4 Structural Performance

The BPAT inspected the structural performance of three primary construction types: reinforced concrete, reinforced masonry, and wood-frame. Inspections focused on the performance of single-family buildings. Isolated examples of success and failure in commercial buildings observed during field investigations were also documented.

It is important to state that wind speeds experienced on the island were not of the strength to test the reliability and adequacy of the reinforcing steel used in all of the reinforced and partially reinforced masonry walls. A more significant wind event striking Puerto Rico would likely have resulted in even more failures than were observed.

Planning Regulation 7 of Puerto Rico (building code) required strict practices for different primary construction types Guidelines that were in place under Planning Regulation 7 for new construction accounted, at least partially, for wind and seismic loads, but these guidelines had not been consistently complied with or enforced effectively. Most of the damage the BPAT observed was directly related to design inadequacies and the lack of enforcement of Planning Regulation 7. Additional damage observed was related to poor quality of workmanship of self-built homes.

The 1987 amendment of Planning Regulation 7, which was in place at the time Hurricane Georges struck Puerto Rico, included wind speed design requirements to 110 mph (fastest-mile) for all buildings and design wind pressures for walls of 30 lbs. per square foot (psf) and for roofs up to 60 psf for residential buildings. Seismic provisions for commercial buildings and one- and two-family homes were also clearly identified. The failure to comply with and enforce this building regulation in all residential building construction resulted in widespread damages from Hurricane Georges. A major seismic event on the island could cause even more damage, since most of the elevated residential structures observed—even those that performed well during the hurricane—are not seismic resistant because they were constructed with inadequate lateral force resisting systems. The adoption and strong enforcement of the 1997 UBC should address many deficiencies observed by the BPAT.

In general, concrete/masonry structures performed well under the wind loading of Hurricane Georges. Structural damage to concrete and masonry structures from floodwater was usually limited to the building foundations as a result of erosion, scouring away of supporting soil, and the impact of waterborne debris.

Wood-frame structures generally performed poorly under wind loads generated by Hurricane Georges and damage was extensive throughout the island. A continuous load path from roof system to foundation was essential for building survival. Figure 4-1 illustrates a continuous load path for a wood-framed structure. The success of concrete and masonry structures illustrated the importance of a continuous load path while the failure in wood-frame structures illustrated the lack of proper wood construction techniques to provide an adequate and continuous load path. Figures 4-2 and 4-3 compare and contrast the success and failure of concrete and wood-frame building systems with similar wind exposure.

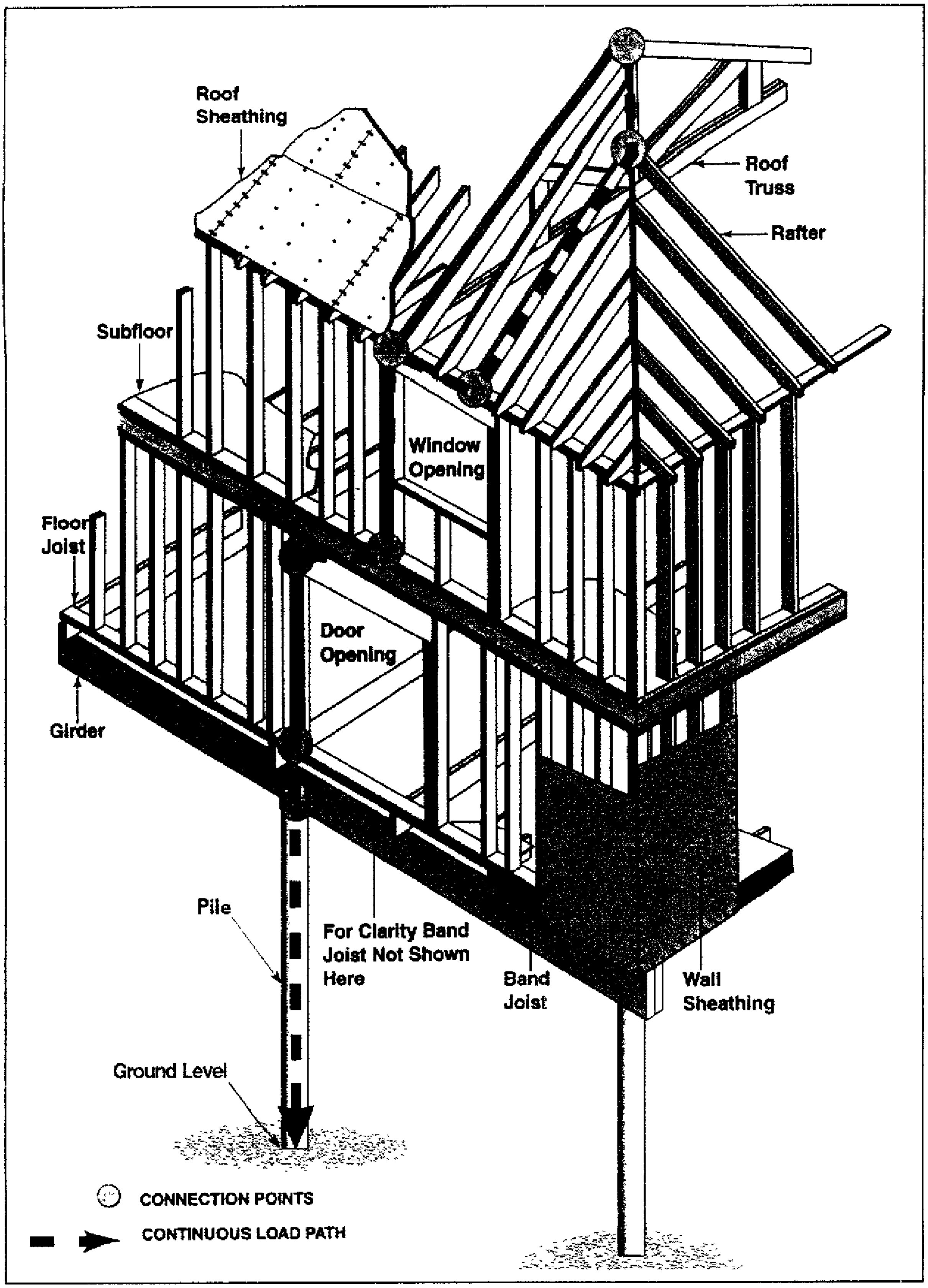

FIGURE 4-1 If a building has a continuous load path, forces and loads acting on any portion of the building will be transferred to the foundation of the building. This transfer occurs through building structural members (i.e., columns and beams) and the connections between these members. In this figure, the load path from the roof structure to the foundation is illustrated for an elevated, two-story wood-frame building.

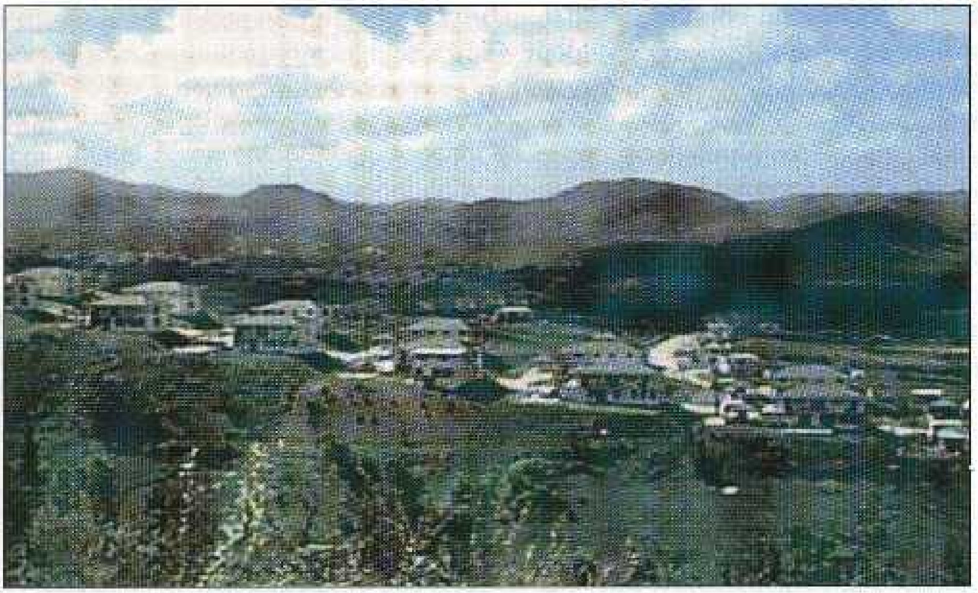

FIGURE 4-2 A residential community constructed of concrete and masonry buildings with concrete roof structures. This community, located to the west of Luquillo experienced no complete building failures. The eye of the hurricane passed to the south of this community, placing it in the strongest wind quadrant of the hurricane.

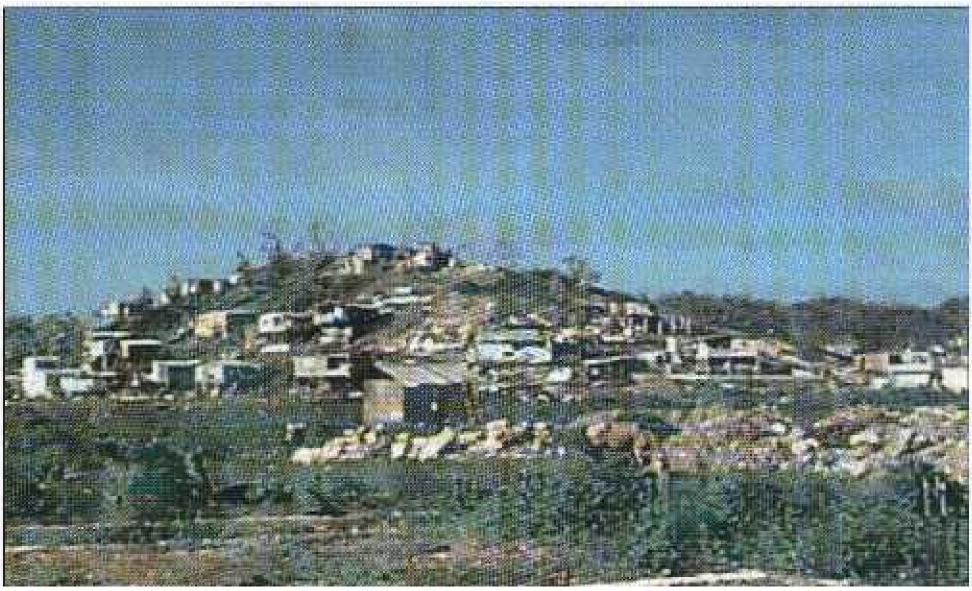

FIGURE 4-3 A residential community constructed of wood-frame structures only. This community located to the north of Canóvanas, experienced significant structural damage and failure to almost all of its buildings. The eye of the hurricane also passed to the south of this community, which is located approximately the same distance from the path of the hurricane as the community in Figure 4-2.

Residential reinforced concrete/masonry structures with concrete roof decks performed well regardless of wind direction or velocity. Concrete/masonry structures with wood wall and roof framing generally performed poorly, regardless of siting. High velocity flood waters caused structural damage in SFHAs. Lower velocity floodwaters (also in SFHAs) inundated houses, causing considerable damage inside the buildings. Several concrete and masonry structures were left unstable from riverine and coastal erosion and mountain landslides (Figure 4-4).

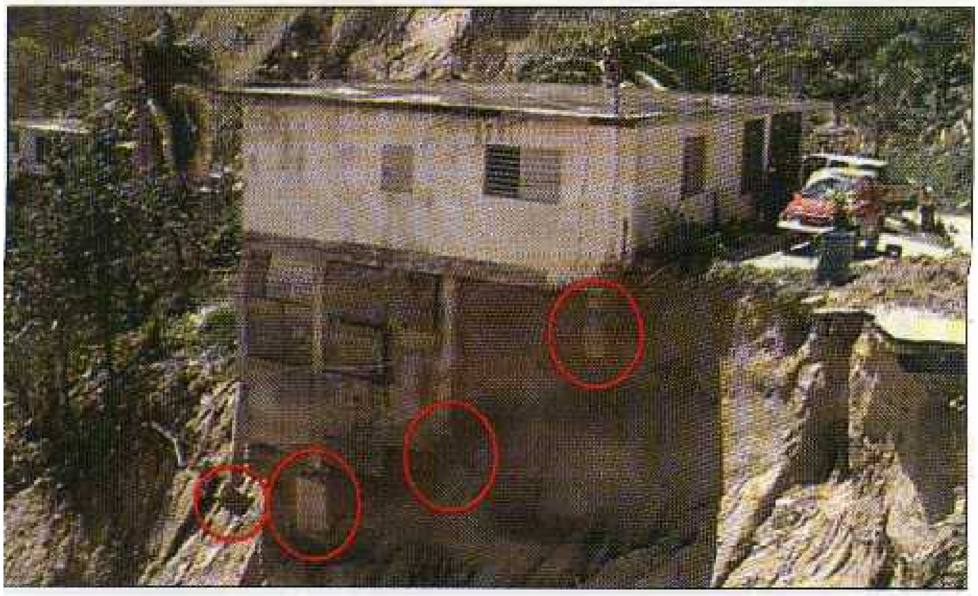

FIGURE 4-4 Concrete residential structure with foundation damage caused by a landslide. Note unstable footings (circled).

4.1 Reinforced Concrete

The BPAT observed no structural damage to reinforced concrete residential or mid- and high-rise buildings. It was obvious that mid- and high-rise buildings received considerable attention from design professionals. Where concrete frames were observed, infill walls ranged from fully glazed to CMU (typically 6-in standard block) to metal and wood stud walls. Exterior cladding was stucco (trowel-applied cement plaster typically [illegible]-in thick), Exterior Insulating Finishing Systems (EIFS), and block, brick, or stone veneer. These wall and cladding systems exhibited varying degrees of success or failure, as discussed in Section 5.2.

4.1.1 Reinforced Concrete Mid- and High-Rise Buildings

The lack of structural damage to reinforced concrete mid- and high-rise buildings was probably related to the role of the design professional in their construction as well as the fact that Hurricane Georges was not a design event. However, several buildings received considerable damage to the building envelope and are discussed in Section 5. The BPAT did not determine the seismic resistance of the mid- and high-rise buildings it observed.

4.1.2 Reinforced Concrete Essential Facilities

The BPAT inspected two fire stations, one in Adjuntas and the other on the island of Culebra, located approximately 20 miles east of the main island. Both fire stations had concrete roof decks. The stucco finish on both buildings prevented a direct observation of the wall systems that reportedly consisted of concrete columns with CMU infill. These structures also had open security grilles in the truck bays rather than large rolling doors. Neither station sustained structural damage during the hurricane. The Adjuntas fire station, which completed construction in 1998, featured a small percentage of exterior windows and an emergency electrical generator that was protected and enclosed within the building envelope (Figure 4-5). The BPAT was unable to determine the seismic resistance of either fire station.

FIGURE 4-5 Fire station in Adjuntas.

4.1.3 Concrete/Masonry Structures with Concrete Roof Decks

Reinforced concrete buildings (single-family homes) with reinforced concrete roof decks generally did not sustain structural damage (Figure 4-6). First floor walls in reinforced concrete residential buildings were usually 6-in to 8-in thick and constructed of reinforced concrete columns with masonry infill, or were solid concrete walls. CMU walls had varying amounts of reinforcement within the cells. Roof decks typically were flat and constructed of reinforced concrete. Many were exposed concrete with no roof covering. This structure type performed extremely well. Even buildings with unprotected wall openings did not experience structural damage.

The most significant damage observed for this type of construction centered around building envelope issues. Buildings (specifically single-family homes) typically had 4-in aluminum jalousie louvers (Miami windows) that were vulnerable to water infiltration during high wind events and allowed development of high internal pressure. Shutter systems are discussed in more detail in Section 5.4.

Residences constructed of reinforced concrete and a wood roof structure generally did not perform well during Hurricane Georges. Buildings without shutter systems were often breached, resulting in pressurization of the building and blown-off roofs. When shutters were observed to have been properly designed and installed, the roof framing and roofing typically were inadequate for lateral and uplift pressures, even without the added pressure from internal pressurization of the building.

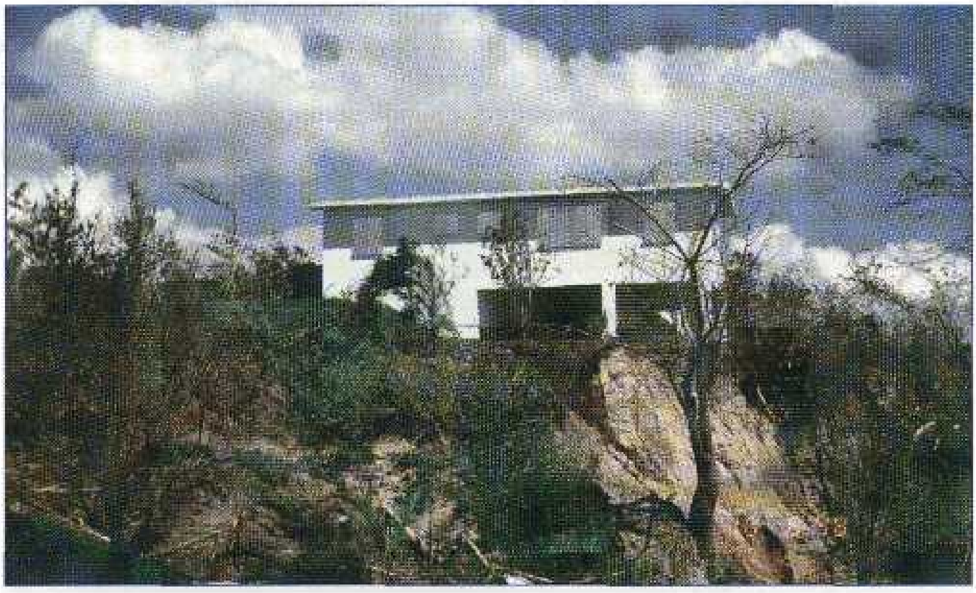

FIGURE 4-6 Residential home constructed of reinforced concrete and masonry with a reinforced concrete roof deck in the mountains outside Adjuntas.

4.2 Masonry

The BPAT investigated a limited number of residential and nonresidential masonry buildings. Most of the buildings observed had wood-frame roof structures that were damaged during the hurricane (Figure 4-7).

FIGURE 4-7 Typical roof system failure between wooden roof system and concrete or masonry wall system.

4.2.1 Masonry Commercial Buildings

The BPAT observed several commercial buildings located on the island. Although many of them weathered the storm with minimal to no damage, this was mainly due to the siting of the buildings in areas of little wind and the buildings' relatively short un-reinforced masonry walls. The BPAT concluded that the commercial masonry buildings observed did not experience design level winds. Nonresidential buildings were observed with masonry wall systems and wood-framed roofs. Some roof failures in these buildings were the result of a poor connection between the wood-roof framing and the masonry walls. Termite damage was also observed in some residential wood-frame buildings, but the problem did not appear to be widespread. Figure 4-8 shows a termite-infested roof member that failed during the hurricane. The wood purlin and metal roof covering was separated from a building constructed with masonry walls and a wood-frame roof structure (Figure 4-9). Termite-weakened wood members were likely the starting point of this roof failure. Figure 4-10 is a close-up of the typical nailed connection between the purlins and the supporting rafters.

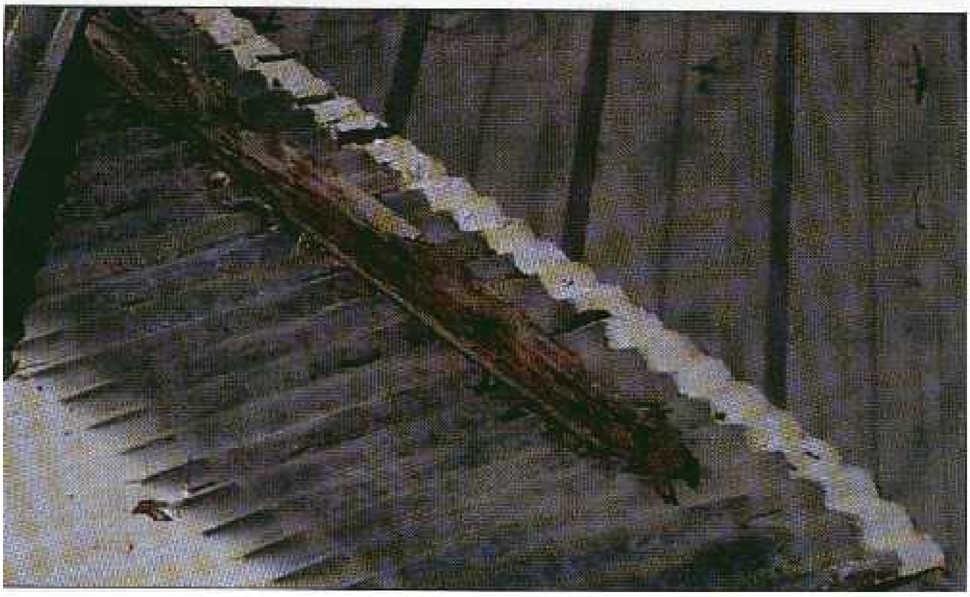

FIGURE 4-8 Termite-damaged wood purlin attached to metal roof panel. The entire roof system of this building failed and is shown in Figure 4-9.

FIGURE 4-9 Masonry wall church that lost roof purlins and its corrugated metal roof. Nails were the only connections used to resist wind loads. The gable ends of this church were unsupported except for purlins resting in the masonry.

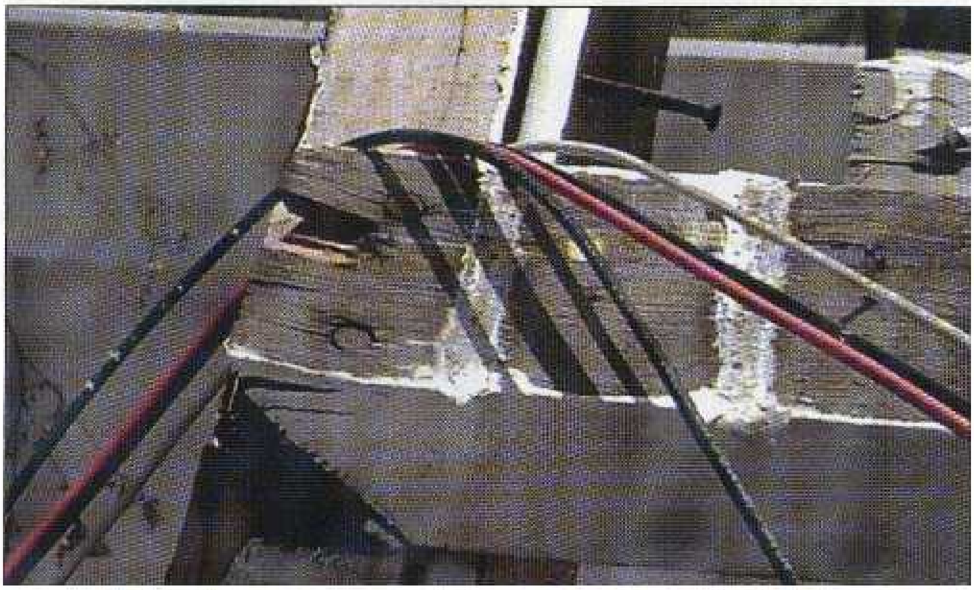

FIGURE 4-10 Nailed roof structure connection from church in Figure 4-9.

4.2.2 Residential Concrete/Masonry Structures with Wood-Frame Roof Structures

Successes and failures in masonry residential buildings were the same as those observed for concrete buildings. Success depended upon the existence of a continuous load path from the roof structure to the foundation for lateral and uplift loads. Conversely, wood-frame roof structures typically did not have a continuous load path to the foundation and widespread failure due to wind-induced uplift was observed. Figure 4-11 shows a typical nail withdrawal failure of a wood-frame roof/masonry wall connection.

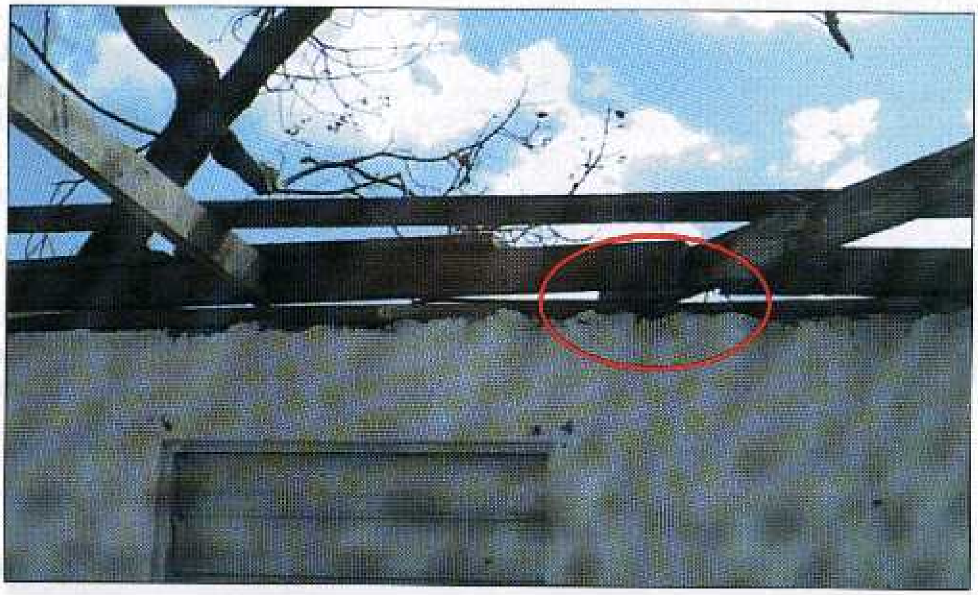

FIGURE 4-11 Typical nail withdrawal failure in a wood-frame structure supported by a masonry wall with little uplift capacity at the connection.

Rafters ranged from nominally sized lumber, 2-in by 4-in or 2-in by 6-in that spanned 10 feet to 16 feet, and were spaced from 2-feet to 4-feet on center. Rafters were typically toe-nailed to the sill plate and not connected with hurricane clips or straps. The ridge rafters bore on a ridge beam (although sometimes the ridge beam was omitted). No connection other than nailing was generally made at the ridge line. Self-built trusses were also used. Similar to rafters, these trusses were connected only by nails to the sill plate. These trusses were sometimes manufactured by nailing the truss members together by toe-nailing, or by use of nominal 1-in lumber, or plywood for gusset plates. These self-built trusses were inadequate for the wind loads. As a result, widespread wood-frame roof failures were observed (Figure 4-7).

Corrugated metal was commonly used as a roof covering, typically fastened to nominal 1-in boards or 2-in by 4-in boards used as nailers to the rafters. Nailers were generally attached with two nails (16 penny or smaller) at the rafters. The trusses were generally unbraced or minimally braced for lateral loads and had little or no shear capacity from lateral loads. The attachment of the nailers for the corrugated metal roofing was completely inadequate for the uplift loads on the roofing. Since the majority of these homes had Miami windows, considerable internal pressures also acted on the roof system.