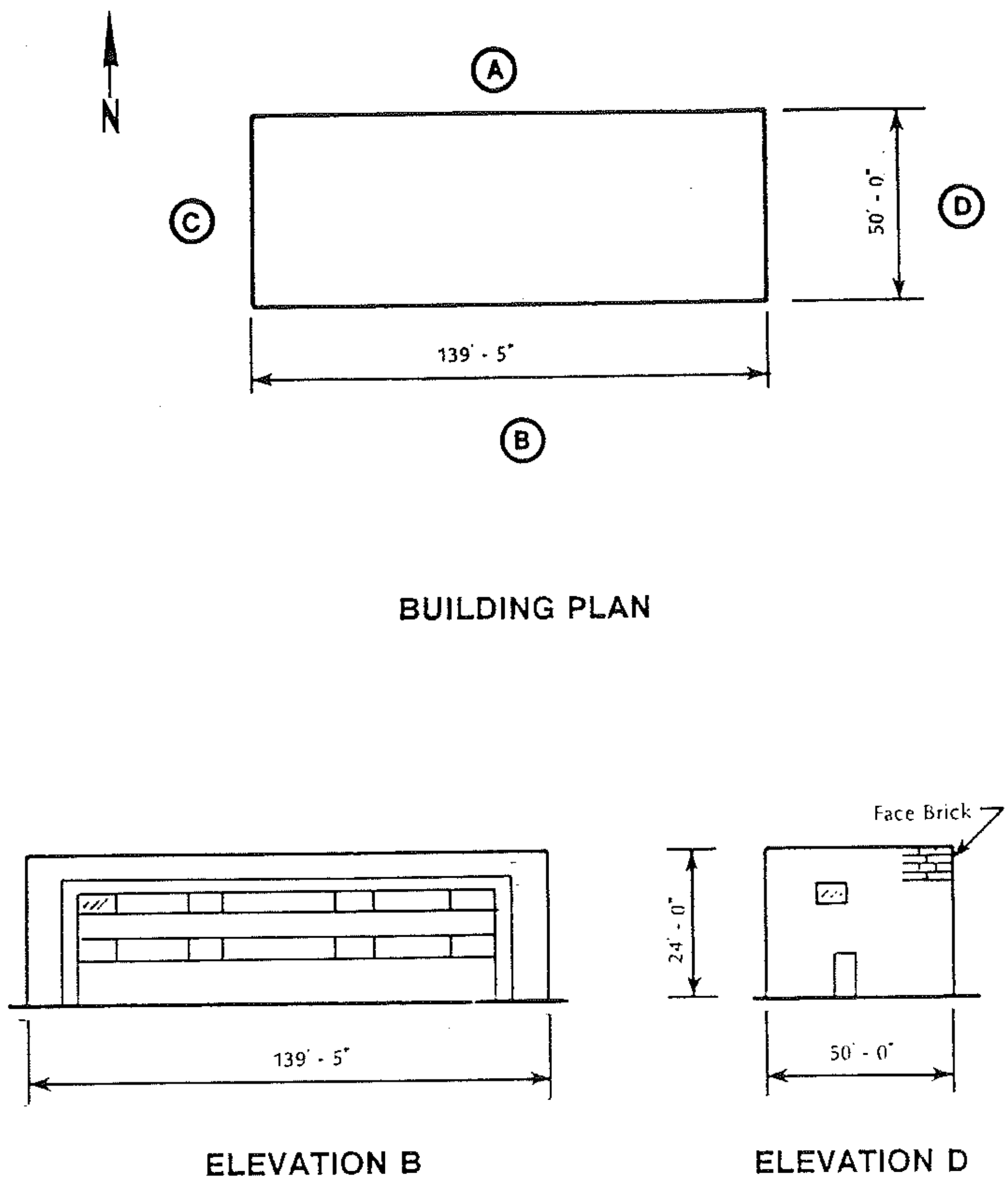


Figure 4.3. Plan and Elevations of Type A Building

Standard Type B Building

The structure is located on the northern side of Galveston Island and functions as a hospital. Figure 4.4 shows two elevations and a typical floor plan of the building. The four-story structure with a penthouse was built in 1984 and covers a floor plan area of approximately 45,000 square feet. The height of the first story is 12.6 feet above ground level. Each succeeding floor is 12.4 feet high. The building codes governing the design include the Standard Building Code (1982), the AISC specifications for the Design, Fabrication and Erection of Structural Steel for Buildings (1980), and ACI 318-77.

The surrounding area consists primarily of commercial low-rise buildings. Fifty feet to the north is an unpaved parking lot and 50 feet to the south is a parking garage, which is connected to the hospital by a walkway. Directly to the west is the original hospital with which this building shares a party wall. Approximately 300-feet to the east of the hospital is a supermarket.

The foundation consists of grade beams at the building perimeter and spread footings within the interior. A rigid, reinforced concrete frame resists the lateral forces. Floors consist of a concrete slab supported by floor beams and joists. The roof is similar to the floor except that the latter also supports a membrane on 1/2-inch thick insulation board and lightweight aggregate. The exterior walls consist of 4-inch metal studs with sheeting and face brick on the exterior. Elevation A consists of 28 cladding units, as does Elevation C. There are 36 claddings on Elevation B and 48 on Elevation D. The size of a typical cladding unit is approximately 20 X 12 feet.

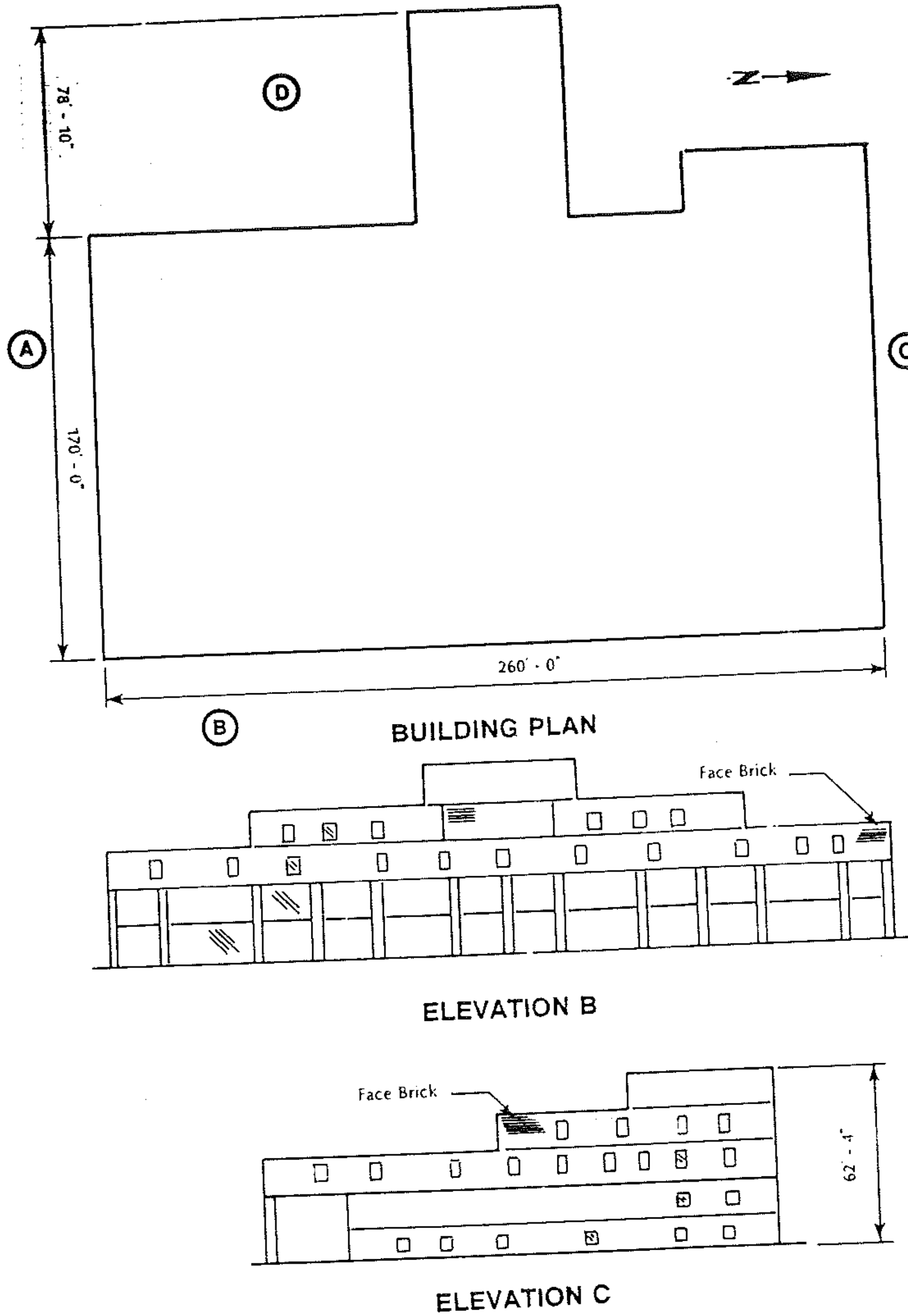


Figure 4.4. Plan and Elevations of Type B Building

Standard Type C Building

The structure is located on the southern side of Galveston Island and serves as a hotel. Figure 4.5 shows two elevations and a typical floor plan of the structure. The structure, built in 1983, covers a floor plan area of approximately 16,000 square feet and has seven stories. The height of the first story is 10.3 feet above ground level and the height of each succeeding floor is 8.7 feet. The height of the seventh floor is 13.4 feet. The building codes governing the design include the Standard Building Code (1979), the AISC Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings (1978), and ACI 318-77.

The terrain to the north, east, and west of the structure consists primarily of low-rise houses and trees. The Gulf of Mexico is to the south of the structure. Fifty feet to the east is a building under construction. Three hundred feet to the north are a row of three-story apartment buildings. One hundred and fifty feet to the west is a 20-story structure. About 200 feet to the south is the Seawall.

The foundation consists of 2.25-feet deep, reinforced concrete, grade beams supported on 1.33-feet diameter, concrete, friction piles. The safe load capacity of each pile is specified at 60 tons. The structural material of the superstructure is concrete. Lateral loads are resisted by four cores (two elevator shafts and two stairwells) and thirteen precast, post-tensioned concrete shear walls. The shear walls also support the floors which consist of precast, prestressed planks. Vertical post-tensioning rods in the cores and shear walls are post-tensioned to 105,000 psi. The shear walls are

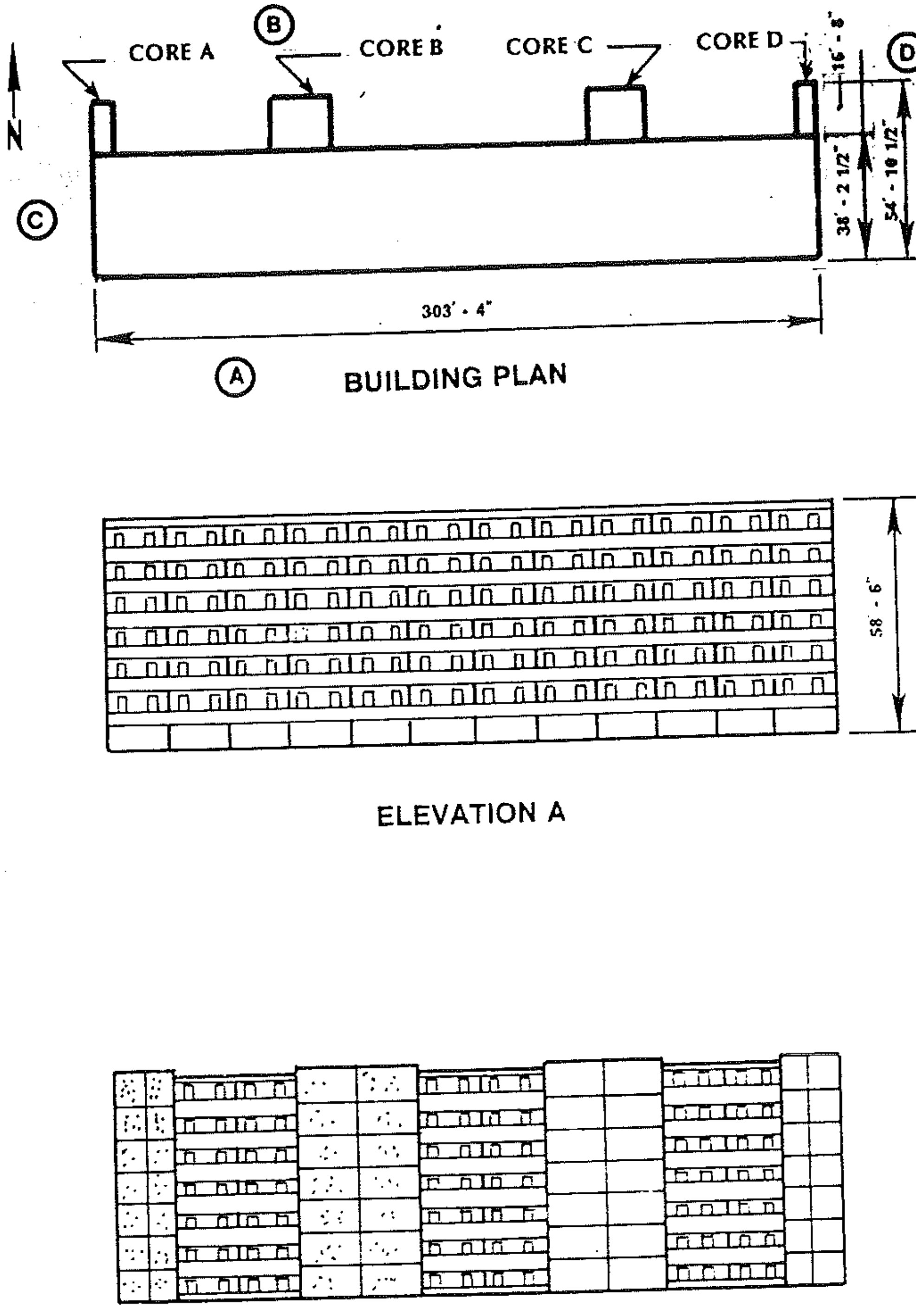


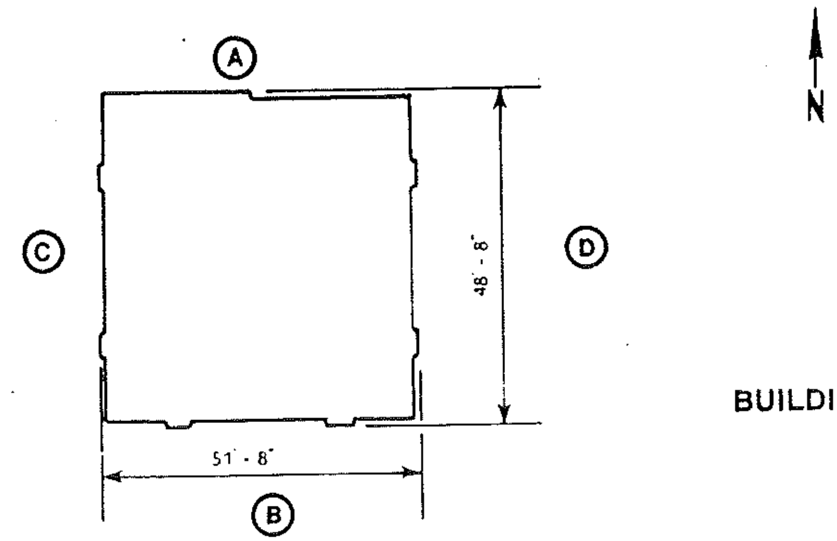
Figure 4.5. Plan and Elevations of Type C Building

attached to the grade beam via post-tensioning and grouting. The floor planks bear on a shoulder in the shear walls and are grouted in-place. The roofing support is the same as the other floors but is covered with a 3-inch thick insulation board over which is applied a four-ply roofing membrane. Wall A, which faces the gulf, consists of 168 window wall units. Each unit is comprised of 1/4-inch thick float glass in bronze anodized frames. Walls C and D consist of the end shear wall with a brick veneer. Wall B is made up of a metal stud wall with a stucco finish.

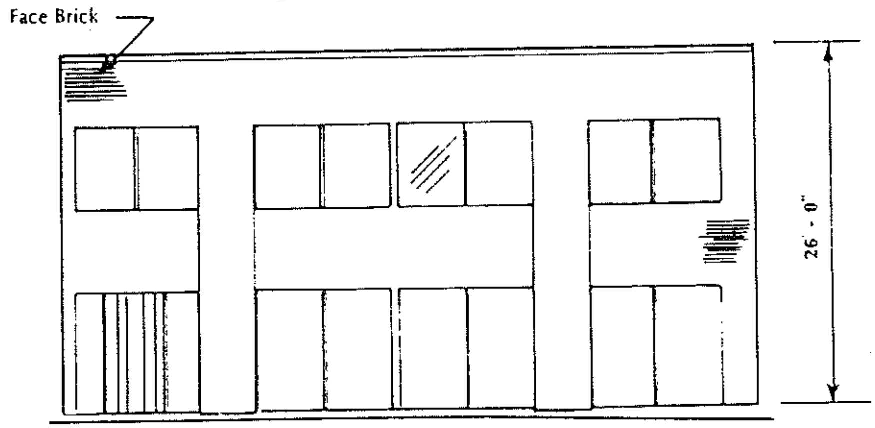
Standard Type D Building

The structure is located on the southern side of Galveston Island and serves as a banking facility. Figure 4.6 shows two elevations and a typical floor plan of the structure. The structure, built in 1981, covers a floor plan area of approximately 2,500 square feet and is two stories high. The height of the first story is 12 feet above ground level and the height of the second story is 14 feet. The building code governing the design is the Standard Building Code (1980).

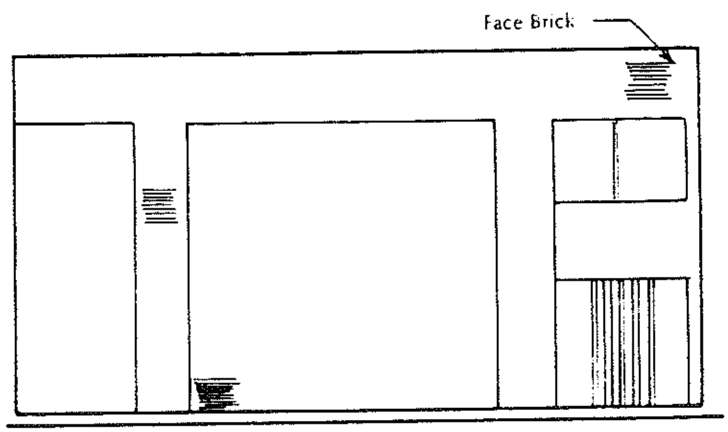
The terrain to the north, east, and west of the structure consists primarily of low-rise houses and trees. The Gulf of Mexico lies to the south. To the north of the building is the bank drive-in facility, 50 feet to the east are several two-story houses and 100 feet to the west is a gas station. Approximately 50 feet to the south is the Seawall.



BUILDING PLAN



ELEVATION B



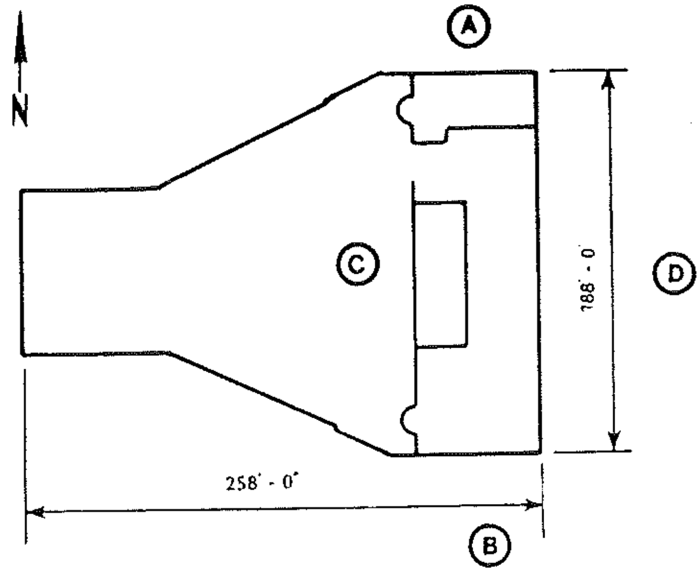
ELEVATION C

Figure 4.6. Plan and Elevations of Type D Building

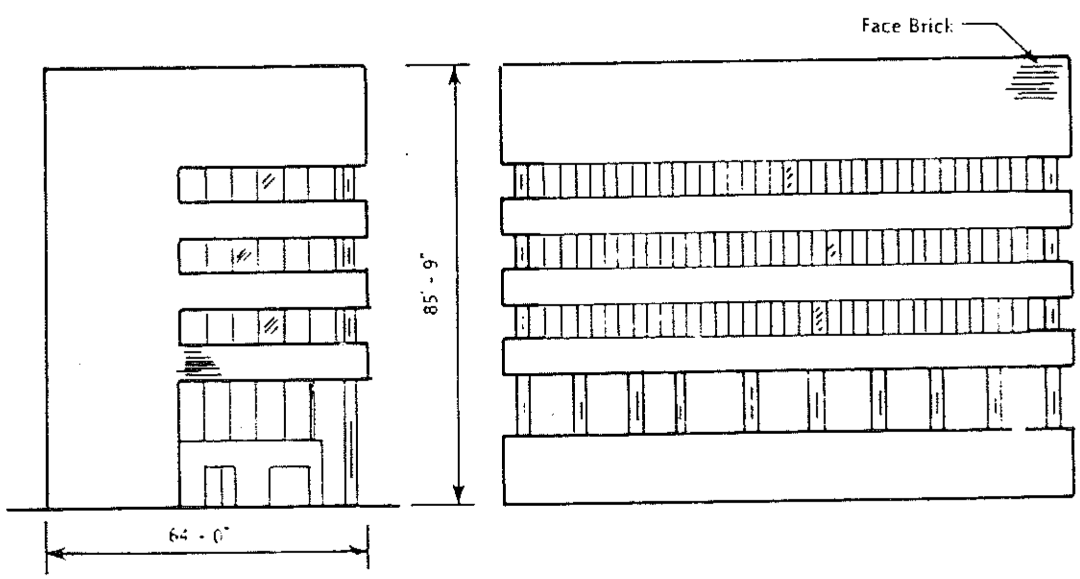
The foundation consists of a grade beam of varying thickness located below the building perimeter and at the center of the building. The grade beam supports a 5-inch thick, two-way, concrete slab. Lateral loads are resisted by a rigid steel frame. Floors and roof consist of 16-inch steel joists supporting a steel deck and 2.5 inches of concrete. The roofing system consists of 5/8-inch gravel and built-up asphalt felts over the concrete deck. The exterior walls are constructed of 4-inch metal studs covered with 4-inch face bricks. Each side of the building consists of 8 cladding units. The size of these units is approximately 10 X 12 feet. The window material is 1/4-inch tempered glass.

Standard Type E Building

The structure is located on the northern side of Galveston Island and serves as an academic facility. Figure 4.7 shows two elevations and a typical plan of the structure. The structure, built in 1981, consists of an auditorium and classrooms. Only the classroom portion of the building was considered in the analysis and the floor plan of that portion is approximately 12,000 square feet and has six stories. The height of the first story is 12.9 feet above ground level and the height of the second story is 16.9 feet. The next three stories are 13.8 feet high and the sixth story is 13.1 feet high. The codes governing the design include the Standard Building Code (1978), the AISC Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings (1978) and ACI 318-77.



BUILDING PLAN



ELEVATION B (HIGH BAY ONLY)

ELEVATION D

Figure 4.7. Plan and Elevations of Type E Building

The terrain on all sides of the building consists primarily of buildings greater than two stories and trees, except for a parking lot to the west. Two hundred feet to the north is a six-story academic building. Two hundred feet to the south is a three-story academic building. Three hundred feet to the east is a three-story library.

The foundation consists of a combination of piles and piers. The 10.5-inch step-tapered, friction type piles are 76 feet deep, with a load limit of 40 tons. Piers vary in depth from 64 to 100 feet and are sized accordingly.

Lateral loads are resisted by a rigid steel frame. Concrete slabs on metal decking form all floors and roof. This assembly is supported by steel joists which in turn are supported by the floor beams. Roofing material consists of built-up roofing over lightweight fill and rigid insulation. Exterior walls consist of a 6-inch stud wall system covered with 4-inch face brick. Elevations A and B contain 15 cladding units each. Sides C and D each consist of 45 cladding units. The typical size of each cladding unit is 20 X 14 feet. A glass atrium connects the classroom portion of the building to the auditorium.

Standard Type F Building

The structure is located on the southern side of Galveston Island and serves as a multiple residence. Figure 4.8 shows a plan and two elevations of the building. Built in 1983, the structure covers a floor plan area of approximately 3,100 square feet and has four sto-

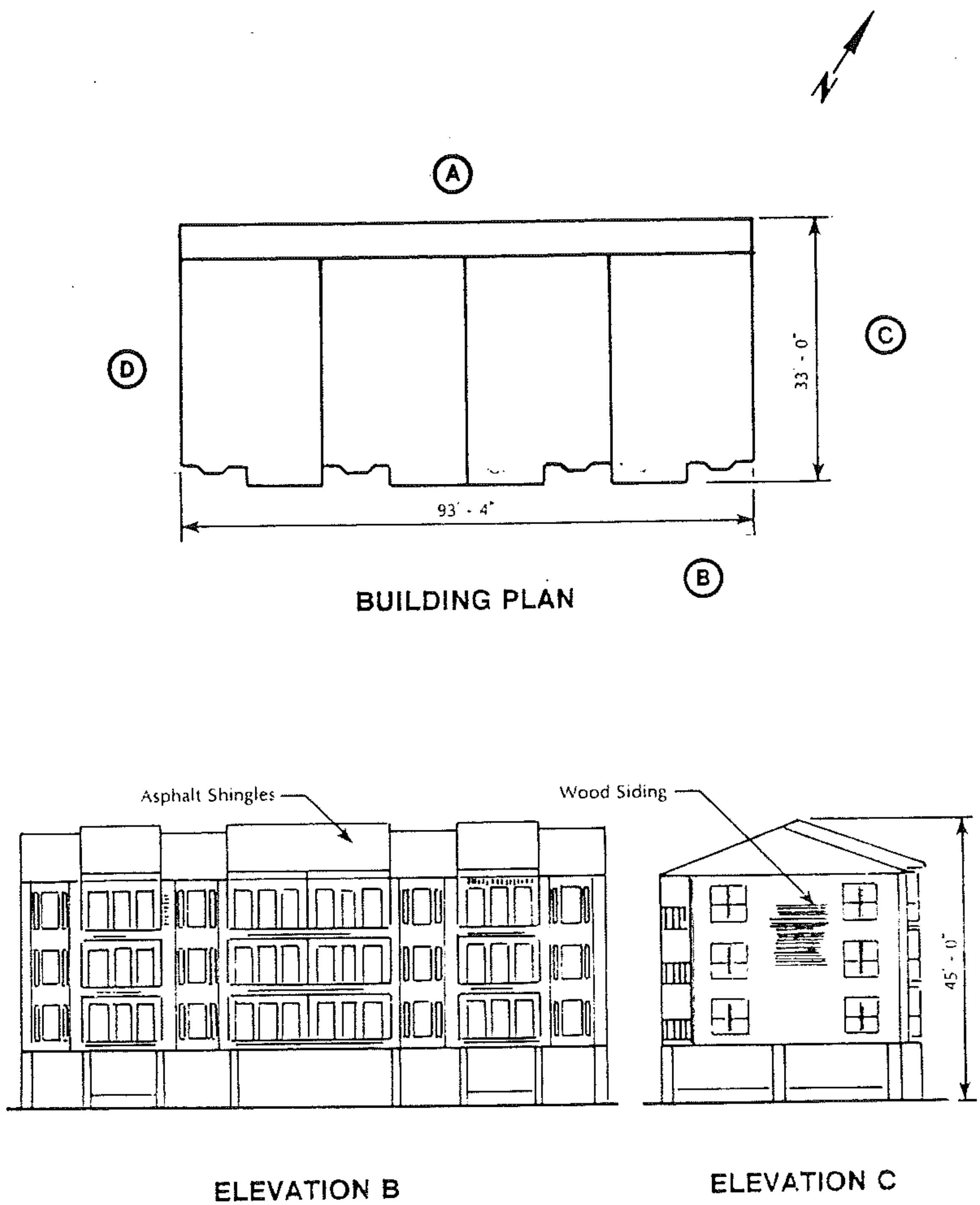


Figure 4.8. Plan and Elevations of Type F Building

ries. Each building is divided into four living units, with the first floor serving as a parking garage. The height of the first story is 11.0 feet above ground level and the second story is 8.5 feet high. The succeeding two stories are 8.75 feet in height and the height of the attic is 8.0 feet. The building codes governing the design include the Standard Building Code (1982), the AISC Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings (1980), and ACI 318-77.

The terrain to the north, east, and west of the structure consists of buildings of similar construction. A total of nine buildings of various sizes are within the condominium complex. The greatest distance between any two buildings is 120 feet. To the north, east, and west of this complex are vacant fields. Approximately 50 feet to the south is the Seawall and the Gulf of Mexico.

The foundation consists of spread footings, six to eight feet square. The footings are constructed of reinforced concrete and are 2.0 feet thick. The superstructure is comprised of concrete and timber. The wooden living quarters were built on atop the concrete parking structure. The second level is supported by 2-feet diameter concrete columns resting on the footings. These columns in turn support prestressed concrete beams (1.5 X 3.0 feet). A precast concrete deck is placed on top of the beams. Exterior walls are of 2 X 4-inch wood studs spaced 1.33 feet on center. Walls B, C, and D are finished with wood siding on the exterior and Wall A is stucco over metal lath. Roofing is supported by trusses spaced 2 feet on center. Elevations A and B contain 15 cladding units and C and D contain three each. A typical size for these units is 20 X 9 feet.

Method Used to Evaluate Safety of Occupants

The occupant safety evaluation considered in this section consisted of the following sequence of steps:

1. Plans, specifications, and other pertinent construction documents were assembled for the structure.
2. From the design information and existing information in the literature (e.g., Ellingwood et al., 1980), resistance statistics for the building components were estimated.
3. Given the location and geometry of the structure, the loading statistics for hurricanes of all categories were developed.
4. Failure functions were next defined for the foundation, lateral load-resisting system, roofing, and cladding of the structure.
5. Failure functions for each of the building components were evaluated using methods from Structural Reliability Theory (Thoft-Christensen and Baker, 1982) to yield failure probabilities for the elements as well as for the major subsystems.
6. The failure probabilities along with death-damage data (which provided information on the consequences of failure) were used as input for the risk model (Stubbs, 1987) of the structure to yield estimates of the mean fraction of fatalities and the standard deviation of the estimate. These estimates were provided for each hurricane category.
7. The structure was upgraded to resist a Category 3 hurricane and steps 2 - 6 were repeated.

These steps, and the interrelationships between them, are shown in Figure 4.9. Relevant descriptions of the documents consulted, calculation procedures, loading models, and material properties used in this evaluation are summarized in Chapter II of this report. Detailed computational results for all buildings studied can be found elsewhere (Stubbs, 1987).

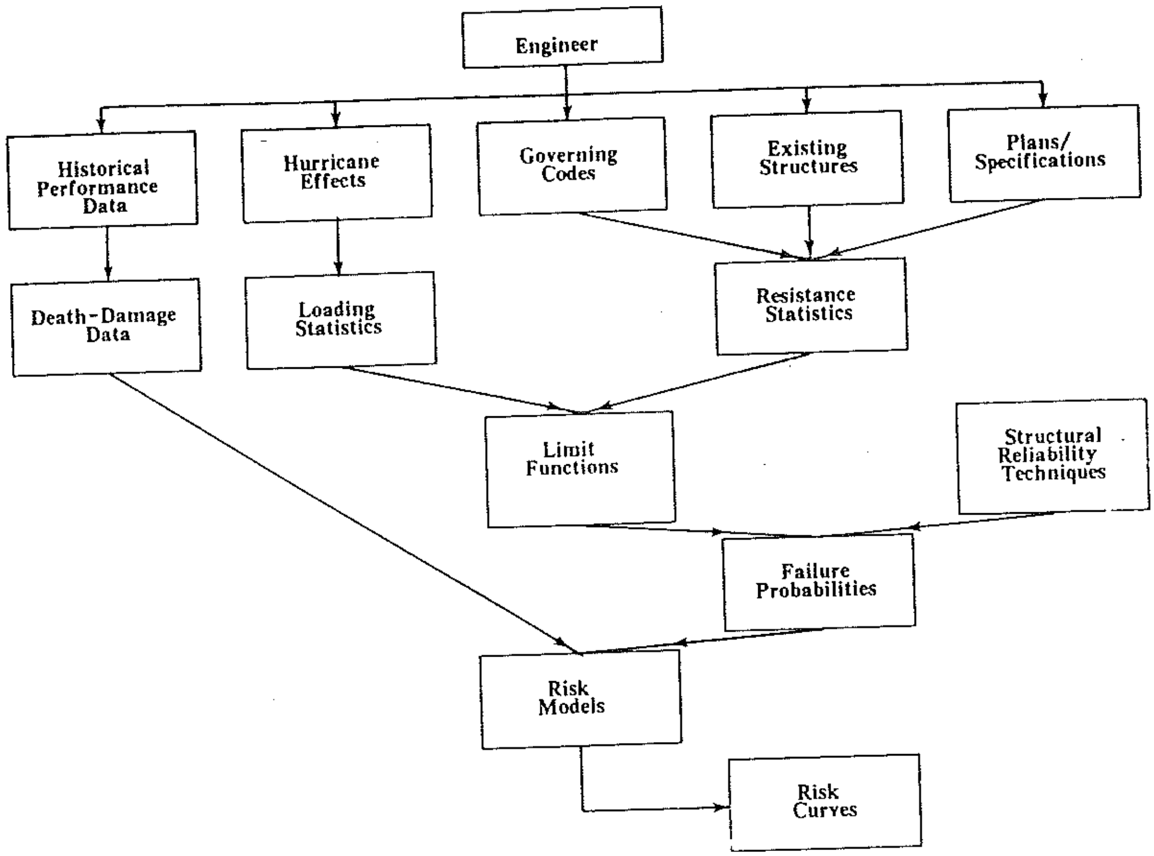


Figure 4.9. Schematic of Evaluation Scheme for Structures

Results of Risk Analysis

The results of the risk analysis are presented in Tables 4.12 to 4.17. Each table lists the risk associated with the structure as a function of the hurricane magnitude and the status of the building (i.e., existing or upgraded). For ease of interpretation, the risks associated with using the same structure are expressed as the number of fatalities per 100 persons in Tables 4.18 to 4.23. In addition, to avoid further confusion the number of fatalities is given to the nearest person. The risk estimates in Table 4.18 were obtained from Table 4.12 by multiplying the expected fraction of fatalities by 100. The risks shown in Tables 4.19 to 4.23 have been obtained analogously. Finally, in interpretating the tables, the reader must keep in mind that the hurricane designations correspond to the Saffir-Simpson scale[1].

One shortcoming of expressing the risk in Tables 4.18 to 4.23 is that only the expectation is utilized. A more comprehensive measure of the risk is provided by using both the mean and the standard deviation about the mean. However, to estimate probabilities we must assume some particular type of probability density function. Here we will assume that the fraction of inhabitants that are killed (described by the random variable X) is log-normally distributed with means and variances given in Tables 4.12 to 4.17. The log-normal probability density function for random variable X is given by:

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[1]See Appendix A.

Table 4.12. Summary of Fatality Statistics for Standard Type A Building

Description of Structure	Expected Fraction of Fatalities (Standard Deviation)					Cost to Upgrade ($000)
	Hurricane Category					
	1	2	3	4	5	
Existing structure[a] including frame and foundation failure	– –	– –	– –	– –	– –	0.0
Existing structure ignoring frame and foundation failure	* (*)	.0893 (.2070)	.4210 (.3050)	.4210 (.3050)	.4210 (.3050)	0.0
Structure upgraded[b] to resist Category 3 hurricane	* (*)	* (*)	.0809 (.1990)	.4200 (.3050)	.4220 (.3050)	133.6

[a]Statistic not estimated.
[b]Upgrading consisted of installation of Roll-A-Way shutters, repairing the roof and replacing the curtain walls.
*Less than 10^{-5}

Table 4.12. Summary of Fatality Statistics for Standard Type A Building

Description of Structure	Expected Fraction of Fatalities (Standard Deviation)					Cost to Upgrade ($000)
	Hurricane Category 1	2	3	4	5	
Existing structure[a] including frame and foundation failure	– –	– –	– –	– –	– –	0.0
Existing structure ignoring frame and foundation failure	* (*)	.0893 (.2070)	.4210 (.3050)	.4210 (.3050)	.4210 (.3050)	0.0
Structure upgraded[b] to resist Category 3 hurricane	* (*)	* (*)	.0809 (.1990)	.4200 (.3050)	.4220 (.3050)	133.6

[a]Statistic not estimated.
[b]Upgrading consisted of installation of Roll-A-Way shutters, repairing the roof and replacing the curtain walls.
*Less than 10^{-5}

Table 4.13. Summary of Fatality Statistics for Standard Type B Building

Description of Structure	Expected Fraction of Fatalities (Standard Deviation) — Hurricane Category 1	2	3	4	5	Cost to Upgrade ($000)
Existing structure including frame and foundation failure	.0004 (.0454)	.0506 (.1620)	.3750 (.3100)	.5530 (.3010)	.5920 (.2940)	0.0
Existing structure ignoring frame and foundation failure	* (*)	* (*)	.0474 (.1570)	.2780 (.2870)	.4220 (.3050)	0.0
Structure upgraded[a] to resist Category 3 hurricane	* (*)	* (*)	* (*)	.0270 (.1210)	.2710 (.2850)	430.4

[a]Upgrading consisted of installation of Roll-A-Way shutters, repairing the roof and replacing the cladding.
*Less than 10^{-5}

Table 4.14. Summary of Fatality Statistics for Standard Type C Building

Description of Structure	Expected Fraction of Fatalities (Standard Deviation)					Cost to Upgrade ($000)
	Hurricane Category					
	1	2	3	4	5	
Existing structure including frame and foundation failure	.0100 (.0900)	.0200 (.1000)	.3100 (.3300)	.7200 (.2600)	.7200 (.2600)	0.0
Existing structure ignoring frame and foundation failure	* (*)	* (*)	.3370 (.3260)	.4520 (.3010)	.5410 (.2970)	0.0
Structure upgraded[a] to resist Category 3 hurricane	* (*)	* (*)	* (*)	* (.0004)	.4520 (.3010)	234.2

[a]Upgrading consisted of replacing window wall units, cladding and strengthening roof systems.
*Less than 10^{-5}

Table 4.15. Summary of Fatality Statistics for Standard Type D Building

Description of Structure	Expected Fraction of Fatalities (Standard Deviation) Hurricane Category 1	2	3	4	5	Cost to Upgrade ($000)
Existing structure[a] including frame and foundation failure	– –	– –	– –	– –	– –	0.0
Existing structure ignoring frame and foundation failure	* (*)	.0306 (.1290)	.4210 (.3050)	.4220 (.3050)	.4220 (.3050)	0.0
Structure upgraded[b] to resist Category 3 hurricane	* (*)	* (*)	.0254 (.1180)	.4200 (.3050)	.4200 (.3050)	58.9

[a]Statistic not estimated.
[b]Upgrading consisted of installation of Roll-A-Way shutters, strengthening the roof and replacing the stud wall system.
*Less than 10^{-5}

Table 4.16. Summary of Fatality Statistics for Standard Type E Building

Description of Structure	Expected Fraction of Fatalities (Standard Deviation)					Cost to Upgrade ($000)
	Hurricane Category 1	2	3	4	5	
Existing structure[a] including frame and foundation failure	– –	– –	– –	– –	– –	0.0
Existing structure ignoring frame and foundation failure	* (*)	* (*)	* (*)	.1050 (.2210)	.2740 (.2860)	0.0
Structure upgraded[b] to resist Category 3 hurricane	* (*)	* (*)	* (*)	* (*)	.0019 (.0339)	364.5

[a]Statistic not estimated.
[b]Upgrading consisted of installation of Roll-A-Way shutters and replacement of cladding with double wythe brick wall.
*Less than 10^{-5}

Table 4.17. Summary of Fatality Statistics for Standard Type F Building

Description of Structure	Expected Fraction of Fatalities (Standard Deviation) — Hurricane Category 1	2	3	4	5	Cost to Upgrade ($000)
Existing structure[a] including frame and foundation failure	– –	– –	– –	– –	– –	0.0
Existing structure ignoring frame and foundation failure	* (*)	.0024 (.0368)	.2140 (.2770)	.4160 (.3060)	.4220 (.3050)	0.0
Structure upgraded[b] to resist Category 3 hurricane	* (*)	* (*)	.0033 (.0434)	.2140 (.2760)	.4000 (.3070)	30.6

[a]Statistic not estimated.
[b]Upgrading consisted of installation of Roll-A-Way shutters, additional hurricane clips and joist hangers, and strengthening the stud wall with blocking.
*Less than 10^{-5}

Table 4.18. Risk Associated With and Estimated Cost to Upgrade Type A Building

Option Number	Description	Risk of Fatalities (Number of Fatalities per 100 Persons)					Cost to Upgrade (upgrade cost/ replacement cost)
		Hurricane Category[a] 1	2	3	4	5	
1	Evacuate vertically to upper floors of existing building	0[b]	9	42	42	42	0
2	Evacuate vertically to upper floors of upgraded building	0	0	8[c]	42	42	0.15

[a]See Appendix A.
[b]Estimated to the nearest person.
[c]Roof beams have not been upgraded.

Table 4.19. Risk Associated With and Estimated Cost to Upgrade Type B Building

Option Number	Description	Risk of Fatalities (Number of Fatalities per 100 Persons)					Cost to Upgrade (upgrade cost/ replacement cost)
		Hurricane Category[a] 1	2	3	4	5	
1	Evacuate vertically to upper floors of existing building	0[b]	0	5	28	42	0
2	Evacuate vertically to upper floors of upgraded building	0	0	0	3	27	0.31

[a]See Appendix A.
[b]Estimated to the nearest person.

Table 4.20. Risk Associated With and Estimated Cost to Upgrade Type C Building

Option Number	Description	Risk of Fatalities (Number of Fatalities per 100 Persons) Hurricane Category[a]					Cost to Upgrade (upgrade cost/ replacement cost)
		1	2	3	4	5	
1	Evacuate vertically to upper floors of existing building	0[b]	0	34	45	54	0
2	Evacuate vertically to upper floors of upgraded building	0	0	0	0	45	0.23

[a]See Appendix A.
[b]Estimated to the nearest person.

Table 4.21. Risk Associated With and Estimated Cost to Upgrade Type D Building

Option Number	Description	Risk of Fatalities (Number of Fatalities per 100 Persons) Hurricane Category[a]					Cost to Upgrade (upgrade cost/ replacement cost)
		1	2	3	4	5	
1	Evacuate vertically to upper floors of existing building	0[b]	3	42	42	42	0
2	Evacuate vertically to upper floors of upgraded building	0	0	3	42	42	0.15

[a]See Appendix A.
[b]Estimated to the nearest person.

Table 4.22. Risk Associated With and Estimated Cost to Upgrade Type E Building

Option Number	Description	Risk of Fatalities (Number of Fatalities per 100 Persons) Hurricane Category[a] 1	2	3	4	5	Cost to Upgrade (upgrade cost/ replacement cost)
1	Evacuate vertically to upper floors of existing building	0[b]	0	0	10	27	0
2	Evacuate vertically to upper floors of upgraded building	0	0	0	0	0	0.08

[a]See Appendix A.
[b]Estimated to the nearest person.

Table 4.23. Risk Associated With and Estimated Cost to Upgrade Type F Building

Option Number	Description	Risk of Fatalities (Number of Fatalities per 100 Persons) Hurricane Category[a] 1	2	3	4	5	Cost to Upgrade (upgrade cost/ replacement cost)
1	Evacuate vertically to upper floors of existing building	0[b]	0	21	42	42	0
2	Evacuate vertically to upper floors of upgraded building	0	0	0	21	40	0.07

[a]See Appendix A.
[b]Estimated to the nearest person.

$$f_X(x) = [1/(\sqrt{(2\pi)}\xi x)]\exp[-1/2(\ln x - \lambda)^2/\xi^2] \quad (4.2)$$

for $X \geq 0$, and where the parameters λ and ξ are given by

$$\lambda = E[\ln X] \quad (4.3)$$

and

$$\xi^2 = Var[\ln X] \quad (4.4)$$

and represent the mean and variance of ln X. The quantities can be computed directly from the mean and standard deviation of X, respectively μ and σ, using the relations

$$\lambda = \ln \mu - \xi^2/2, \text{ and} \quad (4.5)$$

$$\xi^2 = \ln[1 + \sigma^2/\mu^2] \quad (4.6)$$

Finally, the probability that the random variable X is between any two limits a and b is given by:

$$P[a < X \leq b] = \Phi(S_b) - \Phi(S_a) \quad (4.7)$$

where

$$S_b = (\ln b - \lambda)/\xi, \quad (4.8)$$

$$S_a = (\ln a - \lambda)/\xi, \text{ and} \quad (4.9)$$

$\Phi(.)$ is the standard normal distribution function. Risk expressed in terms of various probabilities evaluated using Equations (4.2 to 4.9) are summarized in Tables 4.24 to 4.35. In these tables a practical level of zero (no fatalities occur) is defined to be $X \leq 0.05$ to offset the uncertainty associated with the tail of the distribution. Analogously, $X \geq 0.95$ represents the event that everybody has been killed.

Table 4.24. Risk (Expressed in Terms of Various Probabilities) of Using Existing Type A Building

Description of Probabilistic Risk	Probability: Hurricane Category 1	2	3	4	5
Someone is killed: P(X > 0.05)	0.000	0.399	0.998	0.999	0.999
No one is killed: P(X < 0.05)	1.000	0.601	0.002	0.001	0.001
50% or more are killed: P(X > 0.50)	0.000	0.026	0.277	0.280	0.280
All are killed: P(X > 0.95)	0.000	0.008	0.057	0.058	0.058

N.B. X = Fraction of inhabitants.

Table 4.25. Risk (Expressed in Terms of Various Probabilities) of Using Upgraded Type A Building

Description of Probabilistic Risk	Probability: Hurricane Category 1	2	3	4	5
Someone is killed: P(X > 0.05)	0.000	0.000	0.361	0.998	0.998
No one is killed: P(X < 0.05)	1.000	1.000	0.639	0.002	0.002
50% or more are killed: P(X > 0.50)	0.000	0.000	0.023	0.276	0.279
All are killed: P(X > 0.95)	0.000	0.000	0.007	0.057	0.058

N.B. X = Fraction of inhabitants.

Table 4.26. Risk (Expressed in Terms of Various Probabilities) of Using Existing Type B Building

Description of Probabilistic Risk	Probability — Hurricane Category 1	2	3	4	5
Someone is killed: $P(X > 0.05)$	0.000	0.000	0.206	0.944	0.998
No one is killed: $P(X < 0.05)$	1.000	1.000	0.794	0.056	0.002
50% or more are killed: $P(X > 0.50)$	0.000	0.000	0.011	0.132	0.279
All are killed: $P(X > 0.95)$	0.000	0.000	0.004	0.031	0.058

N.B. X = Fraction of inhabitants.

Table 4.27. Risk (Expressed in Terms of Various Probabilities) of Using Upgraded Type B Building

Description of Probabilistic Risk	Probability — Hurricane Category 1	2	3	4	5
Someone is killed: $P(X > 0.05)$	0.000	0.000	0.000	0.110	0.937
No one is killed: $P(X < 0.05)$	1.000	1.000	1.000	0.890	0.063
50% or more are killed: $P(X > 0.50)$	0.000	0.000	0.000	0.005	0.127
All are killed: $P(X > 0.95)$	0.000	0.000	0.000	0.002	0.030

N.B. X = Fraction of inhabitants.

Table 4.28. Risk (Expressed in Terms of Various Probabilities) of Using Existing Type C Building

Description of Probabilistic Risk	Probability — Hurricane Category 1	2	3	4	5
Someone is killed: $P(X > 0.05)$	0.000	0.000	0.974	1.000	1.000
No one is killed: $P(X < 0.05)$	1.000	1.000	0.026	0.000	0.000
50% or more are killed: $P(X > 0.50)$	0.000	0.000	0.186	0.320	0.459
All are killed: $P(X > 0.95)$	0.000	0.000	0.046	0.063	0.088

N.B. X = Fraction of inhabitants.

Table 4.29. Risk (Expressed in Terms of Various Probabilities) of Using Upgraded Type C Building

Description of Probabilistic Risk	Probability — Hurricane Category 1	2	3	4	5
Someone is killed: $P(X > 0.05)$	0.000	0.000	0.000	0.000	1.000
No one is killed: $P(X < 0.05)$	1.000	1.000	1.000	1.000	0.000
50% or more are killed: $P(X > 0.50)$	0.000	0.000	0.000	0.000	0.320
All are killed: $P(X > 0.95)$	0.000	0.000	0.000	0.000	0.063

N.B. X = Fraction of inhabitants.

Table 4.30. Risk (Expressed in Terms of Various Probabilities) of Using Existing Type D Building

Description of Probabilistic Risk	Probability				
	Hurricane Category				
	1	2	3	4	5
Someone is killed: P(X > 0.05)	0.000	0.127	0.998	0.998	0.998
No one is killed: P(X < 0.05)	1.000	0.873	0.002	0.002	0.002
50% or more are killed: P(X > 0.50)	0.000	0.006	0.278	0.279	0.279
All are killed: P(X > 0.95)	0.000	0.002	0.057	0.058	0.058

N.B. X = Fraction of inhabitants.

Table 4.31. Risk (Expressed in Terms of Various Probabilities) of Using Upgraded Type D Building

Description of Probabilistic Risk	Probability				
	Hurricane Category				
	1	2	3	4	5
Someone is killed: P(X > 0.05)	0.000	0.000	0.103	0.998	0.998
No one is killed: P(X < 0.05)	1.000	1.000	0.897	0.002	0.002
50% or more are killed: P(X > 0.50)	0.000	0.000	0.005	0.276	0.279
All are killed: P(X > 0.95)	0.000	0.000	0.002	0.057	0.058

N.B. X = Fraction of inhabitants.

Table 4.32. Risk (Expressed in Terms of Various Probabilities) of Using Existing Type E Building

Description of Probabilistic Risk	Probability: Hurricane Category 1	2	3	4	5
Someone is killed: $P(X > 0.05)$	0.000	0.000	0.000	0.468	0.940
No one is killed: $P(X < 0.05)$	1.000	1.000	1.000	0.532	0.060
50% or more are killed: $P(X > 0.50)$	0.000	0.000	0.000	0.032	0.129
All are killed: $P(X > 0.95)$	0.000	0.000	0.000	0.010	0.030

N.B. X = Fraction of inhabitants.

Table 4.33. Risk (Expressed in Terms of Various Probabilities) of Using Upgraded Type E Building

Description of Probabilistic Risk	Probability: Hurricane Category 1	2	3	4	5
Someone is killed: $P(X > 0.05)$	0.000	0.000	0.000	0.000	0.005
No one is killed: $P(X < 0.05)$	1.000	1.000	1.000	1.000	0.995
50% or more are killed: $P(X > 0.50)$	0.000	0.000	0.000	0.000	0.000
All are killed: $P(X > 0.95)$	0.000	0.000	0.000	0.000	0.000

N.B. X = Fraction of inhabitants.

Table 4.34. Risk (Expressed in Terms of Various Probabilities) of Using Existing Type F Building

Description of Probabilistic Risk	Probability				
	Hurricane Category				
	1	2	3	4	5
Someone is killed: P(X > 0.05)	0.000	0.007	0.835	0.998	0.999
No one is killed: P(X < 0.05)	1.000	0.993	0.165	0.002	0.001
50% or more are killed: P(X > 0.50)	0.000	0.000	0.088	0.272	0.280
All are killed: P(X > 0.95)	0.000	0.000	0.023	0.056	0.058

N.B. X = Fraction of inhabitants.

Table 4.35. Risk (Expressed in Terms of Various Probabilities) of Using Upgraded Type F Building

Description of Probabilistic Risk	Probability				
	Hurricane Category				
	1	2	3	4	5
Someone is killed: P(X > 0.05)	0.000	0.000	0.010	0.833	0.997
No one is killed: P(X < 0.05)	1.000	1.000	0.990	0.167	0.003
50% or more are killed: P(X > 0.50)	0.000	0.000	0.000	0.088	0.252
All are killed: P(X > 0.95)	0.000	0.000	0.000	0.023	0.053

N.B. X = Fraction of inhabitants.

Relative Safety of Buildings

In future feasibility studies, decision-makers may desire to know the relative safety of two structures. For our purposes, if two structures are subjected to the same set of environmental conditions, then the structure which exposes the occupant to the lesser risk, however defined, is safer. For example, if the six structure types considered here are all subjected to a Category 1 hurricane, the structure with the least-risk, as defined in Tables 4.18 to 4.23 or Tables 4.24 to 4.35, is safest. A ranking of the buildings using the criteria above is presented in Table 4.36. The safest building is ranked No. 1 and the numerical ranking increases as the risks associated with using the structure increases. If more than one structure has the same risk magnitude associated with it, all such structures are assigned the same ranking. For each structure the ranking was performed on the basis of the expected fatalities or the probability that someone will be killed. The rankings based on the latter criteria are listed in parenthesis.

In interpreting Table 4.36, the reader should keep two points in mind. First, the comparison is valid only when all structures are subjected to the same hurricane. Thus, for a Category 1 hurricane the risk associated with using any of the structures is about the same. Second, the change in ranking, for a given structure, when the magnitude of the hurricane increases has no meaning. For example, the numbers in rows 1 and 2 have nothing to do with the numbers in rows 3 and 4.

Table 4.36. Ranking of Buildings as They Exist

Hurricane Category	Ranking of Existing Building on the Basis of Occupant Safety per 100 Occupants[a] — Building Type A	B	C	D	E	F
1	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)
2	3 (4)	1 (1)	1 (1)	2 (3)	1 (1)	1 (2)
3	5 (5)	2 (2)	4 (4)	5 (5)	1 (1)	3 (3)
4	3 (3)	2 (2)	3 (3)	3 (3)	1 (1)	3 (3)
5	2 (2)	2 (2)	3 (2)	2 (2)	1 (1)	2 (2)

[a]1 = Least risky; () = using criteria that someone will be killed.

From Table 4.36 several trends are apparent. Firstly, the relative safety of the structure depends upon the magnitude of the hurricane. Secondly, the ranking of the structures is insensitive to the two measures of risk that are used to rank the structures. Thirdly, the range of protection offered by the structures as a group is smallest for the extreme hurricanes (Category 1 and Category 5) and largest for the intermediate hurricanes. A similar ranking for the upgraded structure is presented in Table 4.37.

Consideration of Buildings With Special Protective Features

So far our analysis of occupant safety has considered the major elements of the building system (foundation, frame, cladding, and roof) and how the chances of failure of these elements are related to the risk of a fatality. For example, if the exterior cladding on the roof failed, the occupant was assumed to be directly exposed to the fury of the hazard. This scenario may be true for a number of buildings (e.g., building types A, B, and F which consist primarily of non-load bearing curtain walls). However, the scenario may not be true for the larger structures. In such cases the existence of load bearing walls and massive stairwells present the possibility of a second line of defense. Even if the ordinary cladding or roof may fail, the occupants may safely relocate to stairwells or rooms surrounded by reinforced masonry, precast concrete, or other types of load bearing walls.

To evaluate the impact of utilizing the stairwells when they are present, this section summarizes the risk analysis of Type C build-

Table 4.37. Ranking of Upgraded Buildings

Hurricane Category	Ranking of Upgraded Building on the Basis of Occupant Safety per 100 Occupants[a]					
	Building Type					
	A	B	C	D	E	F
1	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)
2	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)
3	3 (4)	1 (1)	1 (1)	2 (3)	1 (1)	1 (2)
4	4 (3)	2 (2)	1 (1)	4 (3)	1 (1)	3 (2)
5	3 (3)	2 (2)	3 (3)	3 (3)	1 (1)	3 (3)

[a]1 = Least risky; () = using criteria that someone will be killed.

ings assuming that the occupants are sheltered in the stairwells of the structure. This analysis will provide at least a ballpark estimate of the extra protection afforded by such structures when they are present.

The structure has two identical seven-story stairwells (A and D, Figure 4.10) located at the western and eastern end, respectively, of the structure. Each stairwell has interior dimensions of 7.5 X 13.71 feet and is enclosed by 7-inch thick, post-tensioned, precast panels. The total height of the stairwell structure is 52 feet with stairs connecting floors spaced at approximately nine feet.

For purposes of analysis, the stairwell structure is modelled as a cantilever with a constant cross-section shown in Figure 4.11. Failure for the stairwell (i.e., collapse) was defined as follows: 1) compressive stress at the base of the stairwell exceeds the compressive strength of the concrete at that section, and 2) at the base of the stairwell the tensile stress in the prestressing cable exceeds the tensile strength of the cable. Resistance statistics were based on values presented in the plans and values of the load were determined as discussed in the last chapter. The failure estimates for the above failure criteria are summarized in Table 4.38.

Note that in Table 4.38, for all hurricane categories the failure probabilities associated with concrete crushing due to bending only is relatively small when compared with the failure probabilities associated with the failure of the tendons in tension. As seen in the next column, the failure of the post-tensioning system controls the safety of the structure. In the last column an *a posteriori* prob-

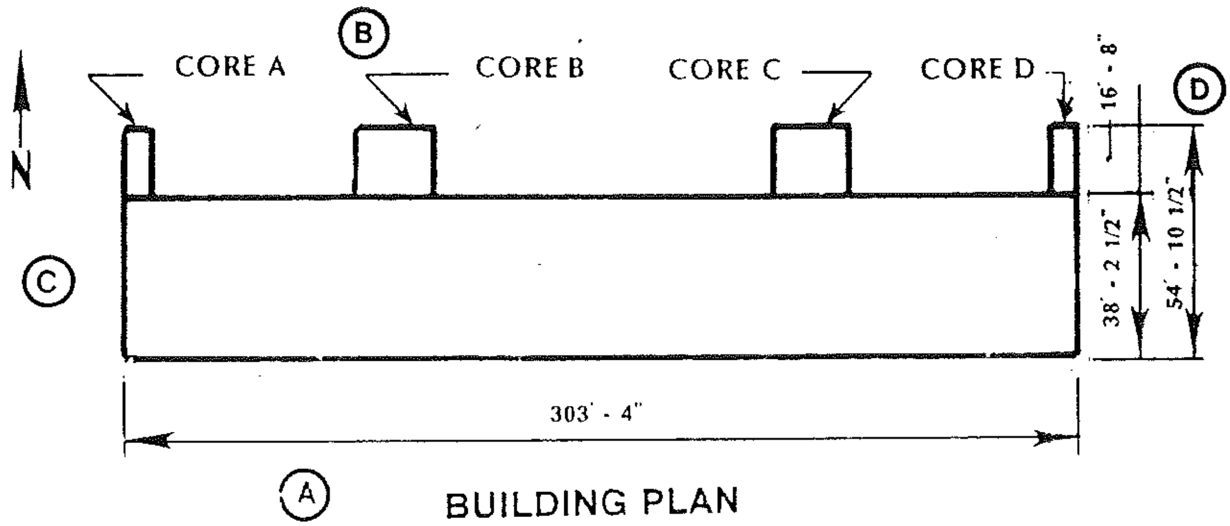

Figure 4.10. Type C Building Stairwell Location

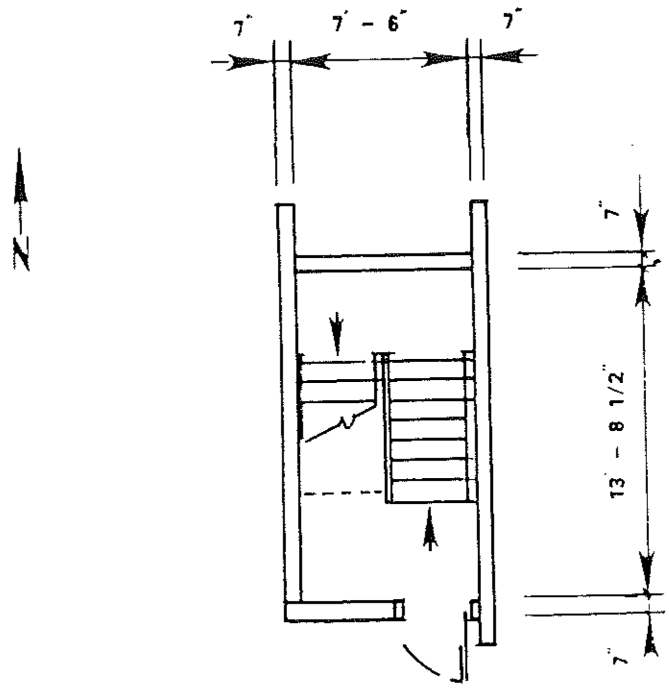

Figure 4.11. Cross-Section of Stairwell Structure

Table 4.38. Building Core Failure Probabilities

Hurricane Category	Failure Due to Crushing	Tendon Failure	P(A∪B)[a]	Revised P_f (One Core)
1	*	3.362×10^{-3}	3.362×10^{-3}	*
2	*	6.789×10^{-3}	6.789×10^{-3}	*
3	*	7.373×10^{-3}	7.373×10^{-3}	*
4	*	8.376×10^{-3}	8.376×10^{-3}	8.376×10^{-3}
5	*	9.626×10^{-3}	9.626×10^{-3}	9.626×10^{-3}

[a] **A** = {Failure due to Crushing}; **B** = {Tendon Failure}.
*Less than 10^{-6}.

ability of failure of the core is estimated on the basis of the observed behavior of engineered structures in a wind environment. For a Category 1, 2, or 3 storm, no engineered structure (in the U.S.), subjected only to wind, has been observed to collapse (Davenport, 1972). Therefore, if we define the event {E} to be "the occurrence of a Category 1, 2, or 3 hurricane" and {F} to be the event that "the structural frame collapses", we may write

$$P[F|E] = P[F\cap E]/P[E] \qquad (4.10)$$

But, so far the event $\{F\cap E\} = \{\phi\}$, where $\{\phi\}$ is the null set. Therefore, since $P[E] \neq 0$, $P[F|E] = 0$. Note that this latter probability estimate is based on past experience and there is no guarantee that in the future the event $\{E\cap F\}$ will not occur. The revised failure probabilities for one core are listed in the last column of Table 4.38. Because of a lack of knowledge of the behavior of engineered frames in Category 4 and 5 hurricanes, no updated estimates of the probabilities are proposed here.

To complete the risk calculation the following modifications were made to the original calculations: 1) instead of neglecting the frame failure, the probability of failure of either Stairwell A or D was used in the risk equation (Equation 3.13); 2) since it was assumed that the inhabitants would all be sheltered in the stairwells, the exposure in the event of roof, cladding, or partition failure was set equal to zero. The resulting input data are given in Table 4.39. The expected fraction of fatalities and the associated standard deviations for each hurricane category are listed in Table 4.40. The measures of risk expressed in terms of expected number of

Table 4.39. Risk Model Data Input for Existing Type C Building Assuming All Evacuees Are In Stairwells

Basic Event	Description of Basic Event	Basic Event Probabilities: Hurricane Category 1	2	3	4	5
X_1	Wind hazard occurs	1.00	1.00	1.00	1.00	1.00
X_2	Lateral forces exceed frame strength	*	*	*	1.67×10^{-2}	1.93×10^{-2}
X_3	Person is exposed|frame fails	1.00	1.00	1.00	1.00	1.00
X_5	Foundation fails	*	*	*	*	*
X_6	Person is exposed|foundation fails	1.00	1.00	1.00	1.00	1.00
X_8	Uplift forces exceed roof strength	*	*	0.74	1.00	1.00
X_9	Person is exposed|roof fails	0.00	0.00	0.00	0.00	0.00
X_{11}	Lateral forces exceed cladding resistance	*	*	*	*	1.00
X_{12}	Person is exposed|cladding fails	0.00	0.00	0.00	0.00	0.00
X_{14}	Lateral forces exceed int. part. resistance	*	*	*	*	*
X_{15}	Person is exposed|partition fails	0.00	0.00	0.00	0.00	0.00

*Less than 10^{-7} or failure mode ignored.

Table 4.40. Risk of Using the Stairwells of Existing Type C Building in Various Hurricanes

Hurricane Category	Expected Fraction of Fatalities	Standard Deviation of Expected Fatalities
1	*	$5.46X10^{-5}$
2	*	$5.46X10^{-5}$
3	*	$5.46X10^{-5}$
4	$4.56X10^{-3}$	$5.08X10^{-2}$
5	$5.26X10^{-3}$	$5.45X10^{-2}$

*Magnitude $< 10^{-7}$.

fatalities per 100 persons and the various probabilistic descriptions are listed in Table 4.41.

Several interesting observations can now be made if we compare Table 4.41 with Tables 4.20, 4.28, and 4.29. Without introducing any modifications to the existing structure, but by simply modifying the exposure of the occupants (i.e., locating them in different parts of the building), fatalities are dramatically reduced. This observation is particularly true for Category 3, 4, and 5 hurricanes. Put another way, the use of the stairwells dramatically increases the chances of occupant survival in the more intense hurricanes. For example, in a Category 4 hurricane, the probability that someone is killed if the stairwells are used exclusively is reduced from unity (i.e., certainty) to less than 2 in 100. Simultaneously, at the other extreme, the probability that 50% or more are killed has been reduced from 1 in 2 (for the case of not using the stairwells) to 1 in 1000 (for the case of using the stairwells). Finally, the option of using stairwells (particularly in Category 3, 4, and 5 hurricanes) is superior to the option of upgrading the structure. In conclusion we make the following point: Although people are aware of the additional protection offered by load-bearing walls or stairwells, we have presented here one of the first quantitative estimates of such added protection.

Table 4.41. Risk of Using Stairwells of Existing Type C Building

Measure Of Risk	Magnitude of Risk				
	Hurricane Category				
	1	2	3	4	5
Expected Fatalities[a]	0	0	0	0	1
Someone is killed: P(X > 0.05)	0.000	0.000	0.000	0.014	0.017
No one is killed: P(X < 0.05)	1.000	1.000	1.000	0.986	0.983
50% or more are killed: P(X > 0.50)	0.000	0.000	0.000	0.001	0.001
All are killed: P(X > 0.95)	0.000	0.000	0.000	0.000	0.000

[a]Number of fatalities per 100 persons.

Scenario Evaluations

In the second chapter of this report, we argued that the feasibility of vertical evacuation, as an option for risk mitigation in coastal communities, depended not only upon the various other mitigative options available but also upon the set of criteria (which are not unique) that may be used to evaluate the options. Furthermore, any single mitigative option, such as vertical evacuation, has associated with it a string of logistic, technical, legal, psychological and political considerations. These nebulous elements must be entered into some sort of qualitative "feasibility equation", developed by the decision-makers, the output of which is a consensus regarding the feasibility of the option.

The purpose of this section is to demonstrate how the structural assessment technique developed in previous chapters can be used to provide decision-makers with quantitative information that reflects the type and number of structures utilized, the number of people sheltered, the governing codes used to construct the buildings, the characteristics of the hurricane, and the state-of-the-art in structural mechanics. Since the structural feasibility of vertical evacuation may depend upon the options available, we present a hypothetical analysis for two scenarios: the first scenario involves a situation in which averting the hurricane hazard by relocating inland (horizontal evacuation) is an option while the second scenario considers a situation in which horizontal evacuation is not an option.

Scenario One: Horizontal Versus Vertical Evacuation

"Galveston Island is threatened by a direct hit of a Category 1 to 5 hurricane. Given the current trajectory and speed of the hurricane, if the order to evacuate is given within the next 8 hours, all assumed 50,000 inhabitants may evacuate horizontally in accordance with the plans already prepared by the Office of Emergency Management. At the same time, the Office of Emergency Management has identified a set of potential vertical shelters on Galveston Island and has the option of replacing the order for a horizontal evacuation, which may turn out to be a false alarm, with that of a vertical evacuation. Using the information compiled on structures in Galveston in the last section and statistics of casualties associated with horizontal evacuation for recent hurricanes in the Galveston area, determine the least-risk option".

Analysis of Risk of Vertical Evacuation

The relative safety of the potential shelters in each hurricane category is summarized in Table 4.36 and the area of floor space available in each building is summarized in Table 4.10. Beginning with these two groups of data we may proceed to allocate people to the various shelters. If we neglect the space available on the first floor (since that region may be flooded) and assume that only 40 percent of the total floor space is available for refuge, then the number of people that can be sheltered in each building (as a function of the space provided for each person) is provided in Table 4.42. Note that in Table 4.42, we have included a Type G building which represent a Type C building in which only the stairwells (or interior regions which offer protection beyond that offered by typical cladding systems) are used for sheltering. On the basis of the results presented in Table 4.42, we estimate that the vertical evacuation capacity of Galveston may range between 90,000 and 360,000 people.

Table 4.42. Potential Shelter Capacity for Galveston

Building Type	Total Area[a] (Thousands of square feet)	Area Available[b] for Shelters (Thousands of square feet)	Capacity (Number of People)			
			10 square feet/person	20 square feet/person	30 square feet/person	40 square feet/person
A	1,020	408	40,800	20,400	13,600	10,200
B	2,607	1,042	104,200	52,100	34,733	26,050
C	2,880	1,152	115,200	57,600	38,400	28,800
D	56	22	2,200	1,100	733	550
E	576	230	23,000	11,500	7,667	5,750
F	1,635	655	65,500	32,750	21,833	16,375
G[c]	78	78	7,874	3,937	2,625	1,968
Total			358,892	179,446	119,630	89,723

[a]Total floor space excluding first floor.
[b]Assumed to be 40 percent of total area.
[c]Building Type C with stairwell, inhabitants sheltered in stairwells.

Therefore, theoretically we have sufficient space to shelter the assumed 50,000 people.

Ideally we would like to locate people in the safest structures available. For a Category 1 hurricane, all of the structures provide, approximately, the same measure of safety, (i.e., on the basis of using the expected number of fatalities as a criterion); therefore, additional criteria may have to be provided to distinguish between the structures. Leaving that choice to other aspects of the feasibility determination (e.g., logistical or economical) we arbitrarily select buildings A, B, and C. If we first use all Type A buildings, then all Type B, and finally place the remaining people in Type C, we obtain the third column in Table 4.43 (if we assume 30 square feet/person).

For a Category 2 hurricane, the safest buildings are Types B, C, E, and F. In the absence of additional constraints, we arbitrarily select Types B and C as shelters. Accordingly, if all Type B structures are first filled, the remaining 16,000 people can be placed in Type C structures. Again we have assumed a sheltering rate of 30 square feet/person. This allocation is summarized in the fourth column, Table 4.43.

For a Category 3, and above, hurricane the safest shelter locations are the stairwells in building Type C, followed by building Type E, followed by building Type B. However, since the capacity of the stairwells is relatively limited, we assume that in order to shelter the maximum number of people in the safest location, we shelter at a rate of 10 square feet/person. Since so few buildings of

Table 4.43. Least-Risk Sheltering Options for 50,000 People in Galveston (Assuming 30 Square Feet/Person)

		Least-Risk Shelter Options (Number of People)				
		Hurricane Category				
Bldg. Type	No. of Bldgs.	1	2	3	4	5
A	85	13,600[1a]				
B	79	34,400[1]	34,000[1]	34,733[3]	34,733[3]	34,733[3]
C	32	2,000[1]	16,000[1]			
D	7					
E	9			7,667[2]	7,667[2]	7,667[2]
F	39					
G[b]	32			7,600[1]	7,600[1]	7,600[1]
Total	283	50,000	50,000	50,000	50,000	50,000

[a]1 = Least risky, 3 = most risky.
[b]Building Type C with stairwell, inhabitants sheltered in stairwells at 10 square feet/person.

Type E are available, only 7,667 people can be sheltered therein. The majority and remaining people must be sheltered in Type B buildings. The results of this allocation for a sheltering rate of 30 square feet/person in building Types B and E is given in the last three columns of Table 4.43. The only alternate to reducing the risks to the occupants is to use a higher sheltering rate. Table 4.44 summarizes the allocation of people when a sheltering rate of 10 square feet/person is used for a Category 3, and above, hurricane.

So far we have considered the sheltering arrangements that would expose the sheltered population of 50,000 to the least-risk. However, we have not yet estimated this risk. If we take the estimated number of fatalities among the sheltered population as the measure of risk associated with vertical evacuation, then the risk associated with vertical evacuation may be computed using the equation:

$$\text{Expected Number of Fatalities} = \sum_{i=1}^{B} N_i n_i \bar{X}_i \qquad (4.11)$$

where N_i = the number of buildings of Type i in which someone is killed, n_i = the number of people sheltered in each Type i building, $\bar{X}_i$ = the expected fraction of fatalities if building Type i is used and B is the total number of building types used. The number N_i may be calculated using risk data developed in the latter part of this chapter. Let $\{Y\} = \{X > 0.05\}$ represent the event that someone is killed. Then, $p = P[X > 0.05]$ represents the probability that someone is killed in a building. In Tables 4.24 to 4.35 this value is listed for every structure, existing and upgraded to resist a Category 3 hurricane. We may use the binomial theorem to estimate the

Table 4.44. Least-Risk Sheltering Options for 50,000 People in Galveston (Assuming 10 Square Feet/Person)

Bldg. Type	Least-Risk Shelter Options (Number of People) Hurricane Category 1	2	3	4	5
A	13,600[1a]				
B	34,400[1]	34,000[1]	19,126[3]	19,126[3]	19,126[3]
C	2,000[1]	16,000[1]			
D					
E			23,000[2]	23,000[2]	23,000[2]
F					
G[b]			7,874[1]	7,874[1]	7,874[1]
Total	50,000	50,000	50,000	50,000	50,000

[a]1 = Least risky, 3 = most risky.
[b]Building Type C with stairwell, inhabitants sheltered in stairwells at 10 square feet/person.

frequency of the event {Y} for each building type and hurricane level. If Y is the number of times that this event with probability p occurs,

$$E[Y] = Np \qquad (4.12)$$

where N = the number of buildings in the given set. Here we set N_i = E[Y], where E[Y] is rounded off to the next highest integer. The number of buildings of each type in which someone is killed is given in Table 4.45.

The remaining quantities in Equation (4.11) can be obtained directly from previous tables. The number of people per building can be obtained from Tables 4.43 and 4.44 and the expected fraction of fatalities can be obtained from Tables 4.12 to 4.17.

Equation (4.11) was used to compute the risks associated with vertical evacuation for sheltering in existing buildings at a rate of 10 and 30 square feet/person, respectively, and 10 square feet/person in the structures upgraded to resist a Category 3 hurricane. The corresponding expected fatalities for horizontal evacuation based on results for Galveston for Hurricane Allen and Hurricane Alicia are also presented (Table 4.46).

From the results presented here we may make several observations:

1. If existing structures are used, and if the hurricane is a Category 1 or Category 2, the risks associated with horizontal and vertical evacuation are comparable.

2. If existing structures are used and if the hurricane is a Category 3 or above, the risks associated with vertical evacuation are orders of magnitude greater than the risks associated with horizontal evacuation.

3. If the structures are upgraded to resist a hurricane of Category 3, and if the hurricane is Category 1, 2, 3, or 4, the

Table 4.45. Number of Buildings in Which Someone is Killed (Existing or Upgraded Structure)

Bldg. Type	Number of Buildings in Which a Fatality Occurs — Hurricane Category 1	2	3	4	5
			Existing Structure		
A	0	34	85	85	85
B	0	0	16	74	79
C	0	0			
D					
E			0	4	8
F	0	0	33	39	39
G[a]			0	0	1
			Upgraded Structure		
A	0				
B	0	0			
C	0	0	0	0	32
D					
E			0	0	0
F					
G[b]			0	0	1

[a]Building Type C with stairwell, inhabitants sheltered in stairwells at 10 square feet/person.
[b]The stairwell was not upgraded.

Table 4.46. Comparison Between Risks Associated With Horizontal and Vertical Evacuation

Type of Risk	Comparative Risk (Fatalities per 50,000 Sheltered or Evacuated)				
	Hurricane Category				
	1	2	3	4	5
V.E. (30 sq ft/ person)	0[a]	0	331	9,148	16,554
V.E. (10 sq ft/ person)	0	0	182	5,909	13,671
V.E. (10 sq ft/[b] person)	0	0	0	0	8,606
Horizontal[c] Evacuation	1	1	1	1	1

[a]Expected number of fatalities = (no. of bldgs. failing)(no. of people/bldg)(expected fraction of fatalities).
[b]Structures were upgraded to resist a Category 3 hurricane.
[c]Based on results for Galveston for Hurricane Allen and Hurricane Alicia.
N.B.:
a) for the number of buildings failing see Table 4.45;
b) for the number of people per building see Table 4.43; and
c) for the expected fraction of fatalities, see Tables 4.12 to 4.17 and Table 4.40.

risks associated with vertical and horizontal evacuation are comparable.

From these observations we draw the following conclusions:

1. Compared to horizontal evacuation, vertical evacuation may be a least-risk option, if certain existing structures (subjected primarily to wind generated force) are used in a Category 1 or 2 hurricane.
2. Compared to horizontal evacuation, vertical evacuation may be a least-risk option, if certain structures are upgraded to resist a Category 3 hurricane but are not used as shelters in a Category 5 hurricane.
3. In all other cases, horizontal evacuation is the least-risk option.

We stress that these results are limited to the structures studied on Galveston Island. A similar exercise at a different location with different building practices and traffic conditions may yield completely different results. However, the methodology used here remains valid.

Scenario Two: Vertical Evacuation as a Last Resort

"Galveston Island is threatened by a direct hit of a Category 1 to 5 hurricane that has rapidly developed nearby in the Gulf. Two weeks prior to this instant a cargo ship accidentally collided with two of the major piers supporting the causeway linking Galveston Island with the mainland. Although repair crews have been working continuously since the accident, the causeway will not be open to traffic for at least another two weeks. Ferry boats and other seacrafts have been transporting people and goods to and from the mainland. Since the causeway is inoperative, horizontal evacuation in the traditional sense is not an option. In addition, since no contingency plans to evacuate the population via sea vessels are known to exist, the only options open to the decision-makers are those involving the use of existing shelters on the Island. There are approximately 50,000 people to be sheltered and the three sheltering options are as follows:

1. Seek shelter in the traditional shelters designated by groups such as the Red Cross.
2. Seek shelter in existing residences in the non-high velocity zone.
3. Seek shelter in the upper floors of multi-story structures

previously designated as vertical refuge shelters.

Using the information compiled on structures in Galveston in the last section, determine which of the three options is the least-risk option, in a structural sense".

Analysis of the Comparative Risks

The first step in evaluating the options is to identify the structures that would be used in each option. The structures selected by such groups as the Red Cross often include schools and churches. It turns out that the majority of these structures are low-rise (1 - 2-story) buildings. From Table 4.5, Type A buildings fit this category; consequently, Type A buildings will be assumed to model the behavior of typical traditional shelters in Galveston. Note that these shelters will be located in the non-high velocity zone. The only residential structures analyzed in this study (i.e., that passed the first structural screening test) are the Type F structures (wooden frame, 2 - 4 stories). A detailed description of a typical structure belonging to this class of structures is given in the earlier part of this chapter. We will model the behavior of residences with Type F structures. Again we assume that only structures located in the non-high velocity zone will be considered.

From Table 4.5, the logical choices for vertical shelters are building types B, C (G), and E. These structures are all multi-storied and have received attention from design professionals. A summary of the three shelter options is given in Table 4.47. It is assumed that all of the 50,000 assumed inhabitants can be sheltered by each option. For example, we show that if traditional shelters

Table 4.47. Shelter Summary for the Various Options

Option	Building Type	Number of Buildings	Shelter Population	People/ Building	Square Feet/ Person
Traditional Shelters	A	85	50,000	588	8-20
Residences	F	39	50,000	1,282	13-30
V.E. (existing buildings)	B	79	34,733	440	30
	E	9	7,667	852	30
	G	32	7,600	238	10
V.E. (existing buildings)	B	79	19,126	242	10
	E	9	23,000	2,555	10
	G	32	7,874	246	10
V.E. (upgraded buildings)	C	32	19,126	598	10
	E	9	23,000	2,565	10
	G	32	7,824	246	10

were involved, we could use all 85 buildings at a sheltering rate of 8 - 20 square feet/person. Also in the same table, note that three options for vertical evacuation are given: 1) using the existing structures at a rate of 30 square feet/person, 2) using the existing structures at a sheltering rate of 10 square feet/person, and 3) using the upgraded structures at a sheltering rate of 10 square feet/ person. Again we stress that the allocation of people represents the least-risk usage of the buildings to shelter the given amount of people at the given sheltering rates.

The second step in evaluating the options is to estimate the risk/ benefits involved in utilizing each option. As in the previous scenario, we will express the risk here as the expected number of fatalities per 50,000 people sheltered. How this number can be converted for one, or more, building types was demonstrated in evaluating the last scenario. Using the same procedure as that outlined in the last scenario, we arrive at the risks, as a function of option, and expressed in terms of the expected number of fatalities, shown in Table 4.48. The table should be interpreted as follows. If, for example, 50,000 people are repeatedly sheltered in traditional shelters - modelled by our Type A building - and those 85 buildings receive a direct hit from a Category 1 hurricane, in the long run (i.e., after many direct hits) no fatalities will occur. On the other hand, if the 50,000 people are repeatedly sheltered in the traditional shelter and they receive a direct hit from a Category 2 hurricane, in the long run the average number of fatalities for a direct hit will tend to 1,779. For convenience, Table 4.48 is reproduced

Table 4.48. Comparison of Risk Associated With Sheltering 50,000 People in Galveston Using the Various Options

Description	Risks (Expected Fatalities per 50,000 Sheltered)				
	Hurricane Category				
	1	2	3	4	5
Traditional Shelter	0	1779	21,000	21,000	21,000
Residences	0	0	1,057	20,999	20,999
Least-Risk Vertical Evacuation 30 square feet/person	0	0	331	9,148	16,554
Least-Risk Vertical Evacuation 10 square feet/person	0	0	182	5,909	13,671
Least-Risk Vertical Evacuation (Upgraded Structure) 10 square feet/person	0	0	0	0	8,606

again in Table 4.49; however, the fraction of fatalities is expressed as a fraction of the total number of inhabitants sheltered using the option. Thus, in a Category 2 hurricane utilizing the option of traditional shelters, we expect 3.6 percent of the inhabitants to be killed in the long run.

From Tables 4.48 and 4.49 we can make several observations:

1. In a Category 1 hurricane, considering only existing buildings, we do not expect any fatalities in any of the structures.
2. In a Category 2 hurricane, the use of traditional shelters, represented by the Type A building, may result in a significant number of fatalities; while the use of the other options will result in no fatalities.
3. In a Category 3 hurricane, the use of vertical shelters will result in significantly less fatalities than traditional shelters or the use of well-constructed residences. At the same time, by tripling the sheltering rate, the expected number of fatalities has been halved.
4. In a Category 4 hurricane, the risk of using vertical shelters is still an order of magnitude less than the risk associated with using traditional shelters or well-constructed residences.
5. In a Category 5 hurricane, the risk associated will all options is of the same magnitude, although the absolute value of the risks associated with vertical evacuation are somewhat smaller (16,554 cf., 21,000).
6. If the vertical structures are upgraded, we do not expect any fatalities in Categories 1 - 4. In Category 5, however, although the expected number of fatalities are significant, the number is an order of magnitude less than the risks associated with the existing structures (8,606 cf., 16,554).

The benefits associated with the use of vertical evacuation (as a last resort) are summarized in Table 4.50. In that table benefits are expressed in terms of expected number of lives saved. From Table 4.50 we see that in a Category 1 hurricane there is no benefit in utilizing vertical shelters. In a Category 2 hurricane, while there is a significant benefit in utilizing vertical evacuation *vis-a-vis*

Table 4.49. Comparison of Risk Associated With Sheltering People in Galveston Using the Various Options

Description	Risks (Percent Fatalities) Hurricane Category 1	2	3	4	5
Traditional Shelter	*	3.6	42.0	42.0	42.0
Residences	*	*	2.0	42.0	42.0
Least-Risk Vertical Evacuation 30 square feet/person	*	*	0.7	18.6	32.0
Least-Risk Vertical Evacuation 10 square feet/person	*	*	0.4	11.8	27.3
Least-Risk Vertical Evacuation (Upgraded Structure) 10 square feet/person	*	*	*	*	17.2

*< 0.02 percent.

Table 4.50. Benefits of Vertical Evacuation

Basis of Comparison	Benefits (Lives Saved per 50,000 Sheltered) Hurricane Category 1	2	3	4	5
Vertical Evacuation in Existing Structures Compared to Traditional Shelters	0	+1,779	+20,818	+15,091	+7,329
Vertical Evacuation in Upgraded Structures Compared to Traditional Shelters	0	+1,779	+21,000	+21,000	+12,394
Vertical Evacuation in Existing Structures Compared to Staying in Residences	0	0	+875	+15,090	+7,328
Vertical Evacuation in Upgraded Structures Compared to Vertical Evacuation in Existing Structures	0	0	+182	+5,909	+5,065

traditional shelters (1,779 more lives saved or 3.6 percent more of the sheltered population), there is no net benefit in utilizing vertical evacuation over staying in well-constructed residences. In Category 3 or above hurricanes, the net benefit of vertical evacuation is significant when compared with the other options: up to an average of 20,818 people may be saved by the option in Category 3 hurricanes alone. Also note that beginning with a Category 3 hurricane, the net benefit of upgrading the shelters becomes positive: according to the last row in Table 4.50, respectively, 182, 5,909, and 5,065 lives can be saved in Category 3, 4, and 5 hurricanes. Table 4.51 provides an estimate of the cost to upgrade the vertical shelters. We estimate, on the basis of upgrading costs presented in Tables 4.12 to 4.17, that approximately $11,000,000 (1986 dollars) would be needed to upgrade, to resist a Category 3 hurricane, the 41 buildings in Galveston that would permit us to shelter the assumed 50,000 people.

On the basis of these results and observations, we draw the following conclusions relating to the available options in Galveston when vertical evacuation is to be used as a last resort:

1. In a Category 1 hurricane, there is no clear-cut least-risk option.
2. In a Category 2 hurricane, the option of vertical evacuation is superior to staying in traditional shelters.
3. In a Category 3 or above hurricane, vertical evacuation in existing structures is the least-risk option.
4. If the vertical evacuation shelters are upgraded, no additional lives are saved until the magnitude of the hurricane equals or exceeds that of a Category 3 hurricane.

Table 4.51. Estimate of Cost to Upgrade Vertical Evacuation Shelters

Building Type	Number of Buildings	Fraction of Replacement Cost Needed to Upgrade Structure	Estimated Cost of Building (1986 $/1000)	Cost to Upgrade Buildings in Group (Thousands of $)
C	32	0.23	1,016.8	7,483
E	9	0.08	4,665.6	3,359
Total Cost to Upgrade				10,842

Again we stress that these results are limited to the scenario and the structures studied on Galveston Island. A similar exercise at a different location and using a different set of structures could lead to different conclusions. However, the rationale for evaluating the scenarios should remain valid.

CHAPTER V

SUMMARY AND CONCLUSIONS

Background

At the outset of this study we identified five objectives: 1) to establish qualitatively the feasibility of using existing structures for vertical evacuation, 2) to develop a consistent methodology for classifying structures according to their suitability for vertical evacuation, 3) to develop a methodology for estimating the cost associated with strengthening existing buildings, 4) to develop a methodology for estimating the evacuation capacity of a given area, and 5) to develop preliminary structural guidelines for future vertical evacuation shelters. The accomplishment of these objectives then permitted us to rationally evaluate the structural feasibility of vertical evacuation in a given setting. These objectives have been accomplished, though not in the given order.

The motivation for the technical feasibility of vertical evacuation has its basis in the historically superior performance of engineered structures in a wind hazard. In the United States, for example, no multi-story structure that was designed by professional architects and engineers and subjected primarily to hurricane or tornadoic generated wind forces has been observed to collapse. Although severe roof and cladding damage has been observed in some of these structures, the collapse of the frame or the foundation has not been observed. On the other hand, small residential buildings and low-rise structures - e.g., shopping centers, schools, and industrial buildings - are frequently decimated by tornadoic or hurricane winds. These observations support the hypothesis that if a structure is subjected primarily to a wind hazard, is multi-storied (two or more stories high), and has been designed and constructed under the guidance of building professionals (i.e., registered architects and engineers) then occupants of that structure have a better chance of survival as compared to occupants in small residential buildings and low-rise structures subjected to the same hazard.

Rationale of Safety Evaluation

Having documented the motivational basis for vertical evacuation, we next tackled the problem of developing a consistent methodology for classifying structures according to their suitability for vertical evacuation. We realized at the outset that any proposed evaluatory method should not only be capable of assessing the physical performance of the structure by rigorously incorporating such variables as the characteristics of the hurricane, the design resistance of the structure, and the present condition of the structure, but also rank the relative performance of the structure to permit arbitrary sheltering scenarios to be rationally evaluated. For example, the selected evaluatory method had to provide technical information that would aid decision-makers in evaluating, say, if horizontal evacuation were better, in some defined sense, than vertical evacuation; or, if horizontal evacuation were not an option, the method had to guide decision-makers in cost/benefit decisions.

Recent methods of structural assessment of buildings in a wind hazard are limited to either determining the potential damage to a structure or establishing whether the structure continues to satisfy prevailing code requirements. These studies often leave the building official with the crucial responsibility of extrapolating the results of structural studies presented, e.g., in the form of building damage to a prediction of occupant safety. To decide on the structural feasibility of vertical evacuation, decision-makers must, *apriori*, be provided with technically sound estimates of the relative safety provided by various structural types. Decision-makers can then compare the risks associated with vertical evacuation with competing alternatives such as horizontal evacuation, using traditional shelters, being stranded, or staying at home.

After a review of existing and potential methodologies, we decided upon a risk assessment approach for the following reasons: 1) the approach was logically defensible, 2) the approach had strong precedence, 3) the approach admitted state-of-the-art techniques in system safety and structural reliability and, 4) the approach satisfied the initial requirements for the proposed evaluatory method.

In the selected assessment method, the safety of the occupant is the indicator of structural performance. Occupant safety is measured by the expected fraction of building inhabitants that would be killed in a given hurricane. The expected fraction of fatalities should depend on such variables as the size of the hurricane, the failure characteristics of the building components - foundation, frame, roof, cladding (exterior skin including windows and doors) - the exposure of the occupant, and the fatality rate given the failure of any component. Vertical evacuation may, therefore, be considered structurally feasible, in a particular situation, if the use of the option leads to a net saving of lives. For a given scenario, the level of risk at which the use of vertical evacuation begins to result in a net saving of lives may be defined as the level of risk at which a building may be considered safe.

Summary of Safety Assessment Approach

We next developed a detailed methodology to evaluate the protection provided by a structure from the perspective of an occupant of the building. The method of Fault-Tree Analysis was reviewed. Using results from the existing theory, a fault-tree model of a typical vertical evacuation shelter was developed. The model was analyzed to provide basic modes of failure and expressions for the probability of a fatality in the hurricane environment. Finally, a numerical example was presented to illustrate the methodology and to insure that the results corroborated with common experience.

Data defining the physical properties of the structure were obtained from three sources: 1) construction plans and specification for the building; 2) building codes such as the Standard Building Code, the AISC Specifications for Design, Fabrication and Erection of Structural Steel for Buildings, and ACI; and 3) a visual inspection of the structure and the surrounding terrain.

The key steps of the evaluation procedure were as follows: 1) failure functions (in the structural reliability sense) for structural units (cladding elements, roof elements, etc.) were defined (to contain the complexity of the analysis, where possible linear failure functions were selected); 2) loading statistics (derived from the hurricane) and resistance statistics (derived from the materials and the design specifications) were determined for the unit; 3) approximate failure probabilities for the units were defined using Mean Value Methods from Structural Reliability Theory; 4) failure scenarios for the building system were synthesized using Fault-Tree Analysis; 5) failure probabilities for the building system were then computed; 6) risks of fatalities were computed using the equation developed from the fault-tree analysis; 7) modifications were made to upgrade the structure to resist a Category 3 hurricane; and 8) new risks of fatalities and costs to upgrade were computed.

Determining the Structural Feasibility of Vertical Evacuation

The last two objectives were automatically accomplished in the exercise of determining the structural feasibility of vertical evacuation in a given situation. We have argued that the structural feasibility of vertical evacuation, as an option for risk mitigation in coastal communities, depended not only upon the various other mitigative options available but also upon the set of criteria (which are not unique) that may be used to evaluate the options. Here we assume that the magnitude of the risk of death to the proposed inhabitants is the deciding criterion. If, compared to all other options, vertical evacuation results in the minimum number of fatalities, then the option is structurally feasible. Of course, other aspects of the problem such as its legal and political components must still be considered. Thus, the problem to be solved in the determination of the structural feasibility of vertical evacuation was formulated as follows: 1) given a scenario involving a hurricane striking some coastal community, define all mitigative options; 2) evaluate the risks associated with all options; then 3) establish the structural feasibility of vertical evacuation using the least-risk criterion. The mitigative options, which are location dependent, may include, but not be limited to, utilizing traditional shelters, staying at home, horizontal evacuation, and vertical evacuation.

To demonstrate the overall procedure we examined the structural feasibility of vertical evacuation on Galveston Island under two scenarios. A summary of our findings follows.

First, we estimated the number, and summarized the physical characteristics, of buildings that may be available for use as potential vertical shelters in Galveston, Texas. We found that:

1. Approximately 256 buildings, ranging from 2 to 12 stories in height are potential vertical shelters;
2. Approximately 12,000,000 square feet of floor space is available in these structures;
3. Of the floor space available, thirty (30) percent is located in public buildings; and
4. Seventy-seven (77) percent of the structures are reinforced concrete frames, sixteen (16) percent are wooden framed structures, and seven (7) percent are steel framed structures.

Second, we developed classificatory criteria for potential structures then categorized each structure. The following six categories were identified: 1) reinforced concrete frames, two stories high; 2) reinforced concrete frames, three to five stories high; 3) reinforced concrete frames, more than five stories high; 4) steel frames, two stories high; 5) steel frames, three or more stories high; and 6) wooden frames, two to four stories high. In addition, the average characteristics of a building in each category were determined on the basis of the properties of the structures in the survey population.

We next demonstrated how the structural assessment technique developed in other parts of the study could be used to determine the structural feasibility of vertical evacuation. We showed that the feasibility of the concept depended not only upon the options available to the given community but also upon the details of the governing scenario. On the one hand, if horizontal evacuation were an alternative, vertical evacuation may or may not be structurally feasible. The structural feasibility either depended upon the level of the hurricane or the decision to upgrade the structures.

If, on the other hand, horizontal evacuation were not an option, vertical evacuation could be structurally feasible for hurricanes of Category 2 and above. Compared to sheltering people in traditional shelters, the use of vertical evacuation in existing structures (i.e., with no upgrading) could lead to a significant saving of lives (e.g., 3.6 and 41.6 percent of the sheltered population can be saved in Category 2 and 3 hurricanes, respectively). Furthermore, if the structures were upgraded to resist a Category 3 hurricane, we estimated that in a sheltering population of 50,000 people approximately 200 lives (over and above those saved using non-upgraded vertical shelters) could be saved for an investment of 11 million dollars to upgrade the 44 existing buildings. Without any additional cost, if the same structures were used as last resort shelters in a Category 4 hurricane, more than an additional 5,000 lives (again over and above those saved using non-upgraded vertical shelters) could be saved. We also demonstrated how factors such as location (in the building) of the sheltered population, the density of sheltering, and the sequencing of the sheltering process could influence the risk to building inhabitants.

Finally, and most importantly, we feel that by focusing on occupant safety we have been able to transform the relative performance of the structure into linguistic terms that non-technical people can readily understand. By expressing the protection offered by the structure as the expected fraction of fatalities - which depends upon the characteristics of the hurricane, the resistance of the structural components (foundation, frame, roof, cladding), and the exposure of the occupant - we have effectively translated the level of protection offered by the structure into language readily comprehensible to decision-makers.

REFERENCES

1. Abes, A.J., Salinas, J.J., and Rogers, J.T., "Risk Assessment Methodology for Pipeline Systems", *Structural Safety*, Vol. 2, No. 3, January 1985, pp. 225-237.

2. American National Standard, ANSI, 1982: "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures", *ANSI A58.1*, American National Standards Institute, New York, 1982.

3. Anagnostopoulos, S.A. and Whitman, R.V., "On Human Loss Prediction in Buildings During Earthquakes", *Proceedings of Sixth World Conference on Earthquake Engineering*, Vol. 1, Sarita Prakashan, New Dehli, 1977, pp. 671-676.

4. Task Committee on Structural Safety of the Administrative Committee on Analysis and Design of the Structural Division, "Structural Safety--A Literature Review", *Journal of the Structural Division*, ASCE, Vol. 98, No. ST4, April 1972, pp. 845-884.

5. Barlow, R.E. and Lambert, H.E., "Introduction to Fault Tree Analysis", *Reliability and Fault Tree Analysis Theoretical and Applied Aspects of System Reliability and Safety Assessment*, Eds. R.E. Barlow, J.B. Fussell, and N.D. Singpurwalla, Society for Industrial and Applied Mathematics, Philadelphia, 1975, pp. 7-35.

6. Bastien, M.C., Dumas, M., Laporte, J., and Parmentier, N., "Evacuation Risks: A Tentative Approach for Quantification", *Risk Analysis*, Vol. 5, No. 1, March 1985, pp. 53-61.

7. Beason, W.L. and Morgan, J.R., "Glass Failure Prediction Model", *Journal of Structural Engineering*, ASCE, Vol. 110, No. 2, February 1984, pp. 197-212.

8. Burton, I. and Pushchak, R., "The Status and Prospects of Risk Assessment", *Geoforum*, Vol. 15, No. 3, 1984, pp. 463-475.

9. Coastal Engineering Research Center, *Shore Protection Planning and Design*, 3rd ed., US Army Corps of Engineers, Washington, D.C., 1966.

10. Culver, C.G., Lew, H.S., Hart, G.C., and Pinkham, C.W., "Natural Hazards Evaluation of Existing Buildings", *NBS Building Science Series Report No. 61*, Center for Building Technology, Institute for Applied Technology, National Bureau of Standards, Washington, D.C., January 1975.

11. Cummings, G.E., "Application of the Fault Tree Technique to a Nuclear Reactor Containment System", *Reliability and Fault Tree Analysis Theoretical and Applied Aspects of System Reliability and Safety Assessment*, Eds. R.E. Barlow, J.B. Fussell, and N.D. Singpurwalla, Society for Industrial and Applied Mathematics, Philadelphia, 1975, pp. 805-825.

12. Davenport, A.G., "Wind Loading and Wind Effects", Theme Report, Technical Committee No. 7, *Planning and Design of Tall Buildings*, Vol. Ib, ASCE, New York, 1972, pp. 335-363.

13. Derby, S.L. and Keeney, R.L., "Risk Analysis: Understanding 'How Safe is Safe Enough?'", *Risk Analysis*, Vol. 1, No. 3, September 1981, pp. 217-224.

14. Ellingwood, B., Galambos, T.V., MacGregor, J.G., and Cornell, C.A., "Development of a Probability Based Load Criterion for American National Standard A58: Building Code Requirements for Minimum Design Loads in Buildings and Other Structures", *NBS Special Publication 577*, U.S. Department of Commerce, Washington D.C., June 1980.

15. Federal Emergency Management Agency, "Flood Insurance Rate Maps, City of Galveston, Texas, Galveston County", *National Flood Insurance Program*, 1984.

16. Fiksel, J. and Rosenfield, D.B., "Probabilistic Models for Risk Assessment", *Risk Analysis*, Vol. 2, No. 1, March 1982, pp. 1-8.

17. Freudenthal, A.M., Garrelts, J.M., and Shinozuka, M., "The Analysis of Structural Safety", *Journal of the Structural Division*, ASCE, Vol. 92, No. ST1, February 1966, pp. 267-325.

18. Gorman, M. and Moses, F., "A Structural Risk Model", Proceedings of the ASCE Specialty Conference on *Probabilistic Mechanics and Structural Reliability*, 10-12 January 1979, Tucson, Eds. A. H-S. Ang and M. Shinozuka, ASCE, New York, 1979, pp. 96-100.

19. Hammer, W., *Product Safety Management and Engineering*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1980.

20. Hart, G.C., *Natural Hazards: Tornado, Hurricane, Severe Wind Loss Models*, J.H. Wiggins Company, Redondo Beach, CA., 1976.

21. Hasselman, T.K., Eguchi, R.T., and Wiggins, J.H., *Assessment of Damageability for Existing Buildings in a Natural Hazards Environment*, Technical Report No. 80-1332-1, J.H. Wiggins Co., Redondo Beach, CA., September 1980.

22. Heine, M.D., *A Hurricane Simulation Model to Evaluate Effectiveness of Building Code Standards on Reducing Wind Related Damage*, The University of Texas At Austin, Department of Mechanical Engineering, Austin, August 1978.

23. Hix, C., *Model Minimum Hurricane Resistant Buildings Standards for the Texas Gulf Coast*, Texas Coastal and Marine Council, Austin, 1976.

24. Kaplan, S. and Garrick, B.J., "On the Quantitative Definition of Risk", *Risk Analysis*, Vol. 1, No. 1, March 1981, pp. 11-27.

25. Kareem, A., "Wind Speed-Damage Correlation in Hurricane Alicia", *Hurricane Alicia: One Year Later*, Proceedings of the Specialty Conference, Galveston, Texas, 16-17 August 1984, Ed. A. Kareem, ASCE, New York, 1985, pp. 81-93.

26. Kuroda, K. and Miki, S., "Reliability Assessment of Field Instruments Based on F.T.A.", *Proceedings of the 4th International Conference on Structural Safety and Reliability*, Vol. III, Eds. I. Konishi, A.H.-S. Ang, and M. Shinozuka, Shinto Publishing, Japan, 1985, pp. 373-382.

27. Lee, L.T. and Collins, J.D., "Engineering Risk Management for Structures", *Journal of the Structural Division*, ASCE, Vol. 103, No. ST9, September 1977, pp. 1739-1756.

28. Liu, S.C. and Yao, J.T.P., "Structural Identification Concept", *Journal of the Structural Division*, ASCE, Vol. 104, No. ST12, December 1978, pp. 1845-1858.

29. Lowrance, W.W., *Of Acceptable Risk Science and the Determination of Safety*, William Kaufman Inc., Los Altos, CA., 1976.

30. Mehta, K.C., McDonald, J.R., and Smith, D.A., "Procedure for Predicting Wind Damage to Buildings", *Journal of the Structural Division*, ASCE, Vol. 107, No. ST11, November 1981, pp. 2089-2096.

31. Minor, J.E., "Window Glass Performance and Hurricane Effects", *Hurricane Alicia: One Year Later*, Proceedings of the Specialty Conference, Galveston, Texas, 16-17 August 1984, Ed. A. Kareem, ASCE, New York, 1985, pp. 151-167.

32. Minor, J.E. and Mehta, K.C., "Wind Damage Observations and Implications", *Journal of the Structural Division*, ASCE, Vol. 105, No. ST11, November 1979, pp. 2279-2291.

33. Petak, W.J. and Atkisson, A.A., *Natural Hazard Risk Assessment and Public Policy*, Springer-Verlag, New York, 1982.

34. Rasmussen, N.C., "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants", *Wash-1400*, USAEC, Washington, D.C., August 1974.

35. Rowe, W.D., *An Anatomy of Risk*, John Wiley & Sons, New York, 1977.

36. Ruch, C., *Hurricane Vulnerability Analysis for Brazoria, Galveston, Harris and Chambers Counties*, Texas A&M University, Research Division, College of Architecture and Environmental Design, College Station, August 1983.

37. Ruch, C., *Hurricane Relocation Planning for Brazoria, Galveston, Harris and Chambers Counties*, TAMU-SG-81-604, Texas A&M University, Center for Strategic Technology, Texas Engineering Experiment Station, Sea Grant College Program, College Station, 1981.

38. Salmon, J.D., "Vertical Evacuation in Hurricanes: An Urgent Policy Problem for Coastal Managers", *Coastal Zone Management Journal*, Vol. 12, Nos. 2/3, 1984, pp. 287-300.

39. Scholl, R.E., Kustu, O., Perry, C.L., and Zanetti, J.M., *Seismic Damage Assessment for High-Rise Buildings*, Final Technical Report, U.S. Geological Survey, Washington, D.C., July 1982.

40. Simpson, R.H. and Riehl, H., *The Hurricane and Its Impact*, Louisiana State University Press, Baton Rouge, 1981.

41. Spangler, B.D. and Jones, C.P., "Evaluation of Existing and Potential Hurricane Shelters", *Sea Grant Project No. R/C - 9*, Florida Sea Grant College, Gainesville, Florida, November 1984.

42. Springer, Marvin and Associates, *Comprehensive Plan Report City of Galveston, Texas*, Prepared for The Planning and Zoning Commission, Galveston, 1973.

43. Starr, C., "Social Benefit Versus Technological Risk", *Science*, Vol. 165, No. 3899, September 19, 1969, pp. 1232-1238.

44. Stubbs, N., "Risk Assessment of Potential Vertical Shelters on Galveston Island", *Technical Report 4968 S-6 NSF CEE 83-09511*, Research Division, College of Architecture, Texas A&M University, College Station, August 1987.

45. Thoft-Christensen, P. and Baker, M.J., *Structural Reliability Theory and Its Application*, Springer-Verlag, Berlin, 1982.

46. Tryggvason, B.V., Surry, D., and Davenport, A.G., "Predicting Wind-Induced Response in Hurricane Zones", *Journal of the Structural Division*, ASCE, Vol. 102, No. ST12, December 1976, pp. 2333-2350.

47. Whitman, R.V., Biggs, J.M., Brennan, J.E., III, Cornell, C.A., de Neufville, R.L., and Vanmarcke, E.H., "Seismic Design Decision Analysis", *Journal of the Structural Division*, ASCE, Vol. 101, No. ST5, May 1975, pp. 1067-1084.

48. Whitman, R.V., Heger, F.J., Luft, R.W., and Krimgold, F., "Seismic Resistance of Existing Buildings", *Journal of the Structural Division*, ASCE, Vol. 106, No. ST7, July 1980, pp. 1573-1592.

49. Whitman, R.V., Remmer, N.S., and Schumacker, B., "Feasibility of Regulatory Guidelines for Earthquake Hazards Reduction in Existing Buildings in Northeast", Department of Civil Engineering, M.I.T., Cambridge, Mass., *Publication No. R80-44*, Order No. 687, November 1980.

50. Yao, J.T.P., *An Approach to Damage Assessment of Existing Structures*, Technical Report No. CE-STR-79-4, School of Civil Engineering, Purdue University, West Lafayette, October 1979.

APPENDIX A

THE SAFFIR-SIMPSON HURRICANE SCALE

Scale No. 1--Winds of 74 to 95 miles per hour. Damage primarily to shrubbery, trees, foliage, and unanchored mobile homes. No real damage to other structures. Some damage to poorly constructed signs. And/or: storm surge 4 to 5 feet above normal. Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorage torn from moorings.

Scale No. 2--Winds of 96 to 110 miles per hour. Considerable damage to shrubbery and tree foliage; some trees blown down. Major damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some damage to roofing materials of buildings; some window and door damage. No major damage to buildings. And/or: storm surge 6 to 8 feet above normal. Coastal roads and low-lying escape routes inland cut by rising water 2 to 4 hours before arrival of hurricane center. Considerable damage to piers. Marinas flooded. Small craft in unprotected anchorages torn from moorings. Evacuation of some shoreline residences and low-lying island areas required.

Scale No. 3--Winds of 111 to 130 miles per hour. Foliage torn from trees; large trees blown down. Practically all poorly constructed signs blown down. Some damage to roofing materials of buildings; some window and door damage. Some structural damage to small buildings. Mobile homes destroyed. And/or: storm surge 9 to 12 feet above normal. Serious flooding at coast and many smaller structures near coast destroyed; larger structures near coast damaged by battering waves and floating debris. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Flat terrain 5 feet or less above sea level flooded inland 8 miles or more. Evacuation of low-lying residences within several blocks of shoreline possibly required.

Scale No. 4--Winds of 131 to 155 miles per hour. Shrubs and trees blown down; all signs down. Extensive damage to roofing materials, windows and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes. And/or: storm surge 13 to 18 feet above normal. Flat terrain 10 feet or less above sea level flooded inland as far as 6 miles. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Major erosion of beaches. Massive evacuation of all residences within 500 yards of shore possibly required, and of single-story residences on low ground within 2 miles of shore.

Scale No. 5--Winds greater than 155 miles per hour. Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Very severe and extensive damage to windows and doors. Complete failure of roofs on many residences and industrial buildings. Extensive shattering of glass in windows and doors. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes. And/or: storm surge greater than 18 feet above normal. Major damage to lower floors of all structures less than 15 feet above sea level within 500 yards of shore. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Massive evacuation of residential areas on low ground within 5 to 10 miles of shore possibly required.

Reference: Herb Saffir: Personal communication.

APPENDIX B

ESTIMATION OF MEAN RESISTANCES FROM DESIGN SPECIFICATIONS AND OBSERVED FAILURE RATE

Let the random safety margin, Z, for a structural element be given by:

$$Z = R - S \quad \text{(B.1)}$$

where, in general, R is the random resistance of the element and S is the random load. If we interpret S as a known design load, i.e., $S = R_{design}$, $\sigma_S = 0$ from Equation (B.1), the reliability index, β, becomes:

$$\beta = (\bar{R} - R_{design})/\sigma_R \quad \text{(B.2)}$$

where $\bar{R}$ is the mean value of the resistance. Since $\sigma_R = \bar{R}V_R$, where V_R is the coefficient of variation, Equation (B.2) may be rewritten:

$$\bar{R}\beta V_R = \bar{R} - R_{design} \quad \text{(B.3)}$$

Since β and V_R can be estimated from experience and calibration studies, we may solve for $\bar{R}$ in Equation (B.3) to get:

$$\bar{R} = R_{design}/(1 - \beta V_R) \quad \text{(B.4)}$$