OCCUPANT SAFETY IN VERTICAL HURRICANE SHELTERS

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OCCUPANT SAFETY IN VERTICAL HURRICANE SHELTERS

ABSTRACT

The concept of vertical evacuation (i.e. the use of multi-story structures as hurricane shelters) has been proposed as a mitigative measure. Traditionally, the protection offered by a structure was evaluated on the basis of either the probability of failure of the structure or the extent to which the major load bearing elements satisfied a particular building code. Fault tree analysis is utilized as an integrative technique to evaluate occupant safety from the perspective of the occupant. The method of fault tree construction and 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.

INTRODUCTION

In the face of a hurricane hazard, evacuation of the coastal population to inland regions or higher ground may not always be possible. For example, insufficient warning time to safely evacuate the population or clogged transportation arteries may interrupt the evacuation process. Post-hurricane observations tend to support the hypotheses that structures that are fully engineered perform best in a hurricane environment compared to pre-engineered and non-engineered structures (Minor, 1985; Kareem, 1985).

Thus, the concept of vertical evacuation (i.e. the use of engineered multi-story structures as hurricane shelters that will be subjected primarily to the wind component of the hazard) has been proposed as a mitigative alternative to horizontal evacuation.

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 a given loading environment a given structure is considered safer if a) the factors of safety of its elements are larger; b) the probability of failure is smaller; or c) 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 failing ceiling or a collapsing partition. Furthermore, factors of safety for 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 focusses directly on the safety of the occupant, and which simultaneously accounts for the structural and the nonstructural failure characteristics of the structure. This paper 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 ANALYSIS OF A VERTICAL EVACUATION SHELTER

Fault tree analysis can provide a rational 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 deduction 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. A description and definition of the symbols used in developing the model are provided in Figure 1 and Figure 2. This method has been 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).

The system of interest in this study is any potential vertical evacuation shelter. The major elements of the building include a foundation, a structural framing system to transfer the loads to the foundation, exterior walls or clading, openings in the exterior walls (doors and windows), a roof, internal partitions and floors, a mechanical sub-system (HVAC), and an electrical 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. Since exactly what constitutes an injury may be difficult to define, the top event will be limited to potential human fatalities.

Figure 3 depicts a typical stage in the development of the fault tree model for a general building structure. According to Figure 3, if a fatality occurs, then the occupant has been killed by a) crushing by structural parts or missile impact, b) drowning, c) fire, or d) electrocution. It is assumed that the fatality occurs while the individual is within the confines of the structure. In 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 non-structural failure will be the most important in a hurricane environment.

This deductive 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, is shown in Figure 4. Note that nineteen basic events (X_1-X_{19}) have been identified and defined in Table 1.

The fault tree presented in Figure 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. The same formulation can be applied to many structural types with little or no modification. Second, the model is highly integrative. It pulls together the occurrence of structural as well as nonstructural failures. It also allows a smooth interface between existing methods of safety evaluation, such as reliability analysis 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 information is needed to perform a safety analysis of occupant safety.

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 non-redundant 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 2.

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 manipulations 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 $X_1, X_2, \ldots, X_n$ are the input events to an AND gate, the output event, X_o, is given by:

$$X_o = X_1 \cap X_2 \cap X_3 \cap \ldots \cap X_n \qquad (1)$$

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;

$$Y_o = X_1 \cup X_2 \cup X_3 \cup \ldots \cup X_n \tag{2}$$

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, $X_1, \ldots, X_n$, the top event probability is given by:

$$P(X_1 \cap X_2 \cap \ldots \cap X_n) = P(X_1)\ P(X_2)\ \ldots\ P(X_n) \tag{3}$$

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 2 statistically independent inputs, Y_1 and Y_2, the top event probability is given by:

$$P(Y_1 \cup Y_2) = P(Y_1) \cup P(Y_2) - P(Y_1) \cap P(Y_2) \tag{4}$$

Using the definitions of the basic events defined in Table 1, the following new events are defined:

$$\begin{aligned} Y_1 &= X_2 \cap X_3 \cap X_4 & Y_2 &= X_5 \cap X_6 \cap X_7 \\ Y_3 &= X_8 \cap X_9 \cap X_{10} & Y_4 &= X_{11} \cap X_{12} \cap X_{13} \\ Y_5 &= X_{14} \cap X_{15} \cap X_{16} & Y_6 &= X_{17} \cap X_{18} \cap X_{19} \end{aligned} \tag{5}$$

Then the top event "T" is given by:

$$T = (X_1 \cap Y_1) \cup (X_1 \cap Y_2) \cup (X_1 \cap Y_3) \cup (X_1 \cap Y_4) \cup (X_1 \cap Y_5) \cup (X_1 \cap Y_6) \tag{6}$$

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

$$T = X_1 \cap (Y_1 \cup Y_2 \cup Y_3 \cup Y_4 \cup Y_5 \cup Y_6) \tag{7}$$

The above equation can be used to construct the nonredundant fault tree shown in Figure 5. In addition, the probability of the top event is now given by:

$$P(T) = P(X_1) \left[P(Y_1) + P(Y_2) + P(Y_3) + P(Y_4) + P(Y_5) + P(Y_6) \right] \quad (8)$$

in which,

$$P(Y_1) = P(X_2)P(X_3)P(X_4) \qquad P(Y_2) = P(X_5)P(X_6)P(X_7)$$
$$P(Y_3) = P(X_8)P(X_9)P(X_{10}) \qquad P(Y_4) = P(X_{11})P(X_{12})P(X_{13})$$
$$P(Y_5) = P(X_{14})P(X_{15})P(X_{16}) \qquad P(Y_6) = P(X_{17})P(X_{18})P(X_{19}) \quad (9)$$

The engineering effort is now focussed on determining the probability of the occurrence of the basic events, using Equation (8) to estimate the probability of occurrence of the top event.

A NUMERICAL EXAMPLE

To illustrate the proposed theory, an example structure is analyzed to estimate the probability of a fatality if the structure is used as a vertical shelter. The structure selected is a five-story, reinforced concrete building, covering approximately 12,800 square feet. A plan and elevation of the structure is shown in Figure 6. The exterior of the building is covered with a glass clading with a median strength of 40 psf and a coefficient of variation equal to 0.2. The roofing system consists of form decking spot-welded to joists spaced at 10 feet. The joists span 40 feet and are simply-supported by the major frames. The foundation consists of footings 10 feet below ground level resting on anchored concrete piers. The structure is assumed to be in the Galveston area and is subjected to a hurricane of 120 miles per hour. The details of a building inspection, the review of existing plans, and the anticipated loads the frame will experience are summarized in Table 3. These quantities are used to estimate the probability of failure of the frame.

From Figure 5 and Equation (8) data are required to establish the reliability of the frame, foundation, roof, clading, interior partitions, exterior openings, and the resultant probability of the consequences given these failures. Defining a deflection of 0.2 ft. at the roof level as failure, the probability of failure for the concrete frame is 7.29×10^{-4} (Kiureghian and Ke, 1985). Conservatively, assuming all five frames as a series network, the system's probability of failure is approximately five times the failure of one frame, which is equal to 3.65×10^{-3}.

The hurricane strike probability is computed assuming a Frechet Distribution and using wind data from 50-year return and 100-Year return wind speed maps (ANSI, 1982). An estimate of the probability based on the procedure outlined by Hart (1976) for a hurricane with a mean windspeed of 120 mph is 3.19×10^{-3}.

At least three modes of foundation failure are likely in a hurricane environment: 1) the sliding mode, 2) the overturning mode, and 3) the uplift mode. Expressions for the safety margin for these modes can be developed and the probability of failure can be estimated using first-order second moment techniques. In the example structure, the probability of foundation failure considering all modes is taken to be 3.0×10^{-5}.

The clading can also fail in several ways: 1) failure may be due to wind pressure exceeding the strength of the clading material, 2) failure may be due to missile impact from windborne debris, 3) failure resulting from excessive stresses caused by differential structural movement and, 4) failure due to the overstressing of anchorages. The clading system for a structure may be considered to have failed when a given fraction of the total surface area has been removed. Expert opinion suggests that if more than approximately ten percent of the windows are broken in an episode, then the damage is considered to be heavy (Hart, 1976). Using this figure as a guide for the entire clading, a criterion of failure for the clading system may be set at ten percent of the total surface area of the wall. Assuming the exceedance of bending stresses to be the only mode of failure (Beason and Morgan, 1984), the probability of losing one tenth the area of clading for the glass material, using 36 sq. ft. sections, selected in this example is estimated to be $3.4X10^{-4}$.

Using the work of Waelti and Thuerlimann (1981) as a guide, failure probabilities for roofing systems can be estimated. For example, based on a wind loading condition of 120 mph on a flat roof using similar materials and supports, a failure probability of $5X10^{-6}$ is anticipated.

Whitman et al (1980) have provided fatality statistics for various classes of buildings as a function of the type of construction material and the level of damage inflicted. That data was used along with a refinement suggested in the earlier work by Anagnostopoulos and Whitman (1977) to estimate the probability of death for failure events with different consequences. The events and the estimates of the probability of their occurrences are summarized in Table 4.

Having quantified the events shown in Figure 5, the probability of a fatality may now be computed. Using Equation (8), the top event is computed to be 0.31×10^{-6}.

SUMMARY AND CONCLUSIONS

This paper presented 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 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. Finally, a numerical example was presented to illustrate the methodology.

ACKNOWLEDGMENTS

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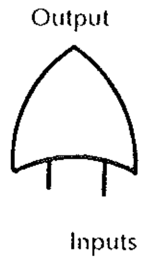
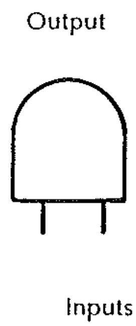
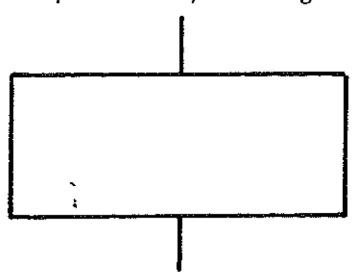
OR Gate This symbol denotes that an output event occurs if any one or more of the n input events occur.



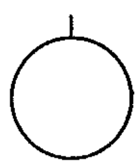
AND Gate This is the dual of the **OR** gate. An **AND** gate denotes that an output event occurs if all of the n input events occur.



Resultant Event This event is represented by a rectangle which is a result of the combination of faults events that precede it.



Basic Fault Event This event is denoted by a circle. It represents the failure of an elementary component or a basic fault event. The event parameters such as the probability of occurrence and the failure rate are obtained from the field failure data or other reliable sources.



Incomplete Event A diamond denotes a fault event whose cause has not been fully determined either due to lack of interest or due to lack of information or data.

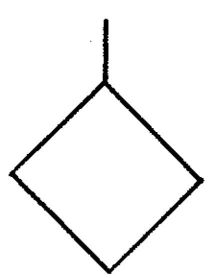


Figure 1. Definition of the Symbols

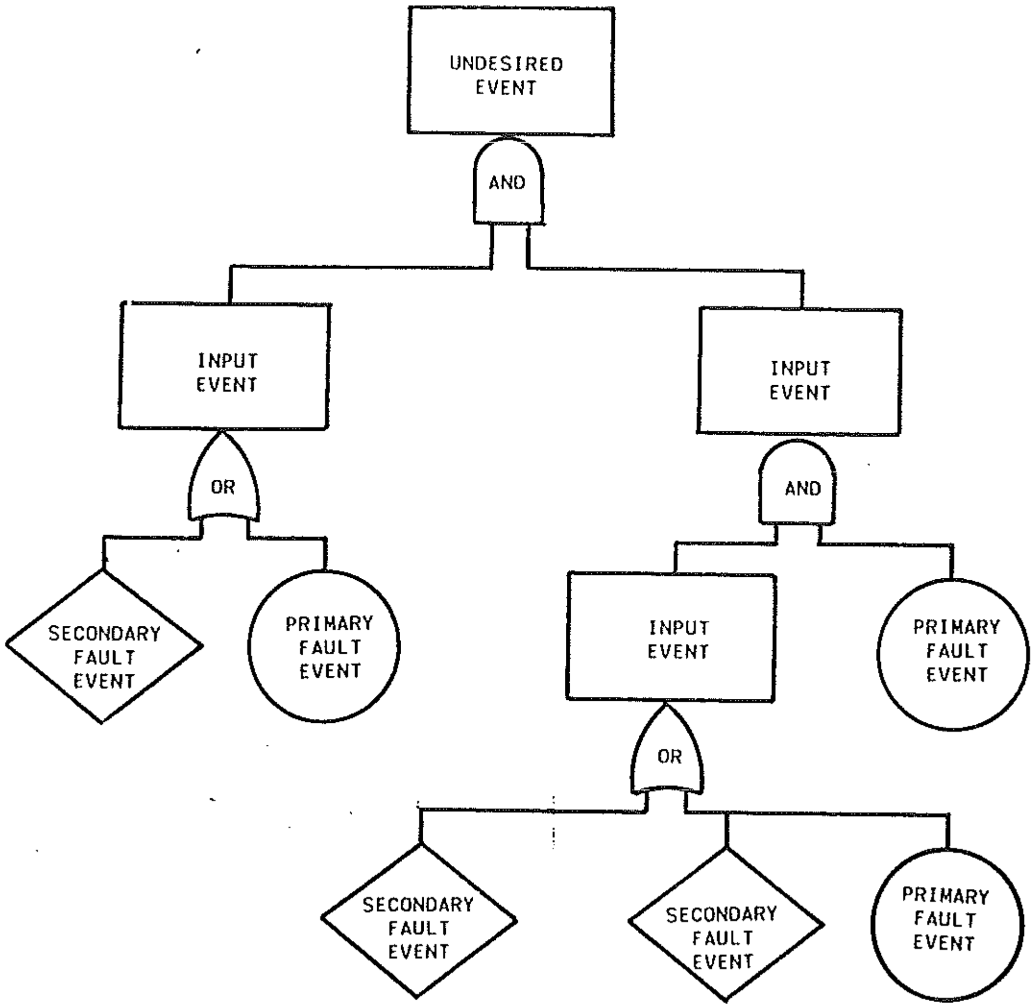


Figure 2. Typical Fault Tree

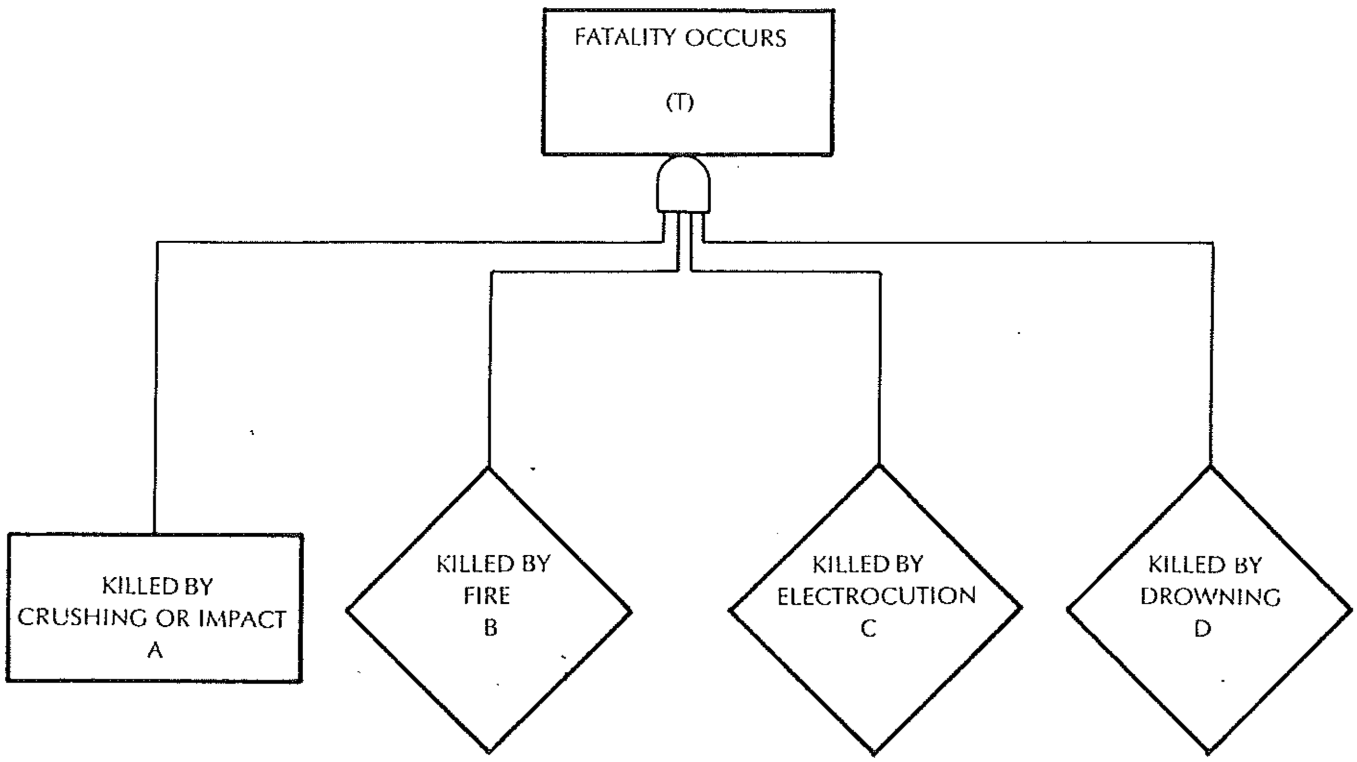


Figure 3. Typical Step in Fault Tree Generation

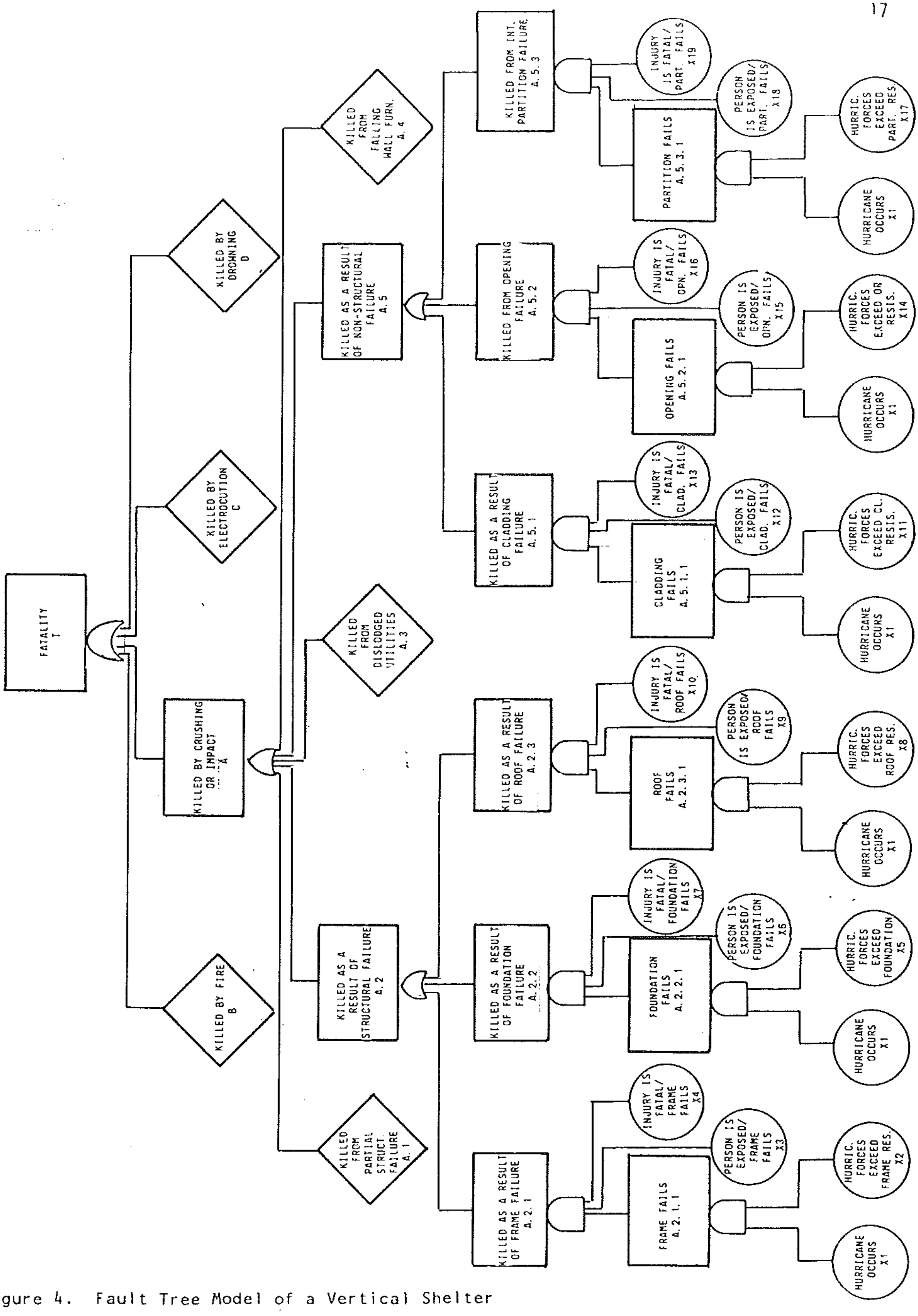


Figure 4. Fault Tree Model of a Vertical Shelter

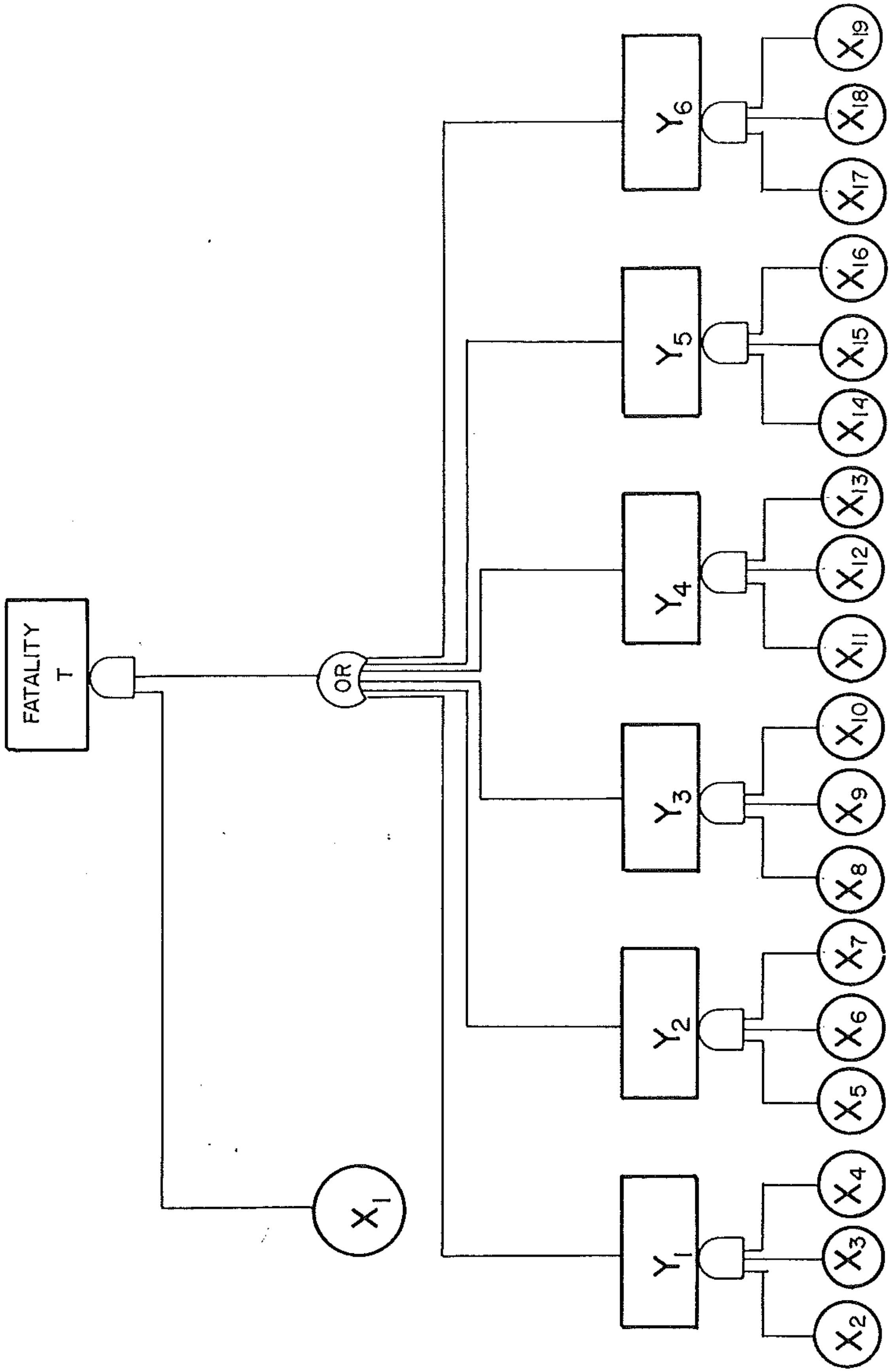
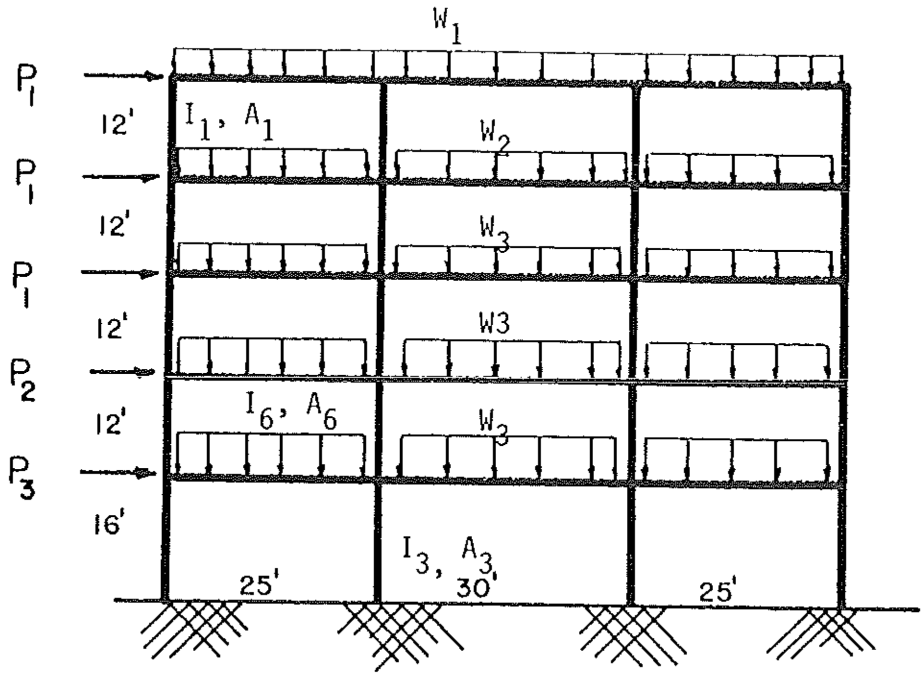


Figure 5. Nonredundant Fault Tree

ELEVATION



PLAN

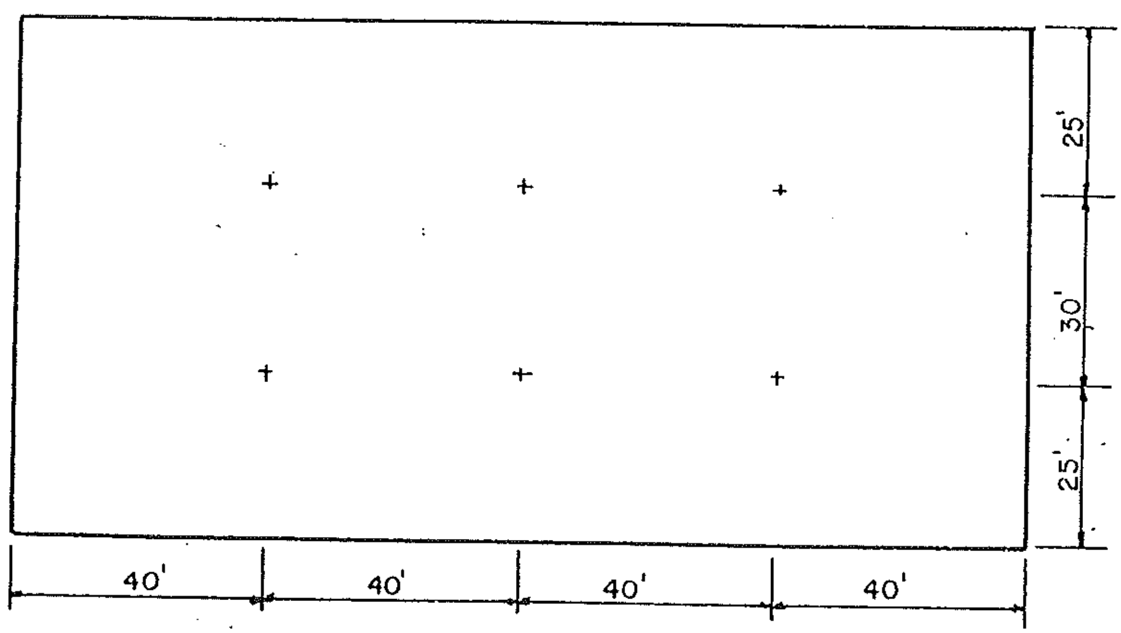


Figure 6. Plan and Elevation of Example Structure

Event		Description of Event
X_1	≡	Hurricane Occurs
X_2	≡	Hurricane Forces Exceed Frame Strength
X_3	≡	Person is Exposed/Frame Fails
X_4	≡	Injury is Fatal/Frame Fails
X_5	≡	Foundation Fails
X_6	≡	Person is Exposed/Foundation Fails
X_7	≡	Injury is Fatal/Foundation Fails
X_8	≡	Hurricane Forces Exceed Roof Strength
X_9	≡	Person is Exposed/Roof Fails
X_{10}	≡	Injury is Fatal/Roof Fails
X_{11}	≡	Hurricane Forces Exceed Clading Resistance
X_{12}	≡	Person is Exposed/Clading Fails
X_{13}	≡	Injury is Fatal/Clading Fails
X_{14}	≡	Hurricane Forces Exceed Opening Resistance
X_{15}	≡	Person is Exposed/Opening Fails
X_{16}	≡	Injury is Fatal/Opening Fails
X_{17}	≡	Hurricane Forces Exceed Interior Partition Resistance
X_{18}	≡	Person is Exposed/Partition Fails
X_{19}	≡	Injury is Fatal/Partition Fails

Table 1. Definition of Basic Events

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}]
6	[X_1, X_{17}, X_{18}, X_{19},]

Table 2. Minimal Cut Sets

Description of Basic Variables

Variable Number	Symbol	Units	Mean	Coefficient of Variation	Distribution
1	W_1	kips/ft	6.00	0.18	lognormal
2	W_2	kips/ft	7.50	0.18	lognormal
3	W_3	kips/ft	8.00	0.18	lognormal
4	P_1	kips	22.5	0.40	type I
5	P_2	kips	20.0	0.40	type I
6	P_3	kips	16.0	0.40	type I
7	E_1	kips/ft^2	454,000	0.09	normal
8	E_2	kips/ft^2	497,000	0.08	normal
9	I_1	ft^4	0.94	0.12	normal
10	I_2	ft^4	1.33	0.12	normal
11	I_3	ft^4	2.47	0.12	normal
12	I_4	ft^4	1.25	0.24	normal
13	I_5	ft^4	1.63	0.24	normal
14	I_6	ft^4	2.69	0.24	normal
15	A_1	ft^2	3.36	0.18	normal
16	A_2	ft^2	4.00	0.18	normal
17	A_3	ft^2	5.44	0.18	normal
18	A_4	ft^2	2.72	0.33	normal
19	A_5	ft^2	3.13	0.33	normal
20	A_6	ft^2	4.01	0.33	normal
21	R_1	kips/ft^2	700	0.14	lognormal
22	R_2	kips/ft^2	500	0.10	lognormal
23	R_3	kips/ft^2	1400	0.11	lognormal

Table 3. Structure Material and Geometric Properties

Event	Description of Event	Probability of Occurrence
X_1	Hurricane Occurs	3.20×10^{-3}
X_2	Hurricane Forces Exceed Frame Strength	3.65×10^{-3}
X_3	Person is Exposed/Frame Fails	1.00
X_4	Injury is Fatal/Frame Fails	2.72×10^{-1}
X_5	Foundation Fails	6.00×10^{-5}
X_6	Person is Exposed/Foundation Fails	1.00
X_7	Injury is Fatal/Foundation Fails	2.72×10^{-1}
X_8	Hurricane Forces Exceed Roof Strength	5.00×10^{-4}
X_9	Person is Exposed/Roof Fails	1.00
X_{10}	Injury is Fatal/Roof Fails	6.50×10^{-4}
X_{11}	Hurricane Forces Exceed Clading Resistance	3.40×10^{-4}
X_{12}	Person is Exposed/Clading Fails	1.00
X_{13}	Injury is Fatal/Clading Fails	6.50×10^{-4}
X_{14}	Hurricane Forces Exceed Opening Resistance	1.00
X_{15}	Person is Exposed/Opening Fails	1.00
X_{16}	Injury is Fatal/Opening Fails	1.00×10^{-5}
X_{17}	Hurricane Forces Exceed Interior Partition Resistance	1.00
X_{18}	Person is Exposed/Partition Fails	1.00
X_{19}	Injury is Fatal/Partition Fails	1.00×10^{-5}

Table 4. Summary of Probability of Basic Events