CHAPTER 8 VULNERABILITY ASSESSMENT

8.1 INTRODUCTION

Vulnerability is a measure of the intrinsic ability of a structure or entity to withstand the forces produced by a hazardous phenomenon. It is commonly expressed as the degree of damage that can be expected to result from the occurrence of a particular hazardous event of a given magnitude. The structural characteristics of entities exposed to hazardous phenomena therefore determines their vulnerability.

A detailed assessment of the structural response to hurricane force winds was carried out for the main building types, utility poles, transmission towers and boats in the BVI. In the absence of detailed studies, general assessments were made of the structural response of the major building types to storm surge, inland flooding and seismic hazards.

8.2 HIGH VELOCITY WIND VULNERABILITY OF BVI STRUCTURES

A detailed wind vulnerability study was conducted to determine the vulnerability of structures in the BVI to high velocity wind damage. The study was conducted by Professor Norris Stubbs, a consultant in Risk Analysis and Damage Assessment from Texas A&M University, betweenNovember 1996 and January 1997. The results of this study is presented below as an edited summary and interpretation of the findings. Further details can be obtained from the actual report as submitted by Professor Stubbs to the Office of Disaster Preparedness.

The general objective of the wind vulnerability study was to determine the damage, which is likely to result from extreme hurricane force winds, to buildings and their contents, boats, utility poles and transmission towers. In order to establish the vulnerability or damageability of structures to high velocity wind damage the following were included in the study:

(1) The establishment of a suitable classification scheme for buildings, boats, utility poles and transmission towers found in the BVI.

(2) The generation of appropriate damage functions for the different classes of structures and other entities derived from (1) and

(3) The provision of relationships between the wind speed and expected damage to the structures.

8.2.1 BUILDING CLASSIFICATION

Several building and structural classes were identified by the author and BVI personnel during field work carried out in the BVI between November 16th and 19th, 1996. The main structural classes which emerged from the detailed survey are listed in **Table 8.1.**

TABLE 8.1: Relevant Building and Structural Classes in BVI

RESIDENTIAL BUILDINGS

Building Class Number	Description
1	1-3 story masonry with glass openings and other roofing
2	1-3 story masonry with metal jalousie openings and other roofing
3	1-3 story masonry with protected openings and other roofing
4	1-3 story masonry with glass openings and concrete roofing
5	1-3 story masonry with metal jalousie openings and concrete roofing
6	1-3 story masonry with protected openings and concrete roofing
7	1-3 story wooden structures

COMMERCIAL BUILDINGS

Building Class Number	Description
8	1-3 story masonry with glass openings and other roofing
9	1-3 story masonry with metal jalousie openings and other roofing
10	1-3 story masonry with protected openings and other roofing
11	1-3 story masonry with glass openings and concrete roofing

12	1-3 story masonry with metal jalousie openings and concrete roofing
13	1-3 story masonry with protected openings and concrete roofing
14	1-2 story metal buildings

TABLE 8.1 (Contd): Relevant Building and Structural Classes in BVI

INDUSTRIAL BUILDINGS

Building Class Number	Description
15	1-3 story masonry with glass openings and other roofing
16	1-3 story masonry with metal jalousie openings and other roofing
17	1-3 story masonry with protected openings and other roofing
18	1-3 story masonry with glass openings and concrete roofing
19	1-3 story masonry with metal jalousie openings and concrete roofing
20	1-3 story masonry with protected openings and concrete roofing
21	1-2 story metal buildings

GOVERNMENTAL/INSTITUTIONAL BUILDINGS

Building Class Number	Description
22	1-3 story masonry with glass openings and other roofing
23	1-3 story masonry with metal jalousie openings and other roofing
24	1-3 story masonry with glass openings and concrete roofing

GOVERNMENTAL/INSTITUTIONAL BUILDINGS (CONTINUED)

Building Class Number	Description
25	1-3 story masonry with glass openings and concrete roofing
26	1-3 story masonry with metal jalousie openings and concrete roofing
27	1-3 story masonry with protected openings and concrete roofing
28	1-2 story metal buildings

TABLE 8.1 (Contd): Relevant Building and Structural Classes in BVI

MARINE STRUCTURES (TENTATIVE CLASSIFICATION)

Class Number	Description
29	Small open crafts
30	Yachts < 35 ft in length
31	Yachts with length between 35 and 70 ft
32	Yachts > 70 ft in length

	INFRASTRUCTURE
Building Class Number	**Description**
33	Utility Poles
34	Transmission Towers

Upon further discussion with personnel of the BVI Office of Disaster Preparedness regarding building classes 1 through 28, it was decided that the structural behavior of the corresponding building classes in sets {8,...,14} (commercial), {15,...,21} (industrial), and {22-28} (institutional) were very similar and for all intent and purposes they could be considered identical.

Thus only fourteen building types needed to be considered: residential buildings {1,...7} and commercial/industrial/institutional buildings {8,...,14}. However, since the contents of the various classes of structures are expected to be quite different, the total damage (i.e., structural damage plus content damage) sustained by the various classes is expected to differ.

For convenience the buildings in the different classes were given the following building codes, **Table 8.2**, for easy reference.

TABLE 8.2: Building codes for BVI structures.

BUILDING CODE	DESCRIPTION
SP	SLAB (CONCRETE) ROOF/PROTECTED WINDOWS
SM	SLAB ROOF/METAL LOUVRE WINDOWS
SG	SLAB GLASS WINDOWS
OP	OTHER ROOF MATERIAL/ PROTECTED WINDOWS
OM	OTHER ROOF MATERIAL/METAL LOUVRE WINDOWS
OG	OTHER ROOF MATERIAL/GLASS WINDOWS
M	METAL SHEETING BUILDINGS
W	WOODEN BUILDINGS

A prefix **R** or **C** is placed before the first six categories code to indicate residential or Commercial/Governmental/Institutional structures

To incorporate the various types of building contents, it was suggested that the project adopt the ISO Content Risk Grade classification given in **Table 8.3.** Accordingly, residential buildings may be assigned contents described as Grade 2 risks while classes 8-28 will have various mixtures of content risk grades 1 to 4.

TABLE 8.3: ISO Content Risk Grade

Content	Risk Grade	Risk Grade ID
Antiques	High	1
Aquarium	High	1
Glassware	High	1
Open Stock	High	1
Electronic Equipment	Medium High	2
Grocery Stores	Medium High	2
Hospitals	Medium High	2
Furniture & Fixtures	Medium Low	3
Department Stores	Medium Low	3
Hotel	Medium Low	3
Generators	Low	4
Grain	Low	4
Heavy Machinery	Low	4
Rubber	Low	4
Vaults	Low	4

8.2.2 STRUCTURE VULNERABILITY/DAMAGEABILITY

One common way to express the damageability of a structure is to utilize a so-called loss function (also referred to as a damageability function, vulnerability function, or damage function). In order to relate physical damage to buildings to other socio-economic issues, damage is expressed in terms of economic loss: the greater the damage the greater the loss. One common measure of damage is the cost to repair the structure divided by the replacement cost of the structure. This is referred to as the damage ratio. Once this ratio is calculated, as a function of wind speed, the economic loss can then be estimated provided the cost to replace the structure is known.

This thinking holds for a single structure as well as a class of structures. The methodology was applied in a similar fashion to evaluate the impact of hurricane force winds on the power distribution system and the boating sector.

8.2.3 STRUCTURAL DAMAGE RATIO CALCULATION

The model that is used here to estimate damage to a structure in a wind environment assumes that a building may be broken down into the following components: roof covering, roof decking, roof framing, roof to wall connection, exterior cladding, openings, lateral bracing, frame-foundation connection, and the foundation itself. The damage to a building is a complex mixture of the damage to the components of the building.

In the model used in this study, the mean damage ratio dr_s (i.e., the repair cost divided by the replacement cost of the structure) is given by:

$$dr_s = dr_s(v) = \left[\sum^{NC} w_i \left(\int^{v} f_{R_i}(r_i)\, dr_i \right)^{\alpha_s} \right]$$

where:

v	=	the wind speed,
$f_{R_i}(r_i)$	=	the density function for the resistance of the ith building component to wind speed,
w_i	=	the relative weight of the ith component,
α_s	=	a parameter which defines the behavior of the building as a system, and
NC	=	the number of building components in the structural damage ratio model.

8.2.4 CONTENT DAMAGE RATIO CALCULATION

The model that is used here to estimate the damage to the contents of the structure is based on the assumption that damage to contents is caused by damage to the structure. Content damage may result from damage to any component of the structure discussed in the latter paragraph. The content damage ratio, dr_c, (i.e., repair cost divided by the replacement cost

$$dr_c = dr_c(v) = \left[\sum_{i=1}^{M} C_i \left[\varphi_i \int_{0}^{P_i(v)} f_B\, subi(b_i)\, db_i \right]^{\alpha_c} \right]^{1/\alpha_c}$$

of the contents) is given by:

where:

$p_i(v)$	=	the damage to component i at wind speed v,
$f_{B_i}(b_i)$	=	the density function for the resistance of the contents given damage to the ith building component,

φ_i	=	a parameter which models the exposure of the contents
c_i	=	the relative weight of the ith mode of content damage,
α_c	=	a parameter which defines the behavior of the content damage modes as a system, and
M	=	the number of content damage modes.

8.2.5 DAMAGE FUNCTIONS FOR BVI STRUCTURES

The building classes defined in Section 8.2.1 above, were analyzed and appropriate parameters assigned to the various building components. For completeness, the value of the components assigned to each structural class and content type are listed in Appendix I, of the original report. The model parameters were then used to generate structural damage ratios and content damage ratios as a function of wind speed. Damage ratios were derived for wind speeds between 60 mph and 200 mph at increments of 10 mph, for residential structures and contents, commercial/governmental/institutional structures and contents, boats, utility poles, and transmission towers.

8.2.5.1 RESIDENTIAL STRUCTURES

The damage ratios for residential structures are presented in **Tables 8.4(a-g).** The wind speed (1 minute sustained) is listed in the first column. Structure Damage Ratios and Content Damage Ratios are designated as $DR_s(v)$) ($DR_c(v)$) respectively. The damage ratios for structure and contents is provided as fractions so that a damage ratio of 0.238 represents damage of 23.8%. The corresponding curves are also presented adjacent to each table for comparison.

The median velocity of a category (4) hurricane, 140 mph, is highlighted in each table for ease of comparison, and also to indicate the potential damage from what is the most likely worst case scenario for the BVI.

The results show quite clearly that for residential buildings, wooden structures are the most vulnerable, and masonry buildings with concrete slab roofs the least vulnerable. It is also demonstrated that 1-3 story residential buildings constructed with roofing materials other than concrete slabs are almost twice as vulnerable than buildings with concrete slab roofs. Buildings with glass openings are the most vulnerable irrespective of the roofing material, and metal jalousie windows offer significant protection. Openings which are protected with shutters have relatively low damage ratios.

TABLE 8.4 (a) and (b)

TABLE 8.4 (c) and (d)

TABLE 8.4 (e) and (f)

TABLE 8.4 (g)

Table 8.5 (a and b) summarize the damage ratios for residential structures and contents for four (SS) hurricane categories. Wind speeds of 80, 100, 120, and 140 miles per hour were used as median wind speeds representing categories 1,2,3 and 4 respectively.

These tables indicate that significant structural damage to all types of residential structures begins to occur at wind speeds of 120 mph representing here a category 3 hurricane. Content damage ratios above 10%, occurs only inside non-wooden structures at wind speeds in the order of 140 mph.

8.2.5.2 COMMERCIAL/GOVERNMENTAL/INSTITUTIONAL STRUCTURES

The damage ratios that were generated for the commercial, governmental and institutional buildings in the BVI are presented in **Table 8.6(a-g),** along with corresponding curves**.** Because these structures are usually built to higher specifications, the damage ratios indicate that these buildings are slightly less vulnerable to wind damage than residential structures.

The damage ratios for the contents of these structures are also presented in **Table 8.6** . Four damage ratios for building contents are given corresponding to High risk (HR), Medium to High Risk (MHR), Medium to Low Risk (MLR), and Low Risk (LR). The ISO Content Risk Grade classification given in **Table 8.3** indicates some of the buildings with these content risk grade designations.

An interesting feature of these damage ratio values is the fact that the content damage ratios for HR contents exceeds the damage ratio for the structure, while the damage ratios of MHR contents are close to the structural damage ratios. This highlights the high vulnerability of the contents of these buildings.

Sheet metal construction is a common building type within the commercial sector. Typically the construction method involves cladding and roofing a steel frame structure with corrugated aluminum sheeting. The damage ratios generated for these structure indicates that they are the most vulnerable building types.

TABLE 8.5 (a and b)

TABLE 8.6 (a)

TABLE 8.6 (b)

TABLE 8.6 (c)

TABLE 8.6 (d)

TABLE 8.6 (e)

TABLE 8.6 (f)

TABLE 8.6 (g)

Table 8.7 summarizes the damage ratios for these structures for specific wind speeds representing the median wind speeds of four SS hurricane categories. Again the low vulnerability of concrete slab roofs and the corresponding high vulnerability of structures with other roofing material and glass windows is demonstrated. The table again shows the dramatic increase in damage ratios for wind speeds above 120 MPH.

8.2.6 BUILDING VULNERABILITY CLASSIFICATION

The building types were ranked based on the damage ratios and represents a vulnerability classification of the building types examined. This classification is shown in **Table 8.8.** The table clearly shows the high vulnerability of sheet metal and wooden buildings as well as the low vulnerability of concrete slab roofed buildings. The results also confirms the significant role of window protection in reducing structural and content vulnerability.

8.2.7 UTILITY POLES AND TRANSMISSION TOWERS

Damage ratios were also generated for utility poles and transmission towers **Table 8.9 (a) and (b)**. **Table 8.9 (a)** shows the damage ratios for typical 30 foot wooden utility poles and 60 foot steel framed transmission towers. The values indicate a generally high vulnerability to wind damage. The damage ratios indicate the fraction of the total stock of poles that would be damaged and considered lost. Table 8.10 shows estimates of potential damage from four (SS) hurricane categories as derived from Table 8.9 (a).

TABLE 8.10: Estimates of the percentage of failed utility poles for different hurricane intensities.

HURRICANE CATEGORY (SS)	**DAMAGE RATIO (%)**
1	NEGLIGIBLE
2	10
3	30
4	60

TABLE 8.7

TABLE 8.8

TABLE 8.9 (a & b)

8.2.8 BOATS

Damage ratios were also generated for boats and their contents. Four categories of boats were examined including:- small open craft, vessels smaller than 35 feet, vessels between 35 and 70 feet, and vessels greater than 70 feet. The figures relate to boats which have not been protected in any way.

The damage ratios shown in **Table 8.11** indicate the high vulnerability of boats in general. The figure suggest for example that even a category (2) hurricane could produce structural damage of up to 30%, while category four winds would cause almost total destruction of all categories of boats.

8.3 SEISMIC VULNERABILITY OF BVI STRUCTURES

No specific study was conducted to establish the seismic characteristics of structures in the BVI quantitatively. In order to establish in general terms the vulnerability of BVI buildings to earthquake induced ground shaking, damage ratio curves were obtained from the ATC 13. These curves are presented in **Figure 8.1.**

The typical low rise, 1-3 story, masonry structures found in the BVI are best approximated as building category (5) in Figure 8.1, which are described as reinforced masonry buildings of medium quality without seismic design. **Table 8.12** shows the approximate damage ratios, expressed as a percentage, that would result from four categories of earthquake as derived from Figure 8.1.

TABLE 8.11(a) and (b)

TABLE 8.11(c) and (d)

Table 8.12 Earthquake Vulnerability of typical BVI masonry buildings

EARTHQUAKE INTENSITY (MMI)	DAMAGE RATIO (%)
V	0.5
VI	1.5
VII	5.0
VIII	17.0

The table suggests that this building type is relatively resistant to earthquakes with an intensity earthquake of VIII resulting in 17.0% damage. Figure 8.1 also indicates that steel framed buildings without seismic design have similar vulnerability to the category (5) buildings. Wooden buildings however have significantly lower vulnerabilities with about half the damage expected from a intensity VIII earthquake.

The most vulnerable buildings in the BVI consist of the older buildings constructed of unreinforced masonry, brick or stone such as the older churches and historic buildings which would be represented as category (2) buildings in Figure 8.1. These buildings would suffer significant damage from an intensity VIII earthquake, in the order of 40%.

8.4 STORM SURGE VULNERABILITY

No specific study was undertaken to establish the vulnerability of structures in the BVI which are susceptible to storm surge, produced by hurricanes. An examination of the structures built in the low lying coastal zone in the BVI does indicate significant attempt at storm surge resistant design. In general the typical structure built along the coastline are 1 to 3 story reinforced, masonry buildings.

These structures are generally in good condition and appear to be strongly built. Wooden structures would however be expected to be more vulnerable. **Table 8.13** is presented as a rough guide to indicate the level of damage that can be expected from high velocity water inundation. The table shows the damage ratios obtained from (ATC-13) and applies to those areas exposed to the full force of storm surge waves and maximum inundation depth, ie. On the immediate shoreline.

Applying these ratios to structures in the BVI would involve assigning the damage ratios from **Table 8.13** to a given location along the shoreline based on the depth of inundation indicated in the storm surge susceptibility maps. The table indicates for example that 4 meter inundation, corresponding to a direct hit from a SS category 4 hurricane in Road Town, could produce up to 80% damage to structures on the immediate shoreline. The effects on structures further inland both from wave action and from inundation is on the other hand difficult to ascertain in specific terms. However indications are that the major effect would result from saltwater inundation.

TABLE 8.13: Expected damage from high velocity inundation.

DEPTH (METERS)	MEAN DAMAGE RATIO (%)
1	10
2	20
3	50
4	80
5	100

Source: ATC-13

8.5 CONCLUSIONS

The vulnerability of the most common building types to both structural and content damage by hurricane force winds is determined by the roof type and the type of openings. The vulnerability study demonstrates quantitatively the low vulnerability of concrete slab roofs and protected openings. In addition the steel framed, sheet metal clad buildings were shown to be highly vulnerable to high velocity winds.

The high vulnerability of utility poles as shown by the wind vulnerability study indicates the vulnerability of the major lifeline distribution systems, since the electrical, telephone and cable television distribution cables are all carried on these poles. The water desalination plants and existing distribution systems also depend on these utility poles to provide power to these installations.

In addition the electrical generators in the BVI are housed in structures which belong to the more vulnerable groups. At Long Bush the generators are housed in one story masonry structure with galvanized sheet roofing, while the generators at Pockwood Pond are housed in a steel frame structure clad in galvanized sheets. A similar situation exists with the structures which house the desalination plants. These are small, one story, metal frame buildings of light construction clad in galvanized zinc sheets.

A large proportion of the storage facilities at Port Purcell, and commercial warehouses also use this type of construction. As mentioned in the discussion above, this type of construction is the second most vulnerable to hurricane force winds. On the other hand the telephone facilities operated by Cable and Wireless are all masonry structures with concrete slab roofs and protected windows which have a very low vulnerability to high velocity winds.

In the BVI two most important private sector economic activities are tourism and offshore company registration (Trust Companies). The tourism product in the BVI is intricately tied to boating which involves the chartering of yachts as well as the provision of marina facilities for mariners. The study highlighted the extremely high vulnerability of boats to high velocity winds.

The vulnerability of hotels and the structures which house the Trust Companies is dependent on the type of building construction. In the case of Trust Companies content damage takes on specific value as the contents are the most important aspect of their business and is largely irreplaceable.

The high dependency of these companies on telecommunications, links their vulnerability to that of the telecommunications system as well as the electrical power system. The vulnerability of the structure which houses the registrar of companies is critical to the Trust Companies as the non functioning of this office closes down the industry.

Most modern structures in the BVI were found to be relatively earthquake resistant, while older unreinforced masonry buildings were shown to be highly vulnerable. The effects of wave action and saltwater inundation from storm surge would be most severe immediately along the shoreline in areas of high storm surge susceptibility.

FIGURE 8.1: Estimated damage ratios for different earthquake intensities (Sauter, and Shah 1978)