# ENGINEERING RESEARCH UNDERWAY FOR THE 90'S

by

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**ABSTRACT** Wind storms, cyclones and tornadoes are estimated to cause average total annual building losses in the United States exceeding that of earthquakes, expansive soils, landslides, and floods combined. Seventy two percent of wind losses result from severe damage or collapse situations, whereas, tsunami, earthquake and storm surge cause only six percent losses in the severe or collapse category. Consequently the severity of losses from wind is greater than the severity of losses from all other natural disaster hazards combined. Nonetheless, by effective use of land zoning, planning procedures, building to codes, and incorporation of modern design information into new structures projected damages could be reduced by 35%. Engineering research now underway for the 1990s should lead to a better understanding of damage physics and failure networks. This research will lead to the introduction of new construction techniques and improved building codes.

## INTRODUCTION:

The ancients had a great deal of respect for the wind. It moved their ships and wrecked them. It pumped water and ground corn, but sometimes it destroyed their crops and homes. Ehecatohatiuh, ancient god of the wind for the Aztecs of Mexico, was believed to have created man in the form of apes in order that they might cling to the earth better and not be carried away by the hurricanes; thus originating the similarity between the human race and monkeys. The word hurricane comes from the Caribbean Indian word 'huracan' for 'big wind'. Similarly the Japanese immortalized the god of the wind 'Fujin' in the mountain of wind - 'Fujiyama'. Today man retains his respect for the impact of extreme winds. The Bangladesh cyclone of 1970 is estimated to have caused a death toll between 300,000 to 500,000. Wiggins (1987) estimates that a $40 billion dollar annual U.S. loss due to hurricanes is as likely as similar losses due to the maximum severity earthquake.

This paper reviews the costs and type of damage associated with wind storms, discusses various mitigation schemes and design techniques to mitigate damage due to wind, and notes current and planned research programs to improve the ability of buildings and structures to sustain high winds.

## DAMAGE TYPES AND COSTS

Insurance companies evaluate the relative cost to a community due to wind storms in terms of the mean annual losses, the variability of annual losses and the maximum possible loss (Walker, 1985a; Friedman, 1980, 1983). Insurance works best when the annual variability of incidents is small. This enables insurance companies to determine premiums with confidence. Information about the maximum possible loss is used to estimate necessary reinsurance.

### Mean Annual Losses

In the United States (U.S.) wind related natural hazards caused about 400 deaths/year or 35% of all natural disaster related deaths (or about 1/250 the death rate of man-made accidents), and annual wind related dollar losses ($5 billion) equal building losses due to fire or more than one-half of the annual dollar losses from automobile accidents. These annualized wind losses are distributed between hurricanes, tornadoes, and severe winds as 55, 40, and 5 percent, respectively. Storm surges account for about 40% of total hurricane damage.

Wiggins (1978) predicted that by the year 2000 annual average U.S. hurricane and tornado related losses would be $11 billion in 1987 dollars. Such increases are due to increase in population, concentration of people and property in cities, settlement in exposed coastal areas, higher construction and repair costs, and more hazardous technologies. Indeed the usefulness of past loss experience data decays rapidly with time because of changes in the number, geographical distribution and density of the elements-at-risk in hazard prone areas. Vulnerability to damage also changes with time due to inflationary trends.

Annual Variability

Annual fire losses have a coefficient of variation (c.o.v.) of about 10%, whereas hurricane wind losses have a c.o.v. of nearly 200%, and non-hurricane wind losses (tornadoes, thunderstorms and winter gales) have a c.o.v of 70%. Thus randomness and spread of risk are not characteristics of wind losses (Friedman, 1983; Walker, 1985a). Since in the past wind losses have been only a fraction of fire losses, most insurance companies offer wind damage coverage as an extension of fire policies even in hurricane prone areas. More recent statistics suggest annual wind losses now equal fire losses in the U.S.. When risk and variability become large, insurance companies are reluctant to insure a peril at all! (In the U.S. today flood losses are not included in most policies.)

Maximum Possible Loss

Munchener Ruck (1982) has noted that the causes of some 400 great natural disasters which have already occurred in this century can be tabulated as 52% inundation, 17% earthquake, 15% wind storm, 7% drought, 3% volcanic, and 6% other. At the beginning of the century there were about three disasters per year based on the existence of an extreme impact on the economies concerned due to the extent of bodily injury or property damage; whereas, currently there are about 15 per year. Between 1960 and 1980, Berz and Smolka (1987) found that 49 of the 89 major natural disasters were attributable to windstorms. In terms of property damage, the worst natural disaster during the period 1960-1980 was Hurricane Agnes which caused a $3.1 billion loss in the U.S. But more recently the 1989 Hurricane Hugo storm is estimated to have caused $10 billion in international and U.S. damage and to have killed 49 people (26 on the U.S. mainland).

Today Wiggins (1987) estimates that a single probable earthquake in the U.S. could cause $63 billion in damage; one hurricane, $10.5 billion; one tornado, $4.8 billion; one storm surge, $2.4 billion; one riverain flood, $3 billion; and one tsunami, $1 billion. Since it is much more likely that multiple hurricanes hit a populated coastline than multiple maximum critical earthquakes occur in one year, he calculated that it is not unlikely that hurricanes could cause maximum annual losses of $40 billion due to wind only. Indeed, Gray (1990) notes that the past eighteen years have been an unusually quiet time for hurricanes along the U.S. coastline. A large portion of the U.S. coastline population has entered the region since the last major storms hit; hence, the next major storm might easily cause damage exceeding $5 billion. Gray predicts the next decade will see a return to normal hurricane activity; in other words, the number of U.S. landfalling hurricanes may double.

A considerable difference exists between the type and magnitude of damage caused by different natural hazards. An earthquake is expected to cause structural collapse or severe damage to less than 0.5% of the buildings exposed, but structural collapse or severe damage is experienced by 93% of the exposed buildings damaged by tornadoes and by 51% of those damaged by hurricanes (Petak and Hart, 1980). Loss of life is generally expected to correlate directly with such extreme damage.

## MITIGATION METHODOLOGIES

There is increased desirability of mitigation as opposed to relief and reconstruction. In general, mitigation which results in reduced losses in human lives and property may be applied to all three driving factors: hazard, exposure and vulnerability. Use of mitigation devices could be coupled to an insurance program as incentives to reduce premium rate increase. Consequential losses can also be mitigated by fast post-event response, which can reduce "second" loss levels substantially.

### Mitigation of the Hazard

Preventing, reducing, or halting an extreme wind event is normally presumed to be beyond the control of mankind. The very scale and intensity of a hurricane tend to make any conceivable response of man irrelevant. Surface level kinetic energy production magnitudes associated with a mature hurricane or a tornado are estimated to be 200,000,000. This compares to 200,000 Megawatts for a volcano or 500,000 Megawatts for the typical thunderstorm (Koenig and Bhumralkar, 1974).

Nonetheless, cloud seeding experiments on thunderstorms in Florida suggest that cloud development can be modified or enhanced by selective seeding with aerosols (Simpson and Woodley, 1971). Furthermore, hurricane damage in the U.S. has been found to correlate with the maximum sustained surface wind speed raised to a power of 4.3. If this is an accurate representation, then a 20% to 25% reduction in maximum surface winds on the right side of the storm might reduce storm damage by as much as 50% . Seeding the inner eye-wall of hurricanes with silver iodide was proposed by R.H. Simpson in 1961, and Gentry (1970) described silver iodide treatment of the inner eye-wall of hurricane Debbie (1969) which was associated with a reported reduction of the peak wind of 31 and 15 percent.

Gray et al (1976) proposed weather modification by carbon dust seeding in hurricanes. Computer models suggested a wind speed reduction of 30 mph could occur, and a 20% reduction in wind speed would have a ratio of yearly average of damage reduction to modification cost of 33 to 1, even if only one-fourth of the storms with speeds greater than 90 mph along the U.S. are included. On a global basis the ratio is closer to 57 to 1. Unfortunately, even though environmental impact of such carbon dust seeding appears negligible, the idea does not appear socially or politically timely. Perhaps the idea will be given further consideration in the future.

### Mitigation of Exposure

Since tornadoes and severe winds are possible over the entire continental U.S. the entire population and its property are at risk ($4000 billion and 250 million people). Hurricane damage is limited to coastal states; hence, wealth at risk is about 1/3 that of tornadoes and severe storms, and people at risk is about 1/3 also. Exposure can be reduced by limiting population growth in large cities and coastal regions, warning and evacuation, land-use planning through microzonation, and better public information.

Elimination of all population growth in a hurricane-prone states and high tornado risk counties after 1980 would reduce average annual property losses by about 8% or $900 million in 1987 dollars during the year 2000 (See Table 1). Societal and political factors suggest that no-growth concepts will be difficult to implement.

Advance storm warning to permit boarding of all windows would save 0.5% of all wind related losses or $50 million in 1987 dollars during the year 2000 (See Table 1). Major evacuation is presumed by many people to be difficult to justify since storm tracking is an inexact science. Indeed, Southern (1986) estimates that even given a 100% accurate correct cyclone prediction the value of the prediction is degraded to 16% by various deficiencies in skill or usefulness of warnings, public authority dissemination and community utilization of the time provided.

Mitigation of Vulnerability

Mitigation of the effects of severe winds can be accomplished, at least in theory, by improving building codes and their enforcement, modifying methods of construction, using different building materials, protective devices, and residential shelters. Absolutely storm-proof construction methods cannot be attained at economically justifiable costs; nonetheless, stricter or more precise design procedures tend to be popular with engineers, who are oriented toward the construction of specific structures and buildings. Insurance companies, on the other hand, are more interested in the cost of an entire overall loss including contents.

The analysis by Hart (1976) suggests that simply strengthening existing building codes by a factor of 3 or 1.5 would result in the reduction of wind losses by 27% and 17% or $1.4 and $0.9 billion 1987 dollars by the year 2000, respectively (See Table 1). But building codes tend to be a combination of engineering data, informed opinion, and economic compromise. For example, current U.S. codes disregard tornado level winds as producing impractical expensive construction.

More conservative design procedures are often used for community sensitive structures, eg. nuclear power stations, schools, hospitals, and warehouses for the storage of critical materials. Designing for a tornado is similar to designing for the effect of a blast wave; hence, information from nuclear explosions are often used to specify wind loads (McDonald et al, 1973).

Walker (1983, 1984, 1987) has examined the characteristics of wind loading on residential housing. He has recently proposed an international simplified code with wind loads expressed directly in terms of pressure enabling much wider application of wind engineering to small buildings. Small buildings are those not over 15 m tall and not over 1000 square meters in area. Eaton (1980, 1985) describes research on low-cost housing for areas in the Caribbean and South Pacific. He observes that supposedly low cost construction, say $12/sq ft, is not cheap in underdeveloped countries; yet it is the loss of such structures which dominates individual loss and suffering.

## WIND ENGINEERING RESEARCH FOR THE 90's

Given the potential for loss, some debate exists concerning the areas for highest pay-back research. In June 1987 a Seminar/Workshop on WIND ENGINEERING: The Past to the Future was held at Colorado State University (Meroney, 1988). An intense debate among researchers resulted in forty-two specific recommendations for research in the areas of wind structure and climatology, structural loads and responses, cladding loads and local effects, pedestrian winds, codes and standards, full-scale measurements and expereience, and information transfer.

In December of the same year researchers from the international community gathered at the U.S.-Asia Conference on Engineering for Mitigating Natural Hazards Damage to propose a program for international research cooperation (Chiu et al., 1988). The public has an increasing desire for mitigation as opposed to post-disaster relief and reconstruction. Top category research recommended related to (1) improving the characterization of winds in hurricanes, (2) improving the specification of design loads on shorter buildings such as warehouse, apartment complexes and private domiciles, (3) developing a rational engineering design approach specified by consistent and clear codes, and (4) disseminating knowledge on wind engineering practices among meteorologists and design professionals.

In September, 1988, researchers gathered at the National Institute of Standards and Technology, Gaithersberg, MD, to discuss the development of better instrumentation to assess and measure structural performance during wind storms (Marshall, 1989). Needs were identified for remote sensing devices (1) to determine wind speed and directions around structures, (2) to measure structural displacements, (3) to measure absolute pressures, (4) to quickly instrument structures in hurricane paths with low-profile load cells, and (5) to determine internal pressures in buildings.

Research programs promoted by a number of government and university organizations are actively pursuing these topics. Prominent during the 1990s will be research on smart buildings, expert systems, computer friendly building codes, response of small and medium size structures to extreme winds, improved building systems, and better post-disaster reconstruction tactics.

### Smart Buildings and Expert Systems:

A "smart building" might be one that measures winds, anticipates winds, and responds to mitigate damage. Components of such systems are already available. Active and passive dampers are being installed in many modern buildings. The World Trade Center uses viscoelastic dampers installed in the two towers as non-load-carrying connections between columns and lower chords of floor trusses. Roof-mounted sloshing dampers are being promoted by Japanese firms. Computer-activated counterweights, pendulum dampers, tuned mass dampers, and hydraulic rams can be activated by "artificial intelligence" computer programs which respond to inputs from wind and motion sensors (Rosenbaum and Usui, 1990). Theoretically such active systems could eliminate building vibration completely. Builders might be able to eliminate the need for moment resistant frames or braced frames, costly connections and atheistically-disruptive diagonals. But engineers are debating the reliability of active systems which require an external power source and a running computer.

"Expert systems" are being developed by wind engineers to promote better use of complex wind-engineering technology during building design. Integrated expert system programs permit novice engineers to share the experience and lore of the specialists. These expert systems (or knowledge based systems) are interactive programs that combine experience, rules of thumb, and intuition with inferential reasoning (Harris-Stewart, 1988).

Computer Friendly Building Codes:

Some engineers and city officials complain that buildings are not built correctly due to misunderstanding or misapplication of complex building codes. Code complexity has led to the need for code-specialists or the attraction of model building codes (Post, 1988; Korman, 1989). Another possibility is the future use of "expert system" computer software. Researchers are currently working to encapsulate the ANSI-A58.1-1982 and ASCE-7 wind load codes into user-friendly expert systems (Chen and Reed, 1989). Sharpe et al. (1989) have already demonstrated a PC-based computer program which guides the designer through the complex wind-load sections of the Australian building code.

Better Wind Load Specification and Construction Techniques:

Construction of modern buildings and structures has become a multi-discipline responsibility. No longer can the civil-engineer or architect work in isolation from the meteorologist, the geologist, or the wind specialist. Hence the National Science Foundation has just funded a joint Cooperative Program in Wind Engineering Research at Colorado State and Texas Tech Universities (CSU/TTU CPWE). The CSU/TTU CPWE combines the wind engineering and wind-tunnel modeling experience of the Fluid Mechanics and Wind Engineering Program at Colorado State with the severe storm experience and full-scale building wind test site of the Institute for Disaster Research at Texas Tech. The CSU/TTU CPWE incorporates the talents of 13 research scientists at the two schools from the fields of Agricultural, Civil, and Mechanical Engineering as well as Meteorology. Over the next five years (1989-1994) research teams will address the characterization of extreme wind statistics in severe storms, wind pressures and cladding loads on small and medium size buildings, the behavior of roofing materials in high winds, ventilation aerodynamics, computational building aerodynamics, and soil and debris aerodynamics.

In its first year of activity the program has been able to demonstrate sensitivity of peak pressure loads on building roofs and sides to wind orientation and building geometry. Laboratory models have reproduced both the mean and peak pressure characteristics of the field facility. During the second year tests will examine the influence of partial failure of building integrity on pressure forces and the wind dynamics of loose-laid roofing materials. Construction and design firms and building material manufacturers are encouraged to participate in the cooperative program. Already the Metal Building Manufacturer Association and the National Roofing Contractors Association advise and participate in the research program.

The great majority of all buildings in the U.S.A. that are subjected to substantial wind-induced damages can be classified as nonengineered, marginally engineered, pre-engineeered and prefabricated. A special issue of the ASCE Journal of Aerospace Engineering (Vol 2, No.2, 1989) was prepared by the Task Committee on Mitigation of Severe Wind Damage, formed under the Aerodynamics Committee of the Aerospace Division. The committee sought for ways to apply aerospace technology to traditional civil engineering applications. Articles were prepared by task force members which identify several areas for profitable research on better construction techniques during the 1990s. Some of these research areas include:

1. Substantial reduction in damage to wood-frame houses can be provided by low-cost improvements to joint connections, tie-down of roofs, tie-down of wall frames to foundations, and quality control against sloppy construction practices; hence

   Methodologys will be sought to analyze stresses and deflections of ordinary wood-frame houses,

   Research will determine the diaphragmatic action of walls made of different sheathing materials, and

   Provisions will be suggested to strengthen building inspection during construction to assure quality control.

2. Tens of thousands of steel-framed, pre-engineered buildings were affected by hurricanes during the last ten years. Closer compliance with existing building codes were found to mitigate most damage; hence

   Quality assurance programs will be developed for manufacturers,

   Standards for building erection procedures and proposals for how to allow for failure of large overhead doors or glazed areas will be promulgated to building fabricators, and

   Methods will be suggested to building code officials which help enforce critical wind related codes.

3. Manufactured homes are popular as single family dwellings due to their low cost per square foot relative to conventional housing. Unfortunately substantial losses of property and life occur each year due to roof loss and tiedown/foundation failure which lead to total collapse of the building. Research will proceed on

   Methods to provide redundancy and ductility in the load-resisting structural system, and

   The relative merits of ground anchors in the tie down/foundation system versus permanent foundations.

Improved Disaster Response:

Often total damage from a storm can be reduced through prompt post-disaster response. Today disaster reconstruction firms are often on the job within hours preparing damage estimates and reconstruction strategies. Techniques developed in the aftermath of Hurricane Alicia such as the active use of computer graphics, expert systems and critical path techniques permits catastrophe reconstruction to begin almost immediately. Continued cooperation between such reconstruction firms and insurance carriers are expected to reduce storm impacts (Lawson, 1988).

## CONCLUSIONS

Mitigation of the effects of severe winds on lives and property loss is in its infancy. The very magnitude of the losses involved makes significant improvements difficult. Mitigation of the severe winds directly appears hopeless to most observers; although, some storm seeding concepts should be examined further. Mitigation of the exposure of property and populace requires massive dislocation of people and a change in the trend for population growth along the world's coastlines. Mitigation of the vulnerability of the property and people exposed can conceivably reduce losses by 25%. Improved forecasting techniques will undoubtedly reduce lives lost, but warning and evacuation is not likely to make much of an impact on property losses. Primary research directions during the 1990s will emphasize better storm characterization, improved estimates of wind loads on structures, the integration of high-technology into smart buildings, the identification of more reliable construction strategies, and the specification of improved building codes.

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TABLE 1: UNITED STATES WIND LOSSES AND MITIGATION EFFECTS
(Revised from Hart, 1976)

EXPECTED LOSSES IN $ MILLIONS (1987)

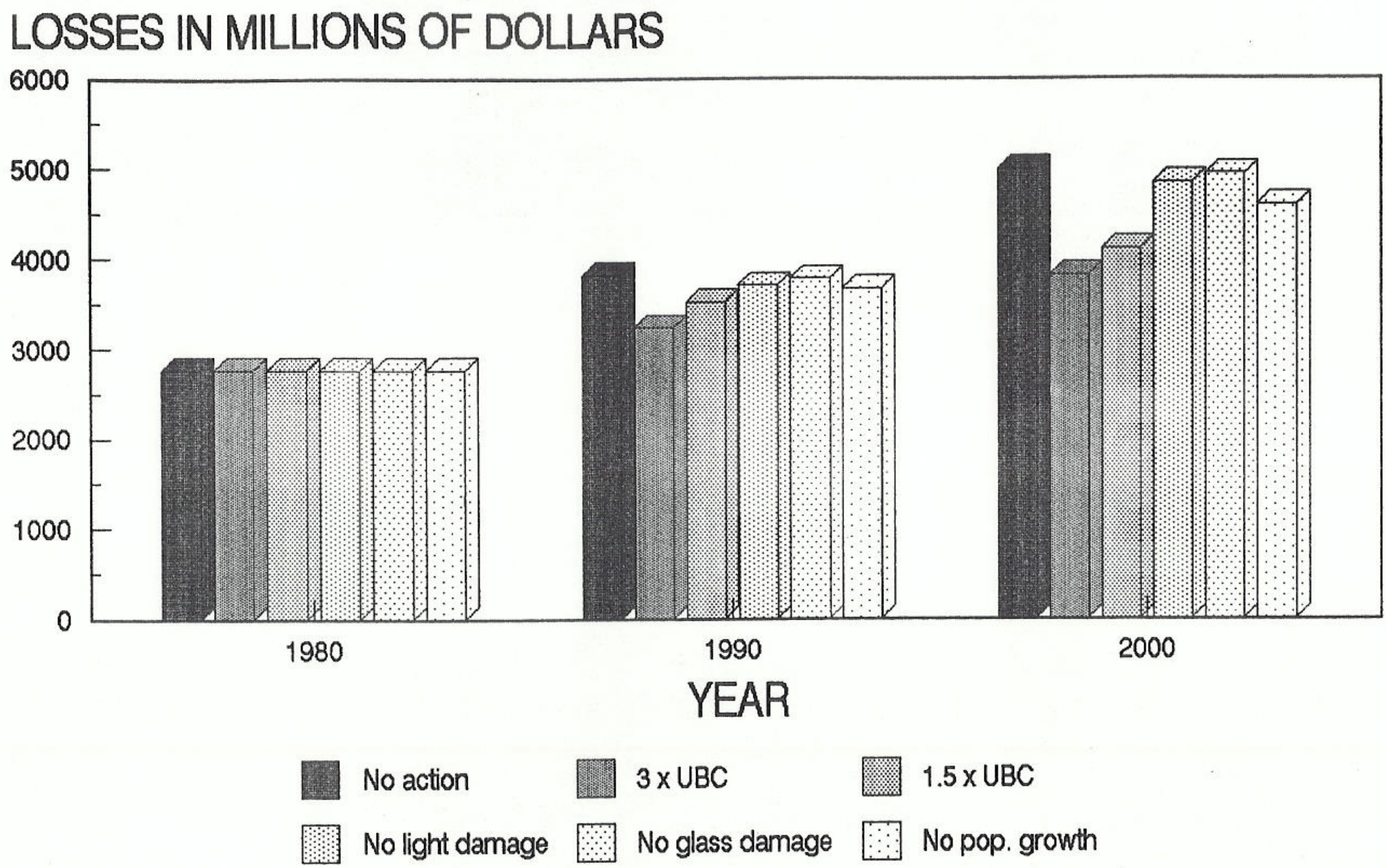
| MITIGATION | HURRICANES | | |
|---|---|---|---|
| | 1980 | 1990 | 2000 |
| Baseline: No mitigation activities | $2,756 | $3,811 | $4,984 |
| (1) All new structures newly built after 1980 must be built to comply with Uniform Building Code times 3.0 | $2,756<br>0% | $3,225<br>-15% | $3,811<br>-24% |
| (2) All new structures newly built after 1980 must be built to comply with Uniform Building Code times 1.5 | $2,756<br>0% | $3,518<br>-8% | $4,104<br>-18% |
| (3) After 1980 all structures are strengthened so that light damage losses are zero | $2,756<br>0% | $3,697<br>-3% | $4,834<br>-3% |
| (4) After 1980, glazing requirements and warnings result in no window damage | $2,756<br>0% | $3,773<br>-1% | $4,934<br>-1% |
| (5) Population growth in hurricane-prone states ceases after 1980 | $2,756<br>0% | $3,659<br>-4% | $4,585<br>-8% |

HURRICANES: Losses due to winds > 73 mph
Does not include storm surge losses

Cost of Living Factor 2.93

# U.S. WIND LOSSES and MITIGATION EFFECTS

## HURRICANE LOSSES (Revised Hart, 1976)



EXPECTED LOSSES IN $ MILLIONS (1987)

| MITIGATION | TORNADOES | | | HURRICANES | | | SEVERE WINDS | | | TOTAL LOSSES | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 1980 | 1990 | 2000 | 1980 | 1990 | 2000 | 1980 | 1990 | 2000 |
| Baseline: No mitigation activities | $3,401 | $4,632 | $6,039 | $2,756 | $3,811 | $4,984 | $44 | $59 | $73 | $6,200 | $8,501 | $11,096 |
| (1) All new structures newly built after 1980 must be built to comply with Uniform Building Code times 3.0 | $3,401<br>0% | $4,045<br>-13% | $4,778<br>-21% | $2,756<br>0% | $3,225<br>-15% | $3,811<br>-24% | $44<br>0% | $50<br>-15% | $56<br>-24% | $6,200<br>0% | $7,320<br>-14% | $8,645<br>-22% |
| (2) All new structures newly built after 1980 must be built to comply with Uniform Building Code times 1.5 | $3,401<br>0% | $4,280<br>-8% | $5,541<br>-8% | $2,756<br>0% | $3,518<br>-8% | $4,104<br>-18% | $44<br>0% | $53<br>-10% | $62<br>-16% | $6,200<br>0% | $7,851<br>-8% | $9,706<br>-13% |
| (3) After 1980 all structures are strengthened so that light damage losses are zero | $3,401<br>0% | $4,632<br>0% | $6,039<br>0% | $2,756<br>0% | $3,697<br>-3% | $4,834<br>-3% | $44<br>0% | $53<br>-10% | $67<br>-8% | $6,200<br>0% | $8,381<br>-1% | $10,940<br>-1% |
| (4) After 1980, glazing requirements and warnings result in no window damage | $3,401<br>0% | $4,573<br>-1% | $6,039<br>0% | $2,756<br>0% | $3,773<br>-1% | $4,934<br>-1% | $44<br>0% | $59<br>0% | $73<br>0% | $6,200<br>0% | $8,405<br>-1% | $11,046<br>0% |
| (5) Population growth is stopped in all counties where tornado strike probability is greater than 10-4 per year per square mile | $3,401<br>0% | $4,251<br>-8% | $5,541<br>-8% | | | | | | | | | |
| (6) Population growth in hurricane-prone states ceases after 1980 | | | | $2,756<br>0% | $3,659<br>-4% | $4,585<br>-8% | | | | | | |

HURRICANES: Losses due to winds > 73 mph
Does not include storm surge losses

SEVERE WINDS: Structurally related losses only
Does not include roofing shingles or contents

Cost of Living Factor 2.93