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Hurricane Elena, Gulf Coast: August 29 - September 2, 1985

Committee on Natural Disasters, National Research Council

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Advisers to the Nation on Science, Engineering, and Medicine

NATURAL DISASTER STUDIES

Volume Two

HURRICANE ELENA, GULF COAST
AUGUST 29-SEPTEMBER 2, 1985

Prepared by:

Peter Sparks (Team Leader),
Department of Civil Engineering, Clemson University, South Carolina
Earl J. Baker,
Department of Geography, Florida State University, Tallahassee
James Belville,
Forecast Office, National Weather Service, Sterling, Virginia
Dale C. Perry,
Department of Construction Science, Texas A&M University, College Station

For:

Committee on Natural Disasters
Division of Natural Hazard Mitigation
Commission on Engineering and Technical Systems
National Research Council

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- — record time-sensitive information immediately following disasters;
- — provide guidance on how engineering and the social sciences can best be applied to the improvement of public safety;
- — recommend research needed to advance the state of the art in the area of natural disaster reduction; and
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JOHN A. DRACUP, Civil Engineering Department, University of California, Los Angeles
DANNY L. FREAD, National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland
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JOSEPH PENZIEN, Department of Civil Engineering, University of California, Berkeley
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WILLIAM J. PETAK, Institute of Safety and Systems Management, University of Southern California, Los Angeles
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METE A. SOZEN, Department of Civil Engineering, University of Illinois, Urbana

RANDALL G. UPDIKE, Office of Earthquakes, Volcanoes, and Engineering, U.S. Geological Survey, Reston, Virginia

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FRED COLE, Office of U.S. Foreign Disaster Assistance, Agency for International Development, U.S. Department of State, Washington, D.C.

ROBERT D. GALE (deceased), U.S. Department of Agriculture, Forest Service, Washington, D.C.

EDWARD M. GROSS, Chief, Constituent Affairs and Industrial Meteorology Staff, National Weather Service, Silver Spring, Maryland

RICHARD J. HEUWINKEL, Senior Policy Analyst, Office of Policy and Planning, National Oceanic and Atmospheric Administration, Washington, D.C.

WILLIAM HOOKE, National Oceanic and Atmospheric Administration, Washington, D.C.

PAUL KRUMPE, Office of U.S. Foreign Disaster Assistance, Agency for International Development, U.S. Department of State, Washington, D.C.

J. E. SABADELL, Program Director, Division of Biological and Critical Systems, National Science Foundation, Washington, D.C.

ALAN SWAN, Office of U.S. Foreign Disaster Assistance, Agency for International Development, U.S. Department of State, Washington, D.C.

GERALD F. WIECZOREK, Office of Earthquakes, Volcanoes, and Engineering, U.S. Geological Survey, Reston, Virginia

ARTHUR J. ZEIZEL, Office of Natural and Technological Hazards Programs, State and Local Programs and Support, Federal Emergency Management Agency, Washington, D.C.

LAWRENCE W. ZENSINGER (alternate), Chief, Office of Disaster Assistance Programs, State and Local Programs and Support, Federal Emergency Management Agency, Washington, D.C.

Acknowledgments

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MIKE CARTER, Hazards Management Group, Inc., Washington, D.C.

NICK COLLINS, Florida Division of Emergency Management

GERALD C. CORCORAN, Gulf Coast Research Laboratory, Biloxi, Mississippi

GUY DAINES, Pinellas County Emergency Management, Florida

EMERY DAVIS, Building Official, City of Gulfport, Mississippi

Col. C. HILTON DUNN, JR., U.S. Army Corps of Engineers, Mobile, Alabama

CHARLES K. ELEUTERIUS, Gulf Coast Research Laboratory, Ocean Springs, Mississippi

JIM GENESSEE, Mississippi Emergency Management Agency

MARTINO GEORGEN, SR., Building Official, City of Biloxi, Mississippi

Lt. D. H. GRIFFIN, Naval Construction Battalion Center, Gulfport, Mississippi

WADE GUICE, Harrison County Emergency Management, Mississippi

MICHAEL HESSIG, Former Graduate Student, Clemson University, South Carolina

JOHN HOLMES, Meteorology Department, NSTL, Bay St. Louis, Mississippi

KENNETH LELAND, Former Graduate Student, Clemson University, South Carolina

RICHARD D. MARSHALL, National Institute of Standards and Technology, Gaithersburg, Maryland

DOUGLAS MASSENGALE, SR., Building Inspector, Mobile County, Alabama

JOHN MURDEN, Former Graduate Student, Clemson University, South Carolina
JAMES PIERCE, SR., Chief Building Inspector, Mobile County, Alabama
ROBERT PROFITT, Resident, Pascagoula, Mississippi
WILLIAM W. SCHROEDER, University of Alabama, Dauphin Island
GEORGE STRAUGHN, Baldwin County Emergency Management, Alabama
HANK TURK, Jackson County Emergency Management, Mississippi
ROSE YOUNG, Mobile County Emergency Management, Alabama

Preface

Hurricane Elena posed special problems for an unusually large section of the Gulf Coast well before it came ashore on September 2, 1985. Following an erratic and difficult-to-forecast course, the hurricane threatened a coastline from New Orleans, Louisiana, to Sarasota, Florida. Considerable wind damage occurred in this area to structures that were ostensibly designed to resist such extreme wind conditions.

From the beginning, the disaster survey team decided that it could best help mitigate future hurricane damage not only by compiling a catalog of hurricane structural damage and emergency response actions, but also by undertaking a more comprehensive study that carefully established the wind conditions in the storm, reviewed in depth the building control process used in the area, and conducted necessary structural and wind tunnel tests. Since similar design conditions and building control procedures exist along hurricane-prone coasts from Texas to South Carolina (with the exception of southern Florida), the conclusions drawn from such a detailed study of performance in Elena should be relevant to a very large number of buildings.

This approach went well beyond that followed in other disaster reports issued by the Committee on Natural Disasters and required considerable time and personal initiative on the part of the survey team members. It required several years to complete. In the meantime, relevant findings have been published as they have become available (for example, Sparks, 1987a and 1987b; Sparks and Saffir, 1989; Sparks and Singh, 1989). These findings have already been considered by a task committee of the American Society of Civil Engineers and have influenced the drafters of the Standard Building Code and the Uniform Building Code.

Contents

Hurricane Elena, Gulf Coast

August 29 – September 2, 1985

1

Executive Summary

METEOROLOGY

The weather system that eventually became Hurricane Elena was initially identified as a well-organized cloud pattern north of the Cape Verde Islands on August 23, 1985. The system moved westward across the tropical Atlantic Ocean at an unusually fast speed (34 mph) and continued through the Caribbean to Cuba. It intensified and was named Elena on August 28 while situated on the northern coast of Cuba.

As the storm moved north-northwest across the Gulf of Mexico, Elena strengthened rapidly and was classified a hurricane on August 29. On August 30, the storm began to decrease its forward speed dramatically. Late on August 30, while located about 200 miles southeast of the mouth of the Mississippi River, Elena made a sudden turn to the east. On August 31 through September 1, this storm moved toward the Florida coast and stalled about 50 miles offshore from Cedar Key. During the afternoon of September 1, Hurricane Elena once again turned westward, increased its forward speed to 10–15 mph, and finally moved ashore at Biloxi, Mississippi, about sunrise on Labor Day, September 2. Figure 1-1 shows the track of Elena, which struck the Mississippi coastal area as a category 3 storm. Figure 1-2 shows that such an event is not uncommon in this area.

WARNINGS AND EVACUATION

Hurricane Elena was a rare Gulf of Mexico storm in that it caused hurricane warnings to be issued along an extensive section of the Gulf Coast from Grand Island, Louisiana, to Sarasota, Florida (population in excess of 5 million). Much of the area was placed under warnings twice. Hurricane

Figure 1-1
"Best" track of Hurricane Elena, August 28-September 4, 1985.

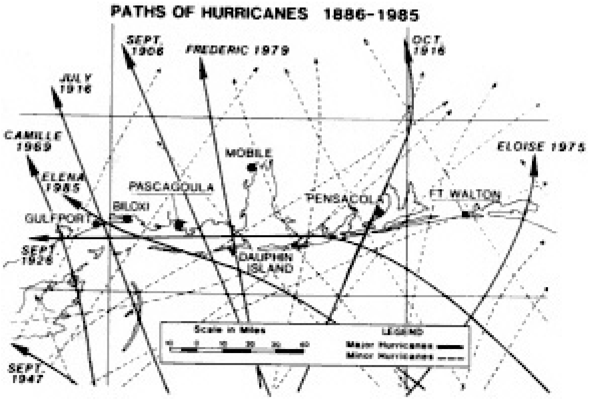

Figure 1-2
Hurricanes in the central gulf region, 1886–1985.

warnings were issued initially at 8 a.m. CDT on August 29 and discontinued at 1 p.m CAD on September 2 after being in effect for 101 consecutive hours. During this time, about 1.5 million people were evacuated to inland areas or local shelters. From southeast Louisiana through northwest Florida, people were within 4 days.

INJURIES AND DEATHS

Injuries and deaths were very low, given the size and scope of the storm. There were 4 storm-related deaths (all in Florida and all due to falling trees) and 98 injuries hospitalization. Another 36 person were hospitalized with stress-related physical problems.

DAMAGE

The insured losses from Elena were reported at $543 million by the Insurance Services Group. The total economic loss from the storm has been estimated to be in excess of $1 billion. The vast majority of the significant damage was caused by hurricane-force winds. Although storm-surge damage was evident from Tampa Bay to New Orleans, its effects were minimal compared with wind damage. From Tampa Bay to Gulf Shores, Alabama, wind damage ranged from light to moderate, with windows, power lines, and trees mostly affected. Severe wind damage occurred from east of Gulf Shores to Biloxi, Mississippi (from the coastline to 20 miles inland). Moderate to occasionally severe wind damage was noted from Gulfport to Bay St. Louis, Mississippi. Damage was light from Bay St. Louis to New Orleans. Figure 1-3 shows a wind damage map prepared by a survey team from the University of Chicago. It should be noted that the wind-speed contours on this map are based primarily on damage observations, a procedure subject to considerable error. Based on subsequent analyses of measured wind speeds, these contours appear to overestimate the maximum *gust* wind speeds by about 10 percent. The detailed analysis of wind-speed data given in Chapter 2 indicates that the wind speeds probably did not exceed the level that has a mean recurrence interval of 50 years, commonly used to design buildings and other structures.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

This report concentrates on three aspects of Hurricane Elena: (a) forecasting and collection of meteorological data, (b) evacuation procedures, and (c) the performance of buildings and other structures in the storm.

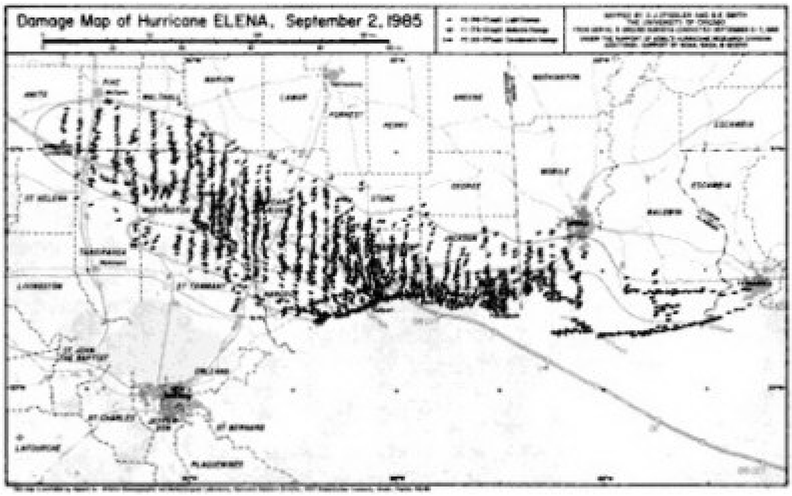

Figure 1-3
Damage map of Hurricane Elena, September 2, 1985. Source: D.J. Stiegler and B. E. Smith, University of Chicago, from aerial and ground surveys conducted September 5–7, 1985.

Need for In-Depth Study Following Postdisaster Investigation

Early in the investigation, it became apparent that unless the wind conditions could be determined with reasonable accuracy and the wind resistance of common structural systems assessed, this report would simply become a catalog of damage rather than a useful engineering analysis. Since extensive wind damage occurred to structures ostensibly designed to resist the conditions encountered in Elena, a more in-depth analysis was considered essential.

Such an analysis—which includes structural and wind-tunnel tests and a detailed study of building codes—is outside the realm of postdisaster investigations supported by the National Research Council. This ability to fund in-depth studies immediately after hurricanes or tornadoes is essential for advancing our capabilities to reduce the impacts of future disasters. Therefore, the study team recommends that adequately funded investigation teams, similar to those that investigate major air crashes, be established through funding from public agencies such as the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), or the Federal Emergency Management Agency (FEMA).

Forecasting, Warning, and Evacuation

On the positive side, considering the scale of the evacuation, the process appeared to have gone well, benefiting from earlier National Weather Service (NWS), FEMA, and local government activities in preparing evacuation plans.

The NWS appeared to communicate the threat well to the general public through the issuance of hurricane watches and warnings. Local emergency management officials also relied heavily on NWS warnings in making decisions about evacuations. It would appear that such officials could have been better informed by using NWS marine advisories and hurricane probabilities more effectively, which could have given a clearer indication of the threat.

The numerical models used by NWS for forecasting had difficulty in predicting, to an acceptable accuracy, the erratic track of Elena, although NWS believed that these models ought to have been able to do so. The NWS has since reevaluated its forecast models in light of their unsatisfactory performance during Elena.

Need for Surface Wind-Speed Measurement

During and after the storm, the determination of surface wind speeds proved a crucial, albeit controversial, undertaking. Wind speeds are important not only in forecasting storm intensity and in planning emergency response, but particularly in evaluating structural performance in areas struck by the storm. Unfortunately, the current business of gathering surface-level wind speeds is fraught with difficulties and inaccuracies. The NWS itself acknowledges that the chances of accurately measuring maximum surface wind speeds in a hurricane moving onshore are small, using existing measurement systems.

The NWS bases its forecasts on wind-speed measurements made by reconnaissance aircraft flying at altitudes of several thousand feet. Surface-level observations of sea state, limited anemometer observations, and correction factors based on well-known pressure-wind relationships are all applied in an attempt to refine these measurements and adapt them to surface-level estimates. While the resulting data may be useful for meteorological purposes and for emergency response planning, they fall far short of the accurate and detailed record of surface wind speeds that the engineering community requires.

In addition, NWS makes use of damage maps that seek to estimate wind speeds based on how much damage is observed after the event—a practice that engineers warn is approximate at best and tends to overestimate wind speeds. As a practical matter, the surface wind conditions that impinged on area structures during Elena had to be established independently after the storm by engineers using mostly non-NWS data.

For several years, users of wind-speed data, such as engineers and emergency management officials, have been concerned about this lack of accurate ground-level wind-speed data from hurricanes. Recognizing the budgetary limitations of NWS and the fact that its primary mission is to issue warnings and forecasts to help safeguard lives and property in the short term, the study team nonetheless recommends that NWS enhance its record-keeping ability so that it can document actual surface wind speeds for postevent analysis. Clearly, this is consistent with NWS's overall mandate to help the populace manage extreme weather events, since such wind data are instrumental in establishing appropriate wind engineering standards for structures located in areas at risk from hurricanes.

One way to produce the much-needed wind data would be to establish a network of portable anemometer stations along hurricane-prone coasts. In any case, the study team recommends that the use of damage observations to assess wind speeds be restricted to meteorological applications where the inaccuracies inherent in this method are tolerable. Such studies should in no case be put forward as sufficient for engineering purposes unless some scientific justification can be provided.

Structural Performance and Building Codes

While the evacuation effort was certainly successful, the engineering performance of certain classes of buildings was poor indeed. The most important group of buildings to perform poorly was schools. Nearly every school in the affected area suffered roof leakage, and many had serious damage. Two schools being used as shelters suffered considerable damage; in one of these cases it was deemed necessary to evacuate the building at the height of the storm.

It is unlikely that the design wind speed actually used by the local building code for at least 15 years prior to Elena, and implied by earlier codes, was exceeded in Elena. Even buildings possessing a very low factor of safety should not have been damaged. Yet damage was extensive in masonry-walled buildings with light roofs (particularly schools and stores), older metal buildings, and wood-framed residential structures in exposed areas.

Some of these problems may have been associated with poor enforcement of the Standard Building Code used in the area, but most were associated with the contents of the code itself. Although using an appropriate design wind speed, the code, until recently, seriously underestimated the pressures generated by the design wind conditions. In addition, allowable forms of construction in wood and masonry have insufficient wind resistance even to meet the rather deficient wind-loading requirements of earlier codes.

Since the code is designed to set performance standards used by professionals to establish appropriate structural forms, it is unenforceable when no design calculations are made, that is, in the case of most residential and small commercial structures. A design professional—architect or engineer—is usually employed when design calculations are made. In this situation a building official usually assumes that the professional has checked the wind resistance of the structure and makes no further checks.

The general public, insurers, and emergency management officials generally assume that a certificate of occupancy issued by a building official indicates compliance with the building code and an ability to resist the design conditions specified in that code. Yet it is unlikely that the wind resistance of any building in the area affected by Elena or in any similar area using the Standard Building Code would have been checked by a building official. At best, such an official may have insisted on certain structural details such as the use of hurricane anchors, which experience had suggested should be used.

It is recommended that:

- deemed-to-comply provisions be introduced into the code for nonengineered structures, as has been done for many years in the South Florida Building Code;
- some form of technical review be conducted for engineered structures;
- wood and masonry provisions inconsistent with the wind-loading provisions be removed from the code; and
- to ensure uniformity and the unbiased use of modern wind-loading principles, the provisions of American National Standards Institute (ANSI) A58.1 be used for the determination of wind and other design loads.

The building control system based on local enforcement and the use of a model code, the provisions of which are determined in a highly political manner, may have served the communities affected by Elena well in other respects, but failed them with regard to wind resistance. A federally imposed system coupled with insurance availability, such as the highly successful Federal Flood Insurance Program, might have served them better. If the present system of building control cannot be reformed, alternative schemes backed by the federal government or private insurers should be considered.

2

Meteorological Aspects

SYNOPTIC HISTORY

On August 23, 1985, a well-organized cloud pattern was first identified on satellite imagery north of the Cape Verde Islands. The unusually fast (34 mph) westward motion, combined with a dry Saharan air mass surrounding the disturbance, apparently inhibited the formation of a tropical cyclone. The rapid motion was the result of a strong high-pressure ridge building westward across the Atlantic, north of the tropical disturbance. The tropical disturbance approached Cuba on August 27. Elena was named on August 28 when the center was over Cuba and reconnaissance aircraft measured winds at 50–55 mph north of the center. It is interesting to note that the central pressure dropped 9 mb while moving over Cuba.

Elena quickly strengthened to a hurricane on August 29. A marked decrease of Elena's forward motion began the next clay as steering currents collapsed with the approach of a frontal trough from the northwest. A deep middle-atmospheric trough had reached maximum intensity west of the U.S. Pacific Coast. Zonal flow was found across the United States at middle-and upper-tropospheric levels. By 0000 GMT on August 30, ridging appeared over the Rockies with a flow from the northwest occurring over the Great Plains. At the same time a middle-and upper-tropospheric trough was forming over the Mississippi Valley. By 1200 GMT on August 30, a middle-tropospheric anticyclone pushing eastward reached the Continental Divide (Figure 2-1). The deepening trough to the east extended into lower latitudes and began to exert influence over the motion of the hurricane, previously on a smooth course toward the north-northwest. Now the motion of the storm was toward the northwest coast of the Florida Peninsula.

By 0000 GMT of August 31, the middle-level trough in the West was filling rapidly and pushing into the northern Rockies (45° to 50° N). Twenty-four hours later, at 0000 GMT September 1, the ridge at upper levels extending from Oklahoma to the Great Lakes was pushing eastward, obviously set up to cut off the southern part of the middle-level trough. A stalling of the hurricane off the west coast of Florida and eventual reversion to westward motion resulted.

Figure 2-1
A middle-trospheric anticyclone reaches the Continental Divide at 1200 GMT. August 30, 1985 (500 mb [approximately 19,000 ft]). Arrows show direction of observed winds. Source: James Belville, National Weather Service.

By 1200 GMT September 1, ridging began across the middle-level trough occupying the eastern United States between 30° and 40° N (Figure 2-2). The middle-level anticyclone was over Missouri and moving eastward. From that time on a new trough development over the west coast anchored the anticyclone over the mid-Atlantic states, steering the hurricane toward the west-northwest and then northwest around it (Figure 2-3).

Figure 2-2
Ridging begins across the eastern U.S. middle-level trough, 1200 GMT, September 1,1985 (500 mb [approximately 19,000 ft]). Source: James Belville, National Weather Service.

It should be clear from this sequence of events that the hurricane motion responded closely to the large-scale changes of flow in the mid-and upper-troposphere of midlatitudes. Indeed, the synoptic event could be concisely defined as a short-lived interaction with a midlevel trough, which caused an interruption of what otherwise was a more straightforward track (a "straight mover" track). Some literature exists describing hurricanes or typhoons of exceptional size, where the storm takes on a motion of its own in response to internal forces and where it does not appear merely to drift on the large-scale atmospheric flow. Hurricane Elena showed no signs of such behavior, presumably because of its modest dimensions. *Therefore, at least in principle, the main aspects of the motion of this hurricane should have been predictable within the present state of the art.*

Figure 2-3
A new trough development over the West Coast anchors the anticyclone over the mid-Atlantic states, September 2, 1985 (500 mb [approximately 19,000 ft]).
Source: James Belville, National Weather Service.

NEARSHORE AND LANDFALL STORM CHARACTERISTICS

Wind Speeds

An accurate assessment of the wind speeds is needed to determine whether or not the design wind conditions for buildings and other structures have been exceeded. Unfortunately, in many hurricanes few, if any, reliable anrecords emometer are available, and forecast wind speeds or those based on damage observations—often exaggerated—eventually become part of the record of the storm. In the past this has led to highly erroneous conclusions regarding the performance of structures.

In this storm a number of anemometer records were available. Unfortunately, none of the records in the critical areas was complete, due to anemometer damage or power failure. Nevertheless, R. D. Marshall at the National Institute of Standards and Technology (formerly the National Bureau of standards) was able to reduce the data to the standard meteorological conditions used as a basis for structural design, that is, as "fastest-mile" wind speeds at 33 ft in open country (Marshall, 1985). (For a complete discussion of the method used for data reduction to standard meteorological conditions, see Marshall, 1984.)

The locations of the anemometer stations used are shown in Figure 2-4 together with the adjusted wind speeds. Table 2-1 gives details of the data used and compares the adjusted fastest-mile wind speeds with those currently used for design in the area. It should be noted that in no case did the adjusted wind speed exceed the basic design wind speed. However, the adjusted wind speeds were based on rather meager data and could be subject to some error. Nevertheless, it seems reasonable to conclude that, at worst, the conditions were within 10 percent of the design conditions and in most instances were

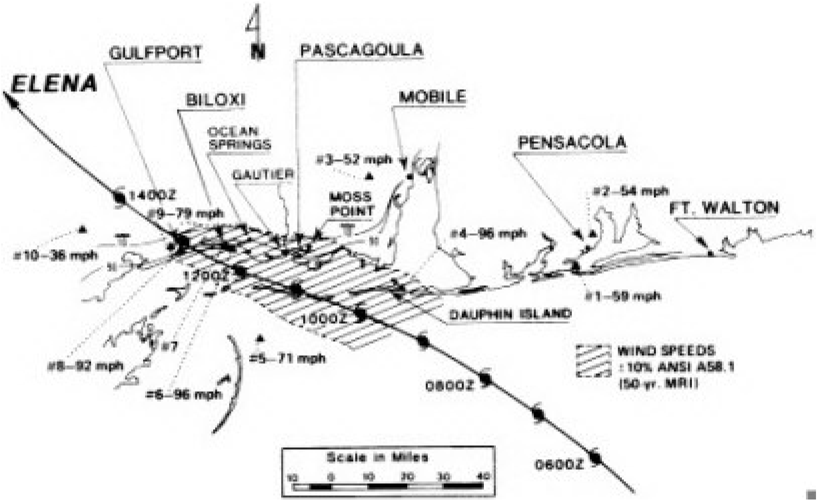

Figure 2-4
Locations of anemometer stations and the adjusted wind speeds. Source: Dale Perry.

TABLE 2-1 Wind Speed Data

Map location number (see Figure 2-6)	Type of data recorded	Recorded peak gust at height h	Time GMT (hrs)	Anemometer height h (m)	Wind azimuth (degrees)	Maximum Estimated[a] roughness length (m)	ANSI[b] terrain exposure	Adjusted fastest-mile speed (mph)	Design fastest-mile wind speed[c]
1 Pensacola Naval Air Station, Florida	Strip chart	73 kts (84 mph)	0800	23.77	100–110	0.20[f]	C-B	59[c]	101
2 Pensacola Regional Airport, Florida	Strip chart	56 kts (64 mph)	0730	6.71	90–105	0.05	C	52[c]	101
3 Mobile Regional Airport, Alabama	Strip chart	52 kts (60 mph)	1230	6.71	70–130	0.05	C	52[c]	98
4 Dauphin Island, Alabama	Partial strip chart[g]	106 kts (122 mph)	0920	10.0	0–90	0.01	D	96[d]	105
5 Bay St. Louis OTP 42007, Mississippi	Periodic observations[i]	43 m/s (96 mph)	1100 1200	10.7	330–220	0.005	Ocean	71[d]	106

6	Point Biloxi, Mississippi	Partial strip chart[g]	122 mph	1130	7.71	340	0.005	Ocean	96[d]	102
7	Keesler Air Force Base, Mississippi	Periodic observations[h]	41 kts (47 mph)	1055	3.96	340	—	—	—	102
8	Harrison County Civil Defense, Mississippi	Peak gust	100 kts (115 mph)	1300	27.13	—	0.25	B	92[d]	102
9	Gulfport Sea Bee Base, Mississippi	Peak gust	75 kts (86 mph)	—	10		0.25	B	79[d]	102
10	NSTL, Canal Buoy 42009, Mississippi	Periodic observations[i]	19 m/s (43 mph)	1400	7.0	300–240	0.10	C-B	36[d]	100

[a] Estimated roughness length used to normalize fastest-mile speeds to standard exposure.

[b] Approximate correspondence.

[c] Based on hourly means.

[d] Based on observed peak gusts.

[e] Based on ANSI A58.1 (1982) including hurricane importance factor.

[f] Roughness based on influence of trees for given direction, see Reinhold (1975).

[g] Record interrupted.

[h] Record terminated 1055 GMT on September 2, 1985.

[i] Based on maximum gust in 8-sec window.

Source; Dale Perry.

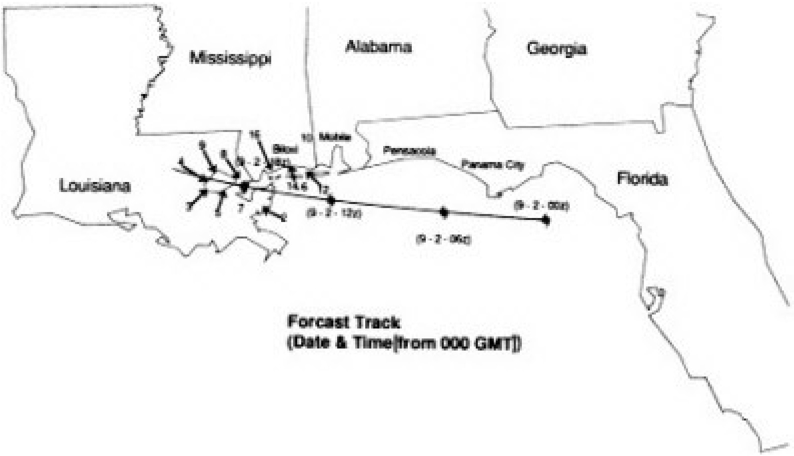

Figure 2-5
SLOSH surges based on the forecast track and intensity. Locations of the hurricane's center axe noted by date and time along the forecast track.

less than the design conditions (see Figure 2-5). In other words, Hurricane Elena was not a storm that significantly exceeded the normally accepted design conditions in use for at least the last 20 years in the applicable building codes and standards (see Chapter 4). Thus, extensive damage observed cannot be blamed on the use of inappropriate wind-speed criteria.

Tides

Tides were generally 3 to 6 ft above normal along the coast from Grand Isle, Louisiana, to Sarasota, Florida. The maximum estimated storm surge was 10 ft above mean sea level (MSL) near Apalachicola, Florida. Along the Alabama and Mississippi coastal areas, surge averaged 6 to 8 ft above normal. The actual magnitudes of storm surge were somewhat less than those that could have occurred had the angle of impact on the coast been larger.

Rainfall

Elena was a rather dry storm, with rainfall amounts averaging less than 5 inches. The maximum reported rainfall was 11 inches at Apalachicola, Florida; the storm was close to this location for an extended time.

Tornadoes

Several tornadoes occurred in central Florida when Elena was stalled off the west coast of Florida. Widespread damage to a number of mobile-home parks was noted to the northeast of Tampa. Several injuries resulted, but there were no reported fatalities.

At least a dozen tornadoes were reported in the coastal counties of Mississippi as the eyewall was crossing the coast. Only in one instance did the survey team find evidence of possible tornado damage in this area.

Pressure

The lowest observed pressure on the coastline was 953 mb at Pascagoula, Mississippi. Elena's minimum surface pressure, extrapolated from the reconnaissance aircraft flights of the National Oceanic and Atmospheric Administration (NOAA), was 951 mb as the storm was south of Apalachicola, Florida. The National Data Buoy Office (NDB) recorded a pressure of 976 mb at a location 35 miles west of the landfall point. This storm filled quite rapidly after crossing the coast. As the storm moved from Pascagoula to Gulfport, Mississippi, a distance of 20 miles, the central pressure rose approximately 17 mb.

FORECAST GUIDANCE

The National Meteorological Center (NMC) produces calculations of atmospheric state and motion around the globe using numerical models of the atmosphere. These calculations are distributed to field stations of the National Weather Service (NWS) and elsewhere as guidance for forecasts. The National Hurricane Center (NHC) in Miami uses this guidance when preparing specific forecasts of hurricane development and motion.

NMC uses several different mathematical models of the atmosphere to produce forecast charts for distribution. Atmospheric models are being continuously improved, and the guidance to the field stations is often in a state of change. The models in use at this time are:

- global medium-range forecast model,
- regional model (LFM),
- new regional model (NGM) designed to replace the LFM model, and
- high-resolution hurricane model (MFM) designed to run within the framework of the global model.

The forecasters at NHC and at other NWS field stations have specific hurricane center forecasts available to them from the LFM, NGM, and MFM models. NHC takes these forecasts into consideration in preparing the official hurricane forecasts and warnings. There is as yet no standard predictive model generally accepted for accurate numerical forecasting of hurricane movement. Information from all available sources is used in preparing the final forecast.

The track followed by Elena was unusually complicated. Important changes in course were:

- an abrupt turn from a north-northwest course toward the east at midday (1200 to 1800 GMT) on August 30,
- a near-stall at midday (1800 GMT) September 1 as Elena executed a tight loop, and
- resumption of motion of the hurricane toward the west-northwest after completion of the loop.

These abrupt changes posed some very difficult forecast problems. To be effective, guidance forecasts from NMC should have shown the eastward turn of the hurricane on August 30 in the calculations from 29/1200 GMT, 30/0000 GMT, and 30/1200 GMT. The MFM forecast from 29/1200 GMT did accurately track Elena for the next 24 hours. It then showed a northeastward turn to take place between 24 and 36 hours. Elena turned sharply eastward during that period. To be useful, the 0000 GMT on August 30 would have been the crucial time for a forecast to show the sharp eastward turn that began 16 hours later. None of the forecast models was successful at this—all of them showed Elena crossing northern Florida into southeast Georgia.

The stalling of Elena off the Florida coast should have appeared in the guidance forecasts from 31/0000 GMT and 01/1200 GMT. The LFM and NGM forecasts from 31/0000 GMT did show the stall for the first 36 hours of the forecast, although the forecast stalling position was about 70 miles west of the actual one. Normally, this is considered to be good forecasting, but when Elena arrived only 40 miles off the Florida coast before stalling, the forecasters at NHC must have found themselves in a very tense situation. By this time, the Tampa Bay area had probably been evacuated.

The final west-northwest motion of Elena should have been shown by the forecasts from 31/1200 GMT and 01/1200 GMT. The forecasts from the NGM model did show this motion. The LFM also forecast the westward motion of Elena from these times, but not as well as the NGM.

A summary of the usefulness of predictions from the three forecast models is presented in Table 2-2. The term "useful" indicates that the general trend of the storm's motion was correctly indicated by the forecast, although the precise forecast location might be in error by 50 to 80 miles. However, at times even this much error is unacceptable for determining who must evacuate and when.

Overall, the best numerical forecasts for this hurricane were obtained from the NGM model. The disappointing forecasts from the high-resolution hurricane model—the MFM model—prompted a reexamination of the model by NMC. The reexamination revealed that an error had been made in conversion of the program from the old to the new NMC computer. The consequence of this error was a significant distortion of the hurricane movement forecast in the test case. Testing of the corrected model is under way.

TABLE 2-2 Usefulness of Hurricane Elena Forecast Information Up To 36 Hours After Initial Data Time

Initial data time (GMT)	LFM[a]	NGM[b]	MFM[c]
20/00	NA	U	U
29/12	A	N	U
30/00	N	N	U
30/12*	U	U	N
31/00	U	U	U
31/12*	U	U	N
01/00	U	U	N
01/12*	U,A	U	N
02/00	A	A	U

Note: NA—not available; A—serious analysis difficulty at initial time; U—useful forecast; U,A—although there was an analysis problem, the forecast was still useful; N—not sufficiently accurate to be useful; *—time of crucial change in direction of storm movement.

[a] Regional model.

[b] Now regional model.

[c] High-resolution hurricane model.

Source: James Belville.

The European Center for Medium-Range Forecasting produces global forecasts once daily. These are generally of excellent quality. Examination of its forecasts for Elena showed an uncharacteristically poor performance from starting times of 1200 GMT on August 29, 30, and 31, most probably because of their inadequate analyses of the initial positions of Elena. Reasons for this miscalculation are unknown, but the matter is under investigation. The center's forecasts from 1200 GMT September 1 onward were generally accurate.

The varying guidance from the three U.S. numerical forecast models was a problem for the NHC forecasters who had to contend with sudden changes in the speed and direction of Elena. While many of the forecasts are indicated as "useful" in Table 2-2, they still require improvement in accuracy. It will take a long time to determine how much of the difficulty in hurricane forecasting is due to sparse data coverage in the Caribbean. It is clear, however, that more upper-air data from Cuba would be useful in improving hurricane forecasts for the Caribbean, Gulf of Mexico, and the United States. The only upper-air observations received from Cuba came from the U.S. Naval Base at Guantanamo Bay. It is also clear that more research and development is needed in numerical analysis and modeling of tropical storms and hurricanes.

Under these circumstances, the forecasters at NHC had to be rather cautious in their interpretation of the numerical guidance. Neil Frank, NHC director, used radio and television broadcasts extensively to explain to the public the uncertainties of the hurricane's motion, and he restricted his projections to times and distances consistent with the given certainties and uncertainties. Interviews by the survey team revealed that Frank's approach to the problem was successful. People seemed to have understood him very well. The survey team encountered no serious criticism of the forecasts or warnings and heard much praise. This confidence by officials and by the public at large was fundamental to the successful evacuations that took place and to the minimal loss of life.

STORM SURGE AND THE SLOSH MODEL

Storm surges are frequently the major cause of death during a hurricane episode. NWS has developed two computer models to predict surges: the Special Program to List the Amplitudes of Surges from Hurricanes (SPLASH) and the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model. SPLASH looks at storm surge only up to the coastline. SLOSH goes further and computes surges over inland water bodies and gives inland inundation. Both models require information about the hurricane's track, intensity, and size, which are difficult to predict. Experience with the SLOSH model indicates that, given an adequate description of the hurricane and its movement, the SLOSH surge forecast is in good agreement with observed high-water data.

SLOSH hurricane simulation studies have been performed in several coastal areas, including the New Orleans and Lake Pontchartrain area, to determine the vulnerable coastal areas. This work has frequently been jointly funded by the Federal Emergency Management Agency (FEMA) and the U.S. Army Corps of Engineers as part of a comprehensive hurricane evacuation plan, which is tested locally. The plan also includes studies of the population, road capacity, and evacuation psychology.

Several hundred SLOSH computer runs are made to simulate hurricanes encountering a basin. Hurricane track direction, landfall location, forward speed, and Saffir-Simpson hurricane category are varied. The result is a comprehensive picture of the flooding possible for an area.

Because of the large amount of data from such a study, composites are made from the individual runs. For example, in the New Orleans basin where a comprehensive hurricane evacuation plan is under development, all of the hypothetical hurricanes of a given intensity category and approaching from the south have been combined and the highest computed water elevation has been recorded for each SLOSH grid square. This type of composite is referred to as the Maximum Envelope of Water (MEOW).

For the New Orleans area, a total of 50 MEOWs were generated for the 5 categories of hurricane, 4 general track directions, and 2 forward speeds for each hurricane. Local evacuation planners found that this number of composites was unacceptably large. They examined the various MEOWs for similar flooding patterns and reduced the data to 12 scenarios. Evacuation planning for the New Orleans area is based on these 12 hurricane scenarios and the results of detailed studies of the population, evacuation routes, and road capacity in vulnerable locations.

New Orleans is one of the nation's most vulnerable cities to hurricane storm surge. Parts of the city are between 5 and 10 ft below sea level. The city is ringed by a variety of levees, which range from roughly 12 ft to over 17 ft in height. The levees are generally earthen, with little reinforcement and vegetation to protect them. In the past, hurricanes have caused breaks in the levee system. Most recently, Hurricane Betsy in 1965 breached parts of the eastern levee in St. Bernard Parish.

SLOSH for Hurricane Elena

Generally, forecasters at NHC have SLOSH computations available to them in two forms: MEOW data (in basins where a simulation study has been performed) and real-time SLOSH model runs. There has been no consensus among forecasters about the usefulness of the SLOSH MEOW data versus the SLOSH real-time forecast computations. MEOW data have the advantage of indicating specific problem areas that may not be encountered in a particular run. Such areas include long, narrow bays where flooding will be excessive if the storm passes to the left of the bay, but slight whenever a hurricane passes over or to the right of the bay.

MEOWs also help to show local officials the uncertainty of hurricane track forecasting. A disadvantage of MEOWs is that they may not be representative of specific storms. A problem arose in New Orleans when local officials expected flooding as depicted by the MEOW, for the lower Mississippi Delta Region, even though this area was many miles to the left of the storm track.

During Hurricane Elena's earliest phases, the storm was intensifying and heading on a northerly track toward New Orleans. Forecasters at NHC needed an estimate of storm surge for their advisories. The SLOSH model had not been run yet at NHC, since the storm was well out in the Gulf of

Mexico. Personnel at NWS Headquarters examined an experimental display of the MEOW data to make the initial surge estimates. The MEOW data were available in computer-graphic form through an experimental display being developed at the Techniques Development Laboratory of NWS. The first MEOW data entered into the system, fortunately, were for the Lake Pontchartrain basin. From this display, surges of 8 to 12 ft appeared likely from a category 2 hurricane moving rapidly in a northerly direction. MEOW showed that the most vulnerable locations were in the area between Slidell and Gulfport.

As the storm later turned eastward with a projected landfall in the Cedar Key, Florida, area, surge forecasts remained in the 8-to 12-ft range, this time based on real-time SLOSH forecasts. When the storm circled and headed westward, the same 8-to 12-ft surge value was retained in the forecast.

As Elena moved closer to landfall in the Biloxi-Gulfport area, two SLOSH runs were made—one with a projected track about 5 miles south of Slidell and a second with a track that crossed New Orleans. The first track was considered by forecasters to be the more likely of the two. However, the second would be more critical for the east New Orleans area.

Figure 2-5 shows the SLOSH output generated from the forecast hurricane, with a track 5 miles south of Slidell. This track, it turns out, produces some of the highest possible flooding along the coast for this category of westward-moving storms. Notice that in the Bay St. Louis area, surge values reach 16 ft. Surge values along the outer coast ranged from about 12 ft at the Rigolets to 15 ft just south of Bay St. Louis and back down to 10 ft east of Pascagoula. The highest water to impact the city of New Orleans was computed in this SLOSH run to be 6 to 8 ft.

The SLOSH run over the New Orleans area indicated moderate flooding in the areas surrounding New Orleans. However, no surges of the magnitude predicted by these SLOSH runs were observed. The reason can be found in a SLOSH run produced with the "best-fit" track and with best-fit storm parameters. These, of course, were not available until after Elena made landfall. Values of best fit were those available just after the storm. As more data are analyzed, an even better fit can be expected.

On the best-fit track, SLOSH surges ranged to 8 ft, with most of the Gulfport-Biloxi area experiencing 7 ft along the outer coast. Bay St. Louis surges were calculated to be only about 3 ft—well below the values computed along the original forecast track. The highest surge noted in this run occurred in the area of Pascagoula Bay.

A SLOSH run done for the Mobile Bay basin, using the best-fit track, is shown in Figure 2-6. The storm-surge values for Gulfport and Biloxi were computed to be 7 ft. Had the hurricane passed on its predicted path, surges of about 15 ft would have been experienced (see Figure 2-5). Because

Elena's actual track passed just 15 to 20 miles closer to the coast, the winds from Elena were mostly offshore winds that blew away from the coastline, generating negative surge values. Local observations indicated that this was, indeed, the case. Figures 2-7 and 2-8 show the time profile of surges at Gulfport and Biloxi. Only after the hurricane's center passed a given location dido, the wind shift to onshore, giving the potential for generating water level at the time of the wind shift was depressed; water had to be brought back in to counter the depressed state before positive surges could be generated. This, coupled with the weakening of the hurricane and the weaker winds behind the storm, led to very modest storm surge values. Figures 2-9 and 2-10 summarize measured values of surges in the region.

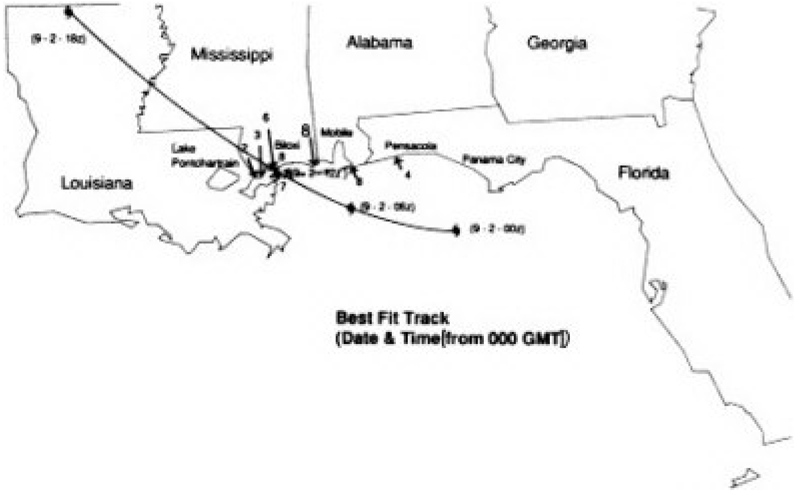

Figure 2-6
Surges from SLOSH for the best fit track and intensity.
Source: James Belville, National Weather Service.

Local officials were unhappy with the SLOSH data used in making evacuation decisions. They state that water heights indicated by the SLOSH model would never occur within the levee system because of the levee heights. It was found that, indeed, levee heights were in error in the Pontchartrain SLOSH basin because of recent levee improvements. However, the increased levee heights produced a larger amount of tidal flooding outside the hurricane-protection levees. This information was not made available to the NWS until after the storm.

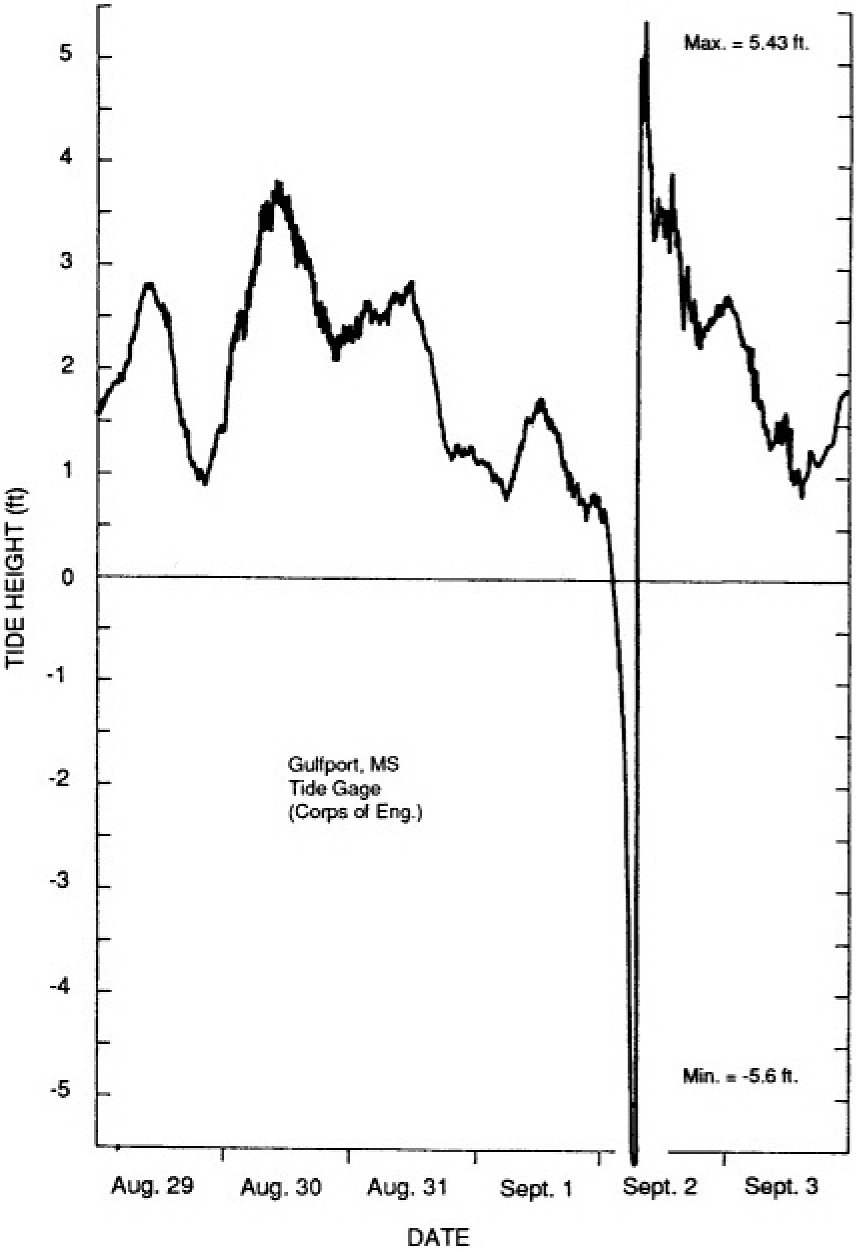

Figure 2-7
Tide gauge, Gulfpork Mississippi. Source: U.S. Army Corps of Engineers.

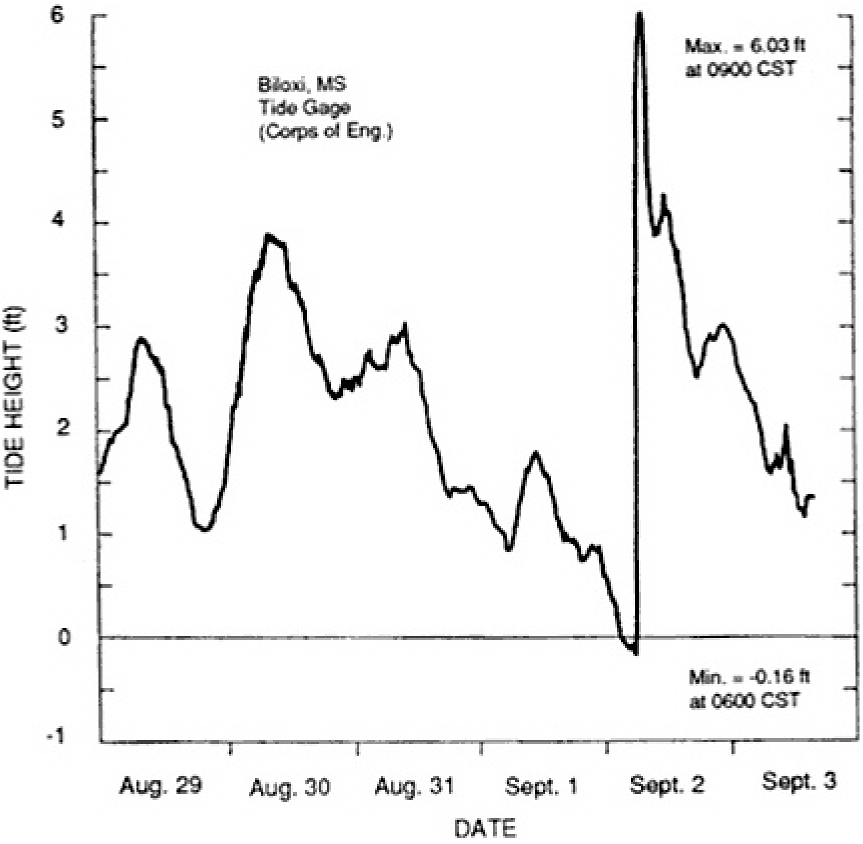

Figure 2-8
Tide gauge, Biloxi, Mississippi. Source: U.S. Army Corps of Engineers.

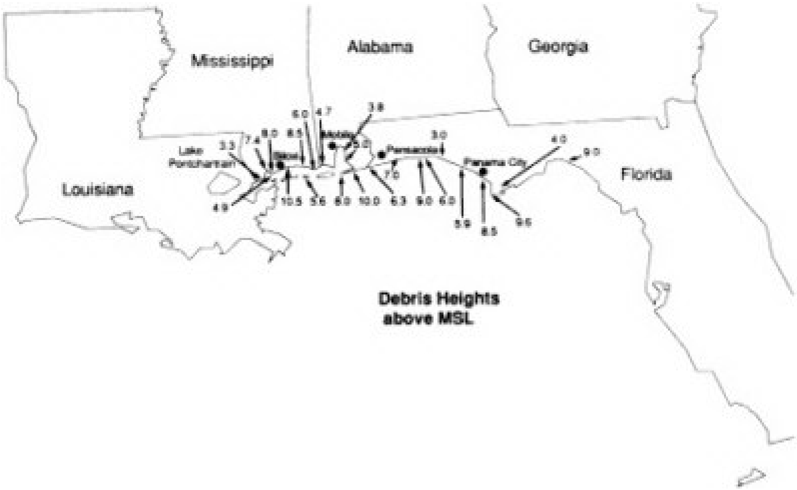

Figure 2-9
Debris heights above mean sea level.
Source: Haag Engineering, personal communication, 1985.

Figure 2-10
Highest tide gauge observations (NGVD) (no tide corrections).
Source: Wilson Schaffer, National Weather Service Headquarters.

3

Preparedness and Response

Even without striking most of the locations it threatened, Hurricane Elena posed a severe test of emergency preparedness systems. In many areas, residents evacuated, returned home, and were then told to evacuate again. In addition, the area from Tampa Bay to Sarasota was evacuated for the first time in many years. This was the first major evacuation since completion of comprehensive, quantitative, regional hurricane evacuation studies in the threatened areas.

The following discussion describes the hurricane warning process in general, the information on the hurricane threat that was available to public officials during Elena, the actions taken by officials, and public response to those actions. The adequacy of prior hurricane preparedness activities and the appropriateness of actions taken during Elena are then evaluated.

THE WARNING PROCESS

With satellites, aircraft, and coastal radar, the National Hurricane Center (NHC) monitors hurricanes and weather systems having hurricane potential. Using data from these and other sources, the NHC issues forecasts of the storm's track, its speed along the track, and its strength. Specifically, forecasts are made for where and how intense the storm will be in 12, 24, 36, 48, and 72 hours. These forecasts are revised at least every 6 hours. Based on these predictions, the NHC issues a hurricane watch for roughly 300 miles of coastline when it appears that a storm will make landfall or pass close enough to the coast to cause hurricane conditions within the next 36 hours. When the storm moves within an anticipated 24 hours or less of making landfall, the hurricane *watch* is changed to a hurricane *warning*.

Two factors make it necessary for the NHC to provide additional infor mation before and during watches and warnings. First, emergency preparedness officials and others may need to take certain actions and precautions even before a watch is issued. Second, the science of hurricane forecasting is such that there is a great deal of error inherent in all three types of hurricane predictions: track, forward speed, and intensity. For example, the average error associated with the 24-hour position forecast is about 120 miles, and the average error of the 48-hour position forecast is more than 250 miles (Neumann and Pelissier, 1981). Error statistics are not reported for intensity predictions, but NHC forecasters say that intensity is even more difficult to anticipate than position. The size of the hurricane watch and warning areas reflects these uncertainties to some extent, but it is often necessary to shift the boundaries of these areas during a threat if earlier forecasts prove to be worse than average. A hurricane warning will sometimes be posted without having been preceded by a hurricane watch, and the time remaining before landfall when a warning is issued can be substantially less than 24 hours. In short, decision makers need more information about the impending hurricane threat than simply whether a watch or warning has been posted for their area.

The principal decision makers during a hurricane threat are local and state emergency management professionals who advise elected officials in their respective jurisdictions. In most states the legal authority to order evacuation of residents is shared by the governor and local officials, such as boards of county commissioners. Through the news media the public will receive much of the same hurricane threat information that emergency management authorities do, but few people actually evacuate until explicitly advised or ordered to do so by public officials.

In response to this need for threat information by decision makers and the public, the NHC issues a variety of notices. Initially, when disturbances that could develop into tropical storms are detected, such as tropical waves and depressions, the NHC typically disseminates "special statements" to indicate their existence. When a disturbance develops certain meteorological attributes (referred to as tropical characteristics), it is called a *tropical depression*, and the NHC begins making regular forecasts of where and how severe it will be in 12, 24, 36, 48, and 72 hours. (The 36-hour forecast was not disseminated prior to 1988.) The forecasts are included in notices called marine advisories. More general information describing the system's strength, current position, movement, appropriate actions for the public, and so forth are formulated into public advisories. Both marine and public advisories are transmitted by hard copy devices, for which agencies and others pay a subscription fee.

If the depression achieves sustained winds of a least 40 mph, it is called a *tropical storm* and given a name. If the winds reach 74 mph, the storm is upgraded and called a *hurricane*. Marine and public advisories are continued for tropical storms and hurricanes.

Public advisories also contain tables listing numerous coastal towns and cities and giving the probability that the center of the depression (or hurricane if it intensifies sufficiently) will pass within 65 miles of the locations. These figures are intended to give decision makers a quantitative indication of how likely the storm is to affect their communities, but also to remind people of the uncertainties in position forecasts. A storm might be predicted to strike Apalachicola, for example, and the probability for that location might be 37 percent. At the same time, however, Tampa's probability might be 18 percent, serving as a caution for decision makers in Tampa to keep their guard up.

Public advisories are normally revised every 6 hours, although intermediate advisories are often issued when a storm gets closer to land or when there is a notable change in its track, forward speed, or intensity. When designated coastal areas are placed under hurricane watches and warnings, that information is included in advisories. Local offices of the National Weather Service (NWS) will issue local statements repeating part of the public advisory information, pointing out its significance for the local area, reporting local conditions such as roadway flooding, and advising appropriate actions by the public.

State and local emergency management professionals receive the above information and decide what responses are appropriate, usually after consulting directly with NHC or local NWS representatives. Private meteorologists are consulted in some cases.

Regional hurricane evacuation studies have estimated the time required to safely evacuate residents at risk in each coastal county during specific multicounty evacuations. When the risk is judged high enough, local elected officials or the governor issue recommendations or orders that people in specified locations evacuate. The evacuation notices are disseminated to the public by the news media (primarily radio and television) and by law enforcement personnel, firefighters, and other officials going through neighborhoods with loudspeakers and, in some cases, knocking on doors. Law enforcement personnel manage traffic flows, and Red Cross workers open public shelters in schools, churches, and shopping malls.

ELENA AND THE GULF COAST'S RESPONSES

At 3 p.m. on Wednesday, August 28, while over central Cuba, Elena received its name upon becoming a tropical storm. Gale warnings were posted for the Florida Keys.

The situation became serious on Thursday, August 29, at 6 a.m. EDT. Elena was still a tropical storm, but intensification was expected, and a hurricane watch was issued from Grand Isle, Louisiana, to Apalachicola, Florida. The eye of the storm was forecast to reach Pensacola, Florida, in just over 24 hours. Pensacola's probability of receiving hurricane conditions was given as 30 percent.

A little less than 3 hours later Elena was upgraded to a hurricane, and at 9 a.m. EDT, the watch was changed to a hurricane warning. The forecast storm track was shifted westward into Mississippi, however, and the warning area extended from Morgan City, Louisiana, to Pensacola. Pensacola's probability dropped to 22 percent, compared with a high of 34 percent at Buras, Louisiana. Local and state officials in southeast Louisiana, Mississippi, Alabama, and Escambia County, Florida, issued evacuation notices for residents of highest-risk locations before or soon after noon.

At midnight (12 a.m. EDT on Friday, August 30), however, the forecast track swung back to Pensacola, with landfall again expected in a little over 24 hours. Warnings were extended eastward to Apalachicola. Pensacola again had the highest probability, 27 percent, but from Buras to Panama City, Florida, probabilities ranged only from 24 to 21 percent, indicating the uncertainty in the forecast. Before noon, evacuation was ordered in Oklaloosa and Walton counties in Florida. At noon the forecast track was shifted to the east once more, this time placing the hurricane's eye between Ft. Walton Beach, Florida, and Panama City. Evacuation was begun in Bay County, Florida.

Despite the forecast shifts, Elena's course over the past day or more had been consistently to the northwest and later more to the north. Friday morning, August 30, the storm slowed, which usually affords greater opportunity for a change of direction. Around 2 p.m. EDT on Friday there was evidence of movement to the east for the first time, and at 6 p.m. warnings were dropped west of Pensacola and extended to Tarpon Springs, Florida, as landfall was forecast near Steinhatchee, Florida, in 36 hours.

Evacuees in southeast Louisiana, Mississippi, and Alabama were allowed to return home, while Floridians in parts of Franklin, Gulf, Wakulla, Jefferson, and Dixie counties were told to evacuate. At 6:45 p.m., a local statement from the Tampa NWS office hinted that evacuation might be necessary. At 7:45 p.m., a press release from the Florida governor's office recommended voluntary evacuation from low-lying areas as far south as Pinellas County. At 9:45 p.m. another statement indicated that residents vulnerable to expected tides should complete evacuation as soon as possible and that local officials were in the process of deciding whether to make evacuation notices voluntary or mandatory.

At 11 p.m. EDT, the easterly drift became more pronounced, and the warning area was changed again, now reaching from Panama City all the way to Sarasota, Florida. Escambia, Oklaloosa, and Walton counties in Florida were dropped from the warning area. The new forecast called for landfall near Crystal River, Florida, in 18 hours. Evacuation notices soon extended through Sarasota County, and evacuees west of Panama City began to return home.

At 8 a.m. EDT on Saturday, August 31, Bay County was dropped from the warning area. Labor Day weekend vacationers were free to visit resort areas in Mississippi, Alabama, and most of the Florida Panhandle on Friday evening or Saturday. Most of the areas filled with visitors to near-normal levels, but Bay County probably never reached 50 percent capacity. As late as noon Saturday, landfall was still expected in the next few hours between Crystal River and Cross City, Florida, but then the storm stalled and remained more or less stationary the rest of the day and night. Around 2 a.m. Sunday, September 1, the NHC began reporting a series of very minor shifts of position to the west, too small to be interpreted as a trend.

Since 8 a.m. EDT Friday, Elena's peak winds had been reported by aircraft to be 100 mph, and gale force winds had extended as much as 125 miles from the storm's center. Thus, although the hurricane still had not crossed the coastline, considerable damage had been done to coastal properties and beaches affected by Elena's outer winds and accompanying waves and tides. At 9 a.m. on Sunday, peak winds in the storm had increased to 110 mph, and for the first time Elena was labeled a major hurricane (a category 3 on the five-category Saffir-Simpson scale).

By noon Sunday, winds had reached 115 mph, and the NHC was noting that those slight moves to the west could be a trend, possibly necessitating that warnings be posted again for the Florida Panhandle. At 2 p.m. EDT, these warnings were indeed reinstated for the Panhandle, as movement was reported to the west-northwest at 5 to 10 mph. The newest landfall forecast was between Pensacola, Florida, and Mobile, Alabama, and warnings reached from Sarasota, Florida, to Bay St. Louis, Mississippi. The Florida governor's office issued a mandatory evacuation order for all of the panhandle area of the state, and similar actions were taken by state and local officials in Alabama, Mississippi, and southeast Louisiana later in the day. Notices were generally more emphatic and urgent than those issued during the earlier evacuation.

At 6 p.m. EDT, winds were at 125 mph, and warnings were dropped south of Yankeetown, Florida. The increase in winds from 100 to 125 mph was more significant than might be obvious. Because damage potential increases with the square of the wind velocity, the 25 mph increase represented a 56 percent increase in damage potential. Advisories were noting that tides could be 10 to 12 ft above normal at the landfall point. Although well to the east of the forecast landfall location, Apalachicola's probability reached 93 percent at 6 p.m. Sunday, because the eye of the storm was only 40 miles away. Panama City's probability was 86 percent because the storm was expected to cause hurricane conditions there, although passing offshore, and Pensacola's eventually reached 95 percent for the same reason.

By midnight, the forecast track had shifted west of Mobile, and Elena kept parallel to the Florida Panhandle. By 4 a.m. EDT on Monday, September 2, the eye had passed west of Pensacola, and the storm eventually made landfall near Biloxi, Mississippi, around 8 a.m. CDT, Monday.

EVALUATION

There were several issues bearing examination following the storm: How well did the evacuation decision-making process function during the threat? How did residents respond to being told twice in just a few days to evacuate? How did the public respond in the Tampa Bay-to-Sarasota area, where few residents had ever experienced a hurricane? How did Labor Day weekend tourists respond? How useful and accurate were the comprehensive, quantitative hurricane evacuation studies that had been prepared for the threatened areas?

Emergency Response Decision Making

The driving force behind most decisions to advise or order evacuation was the posting of hurricane warnings by the NHC. To overstate the case only slightly: When a warning was issued for your area, you ordered evacuation; if you were not in a warning area, you did not.

While issuance of warnings is obviously correlated with other threat factors, the correlation is far from perfect. The threat varies significantly within the warning area, for example, and it might be quite reasonable for communities on the edges to respond differently from those in its center, where probabilities are higher. Responses could reasonably differ within the warning area if the time needed to effect a safe evacuation varied from site to site within the area. Nor should a hurricane warning or even a hurricane watch be necessary to prompt officials to order an evacuation.

Pinellas County, Florida, is an interesting case. At 6 p.m. EDT on Sunday, September 1, warnings were extended southward to Tarpon Springs, which lies at the northern edge of Pinelias County. Most of the county was not in the warning area, and it disturbed the county officials to have the county "split," as their response plans called for coordinated countywide actions. This reaction seemed to imply that they did not feel comfortable evacuating the part of the county outside the warning area, but at the same time they did not feel comfortable not evacuating the part inside. Efforts were made to have the NHC either include the entire county in the warning or exclude Tarpon Springs. The fact is that the *exact* extremes of warning areas are determined somewhat arbitrarily by the NHC and should not sway response decisions as heavily as they often do.

At 11 p.m. EDT, the forecast track moved south and so did the warning area (to Sarasota), so Pinelias decided to order evacuation. However, anxiety was created by the fact that the new forecast called for landfall (around

Crystal River) in just 18 hours, and studies had indicated that 20 to 26 hours would be required to evacuate parts of the county safely. Officials in the county were surprised at the short time apparently remaining before predicted landfall, since they had not previously been under a hurricane warning or even a watch, and the 6 p.m. forecast had predicted that the storm was more than 36 hours away from landfall.

Other 6 p.m. data, however, had indicated that Tampa's probability of receiving hurricane conditions within the next 24 hours *or less* had been given as 12 percent, compared with 19 to 23 percent at the forecast landfall point; Pinelias County was within the 70-to-80 percent probability ellipse for the position where the storm was forecast to be in 24 hours. If at 6 p.m. the warning area had been extended to Sarasota, with other threat information remaining the same, officials in Pinellas would probably have ordered evacuation at that time.

In fairness to Pinelias County, its emergency management office has been recognized as a national leader in addressing this kind of decision dilemma, that is, the problem of making evacuation decisions while fully availing themselves of all the relevant information at their disposal. Pinellas officials, for example, used probability ellipses to interpret the 6 p.m. forecast, used the evacuation times calculated in the region's evacuation study, and relied (probably too heavily) on the time-until-landfall implied by the 6 p.m. forecast. Nor should it be concluded that the county's decision not to order evacuation at 6 p.m. was wrong. The real issue here is the decisionmaking process itself, which, given the pressures of the moment, often relies heavily on one or two types of threat information out of the many types available. This same problem is faced by every community and state emergency management office.

In recognition of this problem, FEMA provided $100,000 in 1982 to Florida's Department of Community Affairs for a consultant to develop a computer-based hurricane decision system. The system, however, reflected only the consultant's judgments about how much risk involving the lives of Florida citizens was acceptable. The state never understood the rationale, implications, or consequences of those judgments, and today the system is nonoperational. More importantly, state officials still are prey to the same overdependence for their evacuation decisions on the NHC's issuance of hurricane warnings and forecast positions as counties are.

Another observation on this matter relates to the role of the NHC in the response decision process. Few evacuation decisions are made without telephone conference calls among state and local emergency management staff with NHC staff, preferably (from emergency management's viewpoint) with the director. The NHC forecasters can then explain the reasoning behind their forecasts, the issuance of warnings for some areas and not others, and so forth. In many cases, the emergency management officials are seeking the advice and approval of NHC staff. It should come as no surprise that these calls tend to reinforce the officials' reliance on warning areas, as it was the NHC staff who decided on the areas initially. Such conference calls can be very valuable to decision makers if they know the right questions to ask about forecast uncertainties, but most do not. The NHC staff is no better equipped to make judgments about acceptable risks in local communities than outside consultants.

In the same vein, emergency response plans in many communities are keyed to the issuance of hurricane watches as well as hurricane warnings. The fact that, during Elena, hurricane warnings were posted for some areas without hurricane watches preceding them caught some communities off guard. The Elena experience should teach communities to interpret prewarning storm-threat information for themselves in the absence of an official watch, but the NHC should also be aware of how heavily some decision makers rely on hurricane watches and warnings.

One final point concerns the availability of storm-intensity information to officials. Advisories issued by the NHC rely heavily, although not exclusively, on wind velocities recorded several thousand feet above sea level by reconnaissance aircraft, and these velocities are in some instances substantially higher than those at sea or ground-level. The NHC's problem, as indicated earlier, is that there is no uniformly applicable method for estimating ground-level winds from data obtained at higher altitudes, and ground-level observations are rarely available, particularly when a storm is still at sea. This sometimes results, however, in an exaggeration of storm intensity at ground-level and can lead to overreaction to the threat by officials.

Whenever possible, it would be valuable for NHC forecasters to apprise emergency management officials and the media if there is reason to suspect that the aircraft data significantly overstate ground conditions. It might have been useful, for example, to know the significance of the fact that when the center of Elena was passing 35 miles south of Pensacola, the local NWS office was reporting maximum gusts of 93 mph, while at the same time the aircraft was reporting sustained winds near 125 mph. Given the wind profile detected by the aircraft, would 93 mph gusts 35 miles from the center at ground-level imply 125 mph sustained winds on the ground at the storm center?

Multiple Evacuations

Studies of past evacuations using sample surveys conducted after hurricane threats indicate that if local officials are successful in reaching the public with evacuation notices, response is excellent (Baker, 1986). On barrier islands and other high-risk areas, more than 90 percent of the residents usually leave when ordered, provided that officials are aggressive in communicating the notice. Such studies were conducted after Eloise and Frederic in the northern Gulf area, and response in those storms was very good. Thus, there was no reason to expect response problems in Elena, at least in the initial evacuation.

The "cry-wolf syndrome" is a concern of many preparedness officials. That is, if people evacuate during one threat and the storm misses their area, are they willing to leave during a subsequent threat? Normally, the subsequent threat is expected to be a different storm. In Elena, two distinct threats were posed by the same hurricane in areas from Louisiana to Apalachicola.

The cry-wolf issue is usually overrated as it applies to hurricanes. In surveys conducted with evacuees after false alarms, 80 to 90 percent of the respondents indicate they would do the same thing again, and empirical evidence suggests they indeed do. Hurricane Diana in 1984 is the only welldocumented case of a single storm causing two evacuations in the same area, and the response in North Carolina was good. Telephone sample surveys conducted in Panama City and Panama City Beach, Florida, did not find a decrease in response from the first to the second Elena evacuation, nor did a third evacuation that occurred in November in response to Hurricane Kate (Baker, 1987).

Several locations reported substantially higher public shelter use in the second evacuation than in the first. In Jackson County, Mississippi, for example, 2,500 people were sheltered the first time and 12,000 the second, although the total number of evacuees in the two evacuations is believed to have been roughly the same. It is normal for local shelter use to be higher in hurried evacuations.

Vacationer Response

When warnings were lifted for Louisiana, Mississippi, Alabama, and the western part of the Florida Panhandle on Friday, August 30, vacationers poured into resort communities late Friday and on Saturday morning for Labor Day weekend. Vacationers increase the population at risk dramatically in some communities, and there is an additional concern about whether vacationers will evacuate during a hurricane threat as willingly as residents. Virtually all the systematic data on public response in actual evacuations stems from studies of how residents reacted.

When evacuation notices were posted Sunday afternoon, they included Labor Day visitors who had arrived only the day before and had not planned to leave until Monday. Emergency management officials throughout the area indicated, however, that vacationers left readily and promptly when orders were issued. Baldwin County, Alabama, for example, evacuated twice as many people during the second threat in half the time required in the first threat. The great majority of evacuating vacationers appear to have returned home rather than go to local shelters.

Public Response in the Tampa Bay-to-Sarasota Area

Many meteorologists and preparedness officials alike are fond of stating that public response is a major problem in many areas because residents have no hurricane experience and therefore do not appreciate the hazard posed by hurricanes. (A variation on this theme relates to a concern over "false experience," whereby people think they have been in a hurricane when they actually have not.) The fact is that postevacuation sample surveys show that previous hurricane experience is uncorrelated with whether residents leave in subsequent threats.

Admittedly, those studies typically test for individual differences within the same community, where the community as a whole often has a fair amount of experience. In the Pinellas, Hillsborough, Manatee, and Sarasota counties area, the entire region has little experience with major hurricanes, because almost all major hurricane activity in the 25 years before Elena had been in the northern and western Gulf of Mexico.

Telephone sample surveys indicated, however, that in the dangerous Pinellas County beach areas, more that 90 percent of the residents evacuated (Baker, 1987). The Red Cross in Pinellas County estimated that 120,000 people went to public shelters, and officials presumed that figure represented 40 percent of the evacuees, which would have been a very high rate of public shelter use. The rate was probably overstated because of an underestimate of the total number of evacuees (officials were assuming that no one evacuated outside the areas where evacuation was ordered), and sample survey results indicated that fewer than 20 percent of the evacuees went to public shelters.

The late hour of the evacuation and its apparent urgency did not provide people the luxury of traveling as far as might have been necessary for them to reach the homes of friends and relatives inland from the beach, and they might not have had time to arrange accommodations either with friends or at motels, so even 20 percent might be higher than one should usually expect in the region. Furthermore, the Tampa Bay Regional Planning Council has been extremely active in distributing public awareness information, including maps showing shelter locations, and assigning particular neighborhoods to them. Those materials might have led residents to depend on the shelters more heavily than they would have otherwise. There is some question, however, whether shelter users went to the locations assigned in the public information tabloids.

Most indications are that the evacuation was very successful. In fact, it appears to have taken less time than the regional evacuation study had calculated for the area. There were, however, instances of public protest following the storm, since beach residents were not allowed to return to their homes when warnings were dropped for the area until officials performed safety checks and preliminary cleanup.

Use of Regional Hurricane Evacuation Studies

Since 1979, the U.S. Army Corps of Engineers and FEMA have been active in providing funds for comprehensive, quantitative hurricane evacuation studies, and the state of Florida has funded updates for some of their earlier studies. Except in Louisiana, all the areas that were under warnings for Elena had been included in such studies already completed or almost completed at the time of the threat. The southeast Louisiana study was under way, and several usable components were available. These studies include quantitative estimates of the following: areas that would be inundated by various hurricane tracks and storm intensities, number of people needing to evacuate in these various scenarios, how the public would respond to evacuation, and how long it would take to safely evacuate the population at risk in various storms.

Evacuation Zones

Clearly, the studies were extremely useful in helping officials decide upon which areas locally needed to be evacuated during Elena. Accordingly, they were also useful in anticipating the number of people who would need to evacuate and in helping officials make resource deployment decisions. Several emergency management officials reported the usefulness of the maps and other study outputs in convincing their elected officials of the need to take various actions. Large-scale evacuation-zone maps were frequently used on television to make local residents aware of the locations being evacuated.

Behavioral Analyses

Behavioral studies estimate the percentage of residents who would be likely to evacuate during a hurricane, the time period over which various percentages of evacuees would be expected to leave, what percentage of evacuees would use public shelters, and so forth. In the Mississippi, Alabama, and Florida Panhandle, such estimates were made from analysis of past hurricane evacuations, establishing rules of thumb for anticipating different responses in different risk areas and in different threat scenarios. In the Tampa Bay region the figures were originally derived from sample surveys in which residents were simply asked how they would respond to evacuation notices. Having been apprised by experts in the field that survey responses to such hypothetical questions have been shown to be extremely poor predictors of actual behavior during real hurricane threats, the regional planning council attempted to modify its original behavioral assumptions in 1984. A new analysis was not conducted by behavioral specialists, however.

The Tampa Bay study was still deficient with respect to some of its behavioral assumptions. It assumed, for example, that only people living in areas instructed by officials to evacuate would evacuate. In fact, 20 to 40 percent of residents outside such evacuated areas also leave during many hurricane threats. That error, combined with lack of awareness of particular circumstances causing higher-than-average shelter use, led to an underestimation of shelter demand in Elena and to the erroneous conclusion that 40 percent of evacuees had gone to shelters. More generally, there is a need for behavioral analyses to recognize that public response will vary from threat to threat, to identify what will occur in various circumstances and situations, and to not make use of hypothetical response data without major adjustments. In an update of the Tampa Bay evacuation study subsequent to Elena, behavioral assumptions were revised by qualified consultants.

Clearance Times

Clearance time refers to how long it takes between initiation of evacuation and its completion, the latter usually referring to leaving the county of origin. Clearance times, therefore, are taken as the time needed to evacuate people. Prelandfall hazard times (the time before actual landfall during which a weather hazard exists and evacuation efforts will be hampered) are added to the clearance times to yield the total time period before expected landfall required to allow the population at risk to be safely evacuated.

Officials in the Panhandle generally reported that clearance times calculated in the evacuation study conducted in their region were close to what they observed in Elena. The study was successful in pinpointing the locations of bottlenecks well inland from the coast as evacuees attempted to reach destinations like Montgomery, Alabama, and it accurately predicted the roughly 10 hours necessary for the congestion to clear. Table 3-1 was compiled by the Mobile district of the Corps of Engineers as a result of conversations with local emergency management and law enforcement officials, but was not based upon structured research.

Although quantitative data of the same sort are not available at this time for the Tampa Bay area, there are reports that roads cleared much more rapidly than analyses had led officials to expect. At this time, the reasons for this are not known, and it is possible that the calculated times were not as far off as people now believe. The study had estimated that such an evacuation in Pinellas County would take 11 hours, for example, and it probably took at least 8 hours, counting from the governor's recommendation at 7:45 p.m. EDT.

TABLE 3-1 Evacuation Times (hours)

	August 29		September 1	
County	Observed	Calculated	Observed	Calculated
Hancock, Mississippi	7	9.5	5	8.5
Harrison, Mississippi	11	11.0	9	11.0
Jackson, Mississippi	12	13.0	11	11.5
Mobile, Alabama	11	15.5	12	14.5
Baldwin, Alabama	16	16.0	12	15.0
Escambia, Florida	12	14.5	10	13.0
Santa Rosa, Florida	7	8.5	7	8.0
Okaloosa, Florida[a]	7	14.0	13	14.0
Walton, Florida	7	9.5	10	11.5
Bay, Florida[b]	11	22.0	11	22.0

[a] Okaloosa had a partial evacuation on August 29.

[b] Bay had partial evacuations in both threats.

SOURCE: U.S. Army Corps of Engineers, Mobile district.

It is likely that calculated clearance times are sometimes overstated because of planners' desires to be cautious in arriving at the estimates. Such a cautious approach may be justified, but it would prove useful to label the calculations to indicate the degree of caution inherent in the assumptions made. In northwest Florida, Alabama, and Mississippi, planners did, in fact, vary assumptions about how quickly people would respond to the threat and how many people would evacuate, and clearance times were calculated based on combinations of those variations in assumptions.

Updates to the Tampa Bay study have subsequently calculated clearance times under various sets of assumptions. There are additional opportunities for such sensitivity analyses, however. In the original Tampa Bay study, analysts reduced their assumptions regarding traffic flow rates by 10 percent to account for prelandfall rain conditions and further reduced the assumed flow rates of evacuees to account for congestion due to normal "background" (nonevacuating) traffic. When there is no rain and little or no background traffic (as was the case at midnight), however, flow rates will be greater than those assumed. Just as behavioral responses will vary from storm to storm, so will clearance time. By the same token, the apparent accuracy of times calculated for the Mississippi, Alabama, and Florida Panhandle area should not lead one to believe that clearance times in future evacuations will always be the same as those observed in Elena.

Regional Boundaries

The regional (multicounty) approach to hurricane evacuation studies was taken after a Lee County, Florida, study was frustrated by the fact that evacuees cross county boundaries, thereby making it difficult to consider their effect on Lee's evacuation times and patterns without considering what was occurring in the adjacent counties simultaneously. The multicounty approach solves this problem to some extent but creates two others.

First, pressure is sometimes created for an entire region to act in concert. For example, disaster management officials may be more likely to order evacuation of adjacent counties at the same time, because clearance times, shelter demands, and so forth for each county were calculated with the assumption that the entire region was evacuating. This might not always be appropriate, given the variations in risk that can exist within a region. The Mississippi-Alabama-West Florida area is very linear, and road networks are such that intercounty movement of evacuees is not substantial, so individual counties need not question whether their calculated clearance times will change depending on the actions of adjacent counties. In a clustered region like Tampa Bay, however, intercounty flow is more important.

Second, evacuees will often cross regional boundaries just as they cross county boundaries within a region, and not all regional plans have an adequate means of anticipating the effects of actions occurring in an adjacent region on their own evacuation times and patterns. The so-called tristate study is an example of a study that considers the effect of adjacent regions. Little flow of evacuees from southeast Louisiana into Mississippi is generally anticipated, although some evacuees from the two areas would probably merge on some of the same northerly evacuation routes after leaving their respective areas. At the eastern boundary of the Mississippi-Alabama-West Florida study area, analysts were able to include quantitatively the flows from the adjacent region, partly because the same consultant performed the analyses for both regions.

As new regional studies are funded and as old ones are updated, analyses should treat the regions in a less unified and isolated manner. Clearance time sensitivities, for example, should include scenarios in which only part of a region evacuates. Similarly, the sensitivities should include scenarios in which adjacent regions do and do not evacuate.

4

Wind Damage to Buildings

This chapter concentrates on areas that sustained major wind damage. These consisted of the cities of Gulfport and Biloxi in Harrison County, Mississippi; the cities of Ocean Springs, Pascagoula, Moss Point, and unincorporated areas, including the community of Gautier, in Jackson County, Mississippi; and Dauphin Island, Alabama. Because of differences in the nature of the communities and the development of building regulations, the damage in Mississippi and Alabama are considered separately.

WIND DAMAGE IN MISSISSIPPI

Building Regulations

Prior to Hurricane Camille in 1969, only the cities of Gulfport and Biloxi in Harrison County and Pascagoula in Jackson County in this coastal region had adopted and enforced building codes. Jackson County had adopted a building code but apparently had no means of enforcing it. The codes in use had been steadily tightened in the light of hurricane experience and by 1969, Gulfport, Biloxi, and Pascagoula had adopted the Standard Building Code. Following the devastation of Hurricane Camille, the Governor of Mississippi's Emergency Council was established because it was determined by the state that "local governments would not or could not institute, maintain, and enforce regulations necessary to protect life and property against disasters through adequate construction requirements and land use regulations" (Leyden, 1985).

A subcommittee of the council, the Gulf Regional Planning Commission, was given the responsibility of drafting a hurricane building code. This document required suitable elevation of structures above the flood level and the use of the 1969 edition of the Standard Building Code (Southern Building Code Congress International [SBCCI], 1969) amended for areas within 1,000 ft of the shore to include the wind load provisions of the then-current South Florida Building Code (Dade County Board of County Commissioners, 1959). Initially, it was intended that enforcement of the code should be on a regional basis, but after a short time this became politically unpopular and control passed to local governments.

At the time of Hurricane Elena, all jurisdictions had adopted the Standard Building Code and were enforcing it with full-time staff. Considering that building codes had been in use in the area from at least 1969 and a serious attempt had been made to enforce the regulations, the extensive damage observed suggests one or both of the following causes:

(a) Wind pressures and forces are in excess of those specified by the building code.
(b) The acceptance of structural systems is incapable of resisting the design wind loads.

These possible causes are now examined in detail.

Design Wind Speeds and Pressures

The wind force exerted on a component of a building depends upon the local wind velocity and the location of the tributary area transferring the load to the component. In general,

$$F = pA = C_p qA,$$

where F = force in lb, p = pressure in lb/ft^2, C_p = pressure coefficient, q = velocity pressure = 0.00256 V^2(lb/ft^2), A = tributary area in ft^2, and V = local wind speed in mph. By convention, C_p, is positive when the resulting force is directed toward a surface and negative when directed away from the surface.

When a component is subject to pressure from both sides, as in a roof or wall element, the force on the element will be the result of the difference between the pressures on the two surfaces.

The earliest building codes simply specified a pressure to be used at a particular location and height, which then had to be multiplied by a shape factor, essentially a pressure coefficient. The Standard Building Code used this type of procedure until the 1974 revisions to the 1973 edition of the code.

A slight improvement on this is to use a basic wind speed derived from meteorological data to determine a velocity pressure that varies in an appropriate manner with height. This is then multiplied by a shape factor based on measurements of pressure coefficients made in wind tunnels. Since these are normally mean-pressure coefficients, the gusting effect of the wind has to be taken into account by using peak wind speeds, typically averaged over about 3 seconds. Unfortunately, the National Weather Service (NWS) keeps its records in the form of fastest-mile wind speeds, a value based on the time taken for a "mile" of wind to pass an anemometer. Thus, the averaging time depends on the wind speed. In typical hurricane conditions (74 to 100 mph), the averaging time would be between 49 and 36 seconds. These wind speeds are about 20 to 30 percent lower than the 3-second gust speed.

Basic design wind-speed maps are produced in the form of fastest-mile wind-speed maps for different probabilities of occurrence. Their use in various building codes and standards has produced considerable confusion over the years. The Standard Building Code is a typical example.

When the 1974 revisions to the 1973 code were introduced (SBCCI, 1974) to make use of this type of wind-speed map, a probability of exceedance in a given year of 0.01 was chosen, commonly known as the 100-year fastest-mile wind speed. The map prescribes approximately 110 mph for the Mississippi coast. However, the code used shape factors that were, in fact, mean-pressure coefficients. Thus, the buildings were, in essence, being designed not for fastest-mile wind speeds of 110 mph, but for gust wind speeds of 110 mph. This gust wind speed is associated with a fastest-mile wind speed of approximately 90 mph, which has a recurrence interval of less than 30 years.

These problems were compounded by the fact that the Standard Building Code provided velocity pressures for design wind speeds taken from the wind-speed map. These pressures are based on wind speeds at the midheight of each zone. While this procedure is acceptable for high-rise buildings, it is unsuitable for low-rise buildings in a range where wind speeds change rapidly with height. For buildings approaching 30 ft, the velocity pressures would be underestimated by approximately 25 percent.

Two factors did help to ameliorate these problems locally. First, the South Florida Building Code was used for areas within 1,000 ft of the shore. Although suffering the same problems regarding fastest-mile and gust wind speeds as the Standard Building Code, it did use a design wind speed of 120 mph and provided velocity pressures at 10-ft instead of 30-ft intervals. Second, all buildings were assumed to be in open country, generally overestimating wind speeds near the ground and taking no account of shelter provided by trees or adjacent buildings.

It is unfortunate that this incorrect use of wind speed was adopted by the Standard Building Code, because a much better standard, the American National Standards Institute A58.1 (American National Standards Institute [ANSI], 1972), was available for adoption. The ANSI standard treated the fastest-mile wind speeds correctly and, perhaps even more importantly, considered the very high negative pressures that can occur locally near the edge of a roof. The simpler Standard Building Code could have been justified had it led to conservative design pressures, but it is shown below that in many cases it seriously underestimated them.

In the late 1970s, an extensive study of wind pressures on low-rise buildings was conducted in a modern boundary-layer wind tunnel at the University of Western Ontario, Canada (Davenport et al., 1977, 1978). The results of these tests formed the basis of revisions to the Standard Building Code. First introduced as an alternative procedure in 1982 (SBCCI, 1982), the provisions became mandatory for low-rise buildings in 1986, finally providing for a more rational treatment of wind pressures on low-rise buildings.

Unfortunately, most of the buildings affected by Hurricane Elena were built to the older versions of the Standard Building Code. Notable exceptions to this were several preengineered metal buildings. The upgrading of the Standard Building Code took place as a result of pressure from the metal building industry, and many manufacturers took advantage of the new regulations when they became an alternative procedure in 1982.

The shortcomings in assessing design wind pressures are best illustrated by reference to the design pressures that would have been used in the design of buildings that sustained the most serious damage in Elena—namely, flat-roofed buildings 10 to 20 ft high.

Table 4-1 shows the design pressures prescribed under normal conditions by the three versions of the Standard Building Code and the South Florida Building Code for a building located on the Mississippi coast. Table 4-2 shows the pressures that might have been used by a prudent designer who anticipated the possibility that an accidental opening might occur in a wind-ward wall as a result, for example, of window damage. It should be pointed out, however, that this eventuality is rarely considered in the design of such buildings. Note that the decking load from Table 4-2, SBC3, is nearly twice the SBC2 value in Table 4-1, the standard to which most of the structures were constructed.

The effect of this underdesign is illustrated more clearly in Table 4-3, taken from Sparks (1987a). Sparks used the best available wind-tunnel pressure coefficients for the roof of a single-story, 80 ft by 80 ft building in a suburban area to estimate the mean recurrence intervals for wind pressure in excess of those prescribed by the Standard Building Code between 1974 and 1986 (SBC2). In this analysis, wind-speed recurrence intervals were taken from Batts et al. (1980), and the wind was assumed to have an equal probability of occurrence from any direction. The corner and edge conditions, appropriate for a roof covering, considered only the external pressure condition. The three alternative quarter-roof conditions, suitable for the design of a roof framing system, included appropriate internal pressure coefficients.

Clearly, buildings of this type were being designed not for events with a 100-year recurrence interval, as the code implied, but for events with a much higher frequency of occurrence.

Table 4-4 shows the factors of safety required to prevent failure in hurricanes with mean recurrence intervals between 50 and 500 years. The fast

TABLE 4-1 Normal Design Pressures (lb/ft2)

Code[a]	Wall[b]	Roof frame[c]	Decking[d]	Membrane[e]
SBC1	± 25	-31	-31	-31
SBC2	± 26	-24	-24	-24
SBC3	± 25	-30	-38	-61
SFBC	± 30	-27	-27	-27

[a] SBC1—Standard Building Code prior to 1974; SBC2—Standard Building Code 1974 to 1986; SBC3—Standard Building Code 1986 to present (alternate from 1982); and SFBC—South Florida Building Code.

[b] Tributary area = 100 ft^2.

[c] Tributary area > 500 ft^2.

[d] Tributary area = 50 ft^2.

[e] Tributary area = 10 ft^2.

TABLE 4-2 Open-Side Design Pressures (lb/ft2)

Code[a]	Wall[b]	Roof frame[c]	Decking[d]	Membrane[e]
SBC1	± 25	-31	-31	-31
SBC2	± 26, -36	-36	-36	-36
SBC3	± 34	-38	-46	-70
SFBC	± 27, -41	-41	-41	-41

NOTE: See notes in Table 4-1.

TABLE 4-3 Mean Recurrence Intervals for Wind Loads in Excess of the Standard Building Code (1974 to 1986, i.e. SBC2)

Location	Recurrence Interval (years)
Corner	12
Edge	35
Quarter[a]	38
Quarter[b]	28
Quarter[c]	15

[a] Minor opening in any wall.

[b] Major opening in only one wall.

[c] Major opening in any wall.

SOURCE: Sparks (1987a).

TABLE 4-4 Factors of Safety Required to Prevent Failure

	Recurrence Interval by Years			
Location	50	100	200	500
	Factor of Safety			
Corner	1.57	1.77	2.17	2.52
Edge	1.37	1.56	1.90	2.22
Quarter[a]	1.13	1.25	1.55	1.81
Quarter[b]	1.21	1.37	1.67	1.95
Quarter[c]	1.47	1.66	2.02	2.37

[a] Minor opening in any wall.
[b] Major opening in one wall.
[c] Major opening in any wall.
SOURCE: Peter Sparks, 1987a.

est-mile wind speeds in Hurricane Elena were, at worst, in the mid-90-mph range, with a recurrence interval of less than 50 years. In addition, many buildings undoubtedly received some shelter from the full force of the wind. With this in mind, the extensive damage observed suggests that not only was the building code inadequate, but typical construction practices provided rather low factors of safety that were insufficient to compensate for the inadequacies of the code, particularly with regard to resistance to high local pressures.

Wind Resistance of Structural Systems

Load Combinations

It has been traditional in structural design to increase the allowable stresses in materials by 33 percent for load combinations that include wind effects. Presumably, the logic behind this is that it is unlikely that the design wind load, live load, and dead load will occur at the same time and/or that the peak wind load will be of short duration. But the procedure is also applied to conditions when the critical loading is a combination of only dead and wind load, as in the case of roofs subjected to uplift. In these circumstances, the design wind load will occur in the presence of the full dead load. In situations where light roofing systems are subjected to high uplift forces, certain steel members might be sized to carry the design wind loads at stresses very close to the yield strength of the material, providing little or no safety margin to accommodate incorrect design pressures or unforeseen occurrences such as window damage.

Wind-Load-Resisting Systems

In a high-rise building the wind-load-resisting system provided by moment-resisting frames, braced frames, or shear walls is clearly identifiable, and failure of part of a roof or wall will have only a marginal effect on the load-resisting system. In a low-rise building, especially a single-story one, the roof and walls resist the wind loads in a complex manner. For example, a roof deck may resist wind forces applied directly to it, may act as a diaphragm to distribute wind forces applied to the walls, and may supply lateral support to those walls. Unfortunately, these structures are often designed as a set of isolated components without regard for their combined role in the complete system or an appreciation for the major structural consequences of an apparently minor component failure, such as window breakage or door loss.

The Standard Building Code also contains some statements that in the light of recent research (Leland, 1988) appear to be incorrect regarding critical structural details—in particular, the anchoring of roofs to masonry walls.

It is unlikely that in hurricane conditions the recommended anchorage using an embedded rod in masonry without a bond beam would be sufficient for any light roof system, relying as it does on the weight of a few masonry units and their bond strength. A second form of anchorage mentioned in the code that uses a bond beam would prove satisfactory only if the bond beam were properly tied to the foundation by vertical wall reinforcement.

The Steel Joist Institute recommends that joists be anchored to walls by welding them to plates attached to either one 3/4-inch-diameter steel rod embedded 1 ft into the wall or, in the case of walls with parapets less than 2 ft high, two 3/4-inch-diameter anchor bolts. No mention is made of how or to what these anchors should be bonded.

In wood construction, the Standard Building Code suggests the use of three 8d nails driven at an angle through a roof truss or rafter into the top plate of the wall, although hurricane requirements contained in the code's Appendix D state that approved hurricane anchors must be used for wooden truss rafters. Fortunately, most coastal jurisdictions have recognized the inadequacy of the toenail connection and require the use of proper anchors, at least for residential construction.

Workmanship and Materials

Few of the professionally designed buildings damaged in Elena were prestigious structures in which careful control of the construction would have been carried out by the designer. Additionally, some of these buildings were exempt from inspection by local building inspectors.

Roofing systems, the primary areas of damage, are notorious for their variability in quality. Good inspection is required for the actual structure to meet the design specification. A classification system for roofing systems, including the waterproof membrane, decking, insulation, and supporting system, is available based on the successful resistance to a series of tests conducted in accordance with Underwriters Laboratories (UL) 580 specification (Underwriters Laboratory, 1980). These tests apply a sequence of negative pressures to the upper surface of the roof and positive pressures to the underside of the roof. Table 4-5 indicates the maximum pressures applied during these tests.

TABLE 4-5 Maximum Pressures of Underwriters Laboratory 580 Specification (lb/ft 2)

Class	Top Pressure	Bottom Pressure	Total Uplift
30	-24.23	+20.77	45.00
60	-40.38	+30.62	75.00
90	-56.54	+48.46	105.00

Based on the requirement for resistance to high local suctions specified by the Standard Building Code for the top surface of the roof, the most stringent classification, 90, would be required for flat roofs in this area. Even still, the test might not exceed the expected suction on the corner of a roofing membrane.

In view of the pressures specified in the earlier editions of the Standard Building Code, it is likely that designers would have accepted a Class 30 roofing system or, perhaps conservatively, Class 60. In exposed locations during Hurricane Elena, the suction on the roofing membranes near the corners probably exceeded the tested capacity of Class 30 and 60 roofs. They may have even exceeded the capacity of a Class 90 roof.

Not surprisingly, many buildings that performed satisfactorily in other respects suffered severe damage to the waterproof membrane. On the other hand, even after windward openings were established, the total uplift probably did not exceed the tested uplift capacity of even a Class 30 roof. However, the UL test does not include the roof-to-wall connections, and it was at these locations that major failures of roof structures appeared to have been initiated.

"Nonengineered" Structures

Despite the existence of a building code, residential and small commercial structures are often built without any formal consideration of the wind resisting system. Compliance with the building code is essentially determined by rules set forth by the local building officials. Following Hurricane

Camille, hurricane straps were required on all small residential structures, but suitable, roof anchors did not appear to have been specified for small commercial structures with masonry walls. These buildings, when located in an exposed area, were often severely damaged in Hurricane Elena.

Detailed Damage Descriptions of Classes of Structures

Traditionally, damage surveys have classified buildings into fully engineered, marginally engineered, nonengineered, and preengineered structures. While preengineered structures can be readily identified as a class, the distinction between fully, marginally, and nonengineered structures has become indistinct in many hurricane-prone areas. At one end of the spectrum, even single-family dwellings are often built to prescriptive building code requirements that indirectly reflect the effect of wind loads on the structure. At the other end, major structures that would be expected to be fully engineered are often designed as a set of components with little regard for the way in which these components might combine to form a complete structural system. For this reason, in describing damage, the majority of buildings are classified by function, with the exception of metal building systems (preengineered structures) and structures that were obviously fully engineered.

Schools

The satisfactory performance of schools in a hurricane is important, since they are often used as evacuation shelters. However, they are, in fact, more vulnerable than most buildings to damage. Although they have the advantage that they must be designed by a registered architect or engineer in accordance with the Standard Building Code, their plans are not checked, nor is construction inspected by the local building official. This is the responsibility of the state s Department of Education. Construction is often on a tight budget, and the buildings are usually located in open areas where they receive the full force of the wind. In addition, when a jurisdiction adopts a particular form of construction, often involving lightweight flat roofs and masonry walls, the design is often repeated, sometimes using the same building orientation.

As a class of structures, these buildings performed very poorly during Elena. The *Gulf Coast Sun* on September 4, 1985, reported the following descriptions furnished by Mississippi school officials:

- Gulfport—Expected to get only the high school operational by the end of the week.
- Biloxi—Roof and interior damage to all schools.
- Harrison County—More than 100 classrooms with ceiling damage.

- Ocean Springs—Damage estimated at $3 million.
- Moss Point—Extensive damage.
- Pascagoula—Every school sustained some damage.
- Jackson County—Most schools damaged.

Some damage was also reported in Hancock County, Pass Christian, and Long Beach.

Damage ranged from roof leakage due to the sucking off of the waterproof membrane to serious roof damage and the collapse of walls.

Leakage Almost all flat roofs and some pitched roofs on schools were leaking after the storm. This was probably the result of a combination of factors, including the use of an inappropriate building code, poor design specification, poor installation, and deterioration; it was probably not the result of excessive wind speeds. Individual leakage apparently was minor, but the widespread occurrence of this type of failure caused considerable damage and disruption. Figure 4-1 shows a typical example.

Failure of Roof Decking As indicated earlier, while the loads on these roofs may have exceeded the design level as a result of a window failure, a properly designed and installed system should have accommodated this overload.

Figure 4-1
Loss of roof covering—West Elementary School.

Failure probably indicates noncompliance with the code in use at the time of construction.

Failure of Roof-Supporting System This failure generally resulted from the pulling out of the joist anchor from a masonry wall, often following the failure of a nearby window. This probably indicates failure to comply with the wind-loading provisions of the code while incorporating a reasonable factor of safety. Unfortunately, in some instances, compliance with the anchorage requirements of the code still resulted in failure. In other cases, the anchorage met neither the wind-lead nor anchorage requirements of the code.

Wall Failures The specification of the wind loads on the walls has generally been quite adequate, except perhaps when a high internal pressure develops. However, two, major failures took place when walls were blown inward where, internal pressure was not a factor. In one case, a tornado may have caused locally high wind pressures; in the other, poor construction and loss of roof support were probably the cause of failure.

Descriptions of some of the more serious school failures are found in Appendix A.

Commercial Structures

Masonry-walled commercial structures with light metal roofs tend to suffer the same problems as similarly constructed schools. The problems, however, are accentuated. Roof spans are usually longer and walls higher. In many cases, such structures are more exposed because of extensive parking areas and are usually more vulnerable to high internal pressure because of large glazed areas.

During Elena, most of the flat roofs of commercial structures leaked, and loose gravel from the roofs sometimes caused serious damage nearby. Figure 4-2 shows a new shopping mall in Gautier. Note the removal of the roofing membrane in the areas of high suction. A shopping center, Jackson Square, opposite this mall suffered much more severe damage (Figure 4-3). In some parts the roof membrane was removed. In others, usually where the glazing system had failed, the decking was also removed. In one location where the wall was not protected by the canopy, the bar joists failed, and the wall, lacking top support, collapsed. This wall was reinforced with steel columns whose hold-down bolts failed in tension (see Figure 4-4).

This serious damage was probably due to some very minor details. The high internal pressure probably resulted not from glass breakage but from failure of the wall-to-window-frame connection (Figure 4-5). The bar joists

Figure 4-2
Roof membrane damage to a shopping mall, Gautier.

Figure 4-3
Collapse of a section of the Jackson Square Shopping Center, Gautier.

Figure 4-4
Detail of roof and wall damage in Figure 4-3.

Figure 4-5
Wall-to-window-frame connection failure, Jackson Square Shopping Center, Gautier.

Figure 4-6
Buckling of bar joists due to roof uplift, Jackson Square Shopping Center, Gautier.

were not properly anchored into the top of the wall, but note also the buckling of the lower flange of the bar joists (Figure 4-6).

The Payless Shoe Source in Pascagoula may have been designed professionally, but it was probably below the size where this would have been required by the code. It was, in essence, a miniature version of the larger shopping center as described earlier.

The glass appears to have failed first, the roof was then stripped off, and a side wall collapsed, taking with it a transverse girder (Figure 4-7). The bar joists in some instances had simply been laid on the girders without welding (Figure 4-8). At the front of the store the bar joist bearing plates had been set in mortar, which apparently had not adhered well to the block or bars (Figure 4-9). This type of anchor has negligible uplift resistance. The walls did not contain bond beams with reinforcement to which the anchor bars could have been welded or wrapped around.

This building is a good example of one in which the components probably met the code requirements (with the possible exception of the unreinforced masonry walls), but the structural system proved inadequate because of poor connections. This was also true of many small, nonengineered commercial structures using unreinforced masonry walls with steel or wood roof construction (Figures 4-10 and 4-11).

Figure 4-7
Collapse of Payless Shoe Store, Pascagoula.

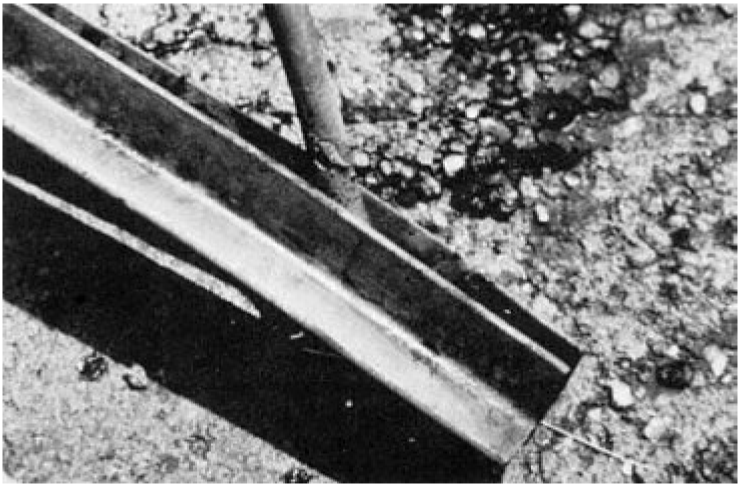

Figure 4-8
Bar-joist-to-wall connection, Payless Shoe Store. Pascagoula.

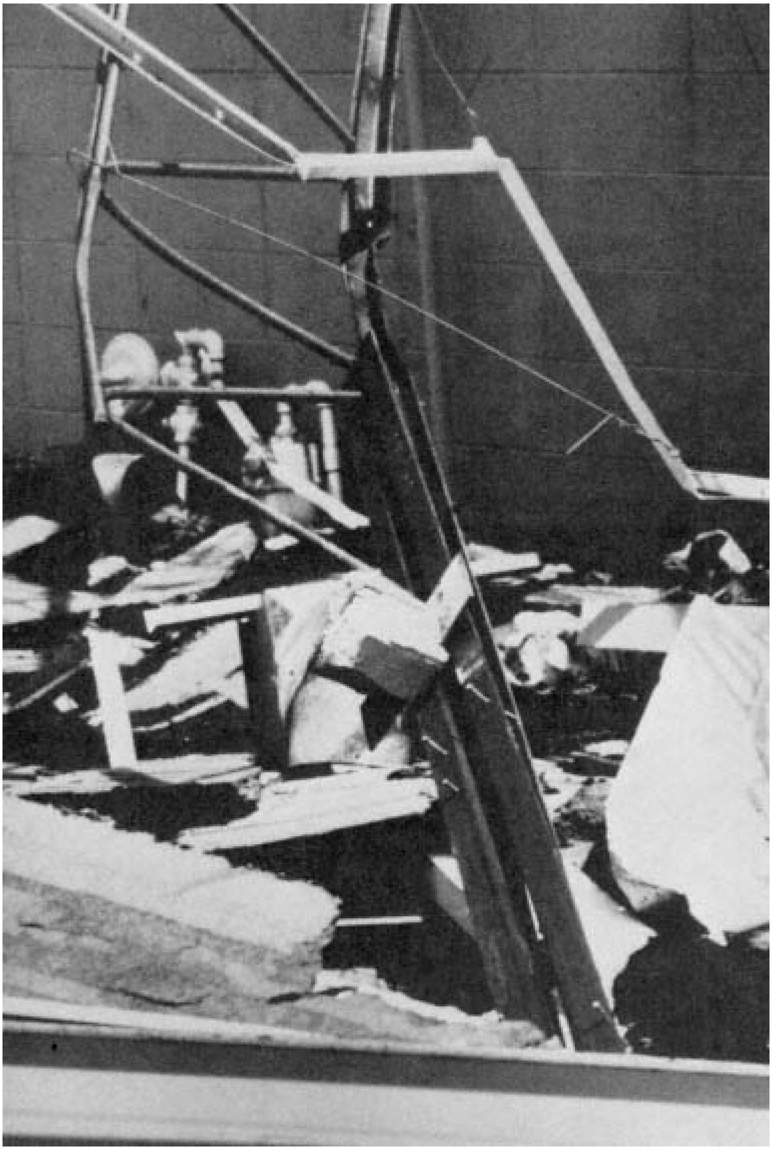

Figure 4-9
Mortar failure at roof anchor, Payless Shoe Source, Pascagoula.

Figure 4-10
Loss of wood roof from masonry-walled building (note sign), Gautier.

Figure 4-11
Collapse of masonry-walled garage following loss of roof, Pascagoula.

It is interesting to contrast the performance of small convenience stores, usually built with little engineering input and to fail in a storm, with similarly sized, fast-food restaurants belonging to national chains. The latter seemed to have survived this storm with little damage and were back in business as soon as they could get power (often supplied initially by a generator). Presumably built to standard designs, these buildings probably receive engineering attention far beyond that normally given to such small structures. Clearly, this attention to detail pays off and shows that it is quite possible to build small commercial structures that can survive hurricanes.

Motels

A number of motels sustained roof damage of the type shown in Figure 4-12. These buildings were probably not designed professionally. The connections between the walls and roof were inadequate to resist the wind forces on the roof overhangs. While the high internal pressure resulting from broken windows might not have been anticipated, the high forces on overhangs were clearly specified in the building code. These buildings probably did not meet the code requirements at the time they were built. However, at that time, there may not have been a means of checking compliance.

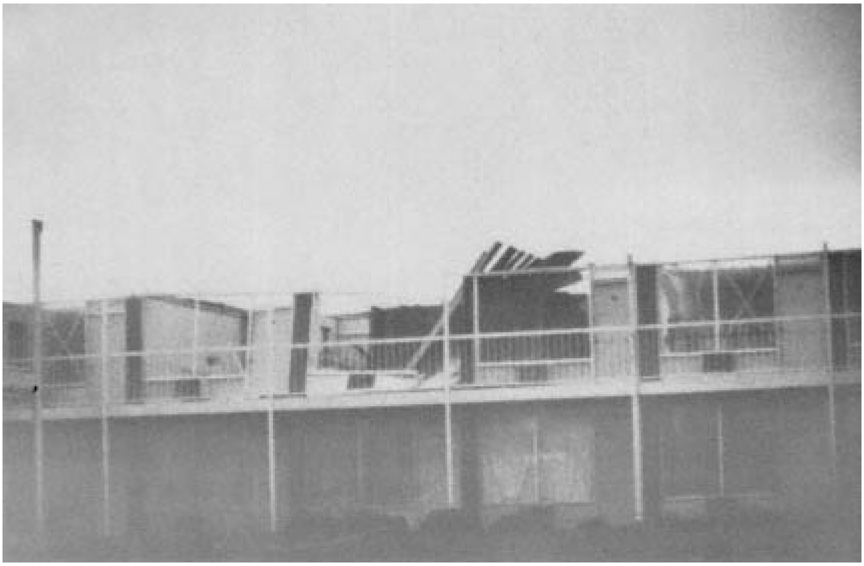

Figure 4-12
Motel damage, Pascagoula.

Churches

Churches generally favor steep-pitched roofs that experience low uplift forces except when the wind is blowing over the gable end. Some received significant damage when the wind was blowing in that direction, the result of poor attention to detail. Figure 4-13 shows a church in which the gable-end overhang had been supported by a joist with virtually no resistance to uplift.

Single-Family Dwellings

As a class of buildings, these structures performed very well. Newer buildings benefited from the requirement to use hurricane anchors to connect the roof to the walls and the walls to the foundation, but both old and new dwellings probably derived their major benefit from shelter provided by neighboring buildings and trees. Nevertheless, virtually all buildings came through a storm close to the "once-in-50-year event" with very little damage.

The most vulnerable buildings were those adjacent to the Gulf of Mexico and the Back Bay of Biloxi. Here a few buildings did suffer some serious damage (Figures 4-14 to 4-16). Interestingly, many of the older houses along the Gulf performed well.

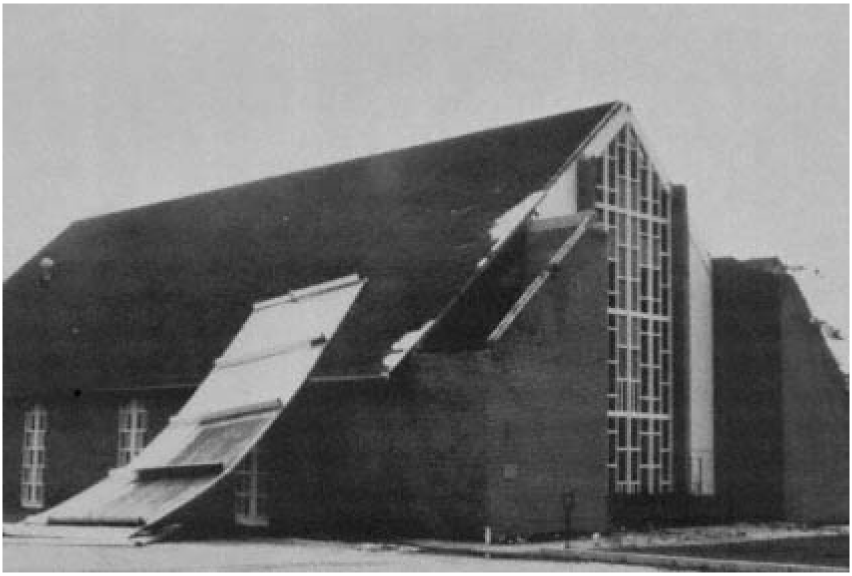

Figure 4-13
Roof damage to church, Gautier.

Figure 4-14
Damaged house using metal deck roof, Pascagoula.

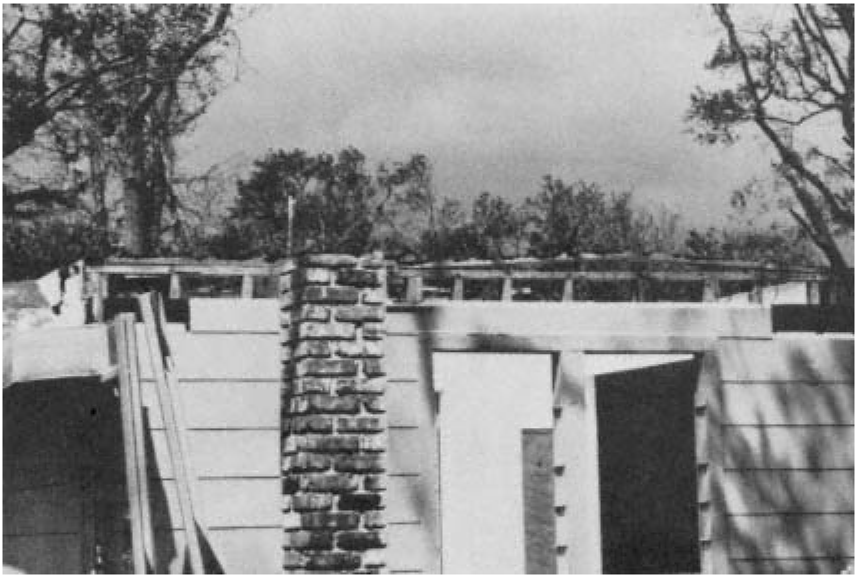

Figure 4-15
Loss of roof due to improperly secured overhang, Pascagoula.

Figure 4-16
Shear failure of house, Pascagoula.

Multifamily Dwellings

Two groups of buildings that would have been designed by an architect or engineer performed very poorly. The first was an apartment building in a fairly exposed location near the center of Pascagoula. Anchor straps were used, but the building did not have sufficient resistance for the wind loads applied to the roof and overhang. Interestingly, the building experienced almost identical damage in Hurricane Frederic in 1979.

The much newer Spinnaker Point Condominiums on the shores of the Gulf of Mexico in Pascagoula are shown in Figure 4-17. Even though they are effectively more than three stories high and have monopitched roofs, the condominiums had been built in the same manner as a single-family dwelling. They were wood panel structures that, despite the occasional use of metal straps, were improperly tied together.

Although these buildings were probably never subjected to a detailed structural analysis, they had certain features that would have made the direct use of the Standard Building Code difficult or inappropriate. The roofs were of a shape not covered by the code. Treating them as bipitched would have underestimated the suction loads. At most, they would have been designed for uplifts of abut 30 lb/ft^2. Some wind tunnel tests suggest that the upper corner of a monopitch roof may experience local suctions of more than 60 lb/ft^2. Failure in a number of buildings appears to have been initi ated in that corner. The wind loading, however, would have been complicated by the irregular shapes of the buildings.

Figure 4-17
Extensive damage to Spinnaker Point Condominiums, Pascagoula. (Courtesy of *The Sun/The Daily Herald,* Biloxi.)

In another respect, the Standard Building Code is ill equipped to deal with this particular location, since the code assumes all buildings are located in open country. For most locations, this assumption is conservative. In this case, such an exposure was probably correct for the wind direction that caused most of the damage, but south winds would come directly over the ocean. Under those conditions, wind pressures for buildings immediately adjacent to the shoreline could be more than 30 percent higher than in open country.

Mobile Homes

A detailed survey of mobile homes was not conducted, but a few mobile home sites were visited. Most were fairly well sheltered; nevertheless, many mobile homes turned over because their anchors pulled out of the ground (Figure 4-18). In cases where the anchors held, damage to the superstructure was extensive (Figure 4-19). At one site in Gautier, many of

Figure 4-18
Anchor failure in mobile home, Gautier.

Figure 4-19
Structural damage to well-anchored mobile home, Gautier.

the mobile homes suffered severe damage, but the conventionally built clubhouse was virtually undamaged.

A more detailed report of the performance of mobile homes can be found in McDonald and Pennington Vann (1986).

Metal Building Systems

Tens of thousands of preengineered metal buildings have been constructed over the past two decades in the areas affected by Elena (1985), Frederic (1979), and Camille (1969). These three storms generated wind-speed regimes at or near design-level events and thus provided a unique opportunity to assess the adequacy and extent of enforcement of the building codes of record for this type of construction.

A review of damage sustained during the two prior events (Marshall et al., 1971; Mehta et al., 1983) compared with that observed by the investigation team for Elena indicates, for the most part, a significant improvement in performance of preengineered metal buildings. Two factors appear to be primarily responsible. First, as mentioned earlier, the Standard Building Code has undergone extensive revisions during this time. The alternative wind-load provisions introduced into the code in 1982 (SBC3), based on the design procedures developed by the metal building industry (Metal Building Manufacturers Association, 1981), more properly prescribe the high localized loads to be resisted at the edges and corners of roofs and walls. A comparison of the fastener and cladding loads for the alternative procedure of 1982 with those prescribed by the 1974 revisions to the 1973 edition and the 1969 code is given in Figure 4-20. It can be seen that fastener loads were increased by factors as high as 2.8 for buildings that are expected to experience only normal internal pressure fluctuations (enclosed buildings) and 3.1 if it is assumed that the building envelope may be breached (partially enclosed buildings).

Clearly, even contemporary wind-load provisions are not meant to adequately apply to a building having the unusual geometry shown in Figure 4-21. This recently constructed building, however, sustained no damage because localized effects had been considered in the design of the fasteners. Figure 4-22 shows a typical contrast between the performance of buildings in which local effects were, or were not, considered in the initial design.

The second factor that probably led to improved performance is the almost uniform acceptance of the UL 580 specification as a marketing strategy by the metal building industry. As noted earlier, this specification provides a definitive measure of the fastener and panel resistance to uplift pressures. Unfortunately, the test procedure falls short of predicting purlin or girt performance, and consequently it is difficult to relate the capacities of Class 60

ZONE		DESIGN LOADS(4)							
		Purlins/Girts (plf) (1)				FASTENERS (psf) (2)			
		SBC-1982 (1206)		SBC-1974 or SBC-1982 (1205)	SBC-1969	SBC-1982 (1206)		SBC-1974 or SBC-1982 (1205)	SBC-1969
		Enclosed	Partially Enclosed			Enclosed	Partially Enclosed		
ROOF	ⓡ	−131	−177	−120	−156	−30	−39	−24	−31
	ⓢ	−160	−216			−39	−48		
	ⓒ	N.A.	N.A.			−66	−75		
WALLS	ⓦ	+148 −159	+148 −214	±176	±167	±27	+27 −35	±26	±25
	ⓔ	N.A.	N.A.			+27 −31	+35 −43		

(1) Based on tributary areas of 125 ft² (roof), 167 ft² (walls)
(2) Based on tributary areas of 5.0 ft² (roof), 6.67 ft² (walls)
(3) Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.
(4) Customary to Metric Conversions—
1 plf = 14.59 N/m; 1 psf = 47.88 Pa
1 ft = 0.3048 m; 1 ft² = 0.0929 m²; 1 mph = 0.447 m/s

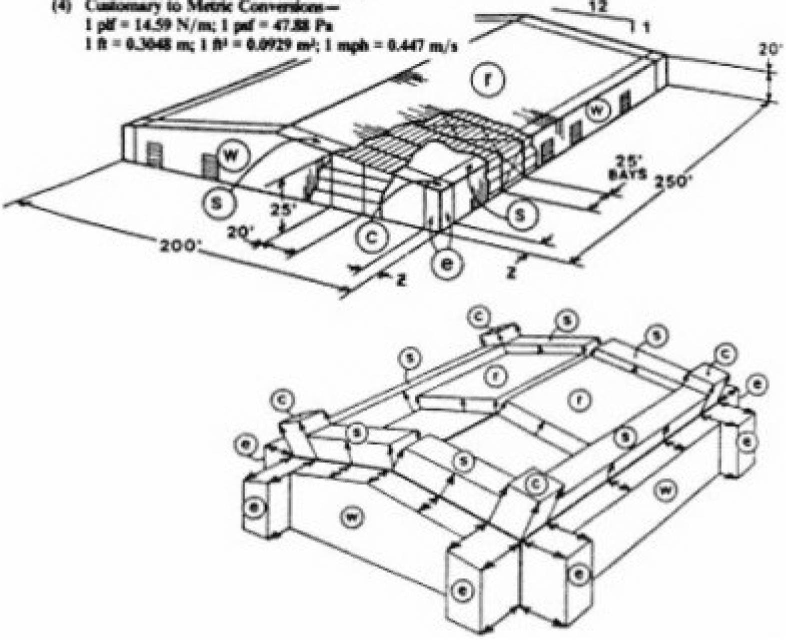

Figure 4-20
Component and fastener loads for design wind speeds of 100 mph.

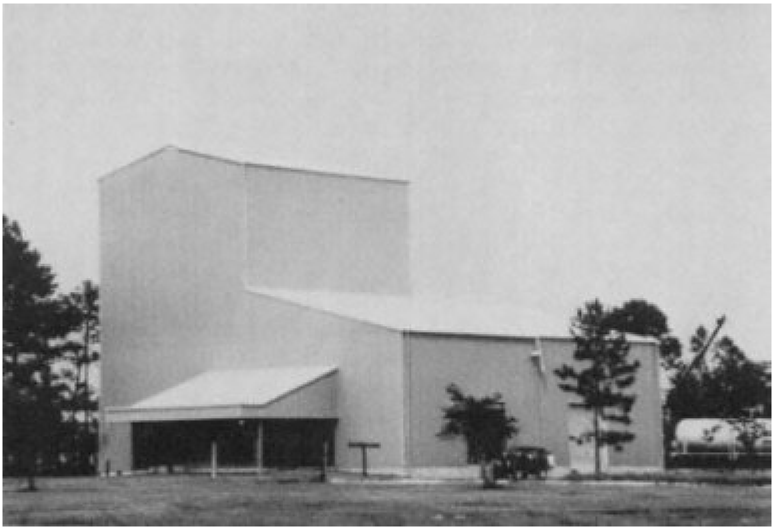

Figure 4-21
Preengineered metal building in Gulfport. No wind damage observed.

Figure 4-22
Preengineered warehouse buildings at Ingalls Shipyard. Wind damage limited to older building (top).

or 90 roofs directly to code prescriptions or design wind speeds, although attempts are often made to do so.

Nonetheless, the increasing customer demand for roofs meeting the UL specification has resulted in a reduction of hurricane damage for engineered metal buildings. Experience has shown that these structures generally perform adequately except when fasteners and sheeting are underdesigned, leading to domino-type failures of roofs and walls. The ability of most metal roof systems to maintain watertightness resulted in minimal damage to building contents and lower business interruption costs, in contrast to the performance of the roofs of the metal buildings in the center of Figure 4-23 with the conventional built-up flat roof on the right.

As noted earlier, school buildings performed very poorly. It is noteworthy, however, that many metal multipurpose school buildings sustained little if any damage (Figure 4-24). Also, the performance of preengineered churches was satisfactory (Figure 4-25). The motel shown in Figure 4-26, a typical of other motels in this area, suffered damage only to the exterior logo and was returned to service immediately after restoration of electrical power.

On the negative side, a number of metal building systems performed in a less than satisfactory manner and sustained damage ranging from minor cladding failures to loss of an entire end bay of the building. Some of these

Figure 4-23
Preengineered metal buildings and conventional construction on west bank of Ingalls Shipyard. Note wind damage to built-up roof and absence of damage to metal roofs.

Figure 4-24
Orange Grove Elementary School in Lyman. No damage to multipurpose metal building.

Figure 4-25
First Baptist Church of Lyman. Wind damage to complex of metal buildings limited to glass breakage due to windborne debris.

Figure 4-26
Preengineered metal building in Pascagoula. Wind damage limited to logo.

buildings had been designed and erected following the new wind-load provisions advanced by MBMA in 1981. However, the Standard Building Code permitted the use of the 1973 provisions (with 1974 revisions) at the time Elena came ashore. Regrettably, economic conditions and the competitive nature of low-rise construction may have encouraged some members of the industry to continue to use the older provisions even though the improved alternative procedures had been adopted by the Standard Building Code in 1982. For a detailed discussion of damage to metal buildings, see Appendix C.

Fully Engineered Buildings

Employing the scheme advanced by Minor and Mehta (1979), buildings that receive specific, individualized design attention from professional architects and engineers for all aspects of the building from cladding to the foundation are classified as fully engineered. Normally, such buildings perform adequately at wind speeds at or slightly exceeding design-level events (Mehta et al., 1983; Kareem, 1984). Although the buildings that fall into this category made up a small percentage of the structures in the areas impacted by

Elena, in general they were observed to have performed well. One exception was that a significant number sustained damage to their roof coverings, resulting in extreme water damage to their contents.

Keesler Air Force Base presented an exposed site for a large number of reinforced masonry two-to three-story buildings (Figure 4-27). Failure of built-up roof coverings caused water damage in several several buildings. Loss of watertightness also proved to be a problem for many other buildings, including the new Vocational High School in Pascagoula and several buildings located at the Jackson County campus of the Mississippi Gulf Coast Junior College (Figure 4-28).

A number of multistory buildings, including an apartment building in Ocean Springs (Figure 4-29) and hospital buildings in Gautier, Ocean Springs, Biloxi, and Gulfport, sustained virtually no damage except that an occasional window was broken by windborne debris. The large industrial complex east of Pascagoula provided a very exposed location for a large number of both fully-engineered and preengineered buildings (Figure 4-30). Only very minimal damage was reported in this area.

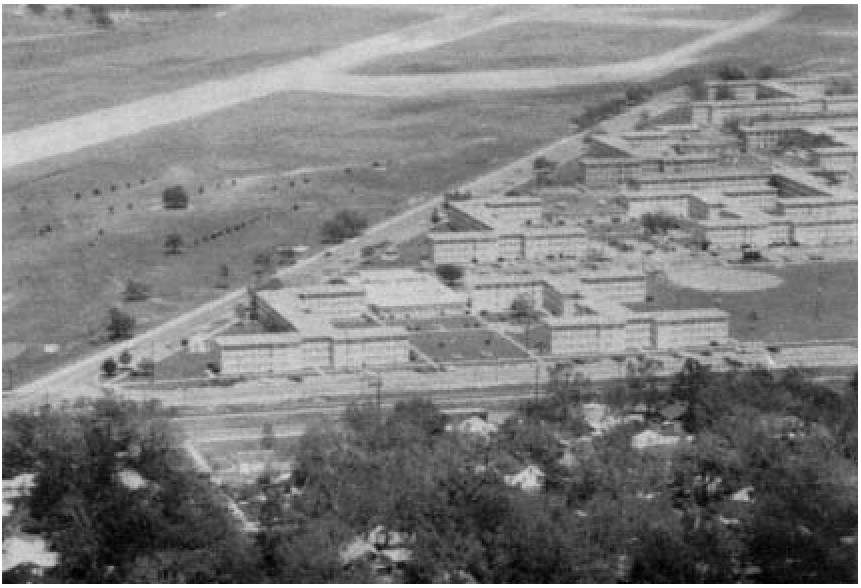

Figure 4-27
Reinforced masonry buildings at Keesler Air Force Base; roof damage caused leakage.

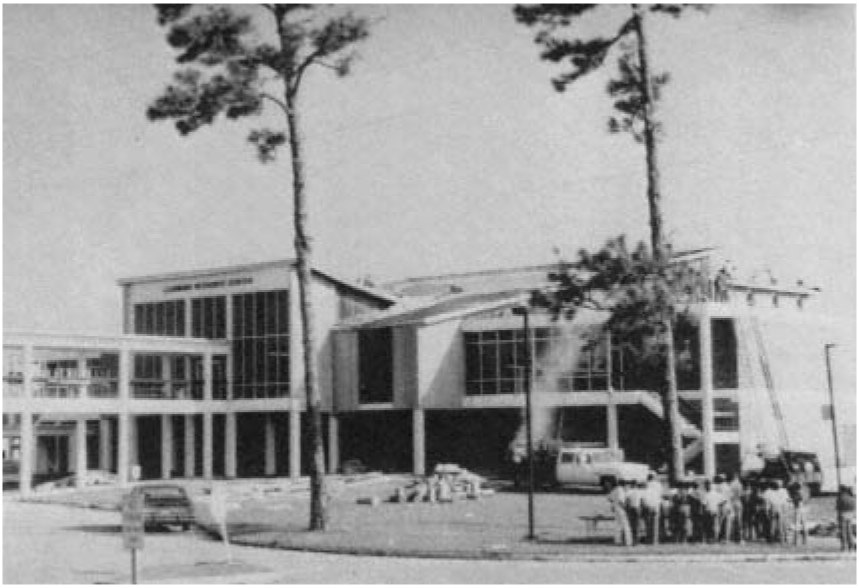

Figure 4-28
Learning Resource Center, Mississippi Gulf Coast Junior College; roof damage.

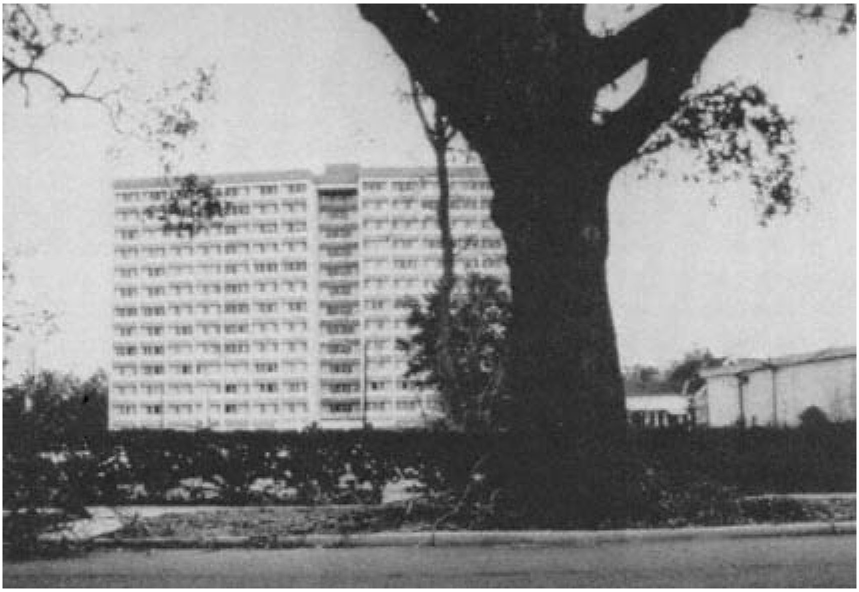

Figure 4-29
High-rise apartment building in Ocean Springs. Building sustained no wind damage.

Figure 4-30
Aerial photograph of Bayou Casotte Industrial Park east of Pascagoula. Only minimal wind damage reported.

Other Structures

A rest area located on either side of Interstate Highway 10 north of Moss Point provided a siting for a large number of open shelters (Figures 4-31, 4-32, and 4-33) consisting of small timber-framed roofs supported on precast concrete columns. The post-and-lintel framing provided little moment resistance either to the bases of the columns (Figure 4-32) or at the roof-to-column connections (Figure 4-33), and all units collapsed in the storm. Despite being rather elaborate structures, they offered little lateral resistance and could well have constituted a hazard to travelers under much less than hurricane-force winds.

Modern highway signs are intended to collapse easily under vehicle impact. They also collapse under strong wind loads (Figure 4-34). Many other signs also collapsed, sometimes causing significant damage to adjacent structures (Figure 4-35). The design of these structures is not a difficult matter, and such failures usually indicate a lack of proper engineering input in the design.

The Broadwater Reach Marina in Biloxi survived this storm and Hurricane Frederic with virtually no damage (Figure 4-36). Although of an unusual shape and in a very exposed location, these relatively heavy concrete-shell roofs had apparently been properly designed to resist the expected wind loads.

Figure 4-31
Collapsed roadside shelter at rest area on Interstate Highway 10 All units failed.

Figure 4-32
Base-to-column connection of shelter of Figure 4-31.

Figure 4-33
Column-to-roof connection of shelter of Figure 4-31.

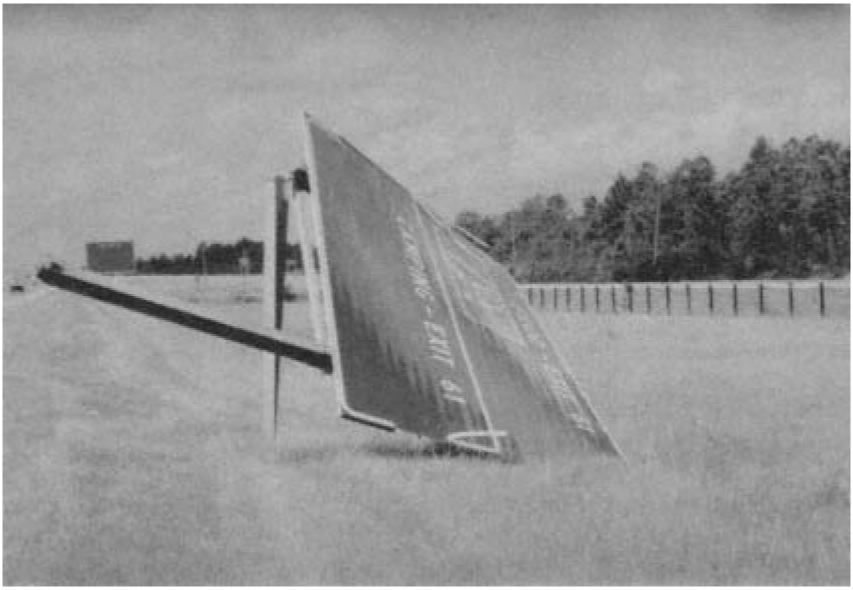

Figure 4-34
Failure of highway sign on Interstate 10.

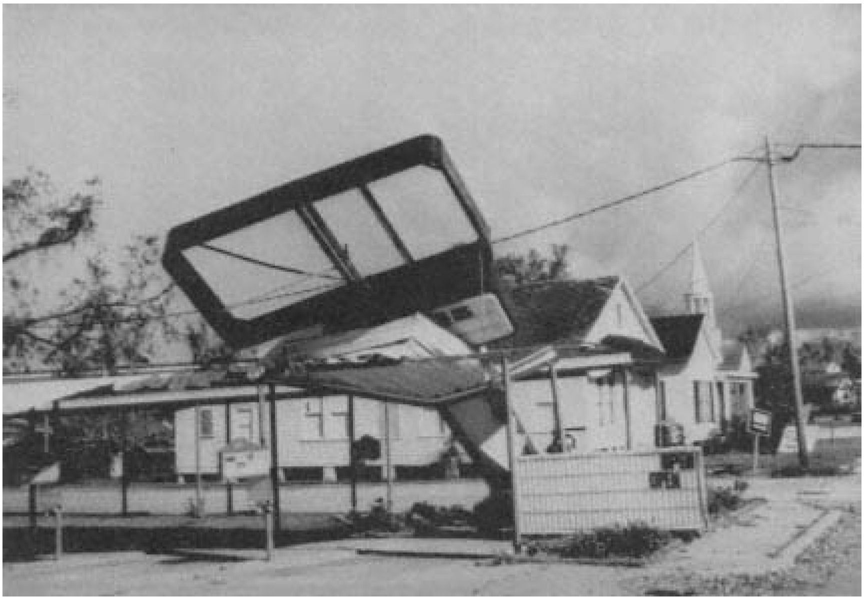

Figure 4-35
Failure of sign in Moss Point.

Figure 4-36
Broadwater-Beach Marina in Biloxi/Gulfport area. Precast concrete shelters sustained no damage.

WIND DAMAGE IN ALABAMA

Most of the damage in Alabama took place on Dauphin Island. Although formed around a hill that became an island when the sea level rose, it contains many of the characteristics of typical barrier islands along the Gulf and Atlantic coasts.

Development of the island began in earnest in 1954 when the Dauphin Island Parkway was constructed, linking the island to the mainland by a bridge. While representing typical topography of coastal islands, Dauphin Island also represents typical forms of construction. Nearly all the buildings on the island are nonengineered. The area is under the jurisdiction of Mobile County, which has adopted the Standard Building Code. Following Hurricane Camille, the county took steps to improve the wind resistance of nonengineered structures.

In wood-framed residential construction, the county requires that hurricane anchors or straps be used to connect each rafter to the top wall plate and that each stud be strapped to a floor joist (Figure 4-37). These regulations, while not the most stringent used by coastal communities, are typical of the regulations used by the more progressive jurisdictions.

On the east end of the island at Fort Gaines, the University of Alabama's Marine Science Program maintains a meteorological station. Although eventually damaged by flying debris, the anemometer at the site appears to have provided

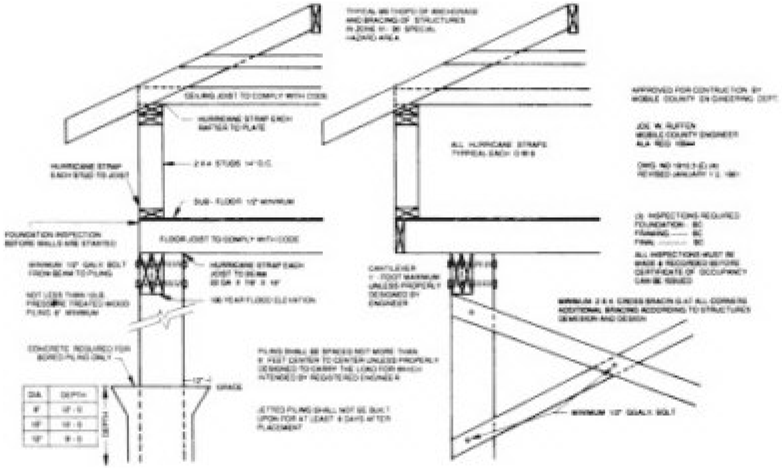

Figure 4-37
Requirements for wood-framed residential construction, Dauphin Island.

reasonably reliable data up to and beyond the peak of the storm. When corrected to standard exposure and height, the record indicated that conditions were probably within 10 percent of the once-in-50-year event as defined by ANSI (1982).

As explained earlier, the Standard Building Code in use at the time of Hurricane Elena actually used the fastest-mile wind speed as a gust wind speed (120 mph for Dauphin Island). The code also did not take into account the higher wind speeds experienced in exposed coastal locations at the anemometer site and on the sand pit to the west of the island. Thus, to compare wind conditions on the island with those specified for design by the Standard Building Code, the peak wind speed, corrected if necessary for height, should be used.

The recorded gust wind speed at the standard height of 33 ft was 122 mph. It is likely that the design wind speed, as defined by the Standard Building Code in effect at the time, was achieved during Hurricane Elena and may have been slightly exceeded at the western end of the island, which was closer to the eye of the storm than the anemometer station.

The design wind speeds on most of the Gulf and South Atlantic coasts are similar to those on Dauphin Island. The performance of various classes of buildings on the island should therefore give good indications of the expected performance in a design storm for many other hurricane-prone areas of the United States.

Single-Family Dwellings

There was virtually no damage to houses in the densely wooded area toward the eastern end of the island. On the more exposed eastern tip of the island, the older military buildings at Fort Gaines, including some dating back to the Spanish-American War, survived with little damage apart from some loss of the waterproof covering of the roofs (Figure 4-38). Newer buildings constructed by the University of Alabama in the style of elevated beach houses suffered only minor vent damage (Figure 4-39).

Virtually all major damage took place in the following exposed areas: (a) the treeless western part of the island, (b) south of the dune line and forest in the center of the island, and (c) on a promontory on the north side of the island that was exposed to easterly winds.

Nevertheless, in these areas many buildings survived with minor shingle damage or no damage at all. These buildings usually had steep-pitched roofs, and many had hipped roofs, including some that probably predated any building control. Nearly all had protected windows, and those that had large porch overhangs had them securely bolted to columns (Figures 4-40 and 4-41).

In some buildings plywood was sucked off the rafters, but this was usu

Figure 4-38
Minor damage to old military building, near Fort Gaines, Dauphin Island.

Figure 4-39
Well-constructed modem building, near Fort Gaines, Dauphin Island.

Figure 4-40
Undamaged older beach house with steep-pitched roof and protected windows, Dauphin Island.

Figure 4-41
Damaged building with low-pitched roof (left) and undamaged A-frame house (right), Dauphin Island.

ally the result of failing to follow the nailing schedule of the Standard Building Code. Note in Figure 4-42 the advantage to be gained by using a hipped roof, in which the areas of high suction are avoided.

Shingles were quite frequently stripped from edges of roofs, again as a result of locally high suctions. Special care is needed in these regions, but an architect or engineer using the Standard Building Code prior to 1986 to specify the uplift requirements would probably have underestimated the need by at least a factor of two.

Glass breakage was common in unprotected windows. In some cases, patio doors were stripped from their mountings, but wood-framed walls generally did not collapse unless the top support provided by the roof was lost. Paneling was sometimes sucked from the corners of buildings.

Major damage and collapse appear to have been restricted to those buildings without hurricane anchors and those using light-duty anchors in which windows or doors had broken or porches had been poorly secured (Figure 4-43). Some recent wind tunnel experiments have shown, in retrospect, that this pattern of damage was to be expected. Based on tests of models of buildings with 24-ft span roofs and 4:12, 6:12, 8:12, and 12:12 gable and hipped roofs, predictions were made (Table 4-6) about the probability of serious damage based on the form of roof-to-wall connection, degree of

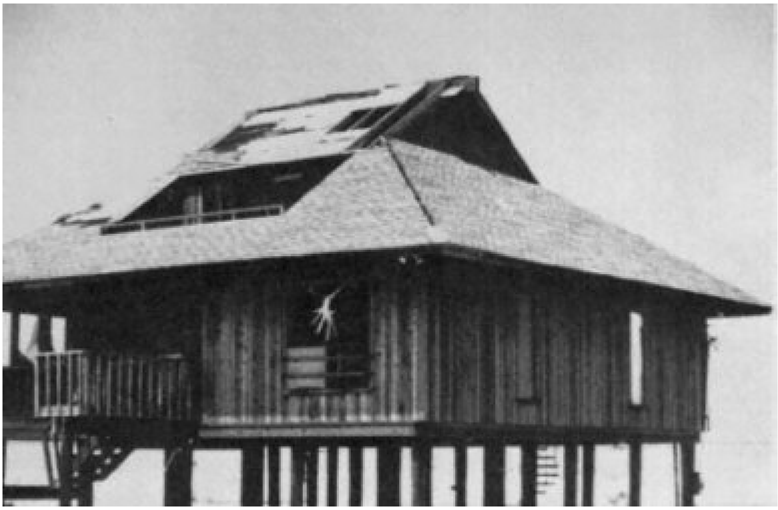

Figure 4-42
Roof damage showing the influence of roof shape, Dauphin Island.

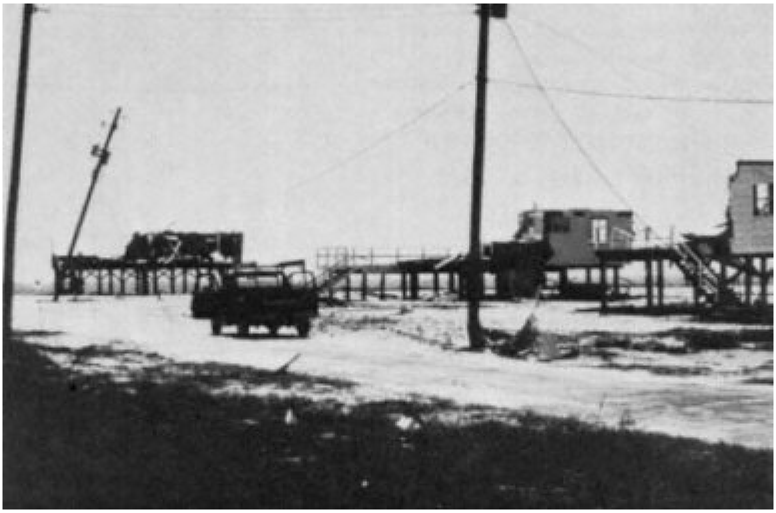

Figure 4-43
Repeated damage patterns in similarly constructed buildings, Dauphin Island.

TABLE 4-6 Risk of Major Structural Damage in a Design Hurricane

	Damage Risk by Structure Type and Class					
	Type 1[b]			Type 2[c]		
Conditions[a]	Class A[d]	Class B[e]	Class C[f]	Class A[d]	Class B[e]	Class C[f]
Sheltered, secured	Low	Low	Low	Low	Low	Low
Sheltered, unsecured	Low	Low	Low	Medium	Low	Low
Open, secured	Low	Low	Low	Medium	Low	Low
Open, unsecured	High	Low	Low	High	Medium	Low
Severe, secured	Low	Low	Low	Medium	Low	Low
Severe, unsecured	High	Low	Low	High	Low/ High	medium

[a] Sheltered—wooded areas, densely packed subdivisions, and centers of towns; open—flat, open country with few obstructions; severe—flat areas adjacent to the sea; secured-windows protected against damage, porches and carports secured against uplift forces; and unsecured—all other buildings with porches and carports or with windows exceeding 5 percent of the wall area.

[b] Type 1—hip roofs with slopes greater than 25 degrees.

[c] Type 2—all other roofs.

[d] Class A—ordinary toenailed connections.

[e] Class B—light-duty hurricane anchors.

[f] Class C—heavy-duty hurricane anchors.

SOURCE: Peter Sparks et al., 1988.

protection of windows, or size of roof overhang and wind exposure (Hessig, 1986; Sparks et al., 1988).

Using the classification in Table 4-6, nearly all older buildings on Dauphin Island would have been class A (using toenailed connections). Mobile County's building regulations do not specify the type of hurricane strap or anchor to be used, but virtually all of the buildings that sustained serious damage used the type of anchor described in class B construction (light-duty hurricane anchors), and this was apparently considered acceptable by the local building inspector.

It is not known on what basis the type of acceptable hurricane anchor was determined. However, a major tightening of regulations came after Hurricane Camille, at which time the South Florida Building Code (SFBC) was widely considered to be superior to the earlier editions of the Standard Building Code (SBC1). It can be seen from Table 4-7 that for a typical single-story house 24 ft by 48 ft, elevated 8 ft above the ground and adjacent to the ocean on Dauphin Island, SBC1 was in fact more appropriate. Furthermore, the amended Standard Building Code (SBC2) dangerously underestimated the forces on steeper-pitched roofs because it ignored the suction generated when the wind is parallel to the ridge of the roof. Fortunately, most buildings on Dauphin Island were not professionally designed. Had they been designed in accordance with SBC2, houses with steeper-pitched roofs would have stood little chance of survival.

The experimental values given at the bottom of Table 4-7 represent the expected upper bound of the forces. They use the measured exterior pressure coefficients from Hessig (1986) and combine them with an internal pressure coefficient for a major windward opening from ANSI (1982). Values for a coastal location as described in ANSI (1982) using both external and internal pressure coefficients from normal and major openings are also given in Table 4-7 (ANSI—fully enclosed and ANSI—partially enclosed). Note that these are considerably larger than those recommended by any of the earlier editions of the Standard Building Code or the SFBC. Using anchors with 500-lb capacity, as suggested by ANSI for normally enclosed buildings, would probably provide sufficient reserve capacity to accommodate the extra force created by the development of a major windward opening.

Anchors generally have capacities in the range of 250 to 350 lb or 500 to

TABLE 4-7 Maximum Roof Anchor Forces (lb)

Roof Pitch	4:12	6:12	8:12	12:12
SBC1	430	419	407	376
SBC2	244	176	80	Compression
SFBC	251	217	211	192
SBC3 (fully enclosed)	398	387	343	291
SBC3 (partially enclosed)	560	552	509	457
ANSI (fully enclosed)	499	474	464	442
ANSI (partially enclosed)	819	766	895	736
Experimental (hip-partially enclosed)	510	560	587	565
Experimental (gable-partially enclosed)	640	730	673	641

600 lb. Clearly, SBC2 or SFBC would permit those with the lower capacity. It is unlikely that such anchors would survive the development of a windward opening. SBC1 and SBC3 would permit only the higher-capacity anchors similar to those required by ANSI.

SBC3 also gives the designer the option of considering the building to be partially enclosed. These values are also given in Table 4-7. Note that these are still lower than the experimental values, but this code uses only 80 percent of the measured values determined by Davenport et al. (1977, 1978) and assumes only flat, open terrain (exposure C).

It must be emphasized that Table 4-7 refers to a rather modest span of 24 ft, with joist spacing of only 16 inches. As land values have risen, beach houses have become larger, and prefabricated trusses spaced at 2 ft on center have become more common. For such a spacing and a 40-ft span, the uplift forces per connection might be as high as 1.5 kips, or more than four times the allowable capacity of a light-duty hurricane anchor. Clearly, something more than an instruction to "hurricane strap each rafter to plate" (Figure 4-37) is required.

The correct design of the roof-to-wall connectors is vital to the integrity of the complete structure. If the roof separates from the walls, complete structural collapse is likely to follow rapidly. In most cases, buildings survived this storm because they had roof-to-wall connections capable of resisting the uplift forces imposed on them. These forces, however, vary considerably depending on the shape of the roof, the weight of the roof, the degree to which the windward wall is open, the size of roof overhangs, and the local wind speed and direction.

Ironically, those structures that failed could probably have been saved had they used anchors of slightly higher capacity or doubled up on the ones used. Compared with the losses sustained, the initial cost would have been negligible. During construction, anchors can be purchased and installed for less than $1.50 each, and the difference between a light-duty anchor and a heavy-duty anchor is a few cents. In most houses there are fewer than 100 connections to be made.

Other Structures

A few other types of buildings did sustain some damage. The Isle Dauphin Country Club lies to the south of the forest cover, among the dunes in an exposed location. The roofing membrane had been removed from most of the buildings. Also, a large portion of a wood roof deck was removed from the most windward building (Figure 4-44) in an area with a large overhang. Figure 4-45 shows a detail of the roof-to-wall connection, clearly unsuitable for the high uplift forces.

To the east of the country club lie two similarly exposed sets of build

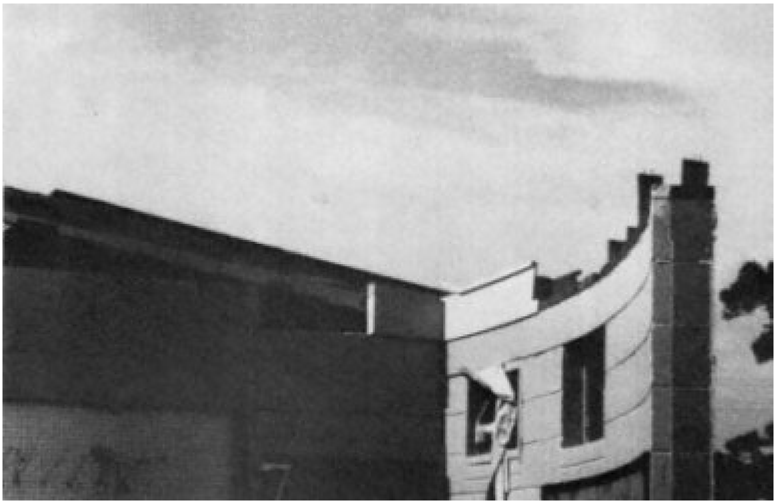

Figure 4-44
Loss of roof, Isle Dauphin Country Club, Dauphin Island.

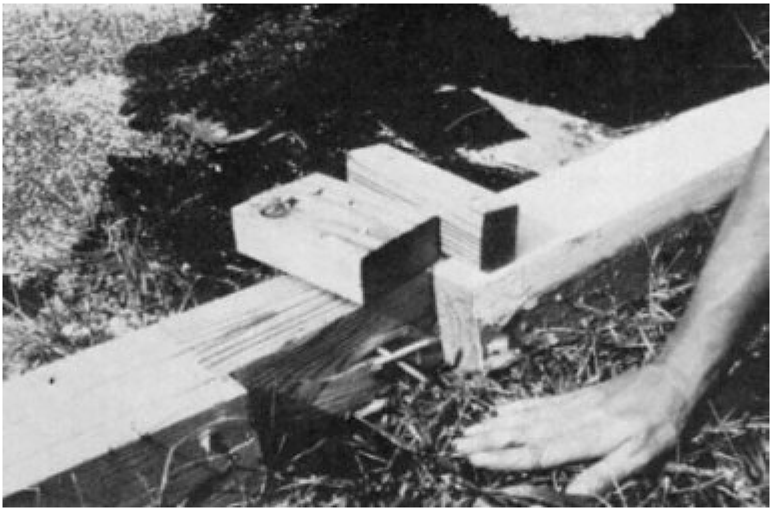

Figure 4-45
Detail of toenailed roof-to-wall connection associated with damaged roof in Figure 4-44.

Figure 4-46
Dauphin Beach Surf Club (left) and Sand Castle Condominiums (right), Dauphin Island.

ings, the Dolphin Surf Beach Club and the Sand Castle Condominiums (Figure 4-46). The former was built about 1970. The buildings are not elevated above the 100-year flood level. Although the high-water mark did not reach the buildings in this storm, they were damaged by water in Hurricane Frederic. Metal straps could be observed tying the roofs to the walls, but the masonry appeared to have been inadequately tied to the stud walls. Similar observations could be made for the upper siding. In one location, the loss of the windward wall precipitated the loss of the the roof.

The Sand Castle Condominiums had just been completed. Figure 4-46 shows the extensive roof damage. The roof trusses had apparently been well secured to the framing system, but the roof sheathing had not been properly nailed to the trusses.

Several reinforced masonry buildings, presumably built in accordance with Corps of Engineers specifications, are located on the easterly tip of the island adjacent to Fort Gaines (Figure 4-47). These buildings survived Hurricanes Camille and Frederic intact, apart from loss of roof coverings. Similar behavior was observed following Elena. The built-up roof was stripped from a high percentage of the buildings by the storm, resulting in water damage to almost all units.

Two preengineered metal buildings were sited near the bridge connecting the island to the mainland. A metal-clad, timber-framed boat storage facility had been completly destroyed in Frederic and was replaced with the preengineered building shown in Figure 4-48. Only superficial damage to cladding was observed, in contrast with the severe damage to the adjacent sign. Of interest is the fact the building had been designed in accordance with the 1974 revisions to the 1973 Standard Building Code (SBC2), but for a wind speed of 120 mph for the cladding and 140 mph for the primary framing; the pressure coefficients selected were based on one wall being open. As seen in Figure 4-48, the walls are free of cladding near the ground. This would have served to prevent any significant increase in internal pressure during the passage of Elena. Other preengineered building was located a short distance from the boat storage facility and experienced minor loss of trim (Figure 4-49).

Considering the damage sustained by many schools on the mainland, it is interesting to note that the small wooden school on Dauphin Island survived with very little damage, as it had in Hurricanes Frederic and Camille (Figure 4-50). Yet, it probably experienced the highest wind speed of any school affected by Elena and probably had the smallest amount of professional input in its design. It did, however, have a fairly heavy, steep-pitched hip roof that generated little if any uplift. This is in stark contrast to the

Figure 4-47
Fort Gaines area showing damage to flat-roofed buildings, Dauphin Island.

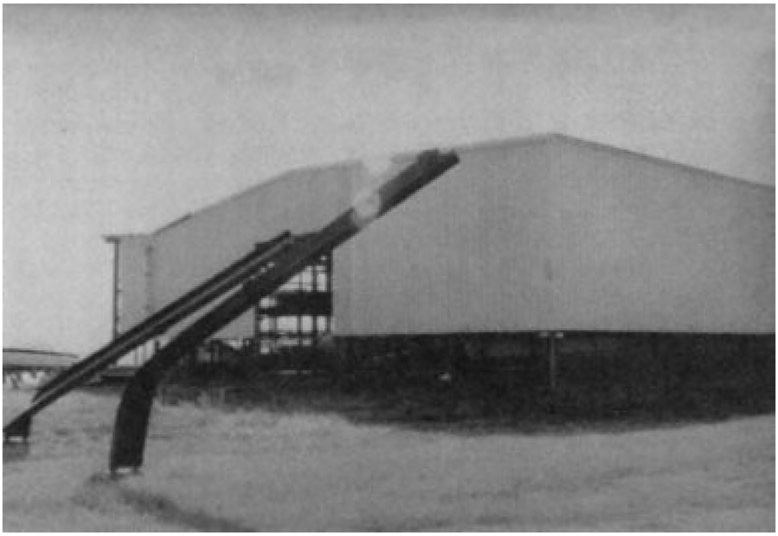

Figure 4-48
This preengineered metal boat storage facility on Dauphin Island suffered only minor damage in Hurricane Elena. (Note damage to sign in foreground.)

Figure 4-49
Undamaged modern metal building, Dauphin Island.
(Note properly designed canopy.)

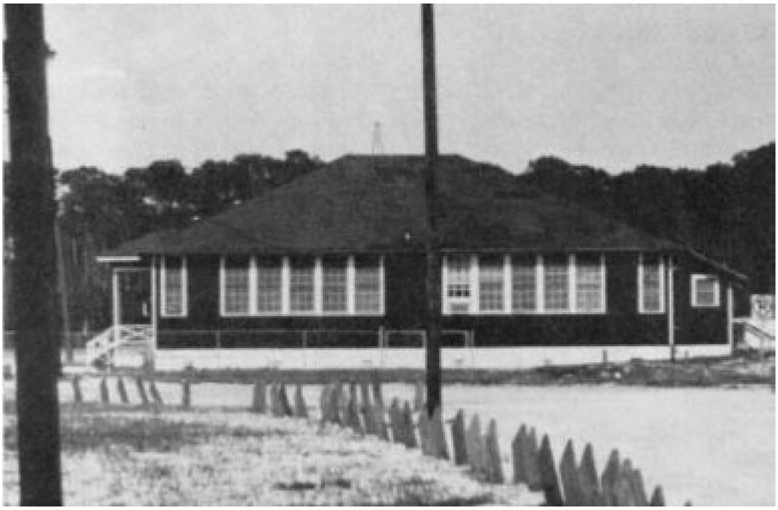

Figure 4-50
Dauphin Island School.

lightweight fiat roofs of the damaged schools that would have been subjected to significant uplift forces.

Comparison with Hurricane Frederic

During the survey, several residents of Dauphin Island reported that many buildings severely damaged by Hurricane Elena had survived Hurricane Frederic with little or no damage. This was confirmed by reference to aerial photographs taken after Hurricane Frederic (U.S. Army Corps of Engineers, 1981).

An analysis of the wind data from the Dauphin Island Bridge by Reinhold and Mehta (1981) determined that the fastest-mile wind speed during Frederic, reduced to started height and exposure, was 106 mph. The fact that very few houses were damaged on the island was considered a triumph of good building regulations.

It therefore appears strange that such extensive damage took place during Elena when the wind speed, reduced to the same averaging time, height, and exposure at Fort Gaines within a few miles of the bridge, was only 96 mph.

As indicated earlier, most of the damage in Elena was on the exposed western end of the island. The eye of Hurricane Frederic passed directly over this area (Figure 1-2), and so it is probable that these buildings did not experience the high winds measured at the bridge. Most of the parts of the island that did experience winds similar to those on the bridge were heavily forested and provided protection to the buildings. Some damage did take place where buildings were exposed.

In contrast, the eye of Hurricane Elena passed offshore, but approximately parallel to the island (Figure 1-2). The exposed western end of the island experienced high winds approaching over the sea for several hours. Thus, although Mobile County had been diligent in requiring hurricane anchors on houses, the difference in the patterns of damage during Frederic and Elena was probably attributable not only to structural factors but also to unusual meteorological and topographical circumstances.

5

Conclusions and Recommendations

POSTDISASTER STUDIES

1. Need for In-Depth Postdisaster Studies

Conclusion: Hurricane Elena struck an area that in recent years had experienced two major hurricanes (Camille in 1969 and Frederic in 1979). The hurricane threat was well recognized by the local communities, which believed they had taken steps to prepare for such events through the use of NWS forecasts, evacuation planning, and appropriate building codes. Forecasting and evacuation efforts appear to have been fairly successful, but there was a considerable amount of wind damage to buildings and other structures.

The present report has attempted a more detailed analysis of the causes of structural failures than has been attempted in the past. Since similar design conditions and building control procedures exist along hurricane-prone coasts from Texas to South Carolina (with the exception of South Florida), the conclusions drawn from such a detailed study of performance in Elena were considered to be relevant to a very large number of buildings.

Unfortunately, funds for such detailed studies are not usually available—a situation that has been strongly criticized by the engineering community, especially considering the influence that such in-depth investigations can have on the safety and reliability of future buildings. In the case of the present report, the detailed work required was undertaken outside of normal funding procedures at the initiative of the study team—clearly not an ideal process.

Recommendation: The federal or state governments, possibly supported by insurance companies and code bodies, should establish properly funded study teams that can conduct investigations of hurricane and tornado damage. These teams should have access to structural testing facilities and wind tunnels and should operate in a manner similar to air crash investigation teams.

WIND CONDITIONS

2. Better Wind-Speed Data

Conclusion: On the basis of aircraft-measured wind speeds and damage observations, the NWS estimated that the maximum surface wind speed in Hurricane Elena, averaged over 1 minute, was 127 mph. Analysis of surface wind speed measurements at landfall suggests that the 1-minute average probably did not exceed 100 mph over the ocean and 90 mph a short distance inland.

The NWS relies very heavily on the Saffir-Simpson scale to relate damage to wind speed. Whenever a detailed analysis of wind speed data is made, as in this case, the estimates based on surface measurements are much lower than those estimated from the Saffir-Simpson scale and by the procedures used by the NWS to convert aircraft measured wind speeds to surface wind speeds. In most cases it has been found that the maximum 1-minute sustained winds reported by the NWS are fairly close to the maximum 2-to 3-second gusts measured near the shoreline.

The speeds reported by the NWS are widely accepted by the press and the public and sometimes find their way into technical reports. Their use gives an inflated impression of the severity of a storm in relation to the conditions used for the design of buildings and other structures.

Clearly, the forecasting role of the NWS has taken precedence over its role as archivist of all important storm data. Since the NWS has a very limited number of anemometer sites along the hurricane-prone coasts, rarely attempts to collect and analyze data from other anemometers, and places its faith in the Saffir-Simpson scale, there has been an erosion of confidence in some quarters of the engineering and meteorological communities in the agency's ability to maintain accurate records of hurricanes. It should be noted that the paucity of good surface-level wind data is not peculiar to the Gulf Coast but is a problem that plagues the nation as a whole.

Much of the current difficulty stems from the lack of adequate funds to fulfill both the NWS's forecasting and record-keeping missions. Moreover, the two communities served by these missions—meteorologists and wind engineers—often have different needs and often do not communicate well with each other. Data that may be entirely adequate for meteorological purposes such as forecasting hurricane movements may be grossly inadequate for detailed engineering studies.

Nor is there much hope of significant progress in this area under the current budgetary restrictions, even though all parties agree that a reliable wind record would be of immense value. Marginal improvement may come when additional data collection stations come on line in the 1990s as part of the NWS's Automated Surface Observing System (ASOS), but the number of new data points will be very limited. (ASOS will ultimately consist of 1,500 sites around the country, each containing an anemometer and a host of other weather-observing instruments.)

The installation of NEXRAD—NWS's advanced weather radar facilities that are scheduled to be introduced in the early 1990s—should help improve NWS's wind data by providing quantitative information on boundary layer winds within 80 miles of each NEXRAD facility. However, such information is far from the direct and accurate measurement of ground-level winds needed by the engineering and meteorological communities.

Recommendation 1: Representatives of the primary users of wind-speed data and senior administrators of the NWS should meet to resolve the problems associated with obtaining accurate ground-level wind-speed data. In particular, it is recommended that NWS—or another appropriate agency, such as the National Institute of Standards and Technology—take responsibility for collecting and analyzing anemometer records. To increase the accuracy of these data, the following steps are recommended:

(a) The ocean data buoy network should be expanded to permit adequate documentation of both hurricane wind speeds and sea conditions.
(b) Inexpensive, portable instrumentation should be developed that could be dropped from reconnaissance aircraft to obtain sea-or ground-level winds.
(c) Inexpensive and perhaps portable land-based anemometer stations should be located along the hurricane-prone coastline and activated during periods of high winds.
(d) The NWS and other organizations that currently possess anemometers (such as the military or local police and fire stations) should be encouraged to standardize their anemometer height and data format to comply with the recommendation of the World Meteorological Organization.
(e) Each NWS station should maintain a list of reliable anemometers in its area together with correction factors to convert data obtained from them to standard conditions.

Recommendation 2: The procedures used to estimate wind speeds using damage observations should be carefully reviewed by the NWS and wind engineers. Until this is done it is recommended that the wind speeds in both the Saffir-Simpson scale and the Fujita Scale be taken as 2-to 3-second gusts.

OTHER NATIONAL WEATHER SERVICE ACTIVITIES

3. Continued Cooperation between NHC and the Local and National Media

Conclusion: The local and national media provided widespread coverage of Hurricane Elena. Many of the broadcasts originated from the National Hurricane Center, with assistance from NOAA Public Affairs in coordinating the effort. This resulted in an extremely high level of awareness by the public, which, in turn, led to a rapid response during the massive evacuation.

Recommendation: The media should receive continued encouragement from the NWS to make live broadcasts from the NHC. In addition, it is imperative that NOAA Public Affairs continue to coordinate the media activities at the NHC in order to ensure smooth operations. Such NOAA assistance would be required only during significant landfalling hurricanes that will impact the United States.

4. Use of Amateur Radio and Hurricane Drills

Conclusion: Amateur radio was employed for emergency communications in many areas threatened by Elena. Valuable information concerning weather conditions, property damage, and needs for assistance were passed to the NWS and emergency management officials in a timely manner by these amateur radio operators.

Recommendation: The NWS should continue to avail itself of the skills offered by amateur radio operators in emergencies to the full extent allowed by law. In fact, the use of amateur radio communication during hurricane emergencies should be expanded to the greatest extent possible. It is also recommended that hurricane drills be held annually with the various amateur radio hurricane networks.

5. Need for Improvement of Numerical Forecast Models

Conclusion: Forecasts during Hurricane Elena derived from the three different NWS numerical forecast models showed considerable differences, especially at the time three critical changes in direction of movement of the hurricane occurred. The consequence of the different forecasts from the three numerical models was a loss of confidence by NHC forecasters.

Recommendation: The National Meteorological Center should continue to make increased efforts to improve its ability to analyze and forecast tropical cyclones. This should include improvement in accuracy as well as a single unified forecast presentation for use by NHC.

6. Continued Effective Use of Telephone Hurricane Information Service

Conclusion: The NOAA, AT&T, and NBC telephone hurricane information service, 1-900-410-NOAA, generated over 64,000 calls and 133,500 call minutes during Hurricane Elena. This provided an excellent source of information for the public during this hurricane.

Recommendation: The NOAA, AT&T, and NBC hurricane information service was useful and cost-effective and should be continued.

7. Need for Quick Information Dissemination from SLOSH Runs

Conclusion: The NWS Sea-Lake-Overland Surge from Hurricanes (SLOSH) storm-surge prediction model accurately forecasted the storm surge for this storm. The SLOSH model was used operationally during this storm to anticipate the potential impact on each section of the coast that was threatened. These scenarios proved valuable for planning purposes by local emergency management officials. However, the model is sensitive to hurricane path, and it proved difficult to quickly provide accurate information to local emergency managers.

Recommendation: NWS and FEMA should explore methods for dissemihating information from SLOSH runs quickly to local emergency managers.

THE EVACUATION PROCESS

8. Incorporation of Forecast Uncertainties in Evacuation Planning

Conclusion: Watches and warnings issued by the NHC are insufficient bases for determining the timing of evacuation notices, yet many government agencies rely upon them almost exclusively for actual decision making.

Recommendation: State and local officials need to make systematic use of threat information provided by the NHC in marine advisories. However, because of the imperfection of forecasts included in marine advisories, agencies also need to incorporate into their decision-making processes ways of recognizing the uncertainty in the forecasts (with regard to hurricane track, forward speed, and severity) and employing that information in assessing the threat.

9. Need for Multiagency Hurricane Evacuation Studies

Conclusion: The multiagency hurricane evacuation studies for both the Tampa Bay and tristate areas proved to be useful for local emergency management officials during Hurricane Elena.

Recommendation: The federal government should continue to support hurricane evacuation studies and to encourage the initiation of studies in those coastal areas where none exist.

10. Hypothetical Behavioral Assumptions Underlying Evacuation Plans

Conclusion: Behavioral assumptions underlying evacuation plans are often based upon hypothetical surveys with area residents. As demonstrated in parts of the Gulf Coast evacuated in Elena, hypothetical surveys alone are invalid for projecting how people will actually behave during hurricane threats.

Recommendation: Behavioral assumptions regarding evacuation should be based primarily upon empirical studies of actual response patterns in past hurricane threats. Generalizations about such patterns can be applied to locations where no evacuation has occurred by matching site, demographic, and response plan characteristics of individual locations to those observed in other places. Evacuation responses will vary from threat to threat in the same location, and responses documented in one evacuation should not necessarily be used for general planning. Hypothetical response surveys have extremely limited utility and should not be used as literal indications of actual response.

11. Calculation of Clearance Time in Evacuation Studies

Conclusion: Clearance times calculated in regional evacuation studies prior to Elena matched times estimated in Elena in some locations, but not in others. Actual clearance times will vary from storm to storm, as public response, actions by public officials, and other factors vary. Further, clearance time calculations are potentially of great value during response decision making but are not yet fully utilized. Clearance time calculations and shelter demand projections can vary, depending upon whether adjacent counties are evacuating.

Recommendation 1: As a part of regional evacuation studies, a variety of scenarios should be modeled—including optimistic ones—to maximize the value of these studies to state and local officials during planning and real-time decision making.

Recommendation 2: Clearance times should be incorporated systematically into structured decision systems employing marine advisory forecasts and other threat information.

Recommendation 3: Studies should vary their assumptions regarding local evacuation patterns in order to assess the impact of such variance in findings, including the shelter demand projections.

PERFORMANCE OF BUILDINGS AND OTHER STRUCTURES

12. Need for Nationally Applicable Wind-Loading Provisions

Conclusion: There has been concern about the adequacy of building codes and their enforcement with regard to wind resistance. When structural failures were not blamed on excessive—and unsubstantiated—wind speeds, the blame was usually attributed to poor enforcement. While poor enforcement may have had some bearing on the quality of construction affected by Elena, the present study has shown that much of the blame must lie with the building code itself. The failure of the Standard Building Code to incorporate adequate wind-load specifications and consistent construction requirements can be traced to the democratic manner in which code changes are made. Although this is a highly controversial issue, it would appear that the lack of a properly prepared national building code of the type used in most other developed countries has hindered the incorporation of up-to-date wind-loading provisions and consistent structural requirements.

Recommendation 1: Since a national building code is unlikely in the foreseeable future, it is recommended that all model and local building codes adopt the American National Standard A58.1 for the specification of wind and other loads.

Recommendation 2: Building codes should be checked to ensure that any prescriptive provisions regarding structural details are consistent with their wind-loading provisions. This is not the case at present with the Standard Building Code or the Uniform Building Code, although steps are being taken to remedy this.

13. Design Needs for Nonengineered Structures

Conclusion: As it stands at the moment, it is virtually impossible for a contractor or a building official to determine whether a nonengineered building is in compliance with the wind-loading provisions of the Standard Building Code. Some form of engineering input must be used in the determination of the structural form of buildings that are not professionally designed. The traditional manner of doing this is to adopt prescriptive requirements that are deemed to comply with the performance requirements of the code. Some of these are now being prepared for use with the Standard Building Code. These deemed-to-comply standards must be based on accurate wind-force determination. The Standard Building Code's present wind-loading provisions assume that all low-rise buildings are in open country away from the sea. In fact, very few nonengineered buildings in hurricane-prone areas are in such a location. Some are in open country adjacent to the sea (where the Standard Building Code underestimates the wind loads), but the majority are in forests or subdivisions (where it overestimates the wind loads).

The deemed-to-comply standards for wood-framed houses, now being issued by the Standard Building Code, are not being well received, because they require radical and expensive changes to traditional forms of construction. Such changes are certainly required for buildings located adjacent to the sea; but it was observed in Elena that houses in forests and densely packed subdivisions performed perfectly well with, at most, the addition of hurricane anchors to attach the roof to the walls. The use of ANSI A58.1 to define the wind loads would enable the exposure conditions to be considered and sensible deemed-to-comply standards to be prepared.

An alternative procedure to the use of these standards has been introduced recently that enables the structural requirements for individual wood-framed houses to be determined. It is a microcomputer-based expert system (Sparks and Singh, 1989). The program uses ANSI A58.1 to determine the wind loads on the structure and checks to see if the structure can be built in accordance with a commonly used prescriptive code (Council of American Building Officials [CABO], 1986). If there is insufficient load capacity, recommendations for ties, anchors, and shear walls are made.

Recommendation 1: Deemed-to-comply standards should be prepared for nonengineered structures using realistic wind-loading requirements and incorporated into building codes.

Recommendation 2: The use of computer-based building codes and expert systems should be explored as a means of designing and checking nonengineered structures.

14. Need for Design Checks of Professionally Designed Buildings

Conclusion: Without making any independent structural checks, building officials usually accept that professionally designed buildings are in compliance with the prevailing building code. This has led to unsatisfactory construction, particularly in low-rise buildings.

Part of this problem arises from the use of empirical design procedures for wood and masonry included in the Standard Building Code. Some of these are inconsistent with the wind-loading provisions of the code. However, in some instances, it would appear that architects or engineers have failed to recognize the effect of wind forces on the structural systems they are designing.

Recommendation: If local jurisdictions are unable or unwilling to provide building officials with the resources to make checks on the wind resistance of professionally designed structures, structural review panels or individual consultants should be employed to review the designs. This is a practice used extensively outside the United States.

15. Insurance against Wind Damage

Conclusion: It is usually assumed by insurers, the general public, and emergency management officials that the issuance of a certificate of occupancy by a building official means that a building is able to withstand, with a reasonable factor of safety, the wind loads specified in the locally enforced building code. Structural failures in storms are therefore attributed to excessive wind speeds. Hence it is reasoned that to reduce insured losses the design wind speed must be raised. Some states have attempted to raise design wind speeds that would appear to have a mean recurrence interval of more than 2,000 years. Yet, even if the design wind speed had been raised to such a level on the Mississippi and Alabama coasts following Hurricane Camille, it is unlikely that the extent and nature of the damage caused by Elena would have been significantly different from that actually encountered, since the design wind speed had very little bearing on the structural form of many of the damaged buildings. However, properly engineered buildings would have been considerably more expensive.

The Federal Flood Insurance Program has shown that insurance can have a beneficial effect on the form of construction used in an area. A similar scheme for wind insurance could have saved many of the buildings in Elena. However, wind insurance is in the hands of private companies and state catastrophe pools, which rely on the building code system to ensure structural adequacy. For certain types of buildings, this system has not performed well.

Recommendation 1: If the building code system cannot be reformed, the federal government or private insurance companies should consider imposing their own regulations or, at the very minimum, using insurance rates that reflect the risk of wind damage.

Recommendation 2: State officials and others concerned with reducing wind damage should consult wind engineering experts concerning the causes of wind damage before proposing legislation or regulations.

16. Concern about Industry Standards

Conclusion: Many industry standards adopted by reference by the Standard Building Code show a very poor appreciation for the effects of wind loads on structures. Most use factors of safety that are lower for wind loads than other loads and in some cases contain empirical design rules that are likely to result in dangerously unsafe structures, for example, the recently adopted ACI-ASCE proposed masonry standard (American Concrete Institute-American Society of Civil Engineers, 1988). (For more detailed discussion of this document see Sparks and Saffir, 1989.)

Recommendation 1: Wind-engineering experts should make a thorough review of the standards adopted by reference in building codes to check their adequacy.

Recommendation 2: Wind-engineering experts should be consulted during the preparation of standards that have an influence on wind resistance, particularly those that contain empirical design rules.

17. Concern about Using School Buildings as Shelters

Conclusion: The extremely poor performance of school buildings calls into question the frequent use of these structures as evacuation shelters.

Recommendation 1: The design of future schools should be checked for structural adequacy, and frequent inspections should be made during construction. This will require significant changes in the present inadequate control process.

Recommendation 2: Existing schools and other buildings designated as evacuation shelters should be checked to ensure that they are able to carry the wind loads specified in ANSI A58.1. Particular attention should be paid to roofing systems and their anchorage to exterior walls. This should be given high priority by emergency planning coordinators along the entire hurricane-prone coastline of the United States. If insufficient public buildings are available to act as shelters, it may be necessary to consider the use of privately owned buildings.

18. Concern about Preengineered and Masonry-Walled Buildings

Conclusion: Preengineered buildings fabricated, marketed, and erected in the "design-build mode" continue to present a problem in that the design and reliability of various components not supplied by the manufacturer (doors, facade, glazing, and foundation details) may be lost to the engineer who designed the building. Similar comments can be made regarding the glazing and doors of masonry-walled buildings using light roofs.

Recommendation 1: Building officials should make every attempt to ensure that all components and details of such preengineered buildings satisfy appropriate wind-load criteria. If components cannot meet the wind loading requirements, the buildings should be designed as partially enclosed.

Recommendation 2: If buildings are designed as enclosed, checks should be made to ensure that collapse will not occur if a component, such as a window, is accidentally damaged by flying debris. Particular attention should be paid to masonry-walled buildings with light roofs and preengineered metal buildings that contain few interior partitions. Such systems are sensitive to internal wind pressure, often lack structural redundancy, and are prone to progressive collapse.

19. Roof Performance

Conclusion: The performance of the roof coverings of otherwise fully engineered buildings continues to be inadequate. The inability of many coverings to maintain watertightness during storms frequently results in damage to building contents and business interruption costs. Additionally, roof coverings that separate from the structure and become airborne provide the largest source of windborne debris, which, in turn, results in an increase in risk to human safety as well as the potential for compromising other structures and property downstream.

Recommendation: Roof systems and testing procedures should be developed that reflect the high suctions experienced by low-pitched and flat roofs in hurricanes.

20. Performance of Signs and Building Appurtenances

Conclusion: Historically, building codes and standards have mostly neglected signs and building appurtenances. While the performance of highway signs has improved, such has not been the case for commercial signs adjacent to shopping malls and residential areas, where the failure of such signs provides a high hazard to life and property.

Recommendation: Code bodies should take the lead in developing more realistic provisions for signs. Additional wind tunnel testing may be necessary.

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Appendix A

STRUCTURAL FAILURES IN MISSISSIPPI SCHOOLS

The following are damage descriptions for the more serious structural failures in Mississippi schools during Hurricane Elena.

Pascagoula Vocational High School Annex The annex was exposed to winds from the east. A failure of a windward window appears to have precipitated the removal of the metal deck roof system (Figure A-1). The bar joists supporting the roof had not been securely attached to the top of the wall; indeed, some appeared to have simply rested on the walls (Figure A-2).

Pascagoula High School Gymnasium Sunscreens broke loose and smashed the windows, leading to the removal of the compressed wood—fiber (form-board) roof decking.

Gautier Junior High School An otherwise well-designed modern school suffered roof damage and the collapse of an in-fill wall of the gymnasium. damage occurred in this area, so the building may have been subjected to uncharacteristically high winds resulting perhaps from a tornado.

Dukate Elementary School, Biloxi This school suffered serious damage from northerly winds. A flat-roofed portion of the school experienced failure (Figure A-3). The gymnasium had a steel-framed gable roof. However, winds from the north would have subjected this roof to suctions similar to those of a flat roof. Either the roof-to-wall connection failed and then the walls, lacking top support, collapsed into the gymnasium or a wall collapsed first, exposing the roof to additional internal pressure. There was evidence that the wall reinforcement lacked continuity, and the small bar joists seen hanging from the first steel frame in Figure A-4 appeared to be of insuffi

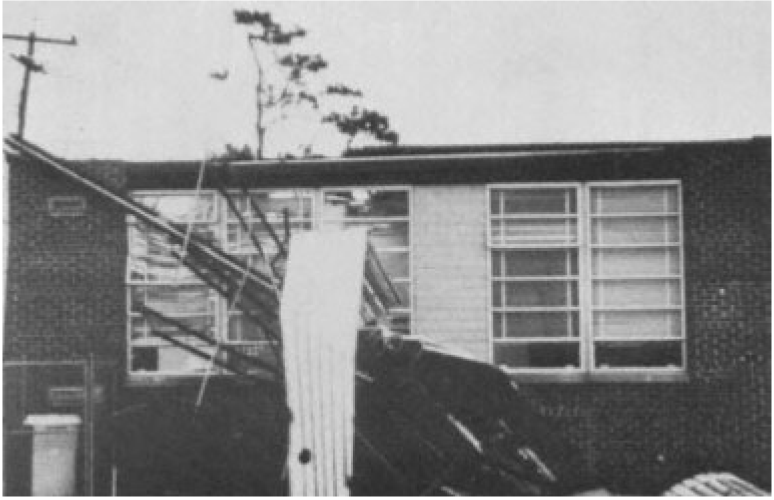

Figure A-1
Loss of metal roof deck—Pascagoula Vocational High School.

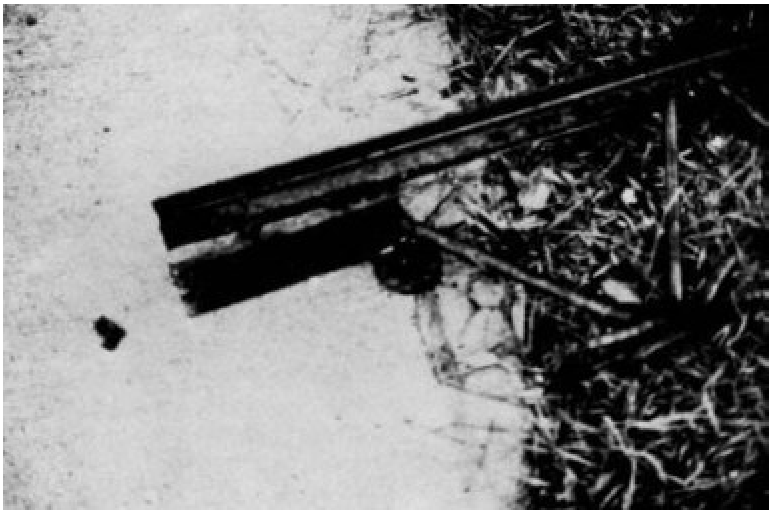

Figure A-2
Bar joist-wall connection—Pascagoula Vocational High School.

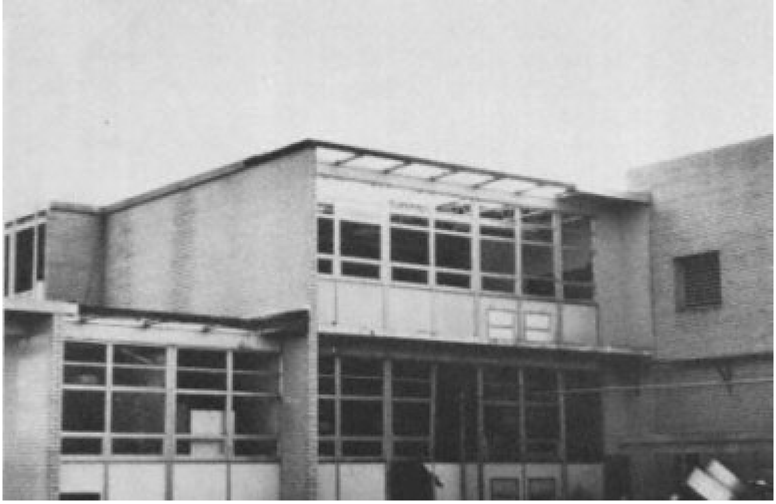

Figure A-3
Window and roof damage at Dukate Elementary School, Biloxi.

Figure A-4
Collapse of gymnasium at Dukate Elementary School, Biloxi.

cient size to brace the top of the wall properly. An older part of the school and adjacent wood-frame houses were virtually undamaged.

Fernwood Junior High School, Biloxi An old masonry chimney crashed through the roof of a classroom. Another wing of the building was being used as a shelter at the time.

Central Elementary School and West Elementary School, Gulfport These two schools, approximately 5 miles apart, possessed identical gymnasia oriented in similar directions with similar exposures. They failed at approximately the same time and in the same manner (see Figure A-5 and A-6). The wood roof decking had been attached to the top chord of the roof trusses by toenailed connections to a nailer attached to the chord of the steel trusses. The windows in the upper part of the wall of both buildings had blown in. If this had taken place before the roof failure, it would certainly have resulted in an increased upward wind load on the roof. Both buildings were being used as evacuation centers. Central Elementary School suffered serious roof damage in other parts of the school as well, causing considerable alarm to the occupants and extensive flooding of the building. At the West Elementary School, the damage was considered sufficient to necessitate the evacuation of the occupants by armored personnel carriers to the nearby naval base.

Building codes in use throughout the United States State do not prescribe the actual combination of loads to be used in the design of strut purlins. This is

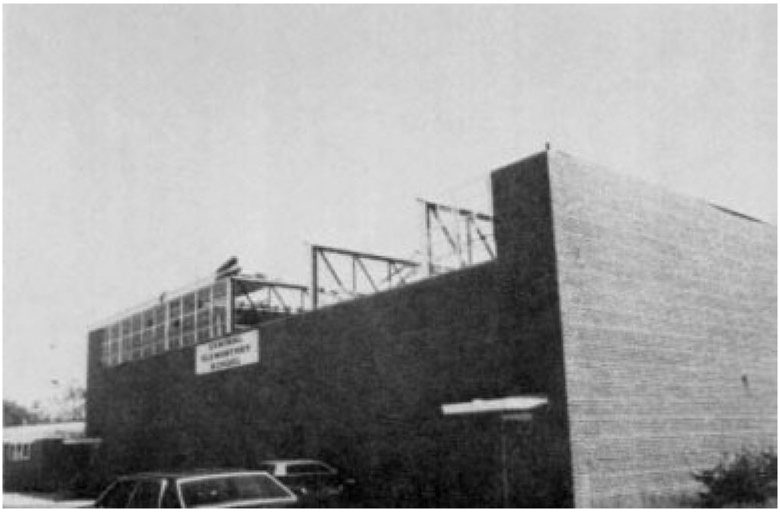

Figure A-5
Gymnasium damage, Central Elementary School, Gulfport.

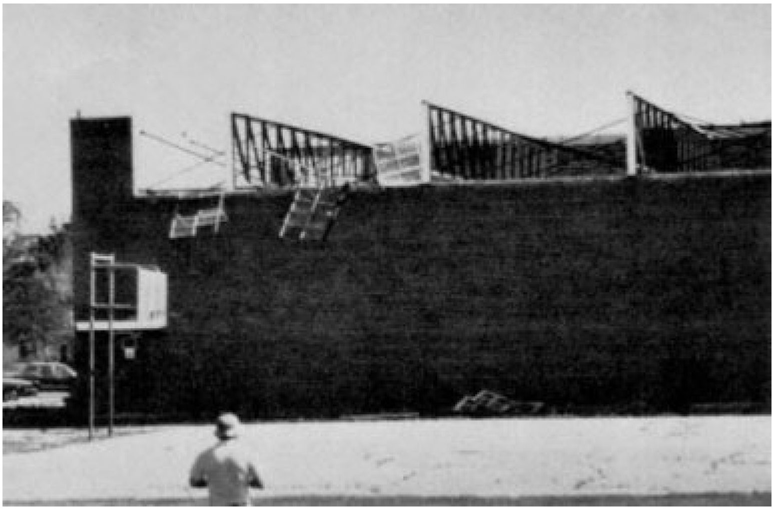

Figure A-6
Gymnasium damage, West Elementary School, Gulfport.

because the appropriate data base has not yet been established from wind tunnel tests. The most recent edition of the low-rise design manual for the metal building industry (MBMA, 1986) provides a caveat with regard to this design application but does not specify the loadings to be considered. Engineering judgment is required. One approach would be to consider a worst-case scenario in which the required axial lead is assessed on the basis of main-framing coefficients: coupled with bending lead prescribed from coefficients given for components and cladding. As the two effects do not occur for the same wind azimuth in this case, the approach would appear to be conservative. Perhaps a more realistic scheme would be to consider two lead cases:

- axial and bending effects based on main-framing coefficients, and
- bending alone based on component and cladding provisions.

Hopefully, wind tunnel researchers will address this problem in the near future. It should be noted that this is only one of many design applications not specifically addressed in codes in which an element or structural assemblage is required to resist both main-framing and high, localized loads.

Appendix B

SHOPPING CENTER DAMAGE: A DETAILED ANALYSIS

Elena inflicted extensive damage on many commercial structures along the Mississippi Gulf Coast. Notable examples were the Jackson Square shopping center in Gautier and the Sears Towne shopping center in Pascagoula. At Jackson Square, sections of the roof membrane were removed, as well as sections of the decking. In one location, the bar joists failed and the wall collapsed. This wall was reinforced with steel columns whose hold-down bolts failed in tension. The failed bar joists were undoubtedly improperly anchored into the top of the wall, but the lower flange of the joists also buckled.

These roofs would have been designed for a live lead of no more than 20 lb/ft^2, and the dead lead was probably less than 5 lb/ft^2. In carrying this lead the compression flange of the joists would have been braced by the decking.

The roof should also have been designed for a wind uplift of either 24 or 29 lb/ft^2, depending on whether a 110 or 120 mph design wind speed was used. The net upward force would thus be of the same order as the net downward lead, but the upward lead must be resisted using a compression flange braced by very lightweight bridging, and the supports must act in tension, not compression. Since these forces include the effect of wind, the allowable stresses would probably have been increased by one-third and may have led the designer to consider the net downward lead as the critical loading case.

Using the present version of the Standard Building Code, these bar joists should have been designed on the basis of 32 lb/ft^2 for normal internal pressure, or 40 lb/ft^2 if the designer had recognized the danger of window damage. Since this building was very exposed and the actual wind speed was probably within 10 percent of the design wind speed, the uplift could well have been about 35 to 40 lb/ft^2, or 30 to 50 percent more than the design level. Since these roofs were probably also designed using the 33 percent increase in allowable stress, it was not at all surprising that this structure failed.

The damaged wall was probably designed on the basis of 26 or 32 lb/ft^2, again depending on the wind speed chosen. The present code would require 28 lb/ft^2. However, the loss of top support would have had the same effect as increasing the wind pressure to more than 100 lb/ft^2. Again, it is not surprising that the component failed.

Similar conclusions can be drawn from the failure of the Sears Towne shopping center in Pascagoula. It is interesting to note that roof failures took place in both instances on the edge nearest the parking lot, adjacent to the glazed wall, but in Jackson Square the damage was caused by north winds and in Pascagoula from southeast winds.

At Sears Towne, the parking lot contained much loose gravel. A large amount was found inside the buildings, suggesting that it had been picked up by storm winds and had smashed the windows, probably precipitating the roof failure.

In a tire store, the bar joists had been laid parallel to the glazed wall. When this failed, the high uplift on the leading edge of the roof was carried primarily by one bar joist. When the connection between the joist and the wall failed, the roof simply rolled back. The joists had been welded to plates set in the top of the wall. Separation occurred at the weld.

The Steel Joist Institute recommends the use of 1-inch-long welding at this point. Assuming a 1/4-inch fillet weld, the joint should have an uplift capacity of at least 12 kips. Even allowing for high internal pressures and full design wind speed, it is unlikely that the uplift load at the joint would have exceeded 3 kips. Since the wind speed would have had to exceed 200 mph to have produced pressure that exceeded the capacity of a properly constructed joint, one can only conclude that the welds did not meet the specification.

Another interesting feature at the shopping center was the failure of an unreinforced masonry wall in an area of high suction between two buildings. Unreinforced block walls 18 to 20 ft high are often found in this type of shopping center. They are considered acceptable because they meet the slenderness ratios given in the Standard Building Code. They cannot, however, be shown by any engineering calculation to meet the wind-loading requirements of the code of a single-story building on a hurricane-prone coast. In this case, the wall was not properly supported at the roof-to-wall connection. Indeed, failure appears to have been initiated in that region.

Appendix C

DAMAGE TO METAL BUILDINGS: A DETAILED ANALYSIS

Most of the observed damage to metal buildings can be grouped into the following categories, in order of their frequency of occurrence:

1. overhead door failures,
2. canopy failures,
3. damage to steel/masonry facade interface,
4. omission of bracing by contractor,
5. improper anchorage of columns,
6. strut purlin failures leading to catastrophic collapse of the end bay of the building.

The first five items have proved troublesome to the metal building industry from the very beginning; however, the cause is easily identified. Perhaps the most important factor that sets the preengineered metal building apart from the other forms of low-rise construction is the manner in which the product is engineered, fabricated, marketed, sold, and erected. Early on, the industry developed a method of doing business in which the building is sold, not directly to a customer, but through a franchised builder who usually acts as a general contractor providing erection service as well. Thus, on the positive side, design, drafting, and fabrication take place under the same "roof" and enable the manufacturer to "fine tune" engineering design and fabrication to achieve the optimum economy consistent with reliability. On the negative side, however, control over the design of components not supplied by the manufacturer (e.g., doors, facade, glazing, foundation details) and erection procedures in some cases may be lost to the engineer who designed the building.

The last item (failure of strut purlins) has been addressed in the industry's new design manual (Metal Building Manufacturers Association, 1986), and hopefully the problem will soon be eliminated. Unfortunately, current building codes remain silent as to the correct combination of loads to be considered in the design of these structural elements.

Overhead Door Failures With the exception of large sliding doors for aircraft hangars, most doors used with metal buildings are not supplied or designed by the manufacturer. Historically, the performance of large overhead doors during severe winds has been poor. Building codes clearly require doors to provide the same wind resistance as components and cladding. Regrettably, experience tells us many builders knowingly, or unknowingly, disregard this requirement. In their defense it should be noted that, at present, no recognized standard test procedure exists to ascertain wind resistance of large door assemblages.

Recent research (Vickery et al., 1984) has served to quantify the role of internal pressure that may significantly increase the net uplift on the roof or outward loads on side walls (see Figure 4-20). Failures of doors enclosing areas of as little as 1 to 5 percent of the area of a windward wall may be sufficient to produce extreme internal pressure fluctuations. The 1982 alternative procedure of the Standard Building Code attempted to come to grips with this problem through provisions for "partially enclosed" buildings, although experience suggests these provisions were only rarely used. Figure 4-20 illustrates the increase in net wind loads on fasteners, purlins, and girts if it is assumed that the building envelope has been breached and a maximum increase in internal pressure occurs. Note that the fastener corner loads have increased from 66 to 75 lb/ft^2 (14 percent increase) and purlin loads from 32 to 42 lb/ft^2 (31 percent increase). A comparison with provisions in the 1974 revisions to the 1973 code is even more dramatic and suggests increases of 80 percent for purlins and 213 percent for fasteners. Adding these increases to the usually permitted one-third increase in allowable stress for load combinations including wind effects clearly uses up any normal factor of safety.

Although the majority of the thousands of metal buildings affected by Elena performed adequately, overhead door failures sometimes leading to progressive failures of roofs and walls were much too common in even relatively new construction (Figure C-1). In the aggregate, the largest percentage of damage to metal building systems due to Elena, and previous severe storms as well, can be attributed to this single problem—one which can obviously be easily addressed.

Canopy Failures Canopies should be designed to resist the uplift contributions from both upper and lower surfaces. Failures were observed that marred the otherwise satisfactory performance of a number of buildings

Figure C-1
Damage to cladding (side and leeward walls) of the Pascagoula Energy Recovery Facility resulting from overhead door failure.

(Figure C-2). Regrettably, canopies often receive only superficial design attention, as they are typically not supplied by the manufacturer and because the cost of repair or replacement is small. Fortunately, no case of canopies separating from the parent structure, becoming airborne, and constituting a hazard to human life and other property were reportS, although this has occurred in past storms. Interestingly, the data base developed at the University of Western Ontario (Davenport et al., 1977 and 1978) for the metal building industry constitutes the best available source of design information to address this all too common problem.

Damage to Steel/Masonry Facade Interface To achieve desired aesthetic effects, architects use masonry, wood, glass, aluminum, and copper to clad metal building systems. Unfortunately, it would appear that until very recently little attention has been given to the proper attachment of the masonry to the steel framework. In some applications, the building is first sheathed with the usual metal sheeting, and the masonry veneer is then attached by metal ties. All too often, this veneer was stripped from the walls by the high suction pressures during Elena's high winds (Figure C-3). Several failures were observed in which unreinforced concrete block walls collapsed. The block walls of the automobile dealership shown in Figure C-4 appeared to have been free-stand

Figure C-2

Wind damage of canopy of metal building in Gautier. Note that overhang has been provided by extending roof sheeting beyond eave, a poor but common practice.

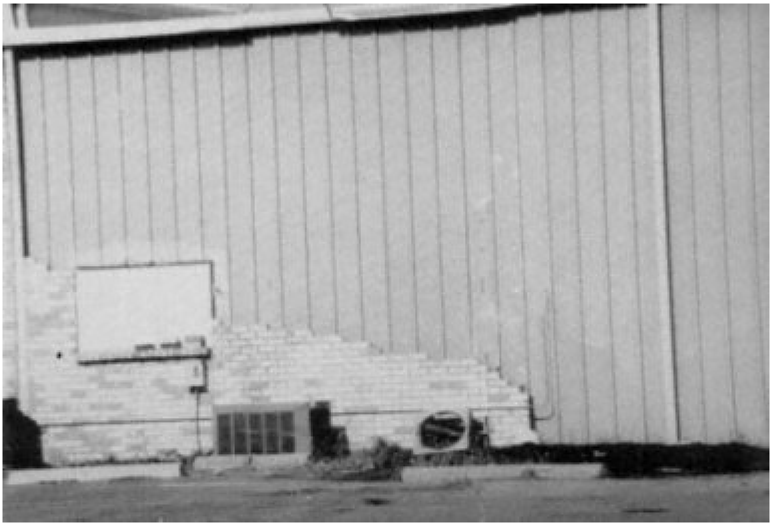

Figure C-3

Brick veneer stripped from metal building by high suction pressures.

ing with only minimal connections to the steel framing. The steel skeleton (frames, purlins, and rod bracing) survived with little damage. Collapse of the walls may have been precipitated by loss of glazing and failure of a number of overhead doors, resulting in high internal pressure.

Some engineers (Ellifritt, 1984) suggest that the masonry must be designed to permit relative movement between the block and the rigid frames. The designer is hampered in this approach because current methods of analyzing building behavior to predict drift do not properly account for diaphragm and frame interaction of the roof and wall assemblages. In all probability, for example, the building shown in Figure C-5 would have behaved essentially as a box, shear-wall structure with the stiff roof diaphragm distributing lateral loads directly to the end walls. The actual lateral deflection of the frames could well have been only 10 to 15 percent of that calculated, assuming pure frame action in the absence of "skin behavior" (MBMA, 1986). The metal building industry is aware of this problem and is supporting research in this area.

Omission of Bracing and Improper Column Anchorage As noted previously, the franchised dealer may lose some control over the installation of bracing

Figure C-4
Damage to unreinforced masonry wall enclosing metal building in Biloxi. Failure may have been precipitated by loss of large overhead doors. Steel framing was undamaged.

Figure C-5
Metal building clad with masonry veneer located in Gautier.

called for in building plans and column anchorage details that are normally not provided by the manufacturer. As more experience has been gained concerning the field performance of buildings subjected to high winds, these problems have tended to disappear in new construction. Some of the older buildings, however; were not properly designed to resist high-uplift forces, and failures were observed.

End Bay Failures A serious deficiency in some buildings designed in accordance with the earlier codes concerns the combined loading effects on strut purlins, as depicted in Figure C-6. The purlins must be capable of transferring the axial loads generated by wind action on the end walls of the building, in addition to resisting the high, localized bending loads produced as a result of suction on the roof surfaces.

A number of cases were observed in which the strut purlins buckled, leading to catastrophic failure of the entire end bays of the buildings. The furniture store shown in Figure C-7 exhibited this type of behavior. Failure was initiated by high internal pressure fluctuations from the loss of the glazing on the windward wall due to windborne debris; roofing material from adjacent upstream buildings was found in the interior of the building. Damage was limited to the first bay, and the building was returned to ser

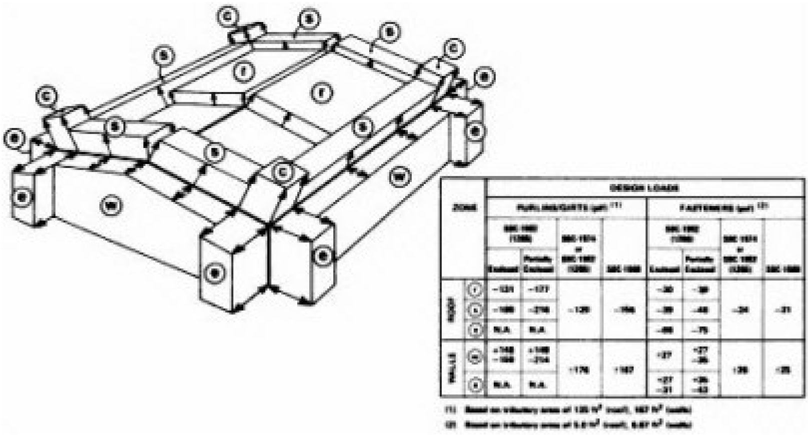

Figure C-6
Design loads for strut purlins of metal building system.

Figure C-7
Metal building system in Pascagoula. Failure due to buckling of strut purlins under combined bending and axial loading. Damage limited to first bay.

Figure C-8
End bay damage to preengineered building in Pascagoula.
Note new, undamaged metal building on right.

vice in a short time. Sensibly, the building was repaired with a facade more resistant to windborne debris.

Another building, which suffered the same fate, is shown in Figures C-8 and C-9. Note the light-gauge base plates that failed to resist the uplift forces on the columns. The vintage of this building is probably early to late 1950s; a current check of industry practice suggests that the minimum thickness of the column base plate used is 3/8 inch. A more recently erected building by the same manufacturer, adjacent to the building in Figure C-8, is shown in Figure C-10. This structure suffered no distress during the passage of Elena and was probably subjected to higher wind loading, since it is sited on a hill. Note the smaller glazed areas and the absence of overhead doors.

Building codes in use throughout the United States do not prescribe the actual combination of loads to be used in the design of strut purlins. This is because the appropriate data base has not yet been established from wind tunnel tests. The most recent edition of the low-rise design manual for the metal building industry (MBMA,1986) provides a caveat with regard to this design application but does not specify the loadings to be considered. Engineering judgment is required. One approach would be to consider a worst-case scenario in which the required axial load is assessed on the basis of main-framing coefficients coupled with bending load prescribed from

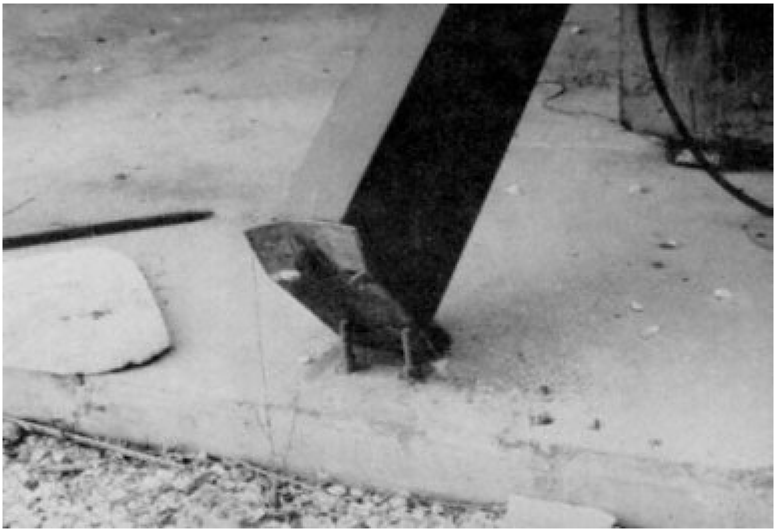

Figure C-9
Failure of column base plates of building in Figure C-8.

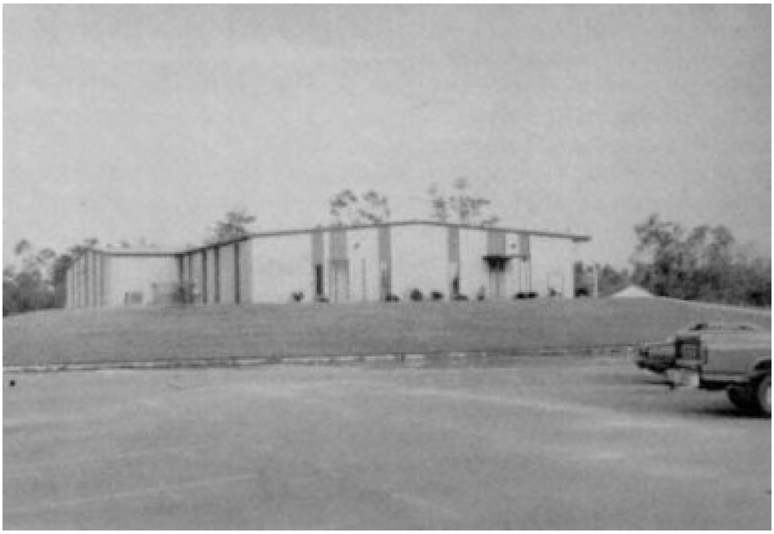

Figure C-10
New, undamaged, preengineered metal building located adjacent to building in Figure C-8. Note absence of overhead doors and large glazed areas. Building was sited in more severe wind exposure.

coefficients given for components and cladding. As the two effects do not occur for the same wind azimuth in this case, the approach would appear to be conservative. Perhaps a more realistic scheme would be to consider two load cases:

- axial and bending effects based on main-framing coefficients, and
- bending alone based on component and cladding provisions.

Hopefully, wind tunnel researchers will address this problem in the near future. It should be noted that this is only one of many design applications not specifically addressed in codes in which an element or structural assemblage is required to resist both main-framing and high, localized loads.