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40th ANNIVERSARY 1955 - 1995

Our Ref: CEP/07101

1996-02-23

CARILEC
Caribbean Electric Utility Services Corporation
Tile World Building
Bois d'Orange
P O Box 2056
Gros Islet
ST LUCIA

Dear Sirs,

Hurricane Damage to APUA (Elec) Facilities

In accordance with your instructions dated 18 September 1995, we have carried out field surveys and analyses of the facilities of the Antigua Public Utility Authority's Electricity Section (APUA-Elec) which were subjected to Hurricane Luis. Your stated Terms of Reference asked us to concentrate on the buildings. However, at your request and that of the Barbados Light & Power Co Ltd (BL&PC), we also reviewed those aspects of the Transmission and Distribution Systems within our non-specialist knowledge.

In addition to reporting specifically on the APUA-Elec facilities we felt it desirable to provide a general background to the event and to provide general comments and recommendations for future action. A power company does not exist in a vacuum. It is part of a community. If the community is badly damaged by a natural hazard the customer base of the power company is directly and adversely affected and business interruption becomes a real issue, even if the power company's facilities are undamaged. Therefore, it is in the interest of power companies not only to reduce the vulnerabilities of their own facilities but also to promote the general adoption of appropriate standards and codes in their communities.

The results of Hurricane Luis in Antigua indicate clearly that success is possible. By success we mean the limiting of losses in Category-3 hurricanes to tolerable levels (low, single-digit percentages) and ensuring that Category-4 hurricanes do not lead to national disasters with losses approaching the GDPs of the countries. We will not be able to eliminate losses completely so there will always be a role for insurance. However, insurance premium levels would sensibly be affordable with the benign scenarios described above.

We wish to thank the personnel of APUA-Elec (Eugene Benjamin in particular), BL&PC (Oliver Jones in particular) and CARILEC (Christopher Farrell in particular) for assisting us with this exercise. We wish also to acknowledge the support of Mr Jan Vermeiren of the Organisation of American States and the presence of Dr Peter Vickery as an observer during most of the field surveys.

Our detailed report follows.

Yours faithfully,
CONSULTING ENGINEERS PARTNERSHIP LTD

Tony Gibbs

TG/acc

Caribbean Electric Utility Services Corporation

Case Study
of the
Effects of Hurricane Luis
on the
Buildings and other Structures
of the
Electricity Section
of the
Antigua Public Utilities Authority

February 1996

Tony Gibbs
Consulting Engineers Partnership Ltd, Barbados

Case Study of the Effects of Hurricane Luis on the Buildings and other Structures of the Electricity Section of the Antigua Public Utilities Authority (APUA-Elec)

CONTENTS

1 INTRODUCTION

1.1 Background

Antigua-Barbuda is in an area subject to multiple natural hazards. Of these, the hazards of earthquakes and hurricanes impact most on the buildings and other structures. In the past fifty years Antigua-Barbuda has suffered from four serious hurricanes and one serious earthquake. In addition, there have been many less-significant events which nevertheless caused damage to the built environment with the attendant disruption of the normal functioning of the Electric Utility Services.

Money spent on repairs and replacements of damaged and destroyed facilities inevitably leads to a pattern of "two steps forward and one step backward". In the past, catastrophe insurance cover was sufficiently inexpensive and available to permit the adequate funding of repairs and loss of profits. At present, and in the immediate future, insurance cover is both scarce and expensive. Some degree of co-insurance is indicated and this therefore focusses the attention of electric utilities on the reduction of vulnerability of their facilities to natural hazards. Also, in the future, there are likely to be increasing demands from the general population for their critical facilities to perform satisfactorily during, and immediately after, hurricanes and sub-catastrophic earthquakes.

The knowledge and materials are available to achieve success. What is lacking is the will.

The efforts of the Caribbean Electric Utility Services Corporation (CARILEC) and the Caribbean Disaster Mitigation Project (USAID/OAS-CDMP)[1] in the area of mitigation are important in the region's thrust towards sustainable development. The recent event of Hurricane Luis in Antigua-Barbuda has provided opportunities, not only for collaborative exercises in reconstruction assistance, but also for learning from the failures and successes and for determining and demonstrating the feasibility of achieving almost total success in future hurricanes.

1.2 Terms of Reference

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[1]The USAID/OAS-CDMP is funded by the United States Agency for International Development and managed by the Organisation of American States.

This Study responds directly to the formal request from CARILEC dated 26 September 1995. It also responds to the request from the Barbados Light & Power Company Ltd (BL&PC) for information specifically on the performance of the transmission and distribution (T&D) systems of APUA-Elec during Luis. The detailed Terms of Reference from CARILEC are reproduced in Appendix 1.

2 HURRICANE LUIS

2.1 General Meteorological Information

Hurricane Luis struck Antigua & Barbuda on 04 and 05 September 1995. Luis was a classical, Category-4 storm; almost perfectly formed; large in extent; loaded with moisture; with a very distinct eye of 70 kilometres in diameter and a forward motion of 17 kilometres per hour. *(See the satellite photograph reproduced as a frontispiece.)* Because of its overall size and slow forward motion, the hurricane impacted on Antigua for an uncommonly long period. Severe storm conditions lasted for about 30 hours during which time about 250 millimetres of rain fell.

> *The real environment in a hurricane consists of strong, turbulent winds (sustained for many hours), that change slowly in direction as the storm passes, and carry large amounts of debris while accompanied by torrential rains.*
>
> *Prof Joseph Minor (modified by Tony Gibbs)*

The above-quoted description of a hurricane was well-exemplified by Hurricane Luis in Antigua-Barbuda.

It is always difficult to get reliable information on wind speeds in hurricanes. The subject event was no exception. At the US Satellite Tracking Station near to the airport the highest recorded gust was 129 knots or 66 metres per second (ms^{-1}). This was at a height of 21 metres above adjacent ground[2]. A reasonable conclusion is that the maximum

[2]The hot-wire anemometer was mounted on a 21-metre tower adjacent to a 9-metre-high building on a small knoll. The equipment is a Case Indicator, CY-2732/GMQ-20, Stock No 6660-00-805-5729, Part No 5114-100, Airflo Instrument Co, Glastonbury, Connecticut, USA. The instrument stopped working at 02:15 on Tuesday, 05 September.

winds in the eye wall were equivalent to 65 to 70 ms^{-1} averaged over 3 seconds at a height of 10 metres at the coastline. The eye passed 50 kilometres north of Antigua so that it was the south-west, south and south-east eye walls that impacted on the northern part of this island. This meant that Antigua, in particular, was spared the full brunt of Luis. Indeed, the wind forces in the north eye wall would have been about 33% greater than those in the south eye wall. It can be concluded that the wind speeds in Antigua during Luis were no greater than are recommended by the current, non-mandated standards in the sub-region. The Caribbean Uniform Building Code (CUBiC) recommends a "reference pressure" equivalent to 56 ms^{-1} and the OAS/NCST/BNSI/BAPE[3] Code recommends a "basic wind speed" of 64 ms^{-1}.

2.2 Post-disaster Reconnaissance

The author (Tony Gibbs) travelled to Antigua in advance of the arrival of Hurricane Luis, once he was reasonably sure that Luis would make landfall in that location. At the invitation of its Director, Mr Patrick Jeremiah, he spent the entire period (30 hours in all) of the storm passage in the Meteorological Station at VC Bird International Airport. There he was able to have a first-hand, gust-by-gust picture of the event, not only visually, but through the various instruments in use at the Station and through the special channels of communication available to such a facility.

Immediately after the storm the author proceeded to inspect the damage done to buildings and other structures in all parts of Antigua. Time is of the essence in these exercises since the evidence is soon tampered with and often cleared away completely. Tony Gibbs has been carrying out post-hurricane assessments for close on two decades and he is of the view that timing is an important factor in these matters.

3 GENERAL ASSESSMENT OF DAMAGE IN ANTIGUA

3.1 General Overview of the Damage

[3] This code was originally prepared by the Barbados Association of Professional Engineers (BAPE) in 1970. In 1981 the (Barbados) National Council for Science and Technology (NCST) commissioned a revision funded by the Organisation of American States (OAS). More recently, the Barbados National Standards Institution (BNSI) adopted the document as a national standard.

A fuller description of the post-Luis conditions of the APUA-Elec facilities in Antigua is given in the following Section 4 of this report.

The level of damage in Antigua was equivalent to two-thirds of the gross domestic product (GDP) of the country. Such an event has the potential to set back the development of a small island independent state by several years. In particular, much damage was done to essential facilities in the country. These facilities include telecommunications; water supply and distribution; electricity generation, transmission and distribution; and the public health services.

Subsequent to his visit at the time of the event the author was afforded the opportunity, through CARILEC and BL&PC, to review the damage done to the electricity sector. The analyses of causes of failures indicate quite clearly how most of the failures could have been reduced to manageable amounts and, in many cases, eliminated completely with little incremental effort and cost.

Damage to buildings was mainly due to weak connections of light-weight roofing and siding materials, impact damage to glazed openings from flying objects, inadequate fixings of windows and external doors and water damage from the torrential rains. There were also examples of catastrophic collapse of entire buildings due to unsound structural concepts. The lack of maintenance of building components contributed significantly to the damage. In the cases of structures not associated with buildings (eg telecommunication towers and transmission systems) inadequate specification of performance criteria at the procurement and design stages was an important factor in the failures. The actual wind speeds were not greater than should have been expected in a 1-in-50-year event. The introduction of mandatory building standards and codes would have a significant, positive impact in reducing losses in future hurricanes.

3.2 Natural Hazards and Disaster Mitigation

Antigua is not only in the regular path of severe hurricanes *(See Figure 1 in Appendix 2 showing the region's isoline map of Category 3 hurricanes, produced by the University of the West Indies)*. It is also located in the most hazardous area of seismic activity in the Caribbean Archipelago. *(See Fig2-Appndx2 showing the sub-region iso-acceleration map, provided by Dr John Shepherd - 1000 gals = gravity)* The interrelationship of (and differences between) wind-resistant and earthquake-resistant design must not be lost sight of in the reconstruction process.

Earthquakes and hurricanes are not natural disasters, they are natural hazards which sometimes lead to manmade disasters. In these days of widespread technological education, sophisticated research, reliable building materials, computer-based geographical information systems and satellite-assisted warning programmes, hurricanes in the Caribbean should not lead to disasters. The one exception to this would be vulnerable agricultural crops, such as bananas. Although much less is known about earthquakes and there is effectively no warning system for these events, sufficient is known about the effects of earthquakes on structures to prevent disasters and to keep damage from earthquakes to tolerable levels.

It is now evident that disasters due to natural hazards are largely preventable and soon the public will demand deliberate actions to protect communities against such hazardous events. Disaster mitigation must therefore be made an essential ingredient in development planning and capital works projects. In the same way that environmental impact assessments (EIAs) have now become routine, so too should natural hazard impact assessments (NHIAs) be a standard requirement in the planning of projects.

4 ASSESSMENT OF DAMAGE TO APUA-ELEC FACILITIES

4.1 Field Visits

The first series of visits made specifically to investigate damage to APUA-Elec's facilities (under contract to CARILEC) was made between 28 September and 02 October 1995. On 28 September the team for the field trip comprised:

Oliver Jones	BL&PC
Eugene Benjamin	APUA-Elec T&D Supervisor[4]
Peter Vickery	Observer from Applied Research Associates
Tony Gibbs	CEP

[4] (work: 462 1391/1470/2229; fax: 462 2573; home: 463 2118)

Other persons with whom contact was made at the Cassada Gardens office were:

Earl Gardner	APUA-Elec T&D Engineer
Peter Benjamin	APUA-Elec General Manager
Hugo Ford	Trinidad & Tobago Electricity Commission

The names of others are given under the headings for the relevant facilities.

Field visits also took place on 29 & 30 September (E Benjamin, Vickery, Gibbs) and on 02 October (E Benjamin, Gibbs).

On 30 October 1995 Barry Pinnock of CEP made further inspections of the three power-station sites in company with APUA-Elec's A B Segu to gather supplementary information for preparing cost estimates. *(Mr Pinnock's report is reproduced as Appendix 5.)*

(62 photographs, with captions, are reproduced in Appendix 4. They are important supplements to the main text of this report.)

4.2 Cassada Gardens Complex

(See Photographs 1,2,3,4,33)

4.2.1 Contact Persons

In addition to the persons mentioned in 4.1 contact was made with:

Ruvan Barnarde	Systems Control Engineer
Winston Smith[5]	

4.2.2 General Description

The principal facilities at Cassada Gardens are:

- The Old Power Station Building which is not in use. It contains Mirrlees generators from the 1960s.
- The current generating plant consisting of 4 x 1 MW Cummins

[5](461 3746)

medium-speed diesels from the 1980s. Only two are functioning and they are run at 60% of their nominal rating.

- The 69/11 kVA Substation. (There is another substation across the main road from this compound. It was taken out of use when the 69 kV system was brought on stream.)

- The Control Centre for Antigua. (There are un-manned substations with automatic switching by telephone lines.) The Control Room was part of the "Italian Project". *(See Photo 27)*

- The Canteen and Workshop. The Workshop housed specialised tools and computers. *(See Photos 5,6,7)*

- Transmission & Distribution (and Water Division and Transport Officer's) Section. This was also part of the "Italian Project".

- The very new (less than 2 years old) Office Building incorporating a Meter Test Shop. *(See Photo 28)*

4.2.3 Damage Assessment

The observations made at the Control Room at the time of the visit were:

- ceiling tiles damaged by leaks;
- control panels were covered before the hurricane as a sensible precautionary measure, even though the roof remained intact *(See Photo 35)*;
- water entered the building mainly through the ducts which were provided for HV cables.

The observations made at the Transmission & Distribution Section at the time of the visit were:

- two broken windows;
- ingress of water;
- water damage to materials in the Storeroom.

The observations made at the Office Building at the time of the visit was:

- damage was only due to water entering the building at door locations.

The observations made at the 11 kV Indoor Switchgear Room at the time of the visit were:

- shutters were fitted over Georgian-wire-glass windows;
- the main damage was to the floor tiles from water;
- on the west side the steel roof beams (encased in concrete) have lifted slightly.

The observations made at the Canteen and Workshop at the time of the visit were:

- the building was very badly damaged with its entire roof removed by the wind;
- the walls were cracked.

The Fence was in reasonable condition.

(The estimates of repair costs for the buildings is given in Table 1a, Appendix 3.)

4.3 Friars Hill Power Station

4.3.1 Contact Person

In addition to the persons mentioned in 4.1 contact was made with:

Conrad Samuel   Station Superintendent

4.3.2 General Description

The principal facilities at Friars Hill are:

- The Power Station Building which was erected in 1965. *(See Photo 8)*

- The generating plant at this facility consisting of 2 x 6.5 MW Mirrlees Blackstone medium-speed diesels installed in 1982. The engines start on diesel and run on bunker C.

- Offices, Stores and Workshop occupying three buildings adjoined to one another. *(See Photos 11,12,13)*

4.3.3 Damage Assessment

The observations made at the Power Station Building at the time of the visit were:

- 30% of the roofing of the south section lost;
- 10% of the roofing of the north section lost;
- 10% of the roofing of the west section lost;
- most of the south gable cladding lost (the fixing of replacement sheets leaves much to be desired) *(See Photos 9,10)*;
- flood damage from water flowing over the land;
- flood damage from ground water flowing through the bases and sides of trenches of the Power Station;
- both alternators were covered with tarpaulin before the advent of the hurricane. (Actually the #1 alternator was out-of-action before Luis.) The covering was not entirely effective because ground-water flooding affected 25% of the equipment which is in a pit;
- salt spray brought inland by the strong winds affected not only the machinery but also the building fabric;
- the exhaust lagging was damaged but it was certain (because of the weathering) that such damage had occurred before Luis;
- guttering was lost and most had been replaced by the end of October 1995.

The observations made at the Offices, Stores and Workshop Buildings at the time of the visit were:

- 50% to 60% of the roofing was lost with consequent water damage *(See Photos 16,17,18)*;
- there was severe damage to the wall cladding of the Workshop Building *(See Photos 14,15)*.

(The estimates of repair costs for the buildings is given in Table 1b, Appendix 3.)

4.4 Crabbs Complex

4.4.1 Contact Persons

Gordon Derrick	Mechanical Maintenance Engineer
Lyndon Francis	Plant Engineer

4.4.2 General Description

The principal facilities at Crabbs are:

- the Diesel Station which was built about 35 years ago. There are 3 x 1.5 MW Fairbanks Morse medium-speed diesels and 1 x 5 MW Mirrlees diesel (which uses bunker C fuel);

- the Reverse Osmosis Plant. (This is a privately-owned facility which supplies 1 million Imperial gallons per day to the general water distribution system);

- the largest facility at Crabbs is the Desalination Cogeneration Plant. It houses 2 x 9 MW Toshiba steam turbines. Installation was circa 1985. The desalination output is 2 million Imperial gallons per day.

4.4.3 Damage Assessment

The observations made at the Crabbs Diesel Power Station *(See Photos 19,20,34)* at the time of the visit were:

- as a protective measure the Mirrlees was covered with tarpaulin before the advent of Luis;
- the roller shutter doors were destroyed *(See Photo 26)*;
- there was water damage and it took a few days to dry out the alternators;
- a glass window at high level was removed by the wind;
- the stacks for the Fairbanks Morse engines (#1 and #3) were damaged *(See Photo 29)*;
- the metal sidings of the 35-year old Diesel Station (which is close to the water) appeared to have been "sand blasted" during the hurricane. With the protective coating thus removed the sheets were rusting;
- the fence was flattened;
- the seawall (10-foot above sea level) was not endangered by storm surge *(See Photo 41)*;
- two interconnector poles were blown down. (They were replaced

by the time of the visit.)

The observations made at the Reverse Osmosis Plant at the time of the visit were:

- o the main wind damage was to the gable-end flashing *(See Photo 21)*;
- o impact damage to metal siding *(See Photo 22)*;
- o roller shutters were destroyed.

The observations made at the Desalination Cogeneration Plant at the time of the visit were:

- o insulation cladding was damaged on the exhaust stack and the intake duct. The cladding used to be rivetted but the repair method is to screw it to the frames *(See Photos 30,31,32)*;
- o a storm surge of 8 feet was reported by personnel at Crabbs *(See Photo 40)*;
- o the Jetty and adjacent shore-protection works were largely destroyed *(See Photos 38,39)*.

The long-term effects of salt-laden winds cannot be established at this time.

(The estimates of repair costs for the buildings is given in Table 1c, Appendix 3.)

4.5 Substations

4.5.1 Belmont Substation *(See Photo 36)*

There was no wind damage nor did flying objects pose any problems.

Water got into the container-type equipment room. (This location has both the masonry&concrete-type and the container-type equipment rooms.)

4.5.2 Swetes Substation *(See Photo 37)*

The windows appeared to be double glazed. They were unbroken. *(See Photo 23)*

69/11 kV outdoor transformer (10MW) is on wheels on rails and not secured. It would be vulnerable in an earthquake. *(See Photo 59)*

4.5.3 Five Islands Substation *(See Photos 24,25)*

Construction work was in progress at the station.

4.5.4 Cassada Gardens, Friars Hill and Crabbs Substations

These were inspected at the same times as the relevant power stations and other facilities.

There was little damage to be seen.

4.6 Transmission and Distribution Systems

4.6.1 General Description

Wallaba poles were used up to 1987. During the British colonial period the use of H-frames was popular.

Wallaba poles are gradually being replaced with southern-yellow-pine poles.

In 1987 lattice-steel towers were introduced. The contractor was MAW spa of Milan, Italy.

4.6.2 Foundations

The planting of poles is generally in accordance with standard Antigua practice:

In volcanic rock	5-foot depth
In other (normal) conditions	6-foot depth

4.6.3 Typical Examples of Failures

In the Jolly Harbour Area poles carrying a single 3-phase 3/0 AAAC-11kV line were uprooted from their foundations *(See Photos 48,49)*.

West of Old Road, after the planting of poles, the adjacent road was rebuilt. The rebuilding entailed reducing the overall level of the road. Thus the nearby poles ended up being founded in the embankment alongside the road. The embankment did not have sufficient lateral containment strength to hold the poles. *(See Photo 52)*

In the Jonas Road area white rot was present in many of the broken wallaba poles *(See Photos 44,45)*.

In the Mental Hospital Road area the presence of knots at critical locations in the poles was a contributory factor in breakages.

In the Jonas Road area the overloading of poles with large telephone cables was evident *(See Photo 56)*.

At the Falmouth - Piccadilly Road Junction the overloading of poles led to many breakages *(See Photos 54,55)*.

4.6.4 Failure Modes and Causes

These can be summarised as follows:

- Foundation failures due to inadequate depths *(See Photo 50)*.
- Foundation failures due to using "standard" procedures in very soft soils. It should be noted that the long duration of a hurricane and the accompanying heavy rainfall can soften clay soils to much greater depths than would occur in normal conditions.
- Pull-out failures of stay anchors *(See Photo 51)*.
- Breaking of poles, usually at the soil line, due to rotting of the wood *(See Photos 42,43)*.
- Breaking of poles at locations where they have been drilled to accommodate anchorages for cable attachments *(See Photo 53)*.
- Breaking of poles because they were overloaded with telephone and television cables *(See Photos 46,47)*.
- Breaking of conductors *(See Photo 58)*.
- Failures due to flying debris and falling branches and trees *(See Photo 57)*.

With the exception of the last-listed item all of the causes of failures are preventable by convenient means.

4.6.5 Amount of Damage

The percentage losses (broken and leaning or uprooted poles) are 14.06% for the 11 kV system and 3.86% for the 69 kV system. There were no losses in the steel towers of the 69 kV system. *(The details are given in Table 2, Appendix 3.)*

I must be noted that the absence of trees in Antigua (relative to most Caribbean islands) was an important factor in keeping losses to such low figures.

4.6.6 Reinstatement of the T&D System

Several teams from other Caribbean companies (including the BL&PC) and from further afield were involved in the reinstatement of the T&D System. *(The programme details are given in Table 3, Appendix 3 and in Photos 61 and 62. See the BL&PC team in Photo 60.)*

5 GENERAL ISSUES AFFECTING FAILURES AND SUCCESSES

5.1 Conceptual Design

This is the single most-important factor determining success or failure of buildings. Once again this was demonstrated during Hurricane Luis in Antigua. With respect to hurricanes, suitable design concepts are particularly important for light-weight structures - timber and corrugated-metal walls and roofs.

Unfavourable features evident in Antigua were:

- L-shaped plans;
- mono-pitched roofs;
- shallow-pitched gable roofs;
- long overhangs at the eaves and gables;
- long overhangs continuous with the main roof;
- corner balconies.

Favourable features evident in Antigua were:

- compact plans;
- hipped roofs;
- steep-pitched gable roofs;
- short overhangs at the eaves;
- canopies discontinuous with the main roof;

- parapets.

5.2 Strength of Materials and Sizes of Construction Components

Building materials are supplied in wide ranges of strengths. For example, commonly in Antigua, the ranges of strengths (in Nmm^{-2}) of basic building materials are as indicated below:

material	**lowest**	**highest**	**ratio**
timber	17	105	6.2
corrugated metal roofing	70	410	5.9
reinforcing steel	210	460	2.2
concrete	17	35	2.0
concrete blocks	5	8	1 6

Clearly, these significant differences must be accounted for in construction. The lack of conscious appreciation of these differences can, and did, lead to failures. (It has to be said that such lack of appreciation also led to some accidental successes.)

As well as strength, brittleness is a factor determining success and failure. The best evidence of this in Antigua was the breakage of corrugated asbestos sheeting used as roofs and sidings.

The sizes of construction components are greatly controlled by strengths of materials. Everything else being equal, the stronger the material the smaller the component size needs to be. Of course, practical considerations and aesthetics also have their influences on sizes. Such influences, when benign, lead to larger-than-necessary sizes from a strength point of view. Inadequate sizing was the contributory factor in some of the observed failures, principally those associated with light-weight roofing.

5.3 Analysis

Some of the APUA-Elec buildings are of such a small scale as may not normally warrant detailed, formal, engineering analysis.

Component sizes for small-scale construction are usually determined by tradition and rules of thumb. With the rapid introduction of new materials there isn't the time to develop new traditions. With the rapid expansion of the construction industry there isn't the time to train artisans and craftsmen through apprenticeships, as was done in the past. Rules of thumb are often not known by the new practitioners.

In such an environment some analysis is indicated, even for buildings of modest size. For critical facilities, including all APUA-Elec facilities, analysis must be used to determine or confirm the adequacy of component sizes.

The absence of a conscious engineered approach to many of the buildings was the cause of failures of some components and their connectors.

5.4 Detailing and Connections

In the words of the famous German architect, Mies van der Rohe, "God is in the details". It is difficult to overemphasise the importance of detailing. This is the process of arranging the structural and building elements in such a way that they perform their intended functions by carrying the applied loads safely. Thus the quantity of material may be sufficient but, if the arrangement of the material is inappropriate, failure may result. Thus was evident in some instances in Antigua.

Real-estate people talk about the three most important factors being: "location, location and location". Likewise, for hurricane resistance of lightweight structures, the three important issues can almost be said to be: "connections, connections and connections". The roof sheeting must be adequately connected to the purlins. The purlins must be adequately connected to the rafters. The rafters must be adequately connected to the wall plates. The wall plates must be adequately connected to the wall studs. The wall studs must be adequately connected to the base sleepers. The base sleepers must be adequately connected to the base walls or piers. The piers must be adequately founded. This litany simply says that the wind forces must be carried from wherever they impact on the building all the way into the ground without any weak links along the load path *(See Figure 3 in Appendix 2)*. Hurricane Luis sought out weak links and found several.

5.5 Quality Control During Construction

All of the good work in the planning stages can (and often does) become unstuck by faulty construction. It is generally felt that poor construction is responsible for most of the damage in hurricanes. This is not the view of the author. However, poor construction is a contributory factor in a significant minority of the failures. It can also be said that whereas poor construction can undo good design, analysis and detailing; good construction cannot make up for bad design, analysis and detailing.

APUA-Elec's buildings and structures had their usual share of failures due to poor quality control during construction.

5.6 Non-structural Elements and Issues

Windows and external doors are the orphans of the construction industry and their acts of revenge for lack of attention can be very embarrassing. Usually engineers are not involved in the specification of these items. Usually architects are not equipped to determine the strength requirements for these items. Usually suppliers and contractors cannot be relied on to provide more than the commercial norm, which is inadequate for Category-4 hurricanes (a reasonable requirement for APUA-Elec buildings and structures). There were several failures to be seen, which is not surprising. The failures were sometimes of the fixings to the walls. At other times glass was broken by flying objects. The only ways to deal with vulnerability to breakage are hurricane shutters and laminated glass. The latter approach would still lead to breakage but the weather would be excluded during the hurricane.

The inadequacy of storm-water drainage can lead to much damage. There was some evidence of this at the APUA-Elec facilities. Not enough attention is paid to this aspect of design. Even where drainage is consciously engineered, design criteria are usually inadequate, especially for critical facilities.

The APUA-Elec facility at Crabbs is located on the coastline. Storm surge and wave action are hazards accompanying hurricanes. Predicting the severity of these marine hazards requires specialist advice which nevertheless is subject to much debate. This is compounded by the lack of reliable records of previous events. What is indisputable, however, is the need to be aware of marine hazards in locating critical facilities in coastal areas.

5.7 Maintenance

On the television programme CNN&Company of 13 December 1995 the main topic was urban infrastructure. The problem of decaying roads, bridges, water supply systems and sewerage systems was the subject of much debate. The cost, and political unpopularity, of preventative maintenance was recognised. It was also recognised that preventative maintenance was less expensive, in the long run, than emergency repairs and reconstruction brought about by inadequate maintenance. So it can be seen that even the wealthiest of nations won't willingly spend the funds necessary for proper preventative maintenance.

The inadequacy of preventative maintenance or, in some cases, the apparent total absence of maintenance is probably the second most important cause of much of the damage to be seen in APUA-Elec's buildings and structures.

6 THE COST OF MITIGATING DAMAGE

6.1 Case I - Favourable Concepts

For the single-storey and two-storey buildings used as APUA-Elec facilities in Antigua the cost of making the favourably-shaped ones virtually invulnerable to future Category-4 hurricanes would have been a maximum of 3% in initial capital cost. Most of this incremental cost would be used in protecting windows and external doors and securing the lightweight roofing and siding.

6.2 Case II - Unfavourable Concepts

Where the APUA-Elec facilities are of unfavourable shape the cost of virtual invulnerability to future Category-4 hurricanes could rise to about 7.5% in initial capital cost. This incremental cost would be used, not only in protecting windows and external doors, but also in adding strength to the entire building envelope because of the higher wind forces generated by the unfavourable shapes.

6.3 Maintenance Costs

These would increase gradually from almost zero for the first year of the life of a new building up to about 4% of the contemporary construction cost in year 20. Thereafter the figure of 4% of the contemporary construction cost should be used as an annual budget.

The above-estimated figures would, of course, vary with the materials of construction. Life-cycle costing should be employed in financial and economic planning of new facilities. Such an approach would likely lead to better quality construction (which could have higher first costs) and lower-cost maintenance. This strategy is usually the more favourable.

This maintenance budget would cover management, other personnel, machines, materials for preventative maintenance and replacements of the entire fabric and "domestic" electrical/mechanical systems for the facility. Under such a desirable maintenance *régime* the buildings should last for up to two generations without noticeable deterioration.

6.4 The Cost of Controlling the Building Industry

6.4.1 Standards and Codes

In the overall context of the construction industry in general and the APUA-Elec facilities in particular, the cost of preparing standards and mandating codes is negligible.

6.4.2 Checking and Monitoring

If these functions are to be carried out effectively for design as well as for construction, an additional, one-off cost of 1% to 2% of the original construction sum is an average estimate. Spread over the (say) 50-year life of a building this figure becomes infinitesimally small.

6.4.3 Regulating the Professionals

This cost is almost zero. Antigua already has in place a Registration of Engineers Act. However, the Regulations have not yet been ratified by the Cabinet, so that the Act is not yet effective. Once the Regulations are ratified, the registering of engineers and the monitoring of the profession would be covered by annual registration fees paid by the said professionals. This would amount to no more than a few thousands of dollars, nothing that can be quantified as a measurable percentage of construction costs.

7 RECOMMENDATIONS

7.1 Mandating of Standards through Legal Codes

It is understood that there was a ministerial decision taken after Hurricane Hugo to institute a mandatory building code in Antigua-Barbuda. Every cloud has a silver lining. There are probably various arrangements still to be put in place to implement that decision. No effort should be spared, now that "the iron is hot", to keep the momentum going so that the Code becomes an integral part of the construction industry at a very early date. That Code is based on the OECS[6] Building Code developed with funding from UNDP/UNCHS[7] and referencing the regional standards of CUBiC.

7.2 Registration of Engineers

The necessary Regulations could be ratified at an early date so that the Registration Act can be put into force in time to support the mandatory Code implementation.

7.3 The Control System

7.3.1 Self Attestation

For buildings coming within the remit of the Engineers Registration Act it should be sufficient for designs, calculations and drawings to bear the stamp of a Registered Engineer and for that Engineer to attest in writing that the works have been designed in accordance with the provisions of the Antigua-Barbuda Building Code. A similar approach could be adopted for the construction process.

7.3.2 Random Audits

Such self-attestation as described above should be buttressed by in-depth audits of projects randomly selected and also selected where there is *prima facie* evidence of under-design or poor construction.

7.3.3 Check Consultants

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[6] Organisation of East Caribbean States

[7] United Nations Development Programme through United Nations Centre for Human Settlements

For critical facilities, such as APUA-Elec facilities, independent check consultants are recommended. The use of check consultants is routine in France, including Martinique and Guadeloupe. It is also the practice in Colombia and, probably, in many other countries.

7.4 Maintenance

This could well be the most difficult recommendation to get acceptance. Facility owners have always balked at spending adequate amounts on this item. Also, budgeted amounts are frequently not drawn down because they get reallocated to other "more pressing" uses.

Notwithstanding these difficulties, however, it must be recognised how critical preventative maintenance is in protecting the APUA-Elec facilities from damage in major hurricanes.

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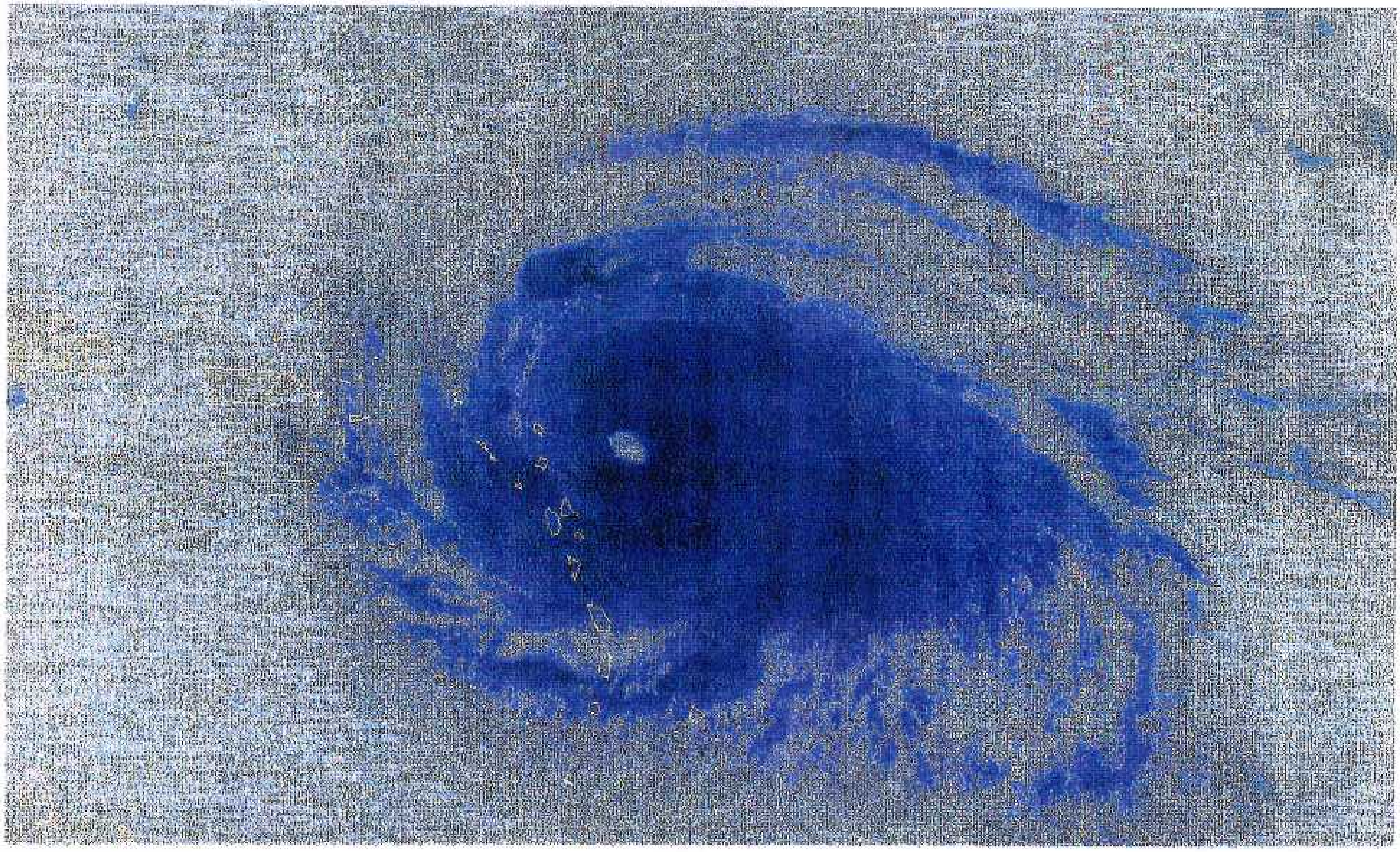

Frontispiece: As seen by satellites 35,000km above the earth, hurricanes appear as white clouds. These same clouds are seen from earth as dark and threatening. The image of Luis has thus been reproduced as a negative to represent better our experience.