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, between November 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**

Class Number	Description
	MARINE STRUCTURES (TENTATIVE CLASSIFICATION)
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

Building Class Number	Description
	INFRASTRUCTURE
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:

$$_s = dr_s(v) = \left| \sum_{i}^{NC} w_i \left| \int^{v} f_{R_i}(r_i) dr_i \right|^{\alpha_s} \right|$$

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 of the contents) is given by:

$$dr_c = dr_c(v) = \left| \sum_{i}^{M} C_i \left| \varphi_i \int^{p_i(v)} f_{B_i}(b_i) db_i \right|^{\alpha_c} \right|$$

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	=	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.

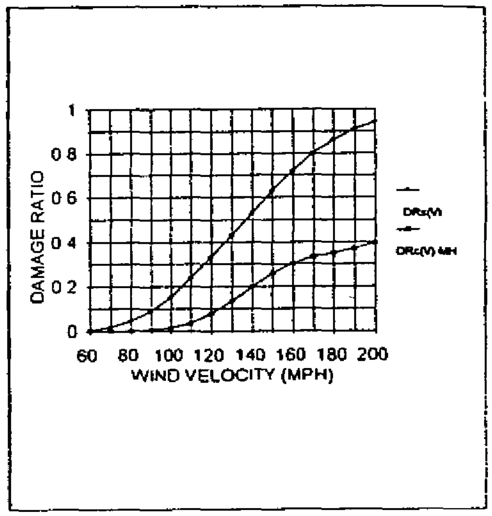
The results show quite clearly that for residential buildings, wooden structures are the most vulnerable, and masonry buildings with concrete slab roofs the least vulnerable. It is also demonstrated that 1-3 story residential buildings constructed with roofing materials other than concrete slabs are 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)

DAMAGE RATIO TABLES FOR RESIDENTIAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH GLASS OPENINGS AND OTHER ROOFING MATERIAL

V	DRs(V)	DRc(V) MH
60	0.002743	0
70	0.015746	1E-06
80	0.043196	0.000695
90	0.08791	0.004361
100	0.15188	0.013903
110	0.238146	0 03414
120	0.333488	0.076693
130	0.430083	0.132235
140	0.527797	0.197501
150	0.625437	0.257712
160	0.718222	0.301857
170	0.798739	0.331635
180	0.860468	0.35021
190	0.908118	0.369342
200	0.941713	0 394547



1-3 STORY MASONRY WITH PROTECTED OPENINGS AND OTHER ROOFING MATERIAL

V	DRs(V)	DRc(V) MH
60	0.00114	0
70	0.009336	0
80	0.028773	0.000458
90	0.062269	0 003113
100	0.111816	0.010186
110	0.180454	0.02562
120	0.258168	0.061404
130	0.344334	0 109948
140	0 442816	0.169191
150	0.55242	0.226929
160	0.668045	0.275556
170	0.771731	0.315227
180	0.85024	0 343453
190	0.906679	0.368352
200	0.941713	0 394547

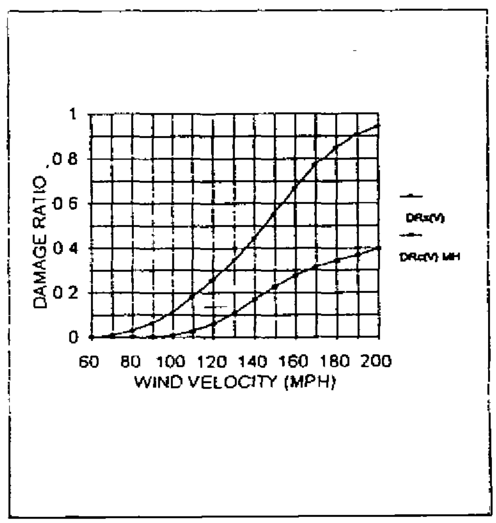
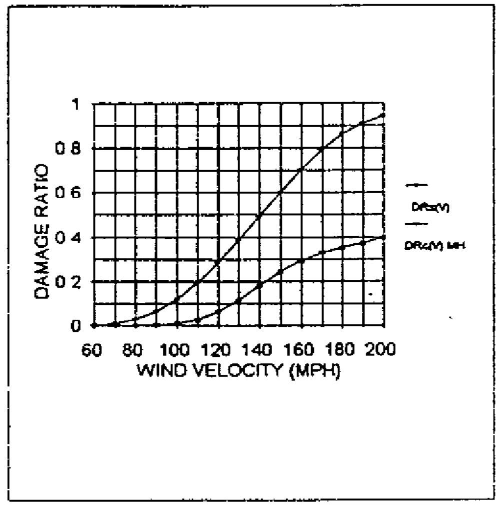


TABLE 8.4 (c) and (d)

DAMAGE RATIO TABLES FOR RESIDENTIAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH METAL JEALOUSY OPENINGS AND OTHER ROOFING MATERIAL

V	DRs(V)	DRc(V) MH
60	0.00114	0
70	0.009336	0
80	0.028773	0 000458
90	0.062824	0.003113
100	0.116807	0.010186
110	0.194317	0 025827
120	0.285339	0.062852
130	0.385255	0.114791
140	0.493222	0.180475
150	0.601481	0 243898
160	0.703654	0.292582
170	0.792329	0 327323
180	0.859381	0.34946
190	0.908118	0 369342
200	0.941713	0.394547



1-3 STORY MASONRY WITH GLASS OPENINGS AND CONCRETE ROOFING

V	DRs(V)	DRc(V) MH
60	0.001603	0
70	0.00641	1E-06
80	0.014423	0.000237
90	0.025641	0.001248
100	0.040132	0.003717
110	0.067559	0.008521
120	0.111852	0.015308
130	0.174376	0.023538
140	0.261327	0.034787
150	0.373147	0.052024
160	0.509803	0 079735
170	0.645919	0.129965
180	0.758814	0 198103
190	0 848554	0 273255
200	0.914393	0 348646

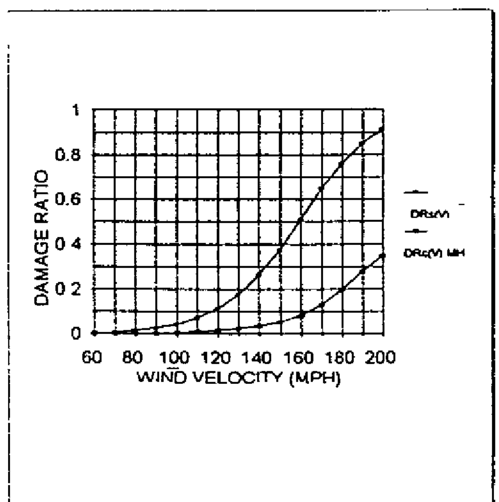
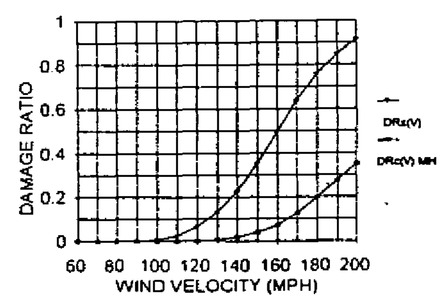


TABLE 8.4 (e) and (f)

DAMAGE RATIO TABLES FOR RESIDENTIAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH METAL JEALOUSY OPENINGS AND CONCRETE ROOFING

V	DRs(V)	DRc(V) MH
60	0	0
70	0	0
80	0	0
90	0.000555	0
100	0.005059	0
110	0.02373	0.000207
120	0.063703	0.001468
130	0.129549	0.006094
140	0.226753	0.017761
150	0.349192	0.03821
160	0.495236	0.07046
170	0.639509	0.125654
180	0.757728	0.197354
190	0.848554	0.273255
200	0.914393	0.348646



1-3 STORY MASONRY WITH PROTECTED OPENINGS AND CONCRETE ROOFING

V	DRs(V)	DRc(V) MH
60	0	0
70	0	0
80	0	0
90	0	0
100	6.8E-05	0
110	0.009867	0
120	0.036531	2E-05
130	0.088628	0.001251
140	0.176347	0.006477
150	0.300131	0.021241
160	0.459626	0.053434
170	0.618911	0.113557
180	0.748586	0.191347
190	0.847115	0.272265
200	0.914393	0.348646

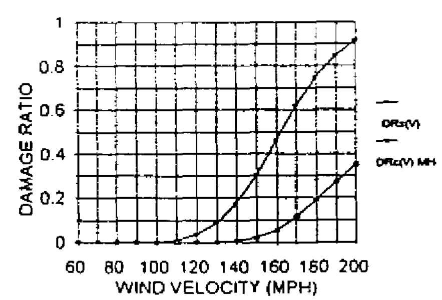


TABLE 8.4 (g)

DAMAGE RATIO TABLES FOR RESIDENTIAL BUILDINGS IN THE BVI

1-3 STORY WOODEN STRUCTURES

V	DRs(V)	DRc(V) MH
60	0.004097	0
70	0.02138	1.9E-05
80	0.057087	0.001318
90	0.114947	0.006955
100	0.198768	0.020862
110	0.304866	0.055141
120	0.41777	0.113546
130	0.535136	0.186571
140	0.655415	0.258067
150	0.772156	0.332724
160	0.873047	0.404284
170	0.939359	0.456659
180	0.978737	0.491415
190	0.995219	0.506575
200	0.998927	0.510326

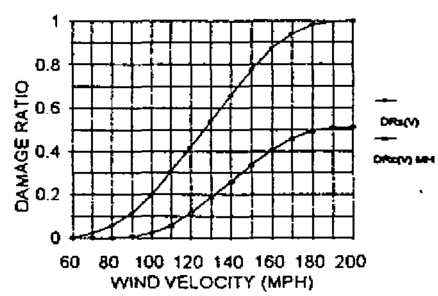


Table 8.5 (a and b) summarize the damage ratios for residential structures and contents for four (SS) hurricane categories. Wind speeds of 80, 100, 120, and 140 miles per hour were used as median wind speeds representing categories 1,2,3 and 4 respectively.

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)

DAMAGE RATIOS FOR RESIDENTIAL STRUCTURES IN THE BVI

BUILDING CODE	CAT 1 (80 MPH)	CAT 2 (100 MPH)	CAT 3 (120 MPH)	CAT 4 (140 MPH)
RSP	0	0	0.037	0.176
RSM	0	0.005	0.064	0.227
RSG	0.014	0.04	0.111	0.261
ROP	0.028	0.111	0.258	0.443
ROM	0.029	0.117	0.285	0.493
ROG	0.04	0.152	0.333	0.528
RW	0.057	0.199	0.418	0.655

DAMAGE RATIOS FOR RESIDENTIAL CONTENTS IN THE BVI

BUILDING CODE	CAT 1 (80 MPH)	CAT 2 (100 MPH)	CAT 3 (120 MPH)	CAT 4 (140 MPH)
RSP	0	0	2E-05	0.006
RSM	0	0	0.001	0.018
RSG	0.0002	0.004	0.015	0.0348
ROP	0.0001	0.01	0.06	0.169
ROM	0.0001	0.01	0.063	0.181
ROG	0.0001	0.0139	0.077	0.197
RW	0.001	0.021	0.113	0.258

RSP	SLAB ROOF/PROTECTED WINDOWS
RSM	SLAB ROOF/METAL LOUVRE WINDOWS
RSG	SLAB ROOF/GLASS WINDOWS
ROP	OTHER ROOFING MATERIAL/PROTECTED WINDOWS
ROM	OTHER ROOFING MATERIAL/METAL LOUVRE WINDOWS
ROG	OTHER ROOFING MATERIAL/GLASS WINDOWS
RW	WOODEN STRUCTURE

TABLE 8.6 (a)

DAMAGE RATIO TABLES FOR COMMERCIAL/GOVERNMENT/INSTITUTIONAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH PROTECTED OPENINGS AND OTHER ROOFING MATERIAL

V	DRs(V)	DRc(V) HR	DRc(V) MHR	DRc(V) MLR	DRc(V) LR
60	0.000301	1.1E-05	0	0	0
70	0.004627	0.001251	0	0	0
80	0.016049	0.01121	0.000359	8.5E-05	3.7E-05
90	0.039597	0.046523	0.005397	0.001281	0.00056
100	0.07727	0.132493	0.022818	0.005416	0.002366
110	0.132789	0.245774	0.062682	0.014877	0.0065
120	0.20828	0.325709	0.135921	0.032534	0.014216
130	0.299215	0.414086	0.22625	0.057471	0.02511
140	0.39988	0.553235	0.355839	0.09537	0.041151
150	0.504123	0.685746	0.511891	0.153781	0.065056
160	0.609562	0.742177	0.634961	0.221445	0.092504
170	0.70851	0.760938	0.70841	0.284069	0.117896
180	0.79449	0.785334	0.741972	0.329998	0.136688
190	0.860766	0.828586	0.778143	0.356455	0.147867
200	0.910303	0.887443	0.833684	0.379262	0.157246

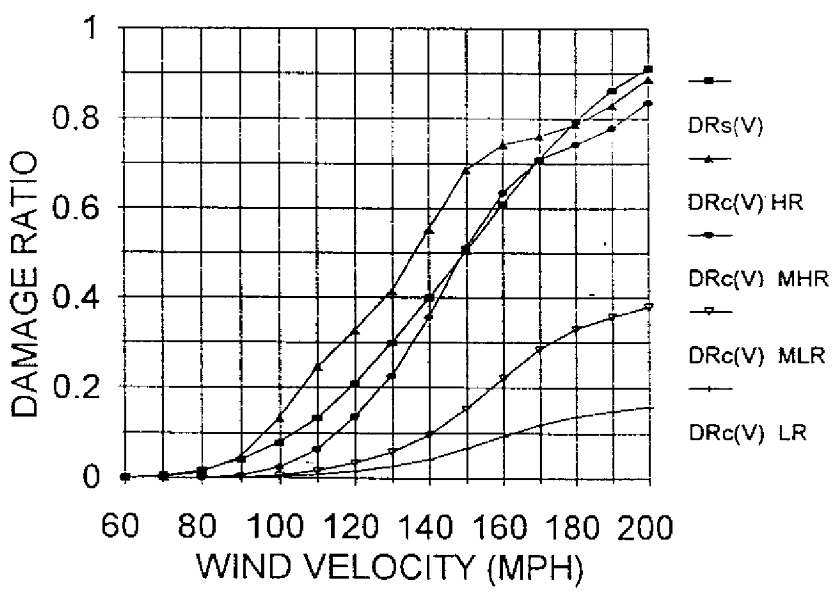


TABLE 8.6 (b)

DAMAGE RATIO TABLES FOR COMMERCIAL/GOVERNMENT/INSTITUTIONAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH METAL JEALOUSY OPENINGS AND OTHER ROOFING MATERIAL

V	DRs(V)	DRc(V) HR	DRc(V) MHR	DRc(V) MLR	DRc(V) LR
60	0.000349	1.2E-05	0	0	0
70	0.005483	0.001359	0	0	0
80	0.017952	0.012109	0.00036	8.5E-05	3.7E-05
90	0.042775	0.049828	0.005824	0.001382	0.000604
100	0.081952	0.14106	0.024472	0.005808	0.002538
110	0.139202	0.262522	0.066745	0.015841	0.006922
120	0.216653	0.338024	0.144088	0.034473	0.015063
130	0.309558	0.415506	0.240371	0.060848	0.026586
140	0.40969	0.553235	0.367048	0.099506	0.042959
150	0.512902	0.685746	0.518912	0.158198	0.066986
160	0.617083	0.742177	0.638859	0.225731	0.094376
170	0.714543	0.760938	0.710211	0.287822	0.119536
180	0.798808	0.785334	0.742577	0.332846	0.137932
190	0.86314	0.828586	0.778245	0.358075	0.148575
200	0.910699	0.887443	0.833686	0.379535	0.157366

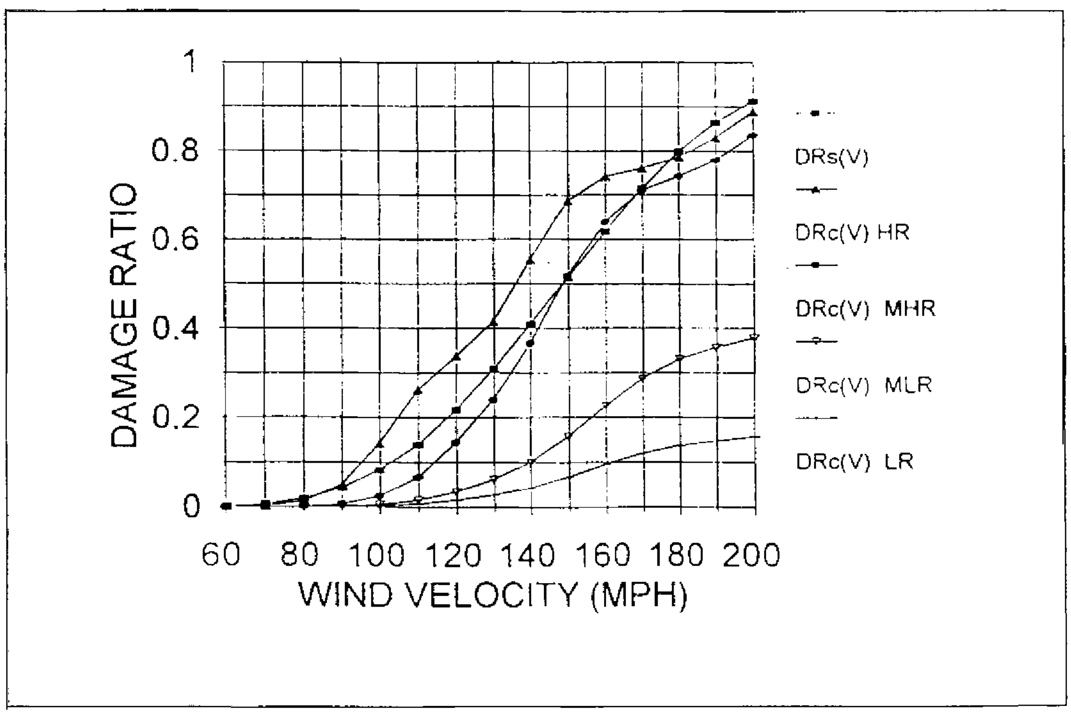


TABLE 8.6 (c)

DAMAGE RATIO TABLES FOR COMMERCIAL/GOVERNMENT/INSTITUTIONAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH GLASS OPENINGS AND OTHER ROOFING MATERIAL

V	DRs(V)	DRc(V) HR	DRc(V) MHR	DRc(V) MLR	DRc(V) LR
60	0.000632	1.7E-05	0	0	0
70	0.006718	0.001641	0	0	0
80	0.020365	0.013986	0.000443	0.000105	4.6E-05
90	0.046591	0.05508	0.006693	0.001588	0.000694
100	0.087396	0.153673	0.027129	0.006439	0.002813
110	0.146499	0.277451	0.072701	0.017255	0.00754
120	0.22603	0.343815	0.15545	0.037169	0.016241
130	0.319312	0.415506	0.252816	0.064653	0.028248
140	0.418435	0.553235	0.37488	0.103706	0.044794
150	0.520412	0.685746	0.52329	0.162362	0.068805
160	0.623132	0.742177	0.640902	0.229437	0.095996
170	0.718907	0.760938	0.71091	0.29068	0.120784
180	0.801261	0.785334	0.7427	0.334517	0.138662
190	0.863576	0.828586	0.778248	0.358377	0.148707
200	0.910699	0.887443	0.833686	0.379535	0.157366

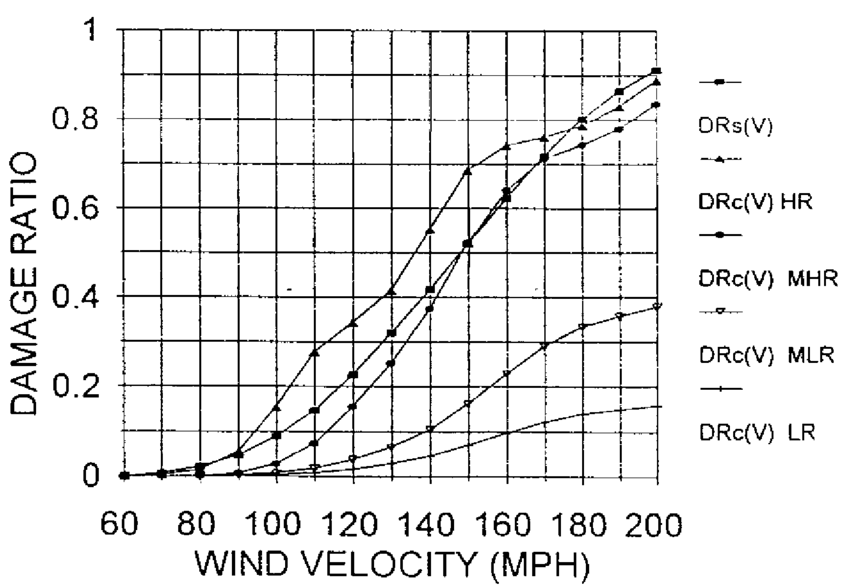


TABLE 8.6 (d)

DAMAGE RATIO TABLES FOR COMMERCIAL/GOVERNMENT/INSTITUTIONAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH GLASS OPENINGS AND CONCRETE ROOFING

V	DRs(V)	DRc(V) HR	DRc(V) MHR	DRc(V) MLR	DRc(V) LR
60	0.000331	5E-06	0	0	0
70	0.00298	0.000427	0	0	0
80	0.008278	0.003331	8.4E-05	2E-05	9E-06
90	0.016617	0.013263	0.001456	0.000345	0.000151
100	0.028405	0.037845	0.005901	0.0014	0.000612
110	0.04556	0.07046	0.015972	0.003791	0.001656
120	0.076028	0.097454	0.035816	0.008501	0.003714
130	0.122243	0.128776	0.062801	0.015782	0.006896
140	0.183709	0.182739	0.089201	0.025298	0.011054
150	0.265823	0.264035	0.127173	0.038686	0.016904
160	0.367955	0.399539	0.182364	0.057145	0.024969
170	0.48587	0.531625	0.258478	0.08171	0.035703
180	0.613479	0.630598	0.401782	0.116138	0.050607
190	0.725178	0.748829	0.583166	0.16823	0.07224
200	0.81728	0.853498	0.749707	0.237423	0.100185

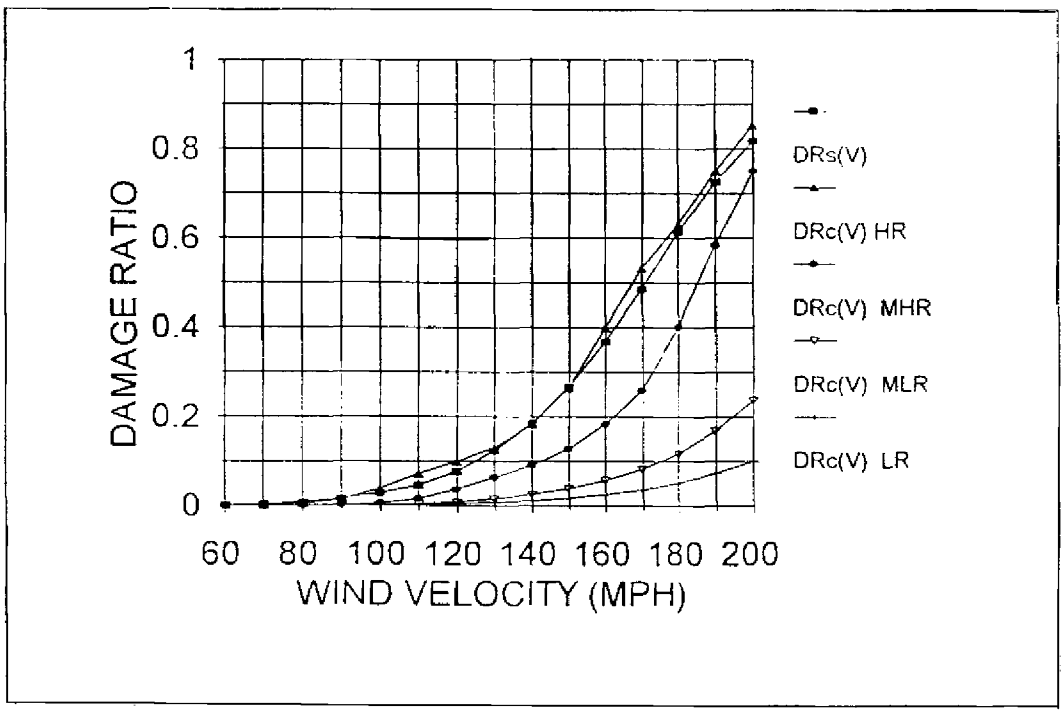


TABLE 8.6 (e)

DAMAGE RATIO TABLES FOR COMMERCIAL/GOVERNMENT/INSTITUTIONAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH METAL JEALOUSY OPENINGS AND CONCRETE ROOFING

V	DRs(V)	DRc(V) HR	DRc(V) MHR	DRc(V) MLR	DRc(V) LR
60	4.8E-05	0	0	0	0
70	0.001745	0.000146	0	0	0
80	0 005865	0.001654	0	0	0
90	0.012801	0.007468	0.000587	0.000139	6.1E-05
100	0.02[illegible]61	0.023031	0.003243	0.00077	0.000336
110	0.038[illegible]	0.055531	0.010016	0.002377	0.001039
120	0.066651	0.091663	0.024453	0.005804	0 002536
130	0 112489	0 128776	0 050356	0.011978	0 005234
140	0 174965	0 1[illegible]739	0.081369	0.021098	0 009219
150	0 258313	0.[illegible]4035	0.122796	0.034522	0.015084
160	0.361906	0.[illegible]539	0.180321	0.053438	0.02335
170	0.481506	0.531625	0.25778	0.078852	0.034454
180	0.611026	0.630598	0.40166	0.114468	0.049877
190	0.724741	0.748829	0.583163	0.167928	0.072108
200	0.81728	0.853498	0.749707	0.237423	0.100185

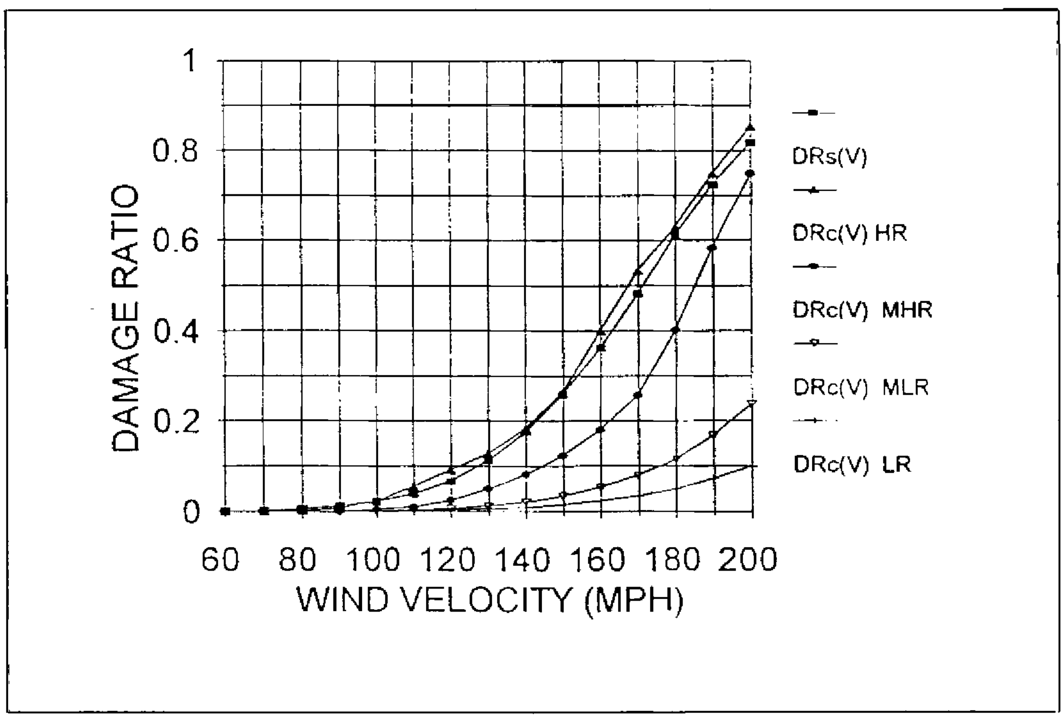


TABLE 8.6 (f)

DAMAGE RATIO TABLES FOR COMMERCIAL/GOVERNMENT/INSTITUTIONAL BUILDINGS IN THE BVI

1-3 STORY MASONRY WITH PROTECTED OPENINGS AND CONCRETE ROOFING

V	DRs(V)	DRc(V) HR	DRc(V) MHR	DRc(V) MLR	DRc(V) LR
60	0	0	0	0	0
70	0.000889	3.8E-05	0	0	0
80	0.003962	0.000755	0	0	0
90	0.009623	0.004163	0.00016	3.8E-05	1.7E-05
100	0.01828	0.014464	0.001589	0.000377	0.000165
110	0.031849	0.038783	0.005952	0.001413	0.000617
120	0.058278	0.079348	0.016286	0.003865	0.001689
130	0.102146	0.127356	0.036235	0.0086	0.003758
140	0.165155	0.182739	0.07016	0.016961	0.007411
150	0.249534	0.264035	0.115774	0.030105	0.013154
160	0.354385	0.399539	0.176422	0.049153	0.021477
170	0.475473	0.531625	0.255979	0.075099	0.032814
180	0.606708	0.630598	0.401055	0.11162	0.048632
190	0.722368	0.748829	0.583061	0.166308	0.0714
200	0.816885	0.853498	0.749705	0.23715	0.100066

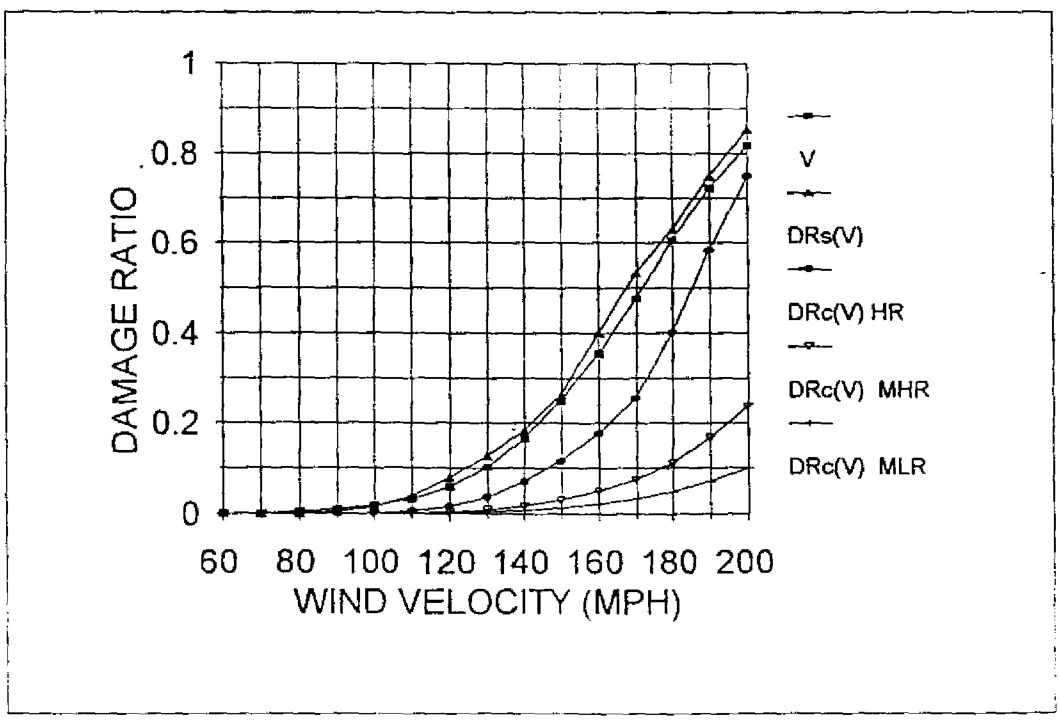


TABLE 8.6 (g)

DAMAGE RATIO TABLES FOR COMMERCIAL/GOVERNMENT/INSTITUTIONAL BUILDINGS IN THE BVI

1-2 STORY METAL SHEET BUILDINGS

V	DRs(V)	DRc(V) HR	DRc(V) MHR	DRc(V) MLR	DRc(V) LR
60	0.000841	9E-05	0	0	0
70	0.007277	0.002816	0	0	0
80	0.023551	0.019276	0.001277	0.000303	0.000132
90	0.054138	0.071656	0.009762	0.002317	0.001012
100	0.099754	0.174735	0.035315	0.008382	0.003662
110	0.162769	0.28563	0.090321	0.021437	0.009367
120	0.244029	0.375525	0.169907	0.042499	0.01857
130	0.338128	0.475203	0.288098	0.073586	0.031913
140	0.432735	0.590061	0.440328	0.124476	0.052829
150	0.527277	0.680987	0.563752	0.188539	0.078682
160	0.621133	0.742372	0.636506	0.250469	0.103593
170	0.710673	0.764219	0.69032	0.299816	0.123647
180	0.789992	0.785715	0.727583	0.330898	0.136748
190	0.852765	0.828589	0.769973	0.348728	0.144479
200	0.902354	0.887443	0.830268	0.370738	0.153522

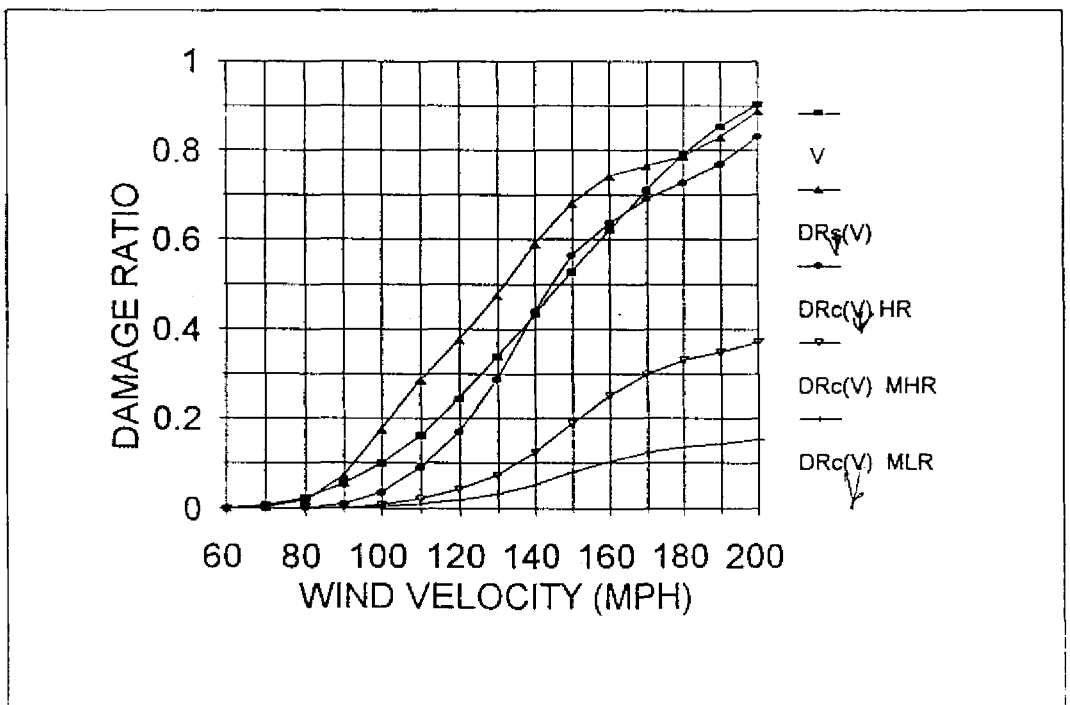


Table 8.7 summarizes the damage ratios for these structures for specific wind speeds representing the median wind speeds of four SS hurricane categories. Again the low vulnerability of concrete slab roofs and the corresponding high vulnerability of structures with other roofing material and glass windows 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

Variation of damage ratios for different hurricane categories.

DAMAGE RATIOS FOR COMMERCIAL/GOVERNMENTAL/INSTITUTION STRUCTURES IN THE BVI

BUILDING CODE	CAT 1 (80 MPH)	CAT 2 (100 MPH)	CAT 3 (120 MPH)	CAT 4 (140 MPH)
CSP	0.0039	0.0183	0.0582	0.165
CSM	0.006	0.022	0.0667	0.175
CSG	0.008	0.0284	0.076	0.184
COP	0.016	0.077	0.21	0.399
COM	0.017	0.081	0.217	0.41
COG	0.02	0.087	0.226	0.418
CM	0.024	0.0997	0.244	0.432

CSP	SLAB ROOF/PROTECTED WINDOWS
CSM	SLAB ROOF/METAL LOUVRE WINDOWS
CSG	SLAB ROOF/GLASS WINDOWS
COP	OTHER ROOFING MATERIAL/PROTECTED WINDOWS
COM	OTHER ROOFING MATERIAL/METAL LOUVRE WINDOWS
COG	OTHER ROOFING MATERIAL/GLASS WINDOWS
CM	SHEET METAL

TABLE 8.8

WIND VULNERABILITY OF BVI STRUCTURES

HIGHEST ↑ LOWEST

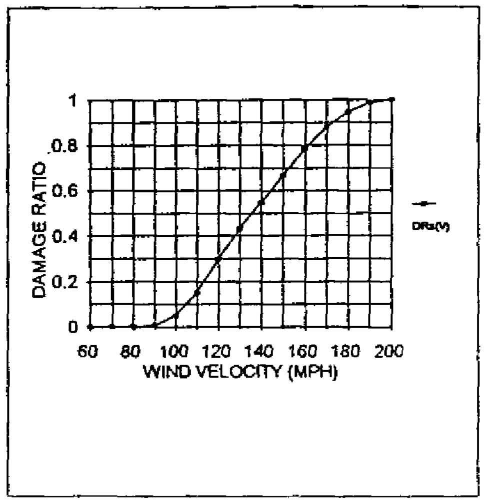
VULNERABILITY	BUILDING CODE	BUILDING DESCRIPTION
1	W	WOODEN BUILDING
2	M	SHEET METAL BUILDING
3	COG/ROG	OTHER ROOFING MATERIAL/GLASS WINDOWS
4	COM/ROG	OTHER ROOFING MATERIAL/METAL LOUVRE WINDO
5	COP/ROG	OTHER ROOFING MATERIAL/PROTECTED WINDOWS
6	CSG/ROG	SLAB ROOF/GLASS WINDOWS
7	CSM/ROG	SLAB ROOF/METAL LOUVRE WINDOWS
8	CSP/ROG	SLAB ROOF/PROTECTED WINDOWS

TABLE 8.9 (a & b)

DAMAGE RATIO TABLES FOR TRANSMISSION NETWORK STRUCTURES IN THE BVI

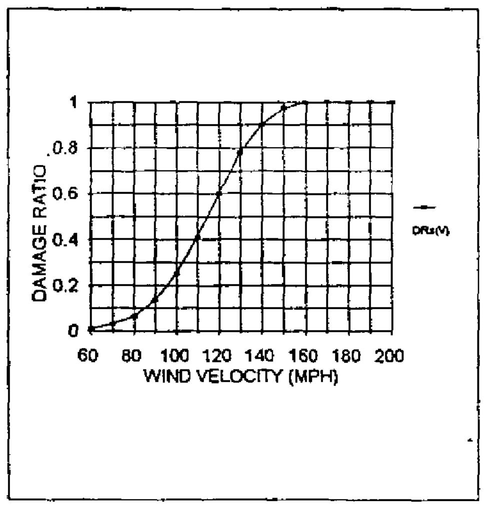
STRUCTURAL DAMAGE TABLE FOR UTILITY POLES

V	DRs(V)
60	0
70	0
80	0
90	0.00551
100	0.049587
110	0.151074
120	0.298512
130	0.431295
140	0.546667
150	0.666667
160	0.786667
170	0.88
180	0.946667
190	0.986667
200	1



STRUCTURAL DAMAGE TABLE FOR TRANSMISSION TOWERS

V	DRs(V)
60	0
70	0
80	0
90	0
100	0.00551
110	0.06292
120	0.191074
130	0.365179
140	0.524628
150	0.666667
160	0.786667
170	0.88
180	0.946667
190	0.986667
200	1



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

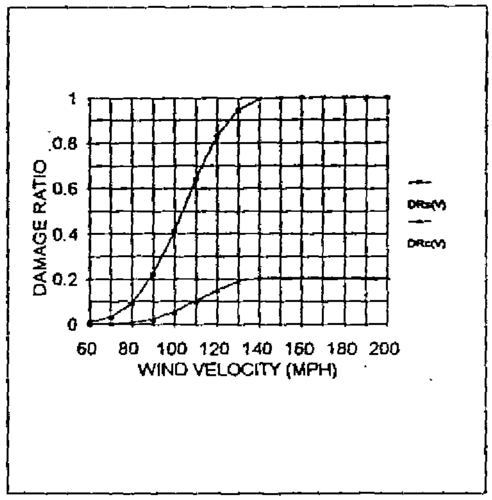
No specific study was conducted to establish the seismic characteristics of structures in the BVI quantitatively. In order to establish in general terms the vulnerability of BVI buildings to earthquake induced ground shaking, damage ratio curves were obtained from the ATC 13. These curves are presented 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)
DAMAGE RATIO TABLES FOR MARINE CRAFT

MARINE STRUCTURAL DAMAGE FOR SMALL OPEN CRAFT

V	DRs(V)	DRc(V)
60	0.009921	3E-06
70	0.029155	0.001061
80	0.089387	0.006379
90	0.221088	0.02126
100	0.410896	0.055401
110	0.64278	0.099958
120	0.830058	0.149711
130	0.945462	0.186902
140	0.994054	0.204475
150	1	0.20775
160	1	0.20775
170	1	0.20775
180	1	0.20775
190	1	0.20775
200	1	0.20775



MARINE STRUCTURAL DAMAGE FOR VESSELS SMALLER THAN 35ft

V	DRs(V)	DRc(V)
60	0.009921	6E-06
70	0.029155	0.002429
80	0.072413	0.014598
90	0.183217	0.048818
100	0.352494	0.131267
110	0.572043	0.240028
120	0.780766	0.364046
130	0.917383	0.457824
140	0.986822	0.503315
150	1	0.511436
160	1	0.511436
170	1	0.511436
180	1	0.511436
190	1	0.511436
200	1	0.511436

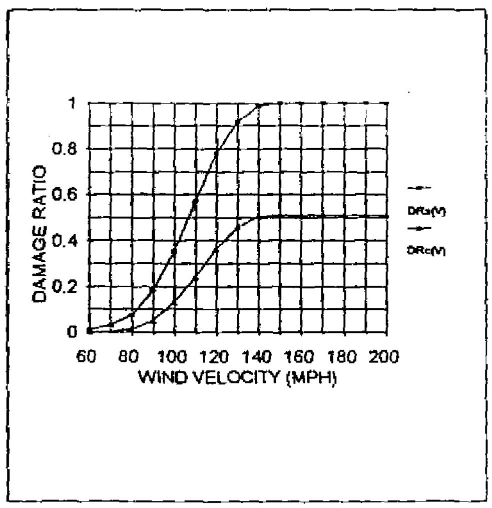
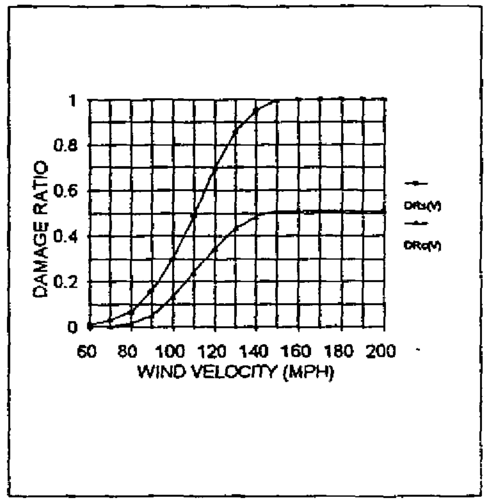


TABLE 8.11(c) and (d)

DAMAGE RATIO TABLES FOR MARINE CRAFT

MARINE STRUCTURAL DAMAGE FOR VESSELS 35 - 70 ft

V	DRs(V)	DRc(V)
60	0.009921	6E-06
70	0.029155	0.002429
80	0.064931	0.014598
90	0.15531	0.048818
100	0.298736	0.131267
110	0.487008	0.239252
120	0.697658	0.345504
130	0.856071	0.431962
140	0.952732	0.484131
150	0.996145	0.509254
160	1	0.511436
170	1	0.511436
180	1	0.511436
190	1	0.511436
200	1	0.511436



MARINE STRUCTURAL DAMAGE FOR VESSELS LARGER THAN 70 ft

V	DRs(V)	DRc(V)
60	0.009921	6E-06
70	0.029155	0.002429
80	0.062762	0.014598
90	0.13267	0.048818
100	0.251856	0.131267
110	0.412341	0.239252
120	0.601415	0.334409
130	0.780348	0.409827
140	0.90152	0.461423
150	0.972991	0.497012
160	0.999777	0.51132
170	1	0.511436
180	1	0.511436
190	1	0.511436
200	1	0.511436

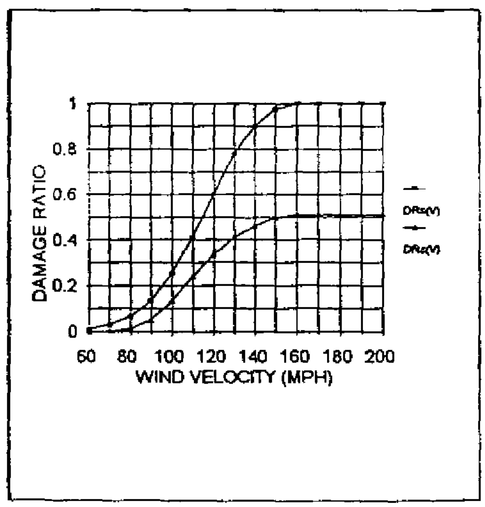


Table 8.12 Earthquake Vulnerability of typical BVI masonry buildings

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.

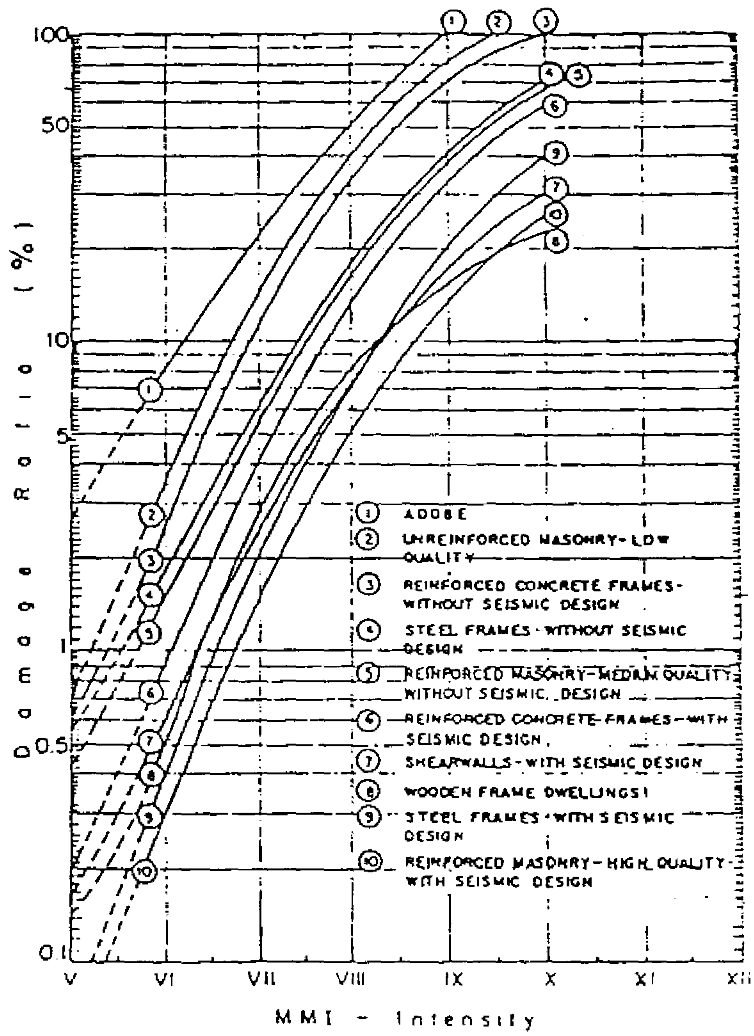
The most vulnerable buildings in the BVI consist of the older buildings constructed of unreinforced masonry, brick or stone such as the older churches and historic buildings which would be represented as category (2) buildings in Figure 8.1. These buildings would suffer significant damage from an intensity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

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



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.