Roof damage by hurricane force winds in Bermuda

The Fabian Experience, September 2003

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1. Introduction

1.1 The storm

Fabian, a category 3 hurricane, approached Bermuda from the south travelling at about 15 km/hr (10 mi/hr). Its closest point of approach to the island was about 80 km (50 miles) to the west on the evening of 5th September 2003 (see Illustration 1). Sustained winds of 190 km/hr were experienced for several hours. These began from an easterly direction in the afternoon, veering slowly through south and finishing from the west, as Fabian passed by. Gusts exceeded 210 km/hr, but maximum winds were not recorded due to equipment failure.

In terms of strength, duration and proximity, Fabian is said to have been the worst storm to affect Bermuda within the last 50 years.

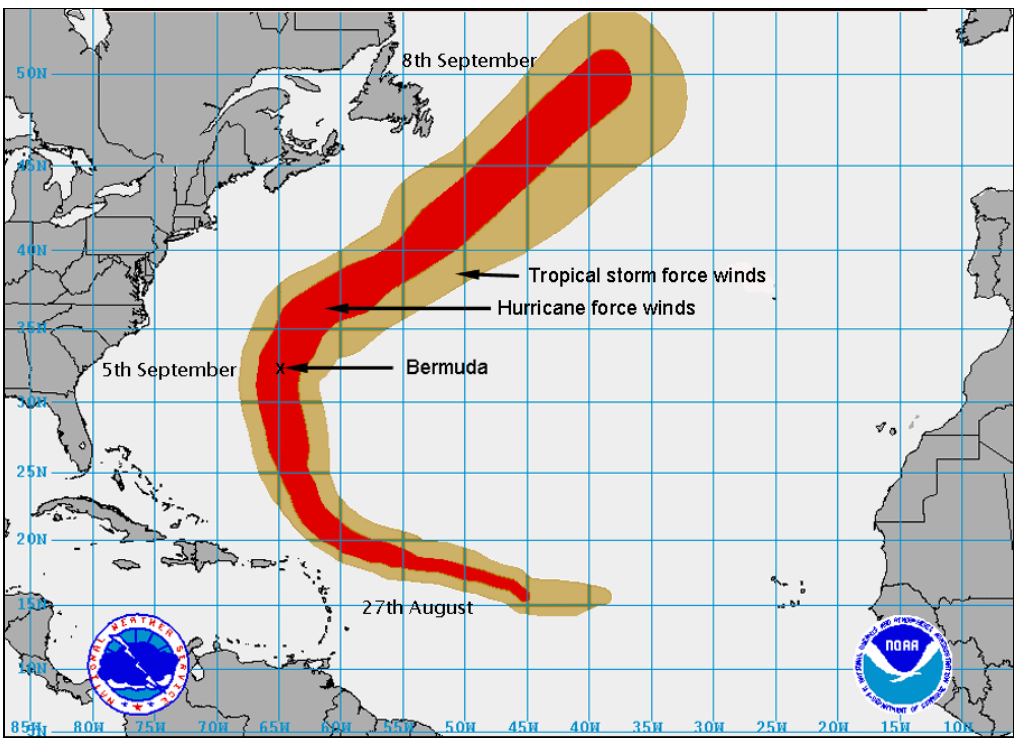

ILLUSTRATION 1. Path and wind swaths for Hurricane Fabian. Based on US National Weather Service map.

1.2 The impact

Bermuda fared well structurally, in light of the dangerous strength of Hurricane Fabian. A visiting expert on disaster recovery termed the damage as “minor”.

We congratulate ourselves on the robustness of Bermudian homes. Yet, putting aside comparisons with damage caused by hurricanes in other parts of the world, in absolute terms the cost and hardship caused by the partial loss of roofs during Fabian has been high.

Fabian demonstrated that roof loss is not necessarily a freak event limited to a swathe of real estate cut through by tornadoes. Roof loss has been an island-wide experience, suffered by many (see Figures/Photos 1 and 2).

The opportunity has been provided by Fabian to discuss roof vulnerability in terms of actual observed damage instead of speculation. It enables theories and models of wind impact on Bermuda roofs to be verified against irrefutable observations.

The outcome of investigations, initiated in this report, might be modifications to the Bermuda Building Code, which could be implemented with minimal delay. There may also be findings that establish fundamental weaknesses in roof construction, which can be corrected by retrofitting existing roofs.

2. Factors that affect roof damage

Many aspects of roof damage, in Bermuda, could be better understood. The large number of roofs damaged by Fabian means that any survey of the nature of the damage will, statistically, be very meaningful. It follows that conclusions can be reached on the factors that determine the occurrence of this damage, namely:

2.1 Construction - This covers:

- the type, weight, strength and age of materials and the manner in which they are fastened together to resist aerodynamic forces. There is an obvious necessity for a well-engineered attachment of the various components of the roof to each other and to the walls. Age is an important factor because the passage of time allows the advance of chemical and biological processes which weaken materials. Age also determines the building practices and types of materials used. Deterioration may have been accelerated in critical structural components of the roof where rot and rust resistant materials were not used.

2.2 Aerodynamics - This covers:

- the geometry of the structure, which influences the speed and deflection of airflow across and around it.

- the compartmentalization of spaces within the structure and their connectivity with each other and the outside (see Illustration 5). This may determine the tendency for damaging pressure differences to build up, or may not be that relevant (see later).

- The topography, which not only determines the exposure of structures to wind, but in itself can deflect wind and magnify both low and high pressure aerodynamic forces which act on roofs.

- The <u>nature of the wind</u>. During a hurricane, winds can persist for long periods and gusts can reach up to 50% higher than the sustained velocity. In addition, the slow and steady change in average direction allows the wind to “dial in” to the angle of attack at which a given roof is most vulnerable.

3. Aerodynamic considerations for roofs

3.1 Geometry

<u>Lift</u> created by an accelerated flow of air, as it is deflected up-and-over the roof of a house, (just as air flows over a wing) is recognized as the main force that must be contended with. Roofs pitched at a low angle of about 15 degrees create a flow that produces the maximum lift or suction (see Illustrations 2 and 4). High-pitched roofs, on the other hand, act as barriers and create turbulence or “stalling”. The result is downward loading, which rarely causes damage (see Illustration 3).

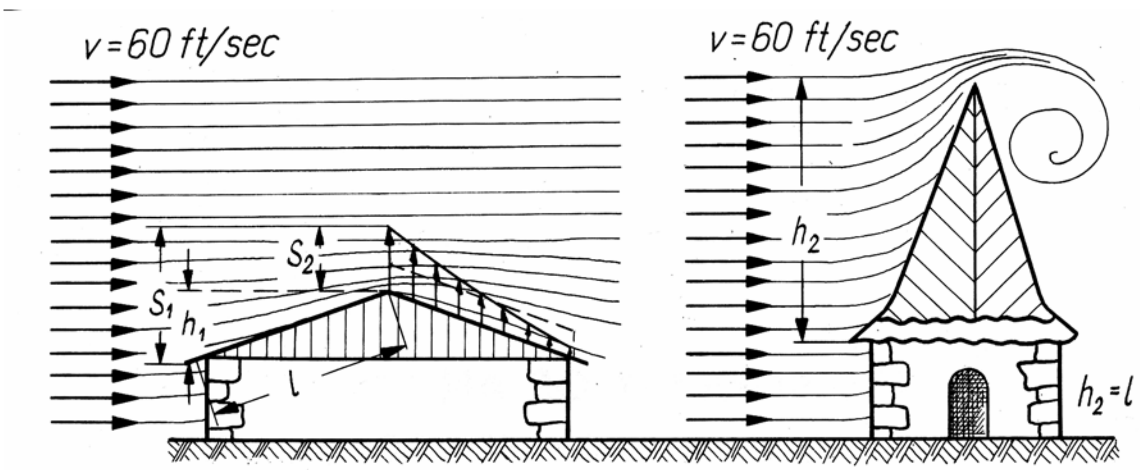

ILLUSTRATION 2. To quote, aerodynamicist, C.A. Marchaj referring to the above diagram “Common sense would say that the steep, high roof is the more likely to be damaged, but in reality, it is usually the low pitched roof which gets lifted off by the wind.”

After the passage of a hurricane over Hawaii it was noted, from aerial video tapes, that all the steep roofed houses remained intact; whereas many with low pitched roofs were extensively damaged. This is confirmed in physical scale modeling, where the addition of a vertical fin, “spoiler”, to the crest of a low pitch roof is capable of substantially reducing the damaging effect of lift by simulating the airflow conditions of a steeper roof.

At a critical roof slope (or pitch), eaves and overhangs can be exposed to exceptional forces. A suction-producing vortex (rotating airflow) can develop above the eave while a pressure-producing vortex can be generated by air trapped against the windward wall and under the eave (see Illustration 4 and 5). The abrupt transitions between adjacent surfaces also contribute to stress concentrations resulting from turbulence and wind shedding.

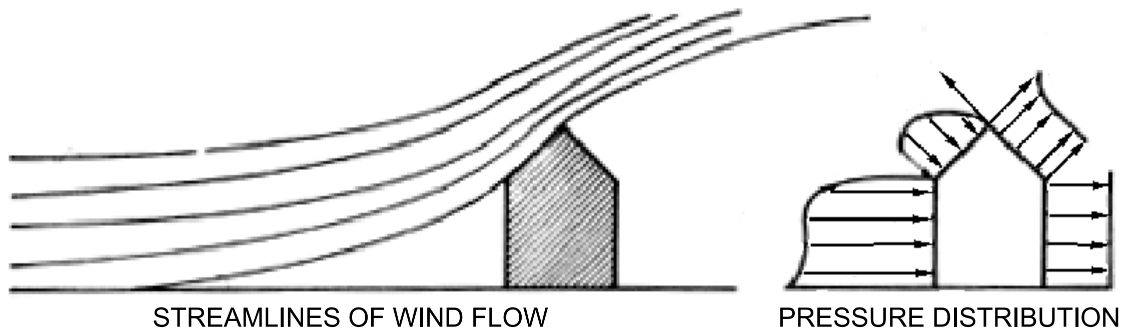

ILLUSTRATION 3*. The high angle of deflected air flow over a steep roof causes downward pressure or loading (indicated by downward arrows) on the windward side of the roof which does not result in damage.

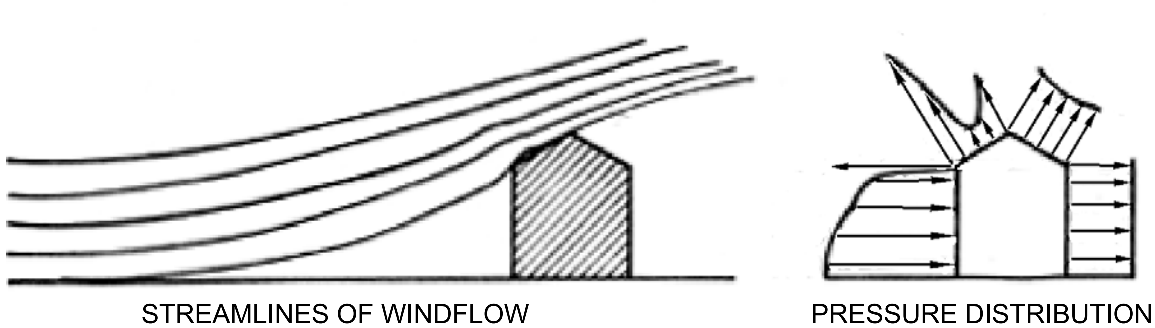

ILLUSTRATION 4*. As the pitch of the roof is reduced a critical angle is reached at which pressure changes to suction (indicated by upward arrows) The nature of deflected air flow at the edge (the eave) can create a zone of maximum suction here, almost twice as powerful as anywhere else on the roof (indicated by the length of the upward arrows).

* After Jensen and Franck, 1965.

3.2 Pressure differences

Lift is created as a result of a pressure difference between the topside and the underside of the roof. The space immediately beneath the roof slate is where potentially damaging, high pressure - relative to that in the fast moving deflected air above the roof – can exist. The net result is then an increased upward force, or lift, on the roof.

Most Bermudian houses are divided vertically into two compartments, separated by a plastered ceiling (See Illustrations 5). Pressure in the lower compartment – the living space - does not act against the roof when the plastered ceiling is effectively airtight. The question arises, therefore, “Does the Bermudian tradition of opening the leeward windows of the house during a storm, have any impact on the pressures acting on the roof?” The practice may be better justified if access hatches to the “attic” space are left open, permitting a degree of pressure equalization.

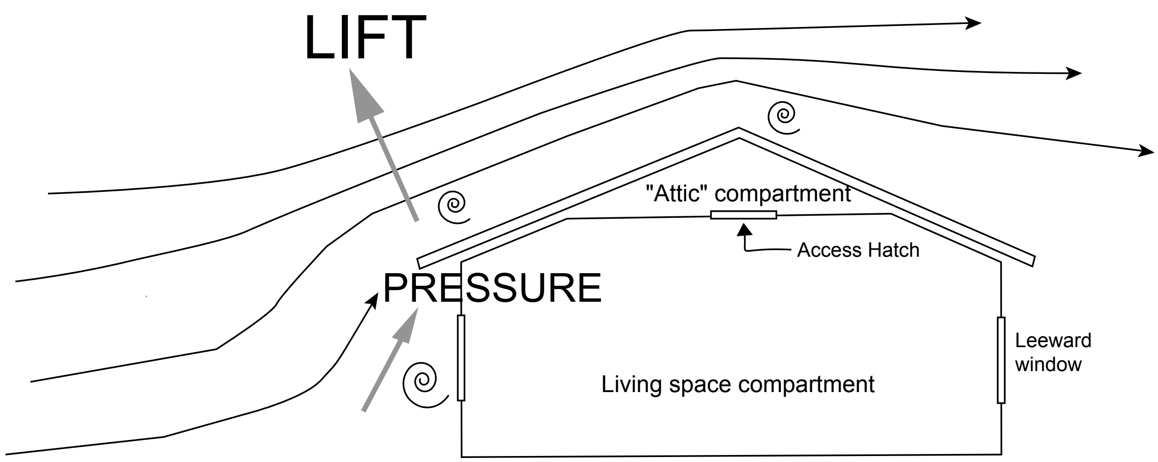

ILLUSTRATION 5. Compartmentalization of a typical Bermudian house. A plaster or drywall ceiling separates the living space from the “attic”.

In Bermudian houses, the gap between the roof and the wall plate is in some cases closed between the rafter feet, and in others open (often in older houses). In other words the “fill slate”, or equivalent barrier, shown beneath the eaves in Illustration 6, may be absent. This, obviously, greatly affects the connection between the “attic” and the outside atmosphere. However, both the sealed and unsealed types failed during Fabian (Figures 5, 6 and Appendix IV) and many of each type survived.

It should be noted that a wing has no enclosed space below it and yet enormous lift is efficiently generated. Also it is not uncommon for tiles or other roof covering to be peeled off roof sheathing, which remains intact. This supports the concept of a “top-down” effect. The relevance of internal pressures within the house (beneath the roof) might therefore be questionable for the types of damage experienced in Bermuda.

4. Observed damage in the aftermath of Fabian

4.1 Leading-edge damage

Leading-edge roof damage, resulting from Fabian, was prevalent. This is where a relatively narrow strip of slate was removed along the windward edge of a roof (Figure 2, 3, 7, 8 and Appendix I). Interestingly, where this damage did occur, it was usually the only roof damage. Despite high suctions that can occur on the leeward side of the roof, damage in this area was almost absent except where it could be attributed to “blowout” (see later).

Observations on leading-edge roof damage:

- Leading-edge damage is likely to be the result of aerodynamic lift creating suction forces, which are predicted to be at a maximum at the eave (see Illustration 4), coupled with the upward pressure on roof overhangs caused by air trapped against the windward wall.

- The damage is commonly on the edge facing the known strongest winds during Fabian – from the east and south. This may be evidence that strong wind gusts were to blame rather than swarms of tornadoes, which probably would not result in such an orderly pattern of damage. This remains to be determined, however.

- The limited extent of the leading-edge damage, on a given roof, may result from there being a structural/design flaw, an "Achilles Heel", which makes the roof edges particularly susceptible to damage (see Illustration 6). On the positive side, the heavy, tiled construction using brittle materials may be responsible for limiting the spread of damage further up the roof.

- Statistics on the types of roofs that suffered from leading-edge failure have yet to be gathered. Of great interest would be the number of these, if any, which were built in compliance with the latest building code (see Illustration 6). This information is being sought and, if available, will be compiled to be included in a subsequent report.

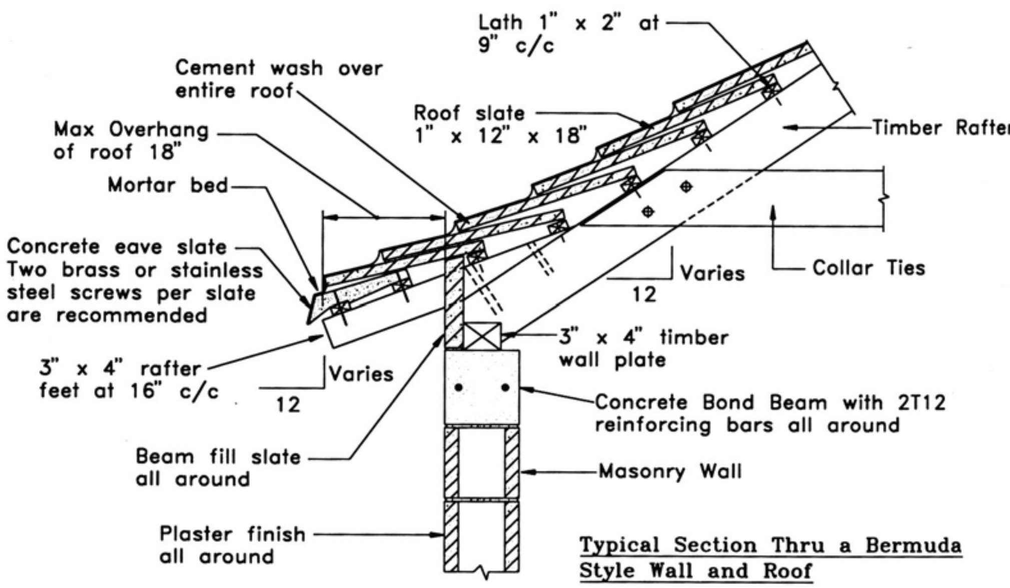

ILLUSTRATION 6. Traditional Bermuda roof. (from the Bermuda Building Code, 1998). See Appendix VIII for photograph of actual roof.

4.2 Other damage

Several variations of roof damage did occur. In a number of cases, there was the removal of slate at, or near, the roof crest while the edges remained intact (see Figures 9 and Appendix V). This seems, often, to have occurred on roofs with gable-ends which faced into the strongest winds. In other instances, where entry of the wind into the structure was possible, pressurization or "blowout" probably contributed to the damage. Verandahs and bus shelters were particularly vulnerable where they suffered from, both, the leading-edge effect and from wind entry (see Figures 10, 11, 12 and Appendix II).

4.3 Topographic effects

Observations clearly demonstrate the importance of topography. Structures protected by hills to their east and south, remained largely unscathed, while up to 80% of houses on certain south facing hillsides suffered damage (Figures 1 and 2). This could be explained simply by the level of exposure of these houses to strong sustained winds and very powerful gusts. However, the upward deflection of wind meeting a hillside may be an important factor. It reduces the angle of attack of the wind on a sloping roof, which has the same effect as reducing the roof pitch. As mentioned earlier, maximum suctions are known to occur where the effective pitch (the angle at which the wind meets the roof surface) is about 15 degrees.

5. Conclusions and recommendations

Leading-edge damage to roofs was widely suffered as a result of high winds during Fabian. First and foremost, this can be understood, in terms of the concentration of aerodynamic lift, or suction, combined with wind pressure, which under the right conditions will target this area of a roof. Second, there may be issues with the design and construction of Bermuda roofs pertaining in particular to the eaves. The Building Code requirements in this area should be reviewed following the gathering of more data and completion of recommended research. The design of concrete eve slates and their fastenings must be sufficient to protect this area from extreme wind-gust forces and to form a solid basis for anchoring the vulnerable "leading-edge".

Damage descriptions should be compiled including the types of roofs, methods of construction, condition/age of materials, details of the failure and photographs. (see "consultation", below).

Statistical studies of Fabian-related roof damage would be very useful. Post-Fabian aerial photos, which the Planning Department is seeking to acquire, could provide information on the effects of topography and orientation of damage relative to the known strongest persistent winds, primarily: east and south and to a lesser degree from the west. Evidence of tornado damage may or may not be apparent.

Wind tunnel tests on scale models, mathematical modeling or wind load calculations could be applied to examine the aerodynamic and structural causes of the types of damage observed. Modeling could replicate the construction of a Bermudian house, so that the effects of the interconnection of the interior compartments with one another, and with the exterior, could be assessed.

Consultation. This report is a discussion paper based on the facts currently available to the author. Engineers, architects, surveyors, building contractors and others are welcome to make submissions based on their expertise and observations, in person or in writing to:
Mark Rowe, Department of Environmental Protection, P.O. Box HM 834, Hamilton HMCX, email: mrowe@gov.bm; Telephone 236 4201 extension 274; Fax: 236 7582.

Footnote on temporary fabric roof coverings:

It has been obvious that there is much left to be desired in the temporary coverings that have been applied to damaged roofs (see Appendix VII). Strong winds and rain since Fabian have played havoc with the majority of these coverings resulting in serious ongoing damage to interiors.

We have learnt:

- *Rope is useful for initial positioning but is ineffective on its own.*
- *Quarter inch plywood slid up under the edge of the damaged slate and nailed to the rafters is more effective than a tarpaulin.*
- *Sand bags can be very useful, and certainly less dangerous than pieces of broken slate, for weighing down tarpaulin edges.*
- *Strong adhesive sealant has been used successfully to hold the edge of a tarpaulin to the roof surface.*
- *Wooden battens nailed to exposed rafters are effective in pinning down tarpaulins.*
- *The useful lifespan of a typical blue tarpaulin on a roof can be measured in weeks not months as may be required.*

Untold hardships have been imposed on households since Fabian due to rain water penetration through deteriorating temporary roof coverings. These unfortunate circumstances were, in fact, much more avoidable than the initial damage.

As a result of what we have learnt, the community could be much better prepared for the aftermath of future similar windstorm emergencies.

Mark Rowe, Department of Environmental Protection.
October, 2003

Ackowledgements

I am grateful to C.L. Rowe, Professional Engineer, for reviewing this report at various stages of completion.

References

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Jensen, M and N. Franck. Model-Scale Tests in Turbulent Wind. Part II, Phenomena Dependent on the velocity Pressure; Wind Loads on Building. The Danish Press, Copenhagen, 1965.

Marchaj, C.A. Sailing Theory and Practice. Granada Publishing. 1964. 450p

PHOTOGRAPHS

Note about the photographs:

The compass direction referred to in brackets in the captions does not refer to the position of the photographer. It indicates the direction that the damaged part of the roof is facing, e.g. “south facing”. This is usually the same direction as the wind that caused the damage.

Figure 1. Widespread roof damage on south facing, Loyal Hill, Devonshire.

Figure 2. Widespread "leading-edge" roof damage on south facing Mullet Bay Road, St George's.

Figure 3. Typical leading-edge damage. Berry Hill Road, Devonshire (south facing).

Figure 4. Less typical, extensive slate loss on windward side. St George's Club (south facing).

Figure 5. Historic house in St George's with exposed rafters (east and south facing).

Figure 6. Newly built house on Knapton Hill with enclosed rafters (west facing).

Figure 7. Leading-edge, "peel back", Swing Bridge St George's (south facing).

Figure 8. Leading-edge damage, Sayle Road, Smith's Parish (south facing).

Figure 9. Roof crest damage, Wellington Lane St George's (west facing).

Figure 10. Rare leeward side damage. Due to pressurization within open structure. (north facing).

Figure 11. Verandah damage, Khyber Pass, St George's (south facing).

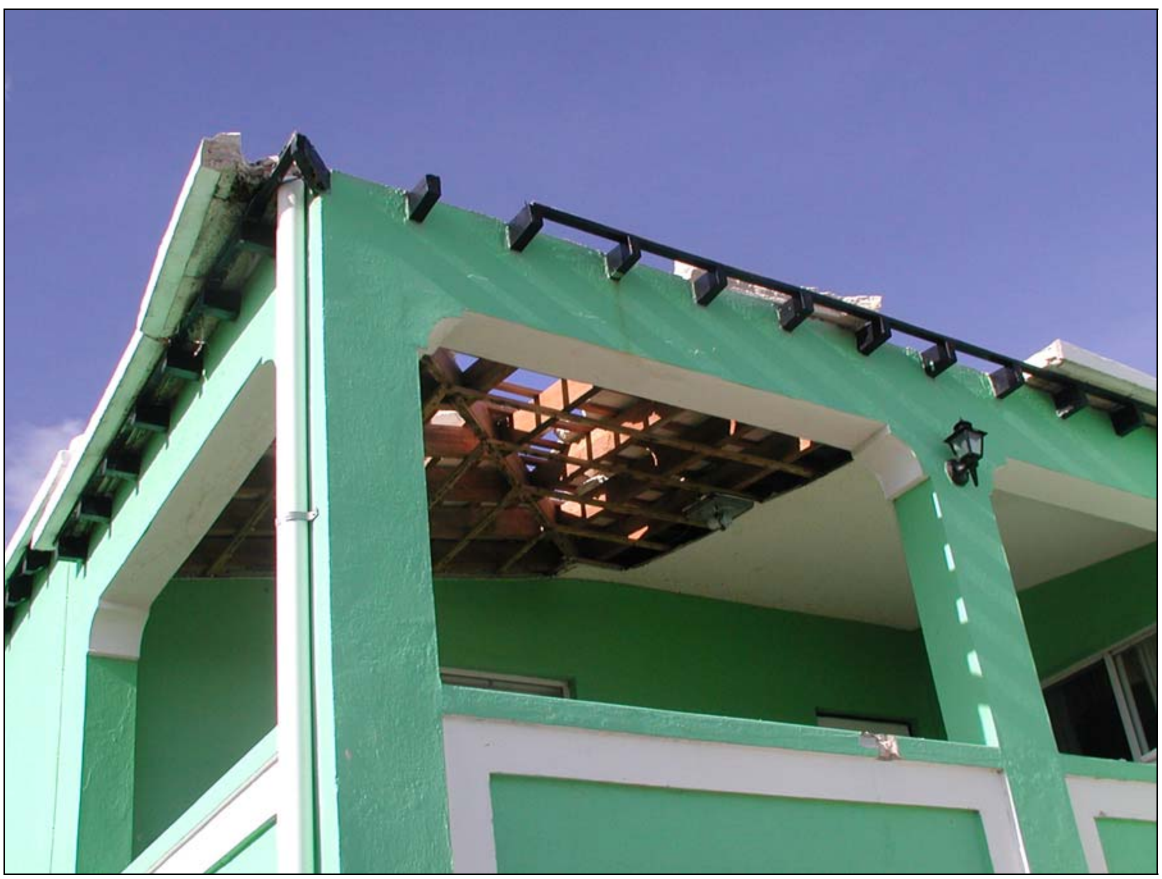

Figure 12. Verandah damage, Knapton Hill, Smith's Parish (south facing).

APPENDIX I

Photographs showing damage on the leading, windward, edge of the roof, as was experienced by the vast majority of houses, which suffered roof damage.

Figure 13. Berry Hill Road (south facing).

Figure 14. Aunt Peggy's Lane (east facing).

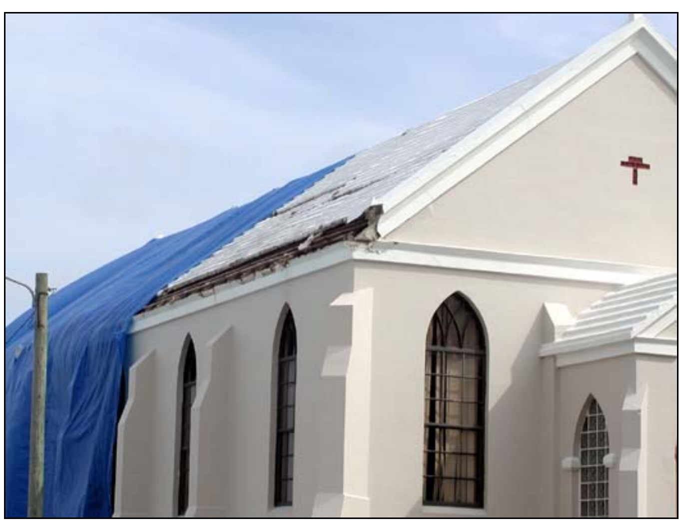

Figure 15. Harrington Sound Road (west facing).

Figure 16. Belmont Property, Warwick (west facing).

Figure 17. Skyline Drive, Smith's Parish (east facing).

Figure 18. Cavendish Road, Pembroke (south facing).

Figure 19. St Paul's Church, Paget (south facing).

APPENDIX II

Photographs showing damage to structures with large openings on the windward side. These were exposed to pressure from trapped air below as well as suction by deflected air above.

Figure 20. Bailey's Bay (south facing).

Figure 21. Middle Road, Paget (south facing).

Figure 22. Dunscombe Road (south facing).

Figure 23. Camden, Devonshire (south facing).

Figure 24. Mariner's Lane, Pembroke (east facing).

APPENDIX III

Older buildings in exposed locations were particularly vulnerable. Note in Figure 25 that the verandah has been completely removed.

Figure 25. York Street, St George's (south facing).

Figure 26. Arcadia, Barrack Street, St George's (south facing).

Figure 27. Barber's Alley, St George's (south facing).

Figure 28. St George's Preparatory School (south and west facing).

APPENDIX IV

Photographs showing that buildings with decorative corner moldings, which enclose the rafter feet, were not immune to damage.

Figure 29. The Laurels, (southeast facing)

Figure 30. York Street, St George's (east facing).

Figure 31. Victoria Street, Hamilton (southeast facing).

Figure 32. Saltus School (south facing).

APPENDIX V

Photographs showing damage to roofs where the edges remained intact. This type of damage seemed more common in roofs with gable ends, which faced into the strongest winds. (See also Figure 9).

Figure 33. Winton Hill, Hamilton Parish. (west facing).

Figure 34. Knapton Hill, Smith's Parish (west facing).

APPENDIX VI

Photographs showing extensive damage to buildings with gable ends (south facing) and sheeted roofs (plywood or cement board).

Figure 35. SeaCadets building, St George's.

Figure 36. Marine & Ports, Hamilton.

APPENDIX VII

Photographs showing the inadequacy of many, temporary fabric roof coverings. Note that figures 39 and 40 were taken 2 months after Fabian hit. (Also see Figures 17 and 25).

Figure 41, 42, 43 and 44 show, respectively, the effective use battens, sand bags, plywood and adhesive for securing temporary fabric roof coverings.

Figure 37. Winton Hill, Hamilton Parish (south facing).

Figure 38. St George's Club (south facing).

Figure 39. Seagull Lane - November 2003 (southeast facing) .

Figure 40. Cavendish Road - November 2003 (south facing).

Figure 41. Printers Alley, St George's.

Figure 42. Somers Supermarket, St George's.

Figure 43. St George's Club (east facing).

Figure 44. Church Lane, St Georges' (south facing).

APPENDIX VIII

Drawing and photograph showing the construction of a traditional Bermuda slate roof.

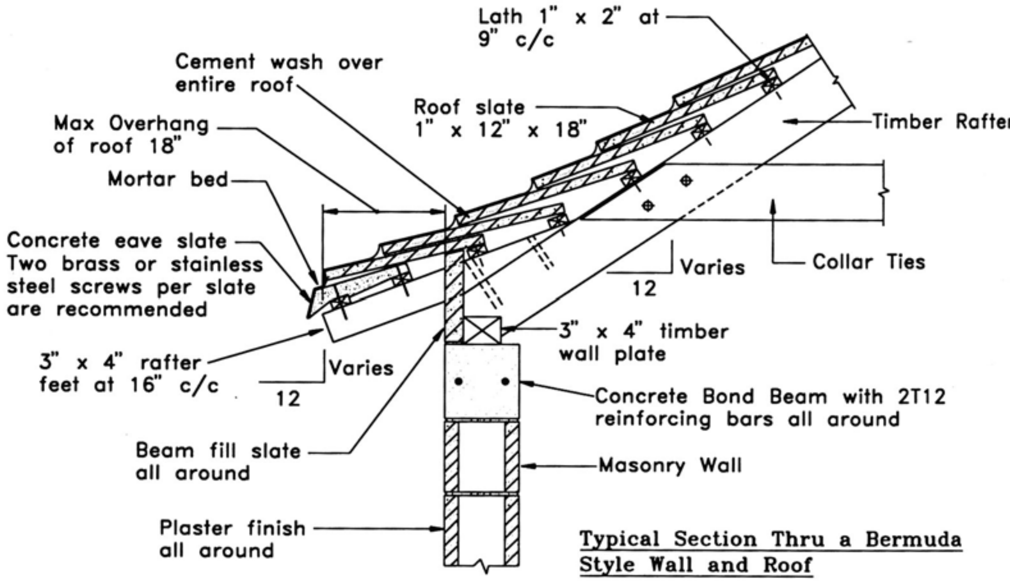

Figure 45. Damage reveals construction details of a traditional limestone slate Bermuda Roof.