NATIONAL ADVISORY COMMITTEE ON WINDSTORM IMPACT REDUCTION

NATIONAL WINDSTORM IMPACT REDUCTION PROGRAM

September 29, 2017

The Honorable Kent Rochford
Acting Director
National Institute of Standards and Technology
Building 101, Room A1134
100 Bureau Drive
Gaithersburg, MD 20899-1000

Reference: NWIRP – NACWIR Report

Dear Dr. Rochford:

We are pleased to submit to you our assessment and recommendations for the National Windstorm Impact Reduction Program (NWIRP), as stipulated in Public Law 114–52—SEPT. 30, 2015. We have worked diligently to review: (1) trends affecting windstorm losses and impacts; (2) the draft Strategic Plan for the Program; (3) coordination of the Program; (4) effectiveness of the Program; and, (5) identify needed changes to the Program.

We believe that the Federal Agencies involved have produced an excellent draft Strategic Plan. Through our review and assessment of trends and the draft Strategic Plan, we have developed a number of recommendations that we hope will be considered as the Strategic Plan is finalized. The two most significant recommendations deal with improving the ability to assess and remediate the vulnerability of existing buildings and other infrastructure and with studying successes and failures of options available for implementing windstorm mitigation measures. The latter will provide communities and agencies with a portfolio of options and guidance on which options may be best suited for their local conditions.

The Committee reviewed coordination of the Program and determined that the structure provided for coordination is working as exemplified by completion of the draft Strategic Plan and coordination of efforts appropriate for the missions of the various agencies. Coordination of efforts germane to NWIRP during and following Hurricanes Harvey, Irma and Maria has been effective despite the short time between events. Members of the Windstorm Working Group (WWG) appear to be working well with each other, building relationships, and in some cases co-funding projects.

In assessing the effectiveness of the Program, the Committee determined that the core agencies are making progress on key projects and programs that align with their missions and the NWIRP goals articulated in the draft Strategic Plan. However, the lack of resources and associated prioritization of the Program within the Agencies is impeding the ability of the Program "to achieve major measurable reductions in the losses of life and property from windstorms," the lofty goal stated in the authorizing legislation.

The two major recommendations the Committee offered for the draft Strategic Plan are our key recommendations for changes in the Program. They also directly relate to improving the effectiveness of the Program. The recommendation to add a strategic priority to develop assessment tools and mitigation measures for existing buildings and other infrastructure addresses problems of buildings and other infrastructure designed to older less windstorm resilient building codes and standards, containing construction flaws or errors, or that have not been adequately maintained. The recommendation to add an objective to evaluate options for implementing windstorm mitigation measures addresses both new and existing buildings and other infrastructure by identifying successful ways to promote, adopt, and/or enforce newer building codes and standards, best practices, and above code design and construction practices.

The impact of windstorms on lives, communities and the Nation continues to grow and the trends we identified are likely to significantly increase those losses in the future. It is time for Congress and the Federal Agencies to commit serious resources and efforts to reducing our vulnerability to these events. We are disappointed that Congress has never appropriated any additional funds for agencies supporting this critical Program. The agencies have done well and made progress on several fronts using available resources. However, we are deeply concerned that unless additional resources are committed to this Program and its priority is elevated within the agencies, losses of lives and property will continue to escalate and the cost of response and recovery to American taxpayers will continue to grow.

Sincerely,

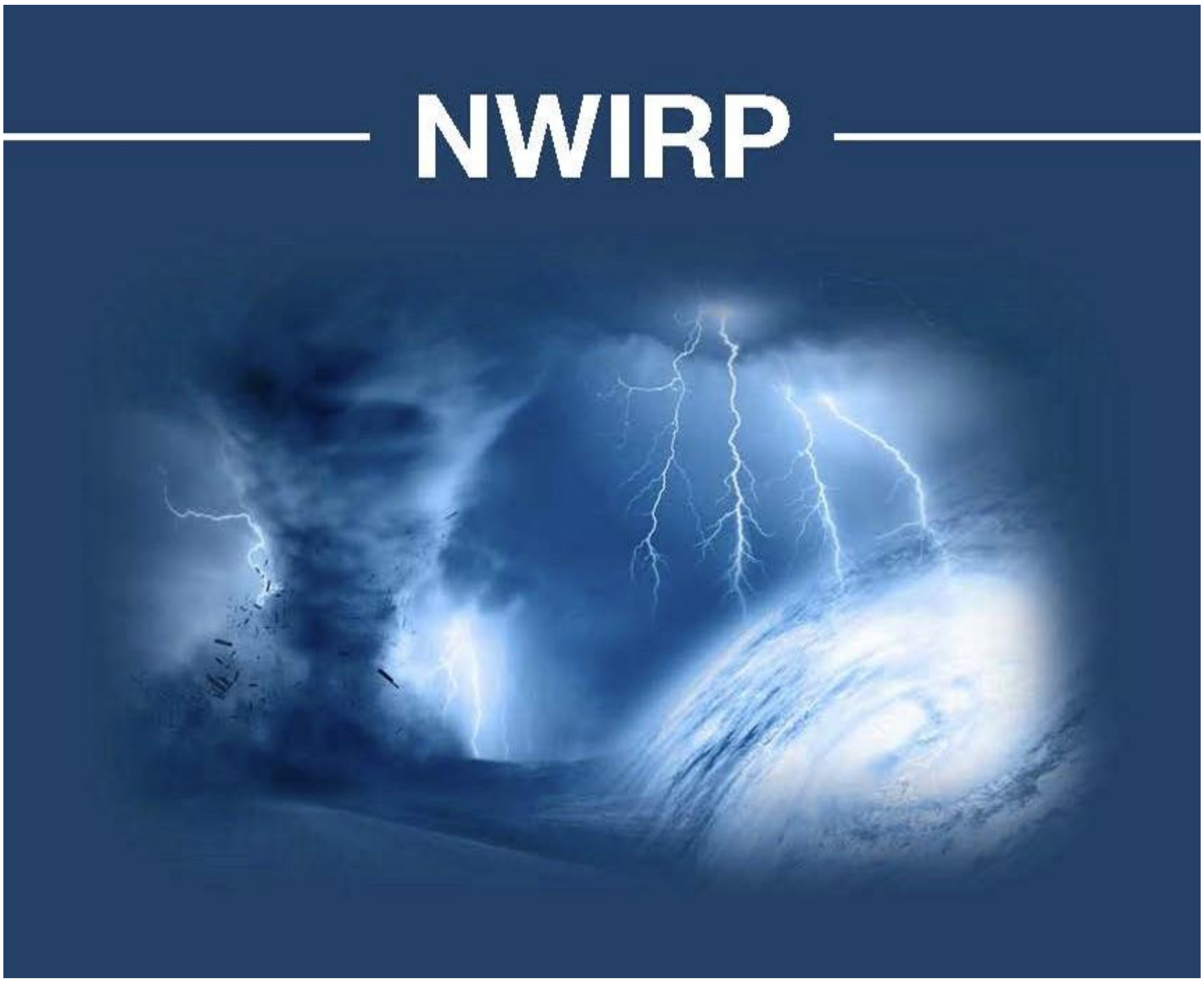
Timothy A. Reinhold

Timothy A. Reinhold Ph.D. PE (Colorado)
Chair
National Advisory Committee on Windstorm Impact Reduction
National Windstorm Impact Reduction Program

Enclosure

Assessments of and Recommendations for

the National Windstorm Impact Reduction Program and its Implementation



A Report from the

National Advisory Committee on Windstorm Impact Reduction

September 2017

Contents

EXECUTIVE SUMMARY

The National Advisory Committee on Windstorm Impact Reduction (NACWIR) has completed its assessment of the National Windstorm Impact Reduction Program (NWIRP) as required by Public Law 114-52. NACWIR is charged with developing assessments and recommendations on:

- trends and developments in the natural, engineering, and social sciences and practices of windstorm impact mitigation;
- the priorities of the Program's Strategic Plan;
- the coordination of the Program;
- the effectiveness of the Program in meeting its purposes; and,
- any revisions to the Program which may be necessary.

This report provides that assessment and the resulting recommendations.

Windstorm related losses in the United States continue to increase unabated due to trends that are exacerbating exposure and risk. Among the most important trends contributing to greater risks identified and discussed in the report are the continuing concentration of development and increases in value of property and contents in coastal areas subject to hurricane risks; urban growth and sprawl creating greater density of buildings and larger developed footprint that increases the likelihood of large numbers of properties and infrastructure being affected by a thunderstorm, microburst or tornado; continuing focus on risks to individual properties in the development of building standards as opposed to considering risks of community impacts; increasing social diversity and vulnerability; lack of uniformity in adoption and enforcement of modern building codes in many parts of the country; and, a general opposition to any and all strengthening of regulations and standards.

In the face of existing risks and these adverse trends where the United States already suffers billions of dollars in losses annually and taxpayers pay out billions for cleanup and recovery, NWIRP was authorized and re-authorized by Congress with a lofty goal "to achieve major measurable reductions in the losses of life and property from windstorms." However, Congress has never appropriated any new funding for this program and the agencies have been left with identifying existing efforts that align with the NWIRP goals and objectives or possibly re-programming existing funding to support the Program. Without a significant increase in funding and a higher priority commitment to the Program within the agencies, the Committee is concerned that the Program will be fortunate to make even small reductions in the trajectory of increasing losses and impacts of windstorms.

Despite the lack of funding and the resultant small size of the NWIRP, there are positive factors that suggest the stage is set for increasing the impact of the Program if additional resources are applied. The Strategic Plan for the Program is in the final stages of completion and the Committee found that it is well written, thoughtfully developed and relatively complete. The main recommendations of the Committee for improvements to the Strategic Plan include: 1.) adding a strategic priority to better identify weaknesses of existing buildings and develop cost effective mitigation measures; and, 2.) adding an objective for studying the effectiveness of elements that would provide communities with a portfolio of options for improving windstorm resistance and resilience and guidance on how they might select the best options given their local conditions. Furthermore, new facilities have recently been completed, some of which are now being supported by National Science Foundation (NSF) Natural Hazards Engineering Research Infrastructure (NHERI) funding, that provide the Nation with research tools and full-scale testing capabilities that have not been previously available. The structure in place for coordinating federal agency efforts is effective and has attracted participation of several agencies beyond the four specifically identified in the authorizing legislation. Given the minimal funding available, the members of the Windstorm Working Group (WWG) are working well together; they drafted the Strategic Plan discussed above, are developing relationships, and are exploiting common needs and developments through some joint funding of projects.

A key missing ingredient is adequate funding at all levels in all the participating agencies for basic research, model development, and even more importantly for research-to-application efforts that would support effective utilization of the research findings. Most of the existing resources for research, other than National Oceanic and Atmospheric Administration (NOAA) research that focuses primarily on storm characteristics and warnings, come from the National Science Foundation (NSF) which focuses on basic research as opposed to applied research. Consequently, NSF-funded research may provide useful underpinnings for applied or research-to-applications projects that could lead to development of cost effective mitigation measures, changes to building codes and standards, and enhance the effectiveness of programs that foster local action to improve windstorm resilience. However, inadequate funding available to mission oriented agencies stymies effective use of this basic research. For example, NSF funds research to improve the understanding and modeling of various windstorm related phenomenon; but, there are no funds available to apply those models to improve guidance for design or to develop tables or enough data to support building code changes. Furthermore, to be effective, the basic and applied research, development of mitigation options, and implementation of programs must be guided through broad based collaborative efforts that combine physical science, engineering, and social science research.

Aside from the two primary recommendations for changes to the proposed Strategic Plan listed above, the Committee's review of windstorm impacts led to the identification of an area not included in the Program where storm impacts are significant but poorly understood and inadequately modeled. Available surge and wave modeling is not able to properly account for highly granular local effects and there is a need to interface surge, wave and rainfall modeling effects in the near coast region to improve loading and flooding predictions. However, the Committee recommends against adding this objective to the existing program unless the current effort is adequately funded and extra funding is provided for this additional effort. Adding additional objectives to this small and underfunded federal program would just further dilute its effectiveness.

With literally billions of tax payer dollars being poured into response and recovery from windstorm-related effects and no end in sight to the exponential growth in these losses, now is the time for Congress to adequately fund this program and for key agencies to raise their commitment to the Program and its lofty goals – goals that are nevertheless critical for reducing the heavy burden of windstorm-related costs to the American people and to the communities and lives that are destroyed or disrupted as a result of these events.

INTRODUCTION

This report provides assessments and recommendations covering the five statutory requirements assigned to the NACWIR by Public Law 114-52 – September 30, 2015. Specifically, it offers assessments and recommendations on: (1) trends and developments in the natural, engineering, and social sciences and practices of windstorm impact mitigation; (2) the priorities of the Program's Strategic Plan; (3) the coordination of the Program; (4) the effectiveness of the Program in meeting its purposes; and, (5) any revisions to the Program that may be necessary.

The first section discusses existing and emerging trends that the Committee believes will affect windstorm impacts either positively in reducing impacts or negatively in increasing impacts such as casualties, property losses and social disruptions. During the Committee's deliberations, a significant amount of time was spent discussing pathways towards creating greater windstorm resilience. This is outlined in the second section as a series of trends the Committee believes need to be fostered or created to effectively reduce future impacts of windstorms.

The third section provides specific recommendations and suggestions concerning objectives and strategic priorities of the Program's Strategic Plan. In general, the recommendations and suggestions flow from the existing and needed trends identified by the Committee. The consensus of the Committee is that the Strategic Plan developed by the NWIRP Interagency Coordinating Committee (ICC), Windstorm Working Group (WWG), National Institute of Standards and Technology (NIST) Staff and NIST Contractors is well thought out, well developed and clearly written. The Committee recommends addition of a Strategic Priority (SP) focusing on windstorm vulnerabilities of existing buildings and other structures that includes among other things, development of tools and methodologies for assessing windstorm vulnerabilities and in-situ capacities as well as cost effective methods for reducing identified vulnerabilities. It also recommends the addition of an objective to evaluate the effectiveness of various options of fostering implementation of windstorm resistant measures by state, regional and local governments or agencies. Other recommendations address ways to expand or change specific objectives included in the NWIRP Strategic Plan. Specific tweaks to language are offered as suggestions. The Committee hopes that the WWG will find these recommendations and suggestions helpful as it works to finalize the Strategic Plan.

The fourth section addresses Program coordination and cooperation. The structure in place for coordinating federal agency efforts is effective and has attracted participation of several agencies beyond the four specifically identified in the authorizing legislation. Given the minimal funding available, the members of the WWG are working well together; they drafted the Strategic Plan, are developing relationships, and are exploiting common needs and developments through some joint funding of projects.

Program effectiveness is assessed in the fifth section of the report. A key missing ingredient is adequate funding at all levels in all the participating agencies for basic research, model development, and even more importantly for research-to-application efforts that would support effective utilization of the research findings. Most of the existing resources for research, other than National Oceanic and Atmospheric Administration (NOAA) research that focuses primarily on storm characteristics and warnings, come from the NSF which focuses on basic research as opposed to applied research. Consequently, NSF-funded research may provide useful underpinnings for applied or research-to-applications projects that could lead to development of cost effective mitigation measures, changes to building codes and standards, and enhance the effectiveness of programs that foster local action to improve windstorm resilience. However, inadequate funding available to mission oriented agencies stymies effective use of this basic research. For example, NSF funds research to improve the understanding and modeling of various windstorm related phenomenon; but, there are no funds available to apply those models to improve guidance for design or to develop tables or enough data to support building code changes. Furthermore, to be effective, the basic and applied research, development of mitigation options, and implementation of programs must be guided through broad based collaborative efforts that combine physical science, engineering, and social science research.

The sixth section addresses recommendations for changes in the Program. The two recommendations for changes to the proposed Strategic Plan identified above are the primary Committee recommendations for changes to the Program. They also directly relate to improving the effectiveness of the Program. The recommendation to add a strategic priority to develop assessment tools and mitigation measures for existing buildings and other infrastructure addresses problems of buildings and other infrastructure designed to older less windstorm resilient building codes and standards, containing construction flaws or errors, or that have not been adequately maintained. The recommendation to add an objective to evaluate options for implementing windstorm mitigation measures addresses both new and existing buildings and other infrastructure by identifying successful ways to promote, adopt, and/or enforce newer building codes and standards, best practices, and above code design and construction practices. The Committee's review of windstorm impacts also led to the identification of an area not included in the Program where storm impacts are significant but are poorly understood and inadequately modeled. Available surge and wave modeling is not able to properly account for highly granular local effects and there is a need to interface surge, wave and rainfall modeling effects in the near coast region to improve loading and flooding predictions. However, the Committee recommends against adding this objective to the existing program unless the current effort is adequately funded and extra funding is provided for this additional effort. Adding additional objectives to this small and underfunded federal program would just further dilute its effectiveness.

EXISTING AND EMERGING TRENDS

SOCIAL/SOCIETAL AND DEVELOPMENT PATTERNS

Population Growth and Urban Sprawl

The U.S. population has more than doubled since the mid-20th century, with the character of housing for this population transitioning from a dichotomous urban or rural quality to a more sprawling quality. Over this period, the number of housing units in the U.S. has increased by nearly 100 million, or 400%, while the developed spatial footprint has increased by over 600%[1]. This increasing magnitude and spread of the built-environment[2] exposure is a primary contributing factor to growing losses and impacts realized due to windstorm and other weather-related hazards. Thus, while the individual odds of being affected by a tornado or other windstorm hazard may not be changing, the odds of a windstorm hazard affecting something or someone somewhere have increased significantly. This increasing footprint of the built-environment, as well as increasing value of assets within the nation's developed footprint, are a strong headwind working against the important goals of reducing losses of life and property laid out in NWIRP's Vision and Mission statements.

Development in High-Risk Areas

Much of the built-environment development during recent decades has taken place in high-risk areas, particularly the Southeast, Sun Belt, and Coastal regions. Take, for instance, as of 2010, nearly 40% of the U.S. population lived in highly-vulnerable and at-risk coastal counties[3]. Over 20 million new housing units have been built within 50-km of the East and Gulf Coasts since the mid-20th Century[4]. Most of this development has been in high-density urban and suburban areas of coastal cities, which has increased markedly the odds of catastrophic impact from tropical and extratropical cyclones and their affiliated hazards. Demographic projections suggest that an additional 20 million housing units will be built in this coastal zone by 2100, increasing the potential number of housing units that could be impacted in a hazard event. Development in some of these regions is outside of existing levee systems and many of these housing units have low economic status, increasing the friction preventing implementation of effective mitigation strategies.

Areas particularly vulnerable to the tornado hazard have seen similar dramatic increases in population and related development. For instance, since 1950, the highly vulnerable Mid-South region has had a 1,700% increase in land area designated as urban and an increase of over 800% in land area designated as suburban and exurban[1]. This region has experienced a tenfold increase in housing units impacted by tornadoes since the mid-20th century.

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[1] Ashley, W. S., and S. M. Strader, 2016: Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bulletin of the American Meteorological Society*, **97**, 767-786. http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-15-00150.1

[2] The built environment is also known as civil infrastructure.

[3] National Ocean Service, 2014: What percentage of the American population lives near the coast? http://oceanservice.noaa.gov/facts/population.html

[4] Freeman, A., and W. S. Ashley, 2017: Changes in the U.S. hurricane disaster landscape - The relationship between risk and exposure. *Natural Hazards*. http://chubasco.niu.edu/pubs/Freeman%20and%20Ashley%202017.pdf

These demographic trends exemplify the need to have an expansive and proactive policy toward reducing windstorm impacts if the NWIRP goals are to be met in the face of continued development.

Trends in Diversity and Inequality

The United States is becoming an increasingly diverse population and, unfortunately, a more inequitable society in terms of income and wealth. For example, racial and ethnic diversity is increasing so rapidly that by the middle of the 21st century no single racial/ethnic group – White, Black, Hispanic, or Asian – will be in the majority. Since the latter part of the 20th century the United States has also seen the bedrock of its society, middle-income households, diminished considerably. Adults in middle-income households represented 61% of all US households in the early 1970s, but by 2015, that percentage fell to just 41%. Furthermore, the share of income going to upper income households grew from 29% to 49% of total household income, representing 7 times the share of income going to middle-income households. The picture that emerges is of a more demographically diverse population in terms of race, ethnicity, culture, and language, but also in terms of economic resources, particularly disposable income.

These trends have consequences for attempts to become a more windstorm resilient society. In seeking to move toward a more resilient society, it is important to consider how language, culture, and social capital, for example, can have consequences for storm warning messages, trust in government and local authorities, and the framing of risk and vulnerability information to promote mitigation actions. Furthermore, and perhaps more significantly, these socio-demographic and economic factors have consequences for a household's ability to cope with, adjust and undertake mitigation actions, as well as respond and recover from hurricanes, tornadoes, and floods. Taken together these factors will shape the changing patterns of social vulnerability[5], and ultimately risk within communities, states, and the nation.

Changing Patterns of Community Planning

The adoption of the Disaster Mitigation Act of 2000 marked a sea change in mitigation planning throughout the United States. This act (Public Law 106-390) established new hazard mitigation planning requirements at the state and local level in order to gain access to federally authorized hazard mitigation funding. In addition to stimulating the expansion of local hazard mitigation planning throughout the country, there has been an expansion of the inclusion of hazard mitigation planning as part of comprehensive and general municipal and/or regional plans. Recent hurricane disasters – Katrina, Ike, and Sandy –have also stimulated more communities to consider the adoption of disaster recovery plans prior to hazard events, rather than attempting such planning efforts in the chaos following a disaster. Harvey, Irma and Maria will likely spur more planning efforts. These growing trends in hazard, recovery, and comprehensive planning efforts open opportunities for increasing utilization of

[5] Social Vulnerability in this context is generally defined as a person or group's capacity to anticipate, cope, resist, and recover from the impacts of a natural hazard. That capacity is shaped by socio-economic factors such as income, wealth, education, social capital, and other socio-demographic factors like age, gender, race, language, and ethnicity. The most socially vulnerable groups tend to have the fewest economic and social resources to prepare for, respond to, and recover from a disaster.

research-driven improvements in hazard assessment and physical/social vulnerability analyses and mapping tools within these planning processes which can lead to improvements in windstorm resilience.

Insurance

Insured damages are usually paid out either in Actual Cash Values (ACV), where the insurance company replaces damage less any depreciation and deductible, or Replacement Cost Value, (RCV), where the insurer pays all costs to restore the building to pre-storm conditions without factoring in depreciation. These differences are generally not well understood by insurance consumers.   Because of severe hail and wind damage in recent years, insurance companies have moved more to ACV-based policies, higher deductibles, certain exclusions, etc., likely leading to a gap between the actual and the perceived coverage the consumer believes they are receiving. While these changes may encourage homeowners, and building owners to improve their building maintenance practices, it is more likely that they will not adequately understand their share of the financial risk and many will find themselves unable to cover the costs of recovery following an event. Furthermore, as costs of insurance rise, many low-income homeowners may opt out of coverage entirely, which will further exacerbate the ability of at-risk communities to recover.

DESIGN AND CONSTRUCTION

Building Code Development, Adoption and Enforcement

Hurricanes:

At the time Hurricane Hugo (1989) impacted South Carolina, model building codes had very few wind provisions pertaining to non-structural building envelope elements. But, this eventually changed because of Hurricane Hugo and the extreme damage caused by Hurricane Andrew (1992) on South Florida. In the aftermath of these two hurricanes, attention began to focus on wind resistance. Improvements were made to test methods, new test methods were developed, wind requirements were added to model building codes, and the importance of adequate inspection and enforcement by local building departments became recognized. Also, new products were introduced, improvements were made to some existing products, specific wind pressure or wind speed ratings began to be included in product labels and information, and there has been increased awareness of wind loads and effects in design and construction.[6]

Hurricane Andrew revealed that inadequate construction practices had been common in Florida for several decades. Similar to the experience with Hurricane Hugo, there were many failures of structural elements (e.g. roof decking, roof framing, bearing walls, main frames). Significant public attention was drawn by investigative reporting to poor inspection and enforcement practices. As a result, the South Florida Building Code (SFBC) was upgraded in 1994 to include elements to mitigate wind damage and significant changes were made in administration of the building code and standards. Building officials from coastal areas around Florida helped out with the recovery in South Florida and took lessons

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[6] Smith, Thomas L., 2009: Historical Performance of Critical Facilities Exposed to Hurricanes: Lessons learned and Opportunities for Improvement. *Proceedings of Hurricane Hugo 20th anniversary symposium on building safer communities – improving disaster resilience*. *Applied Technology Council*.

learned back with them to their local jurisdictions. In the following years, some of the South Florida provisions and the high-wind provisions of the Standard Building Code were adopted throughout many Florida coastal communities and code enforcement was strengthened. These changes culminated in 2001 with Florida's adoption of a statewide building code, the Florida Building Code (FBC) which incorporated many of these wind resistant provisions. This was accompanied by a major education and training effort for builders and building officials throughout the state. Hurricane Charley in 2004 provided an impromptu experiment to test the effectiveness of the FBC and the education and training efforts; it was found that homes built under the FBC had fewer claims and suffered reduced loss, when homes did have a claim, versus homes constructed under previous building codes.[7] Later research confirmed the Hurricane Charley result, using all wind loss data in FL from 2001 to 2010, resulting in an estimated 5 to 1 benefit to cost ratio.[8]

Improved building performance that was found for new construction in the aftermath of Hurricane Charley, was also found with new construction exposed to Hurricane Ike (Texas 2008), where building envelope breaches were uncommon in new construction. The improved building performance, including both residential and non-residential construction, is attributed in part to the addition of building envelope requirements in model building codes, improvements to wind load provisions in the American Society of Civil Engineers Standard 7 (ASCE 7) *Minimum Design Loads for Buildings and Other Structures*, and improved and new test methods. Improved building performance is also attributed to better building code enforcement. Besides checking construction and installation issues, better code enforcement frequently results in local building suppliers stocking products that have the appropriate pressure or wind ratings, because they know the building inspectors will be checking to make sure the products meet the minimum requirements.

While structural performance has improved as a result of the factors listed above, non-structural damage that can result in displacement of families and businesses continues. In both Hurricanes Charley and Ike, some newer buildings that did not experience broken windows or loss of roof or wall sheathing did experience significant wind-driven rain infiltration when the roof covering was damaged or blew off and others without roof covering damage still suffered interior water damage due to water entry through soffits or roof vents, windows and/or doors. And, many older buildings that had not been mitigated continued to experience damage to structural elements. Reducing the vulnerability of older buildings and reducing wind-driven rain infiltration remain research and implementation challenges.

Tornadoes:

In the aftermath of the F5 tornado that struck Lubbock, TX, in 1970, Texas Tech University (TTU) established the National Wind Institute[9]. Faculty and students investigated that event and pioneered field research investigations of tornadoes and hurricanes. Post-tornado damage observations by TTU and the Federal Emergency Management Agency (FEMA) have often revealed that small interior rooms, such as bathrooms and closets, were the only portion of a building that survived. These observations led

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[7] Institute for Business and Home Safety, 2004: Executive Summary – Hurricane Charley: Nature's Force vs. Structural Strength. http://disastersafety.org/wp-content/uploads/hurricane_charley.pdf

[8] Simmons, K.A., Czajkowski, J., Done, J.M., 2017: Economic Effectiveness of Implementing a Statewide Building Code: The Case of Florida. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2963244

[9] The National Wind Institute was formerly known as the Wind Science and Engineering Research Center.

to the development of strategies for designing rooms within buildings that would protect occupants. TTU initially developed a design for an in-residence shelter. That work was refined and published as FEMA P-320 in 1998.

The next evolution in tornado safe room design occurred after the May 3, 1999, Kansas and Oklahoma tornado outbreak. In the aftermath of that event, FEMA P-361 was published. With that publication, architects and engineers were given reliable criteria for designing tornado safe rooms in non-residential buildings. FEMA P-320 and P-361 were the basis for a standard (ICC 500) that is referenced in the International Building Code (IBC). The 2015 IBC requires tornado shelters in new schools and first responder facilities in the areas of the nation with the highest tornado risk. The 2018 IBC extends the requirements to include additions to existing school campuses. The May 3, 1999 outbreak also led to the publication of FEMA P-431, which provides guidance to architects and engineers for selecting best available refuge areas in buildings that do not have tornado safe rooms.

Prior to 2011, the emphasis was on protecting building occupants. However, in the aftermath of the tornadoes that spring, attention was given to minimizing building damage. FEMA published technical guidance for strengthening facilities to minimize damage from weak and strong tornadoes (FEMA P-980 [RA6]). The guidance also includes enhancements to avoid interrupted operations of special critical facilities (such as Emergency Operations Centers (EOCs) and hospitals) during and after violent tornadoes.

Moore, Oklahoma suffered a tragic tornado in 2013, costing almost $2 billion in loss and 24 lives, including 7 children at Plaza Towers Elementary School. The next year, the city adopted an enhanced building code that increased the design wind speeds from 90 to 135 mph.[10] Given the estimated cost of the enhanced code requirements and engineering estimates of reduced loss, the code enhancement is expected to provide a $3 in benefits for every $1 in cost.[11,12] Moore's code enhancements are intended to reduce building damage. For occupant protection, ASCE 7-16 recommends that consideration also be given to including a tornado shelter complying with ICC 500 or a safe room complying with FEMA P-320.

Adoption and Enforcement:

Development of strong, scientifically sound building codes is only a first step; the critical next steps are the adoption of building codes by states and local jurisdictions (counties and municipalities), their implementation sometimes with or without amendments, and the critical process of compliance and enforcement. While some states and local jurisdictions have adopted recent residential and commercial building codes, others lag in the adoption process of either or both, and some fail to adopt any form of building code. There are attempts by some states and organizations to gather data on the prevalence of building code adoption. However, there are few systematic attempts at collecting and maintaining these data, particularly at the county and municipal levels. Additionally, organizations such as The Insurance

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[10] City of Moore, 2014: City Adopts New Building Codes, First in the Nation. https://www.cityofmoore.com/node/2111

[11] Simmons, K. M., (2015, May 14) An Oklahoma Suburb, Tornado-Ready. *The New York Times.* https://www.nytimes.com/2015/05/14/opinion/an-oklahoma-suburb-tornado-ready.html

[12] Simmons, K.M., Kovacs, P. Kopp, G., 2015: Tornado Damage Mitigation: Benefit-Cost Analysis of Enhanced Building Codes in Oklahoma. *Journals Online: American Meteorological Society*. http://journals.ametsoc.org/doi/abs/10.1175/WCAS-D-14-00032.1?af=R

Services Organization (ISO), through its Building Code Effectiveness Grading program offers a tool to evaluate the effectiveness of jurisdictions that chose to participate by providing extensive data on their adoption, implementation, and enforcement of building codes. However, these data are proprietary and based on a selective periodic sample. There is a critical need for systematic research into the prevalence of and factors shaping the adoption of building codes, issues in the implementation and amendment processes, and enforcement of building codes. Particularly important is the need for research into the development and evaluation of peer reviewed and publicly available metrics assessing the effectiveness of implementation and enforcement regimes and factors shaping each. Results of this research will help communities identify which options may be most successfully employed for adopting or strengthening and enforcing building codes in their particular community or jurisdiction.

Summary:

It is an encouraging trend to find that some communities and states are adopting building codes with enhanced windstorm resistant provisions. However, the motivation for adoption appears to be triggered by catastrophic and/or tragic events. Proactive adoption is preferred, making the challenge going forward one of finding ways to encourage vulnerable communities to consider adopting current codes and code plus[13] options before tragedy strikes. One approach may be to move beyond codes and standards that focus on the risks to individual properties and instead, heeding the warnings raised in the first two trends discussed above, consider risks to a community as a whole and to the infrastructure that supports and binds the community together.

In general, changes incorporated in building codes and standards over the past 25 years continue to promote better windstorm design and construction. Nevertheless, improvements in codes and standards, analysis and assessment tools, and design methodologies are still needed to help assure cost effective use of resources and production of infrastructure that performs as expected. Furthermore, the incidence of more frequent and more powerful wind events will prompt the need to assess the standards to which codes are developed. The Strategic Plan's emphasis on support of performance based design for windstorms is appropriate and much needed.

At the same time, the code requirements continue to become more complex, and this complexity makes their application, more challenging to design professionals and contractors. Also, product manufacturers in the solar, vegetative roofs, roofing, cladding, and fenestration industries continue to introduce product innovations into the marketplace at a rapid pace. The testing standards, building practices, and code provisions for such product innovations and technologies have been slow to adapt to these changes, oftentimes leading to building practices that are not adequately tested and understood prior to being introduced to the marketplace. For example, only now have provisions for determining design wind loads on solar PV panels been included in the 2016 edition of ASCE 7 and the 2018 edition of the IBC.

The US is experiencing a strong backlash against regulations of almost any sort and efforts to change building code provisions has frequently experienced these forces. Code change proposals are supposed to include a cost impact statement and it is expected that this will become an even more important

[13] In this context, code plus generally refers to the adoption of provisions that provide enhanced protection (beyond the minimum values adopted in the building code) for buildings from the effects of natural hazards. These frequently reflect best practices for improving resistance to specific hazards or effects.

requirement in the future. Development of robust modeling tools that can be used to assess the benefit/cost ratio for specific code changes relative to today's risk as well as future risk is a natural extension of efforts outlined in Objectives 6 through 9 and will provide critical support for achieving Objectives 11 and 12.

Existing Infrastructure

The Committee recognizes and applauds the positive changes in building codes and standards that are resulting in more wind resistant buildings and other structures in communities that adopt and enforce these stronger codes, as discussed in the previous section. However, much of the existing building stock was built and some new construction continues to be built under either no codes and standards or older codes and standards lacking provisions that produce more wind resistant buildings. Furthermore, as buildings age, components and connections may degrade because of environmental exposure or repeated loadings. Consequently, existing buildings and other structures are and will remain an important source of windstorm related vulnerabilities for their owners and the communities where they are located. It is important to take opportunities to strengthen these buildings when costs can be minimized and benefits can be maximized.

Building codes such as the IBC contain provisions that are to be applied to both new and existing buildings. The International Existing Building Code (IEBC) specifically addresses the repair and alteration of existing buildings and includes triggers for certain types of remedial measures, many of which are focused on seismic remediation. Since the provisions of the two codes are not identical, conflicts between code provisions arise in communities where both have been adopted. While these conflicts are generally resolved in favor of the more stringent requirements, there is a clear need for coordination between the codes as they are applied to existing buildings. Furthermore, there is a clear need for expansion of practical cost-effective wind related remedial measures targeting the key vulnerabilities of older buildings that may not have been properly maintained or were built in communities with inadequate or no building code. These techniques need to be included as appropriate in the IBC, International Residential Code (IRC), and the IEBC.

Some states or jurisdictions do enact their own triggers that seek to force upgrades or mitigation measures when a modification or addition to the building exceeds a certain fraction of the building's value or habitable area. It is not uncommon to find building owners avoiding these remedial measures by limiting the scope of modifications or staging them over several years so that the incremental changes stay just under the triggers. Unfortunately, certain triggers can also lead to significant increases in un-permitted or unlicensed modifications and many jurisdictions allow unlicensed residential building modifications if the homeowner pulls the permit. Research is needed to determine the best public policy options for achieving mitigation goals for older buildings.

A critical need, with respect to research related to windstorm impact reduction for existing buildings and other infrastructure, is the development of tools (equipment) that can be used in the field to perform wind vulnerability assessments. This is discussed in more detail later in the report.

Failure or disruption of existing power, water, wastewater, and communications systems have a significant negative effect on response and recovery following an event, especially when it affects a large geographical area and extends for more than a few days. Access to communications systems and social media played an important role in identifying and locating individuals needing rescue throughout the Houston area following Hurricane Harvey. A disruption of those systems would have significantly impacted the response following the storm. Problems with transportation and logistics infrastructure including ports, airports, refineries, pipelines and highway systems can have a significant impact on re-supply of impacted areas and the recovery process. Gasoline shortages in Florida began before Hurricane Irma impacted the state and extended for days following the storm. In addition, flooding of distribution warehouses and loss of power in stores led to significant delays in re-supply at grocery stores.

At the individual family or business level, developments in photovoltaic systems and power storage systems will likely lead to a greater proliferation of distributed power generating capacity. There has already been a growth in natural gas-based generating capacity that can supply power to critical systems in a home or business. Adoption of these systems will likely lead to greater disparity in social vulnerability as the wealthy are most able to afford these systems.

Land Use and Development

The potential effectiveness of broad based land use and development policies for shaping building standards and patterns and avoiding development in high hazard areas is also lacking in systematic, science based research. Indeed, much of the discourse on these topics is based on limited information and ideology at this point. There have been a host of policies and approaches for promoting mitigation offered by the federal, state and local governments, and still more proffered (and often rejected) by many organizations such as the American Planning Association, State and County associations, and private and public interest organizations. For example, information dissemination, education and risk awareness programs target "the public" or specific groups such as building trades, do- it-yourselfers (DIYs), or schools seeking to change behavior by providing information and knowledge. Similarly, incentive based programs such as density bonuses, cluster development, FEMA's Community Rating System, lower tax rates, performance based zoning, and the transfer of development rights have been adopted by many communities and offered as solutions by of the aforementioned organizations and association. And finally, there are also more proscriptive based policies such as hazard setbacks, storm water retention requirements, development and deed restrictions, impact fees, special tax assessments or fees and, of course, zoning that have also been adopted by many jurisdictions and suggested as solutions or actively thwarted by organizations. In other words, there exist an amazing array of alternative approaches for shaping how and where communities expand and build which ultimately determines a community's windstorm and associated hazard risk profile. In a very real sense each State, with its unique legal and regulatory environment, represents an experimental laboratory for these approaches, with some environments favoring some approaches or combinations of approaches over others. Furthermore, each county and local jurisdiction, with their varying degrees of capacity, commitment, exposure, and jurisdictional characteristic, represents an opportunity for systematic data collection both within and between these State laboratories. What is needed is systematic research conducted before and after hazard events to understand factors shaping (promoting and thwarting) the adoption and implementation of these alternative mitigation policies both individually and as complementary portfolios. And, what is ultimately needed is sound scientific research seeking to quantify the effectiveness or weaknesses of these policies for not only reducing risks, but saving lives and reducing losses. We have a unique opportunity in the United States to undertake analyses on the adoption, implementation, and enforcement building codes as well as the effectiveness of other mitigation policies in unique state-based testing grounds. From this research, we can learn from our own experiences, develop best practices, and share them to reduce future windstorm risk and thereby make our nation more disaster resilient.

Workforce Diversity and Skill Level

The 2008 housing and financial crisis resulted in a dramatic drop in both residential and commercial construction, the layoff of many design professionals and construction workers and a dramatic shrinkage of the construction workforce. As the construction industry has slowly rebounded, many of the experienced construction workers have not returned. The result is a more diverse, less well-trained workforce where communication issues are an important impediment to understanding and appreciating the need to follow manufacturers' recommended installation requirements and one where experience with best practices has been lost.

Workmanship deficiencies are a primary cause of many wind failures. Consequently, Strategic Priority 7 should address workmanship deficiencies and the construction trades. It should also address construction robotics.

Research Facilities

There has been an expansion of research facilities and deployable equipment over the past 15 years that are producing valuable wind load and wind effects data. Insights gained from these facilities are helping refine the understanding and assessment of windstorm loads and effects as well as the strengths and weaknesses of typical design tools and construction norms. New research facilities for studying straight-line wind effects on buildings and other structures include Florida International University's "Wall of Wind", Insurance Institute for Business & Home Safety's full-scale wind test facility, and the University of Florida's (UF) automated boundary layer wind tunnel and other experimental resources for high-wind-speed/debris impact/high-wind-load testing of building components. New facilities for studying vortex flows and their effects on models of buildings include tornado simulators at Texas Tech University (TTU) and Iowa State University plus the newest large vortex flow "WINDEEE" facility at the University of Western Ontario. Field instrumentation includes the University of Oklahoma's Doppler on Wheels (DOW) and an assortment of deployable meteorological stations including TTU's stick-net system and an assortment of 10-m mobile towers deployed by UF, Louisiana State University, and TTU. The State of Florida also supported house instrumentation systems that collected wind pressure data on six houses experiencing hurricane eyewall winds during the 2004 and 2005 hurricane seasons. These hardwired systems are being replaced by wireless technology developed at Florida Institute of Technology.

Despite these advances, new and expanded facilities and deployable equipment – including steady streams of funding for deployments – remain a critical need. In particular, better understanding of system performance benefits and issues are a critical need for improving building design and performance. Opportunities exist to better target resources and improve efficiencies that will help offset the additional costs associated with improved windstorm resistance.

TECHNOLOGY AND DATA

Technology

Architects and engineers are increasingly relying more on technology to design, construct, operate, inspect, maintain and conduct research on civil infrastructure and lifelines. This trend signals that a major transformation in civil engineering is underway, i.e., the use of human workers will give way to artificial intelligence and autonomous systems that automate workflow, produce more reliable performance, and further accelerate the rate of technology adoption. Today, new technologies are already being contemplated and developed which could revolutionize the construction industry. Robots will be used in the future to prefabricate building parts which are shipped to jobs and assembled onsite; 3D printing, laser scans used to make 3D images, and artificial intelligence will not only increase productivity, but enable more precise and sophisticated construction. Monitoring and collection of data will be easier with cheaper, more reliable sensors; The Internet of Things (IoT) will improve the capture of data but will likely add significant new security challenges as well as questions concerning data access and data sharing. The challenge of new technologies will be in integrating and utilizing these technologies to improve construction, monitor the condition of buildings, and to use that information to reduce windstorm damage and losses.

New and existing technologies will also support advances in search and rescue, as well as response and recovery. Reverse pinging of cellular technology was offered as an example of existing technology that could help search and rescue teams locate individuals after a disaster by identifying the location of their smart phones. A current requirement is that the phone owner must enroll-in/permit-access-to the service so that authorities can use it to locate their phone. In many cases, the ability to push access to these technologies down to the local level is a prime impediment.

NWIRP is critically positioned to steward these developments, which align with NIST's stated mission of stimulating innovation and advancing technology. Examples of critical areas include the (pre)manufacturing of hazard-resistant infrastructure using 3D printing and robotics, development of future standards to optimize engineered structures, advancement of computational methods to reduce reliance on physical testing, and measurement science that underpins real-time (remote) sensing and data fusion. Further, NWIRP should play a critical role in future workforce development. Within decades, the employment consequences could be staggering if workers do not keep pace with technological change.

Big Data

The dramatic growth of Big Data, starting with efforts to create extensive mapping and resource databases can lead to changes in the way local and regional planning agencies and industries make decisions and manage. When it comes to the built environment, (buildings and other infrastructure), jurisdictions and companies are compiling large data sets on building locations and attributes and on infrastructure networks and linkages. Where local jurisdictions require building permits and store the data electronically, these jurisdictions and a variety of companies can search building permit databases to capture permit data for new construction as well as remodeling and reroofing. Several companies periodically fly and/or drive the country to capture high-resolution images which can be mined for building foot-print size, roof area, roof complexity and other features of buildings and other infrastructure. Tax assessor databases are being mined and routinely used to populate large databases with building characteristics. It is possible to use current and historical image datasets to track development of areas of the country. While data confidence remains an issue, database managers have been developing tools for assessing data quality for some items such as permit data by controlling for typical permitting rates given population data for the jurisdictions and census data. Real estate databases typically contain information about building size and a number of building features including types of heating and cooling systems, numbers of bedrooms and baths, and historical sales records including price paid.

Limitations to use include fees charged for access to the large databases and to the tools developed to facilitate their use. From a wind performance perspective, a challenge is that the databases typically do not contain the level of granularity on construction details that are considered important from a windstorm resilience perspective. Some estimates are made by risk modelers using age of construction as a means of estimating code requirements, code compliance and quality of construction. This works best for portfolio or community level assessments; but, is less useful for developing mitigation plans for specific buildings or other structures as well as parts of communities. Nevertheless, significant resources continue to be dedicated to expanding and improving these databases.

A study in New York City is on-going that will capture detailed windstorm vulnerability data for certain types of buildings. A series of “Safe Home” programs in Florida, South Carolina, and Alabama as well as the Insurance Institute for Business & Home Safety (IBHS) FORTIFIED Home program are compiling data on building and construction details for thousands of existing homes in selected states. Some commercial property insurers routinely inspect buildings and businesses they insure to assess their vulnerability and develop mitigation plans and recommendations. Some data from these sources may become available to researchers involved in the NWIRP; but, much will likely remain proprietary for privacy or competitive reasons.

Ultimately, “Big Data” is likely to provide the underpinnings for new classes of very granular vulnerability data that may include the ability to map both windstorm hazard physical vulnerability as well as socio-economic vulnerability.

Modeling and Computational Capabilities

Computational power continues to grow at an exponential rate and availability of computing capacity is expected to increase while costs and barriers to its use are expected to decrease. These capabilities will enable rapid analysis and synthesis of data for a variety of applications involving hazard prediction and building and other structure performance. Improved predictive models of hazards will include wind loads, wind effects, wind-driven coastal and riverine surge, waves, and currents. Building and other structure performance will include wind loading of components and systems, wind effects such as wind driven water intrusion, component and system resistance, and overall probabilistic evaluations of building and structure performance for a given hazard level or expected site risk profile.

A heavy reliance on testing of individual products will likely give way to computer modeling that has been validated against physical testing. These models will offer opportunities to incorporate serviceability issues and to account for the beneficial effects of regular maintenance. Computer modeling will likely open the door for including effects of environmental conditions that contribute to degraded performance as the products age and are exposed to influences such as ultraviolet light, extreme temperatures, thermally-induced cyclical movements, moisture, mold, and mildew.

Advances in the development of synthetic population and economic data by a variety of agencies, companies, and the research community are generating highly granular data on the locations and socio-economic and demographic characteristics of jobs, individuals, and households within U.S. communities. These data, in combination with high resolution housing, infrastructure, windstorm and associated flooding data, offer unprecedented opportunities to map and analyze physical *and* social vulnerabilities critical for mitigation, response, and recovery planning to lower the nation's risks.

NEEDED TRENDS

EDUCATION, TRAINING, AND WORKMANSHIP

The Committee devoted significant time discussing needs for improved/expanded education opportunities related to windstorm hazards and performance of buildings and structures at all levels from kindergarten through college/university and to the development of researcher resources. Improvement and expansion of education and training for design professionals, builders, developers, building officials and construction trades is considered of equal importance if mitigation goals are to be achieved. Homeowners and building owners need education and awareness about windstorm vulnerabilities so that they will value and ask for windstorm resistant features in their homes, businesses, and critical infrastructure, and will allocate resources for maintenance and replacement of weathered components/systems. General public education is also important to promote understanding of and the need for adopting building codes and standards along with land use and development regulations that can reduce a community's risk profile.

Discussion also focused on the need for improved workmanship since proper installation plays a major role in providing windstorm resistance. It was brought to the attention of the Committee that the Board of the National Roofing Contractors Association has charged the organization with training and certifying 180,000 roofing workers over the next 5 years and has approved an expenditure of millions of dollars to support that effort. There may well be other educational programs and efforts where NWIRP can partner to help improve the Nation's resilience to windstorms.

SOCIAL ECONOMICS

Two primary themes were identified by the Committee as needs in this area. The first was creating a broader acceptance of the benefits of adoption and enforcement of modern engineering-based building codes and standards, the benefits of code plus construction, and the quantification of the economic impacts of building code adoption and enforcement. The second was an assessment of benefits, costs, and propensity of communities to accept policies and mitigation measures, including building code adoption and land use planning that will provide communities with a portfolio of options for implementing windstorm resilience measures. This second need will require economic and social research as well as effective communication and is addressed in Objective 7 of the Strategic Plan. One objective would be to build on limited studies that show adoption and enforcement of building codes is not disruptive to the local economy and can have a positive benefit/cost ratio. A second objective would be to build on approaches developed in the National Institute of Building Science (NIBS)/Applied Technology Council (ATC) study on saving from mitigation expenditures[14] that broke new ground in trying to quantify societal benefits of mitigation activities.

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[14] National Institute of Building Science, 2005: Natural Hazard Mitigation Saves: An Independent Study to Assess the Future savings from Mitigation Activities. *Multihazard Mitigation Council.* http://www.floods.org/PDF/MMC_Volume1_FindingsConclusionsRecommendations.pdf

SERVICE LIFE BASED DESIGN

Many products are developed to meet requirements of specific test standards at the time of manufacture and are not subjected to any type of aging effects. The Committee discussed the need for a broader view of products and systems that focuses clearly on real-world performance over the expected service life of the product or system, taking into account potential future increases in risks. Some years ago, testing of glass that had been in service for many years demonstrated that the in-situ capacity had decreased significantly compared to that of new glass. The industry stepped up and changed its design requirements so that the in-situ expected capacity met the design load requirements. These types of assessments and approaches to evaluating product and system performance need to be extended to other products and systems that may also be susceptible to degradation during their service life and consider potential increases in future precipitation, heat or wind.

COST EFFECTIVE MITIGATION OPTIONS

Committee discussion returned several times to concerns about adequately addressing the vulnerabilities of existing buildings and other structures. The Committee believes that the Strategic Plan does not adequately emphasize the need to develop technologies for assessing the vulnerability of existing buildings and particularly building envelope related wind, windborne debris, and wind-driven rain vulnerabilities. There is a clear need for nondestructive technologies that will assess the health and residual capacity of existing buildings. There is also a critical need for developing retrofitting alternatives to address various vulnerabilities that recognizes the wide variety of materials, components and systems used to construct older buildings as well as newer ones. Finally, there is a need for an overall framework, like the one developed for rapid screening of buildings for seismic risks, that can be applied to the assessment of windstorm related vulnerabilities and the identification of cost effective mitigation measures. Research is also needed to determine effective approaches for incentivizing and/or mandating mitigation activities and the triggers used to require certain mitigation activities.

CONVERGENCE RESEARCH

Basic science research is still needed on windstorm characteristics and the relationship between those characteristics and the response and performance of buildings, structures and systems exposed to these events. To optimize the benefits for the NWIRP goals, the research needs to be inter-disciplinary, multi-disciplinary and trans-disciplinary. There was a sense by some committee members that the NWIRP needs to move beyond linear expectations for progress and changes, to embrace changes that may be possible by better anticipating and utilizing the exponential changes that are occurring in technology. The development of new technologies, codes, and standards does not guarantee their adoption by industry, homeowners, developers, communities, or even states; hence the need for multi-disciplinary research to understand factors shaping adoption by all of these constituencies to promote adoption and thereby reduce risks. The exponential growth in windstorm vulnerability and losses due to population, value and location stresses outlined in the trends section of this report requires disruptive changes to the status quo.

COMPUTATIONAL RESOURCES

Given the large and expanding availability of computer and physical facilities for application to wind and wind-related effects (wind-driven water, surges, waves, currents, etc.) as well as building and other structure performance (component, connection, system resistance to wind and wind-driven water), it is important that modeling and analysis tools be refined/developed to effectively utilize these assets. Computational assets are needed to fill critical roles in the following areas:

- Providing higher resolution information that can guide the selection of appropriate actions for a particular stage of a threat (early warning, imminent, and ongoing). Feedback from additional elements described below can provide information to improve the accuracy and value of synthesized data to the end user, essentially a form of data-mining. This is also an area where "NSF big data" groups should contribute information from their ongoing research.
- Storage and maintenance of non-sensitive historical data sources, large-scale experimental data, and laboratory simulations in openly available downloadable databases. A combination of statistical and computational models will need to be developed to distill and translate these data into information that can meet specific end-user needs. A complementary part of this effort will be the identification of needed improvements to existing predictive models and the development of models that are maintained to meet the state of the art, wherever possible.
- Improved modeling of storm effects including highly granular surge modeling capabilities and linkage of wind related flooding with rain- and runoff-related flooding. Current surge modeling does not adequately account for local variations in coastal geometry and bathymetry. Furthermore, surge modeling and rain-induced flood modeling are carried out separately although their interaction can significantly affect local flood risks.
- Improved modeling of infrastructure performance that captures and retains uncertainty in the expected outcomes. In most large disasters, the loss of hospital services, transportation links/hubs (roads, rail, bridges, tunnels, subways, etc.), major utilities (electric, water, communications, etc.), and other elements needed to meet necessary post-storm activities, significantly increase the impact of the event. Often, it is the loss of these infrastructure elements that transforms a disaster into a catastrophe. The replacement or repair of these elements is often very slow and extremely expensive and can affect large portions of the recovery area. Similarly, there is a need for improving building performance modeling that will support the development of performance based design (included in objective 10). In both the estimation of hazards and risks/impacts, it will be important to retain estimates of uncertainty in any effort toward developing robust estimates of expected losses and the cost reduction (life/health, economic, ecologic and social) afforded by different decisions. Such information could provide valuable feedback to guide investments in future research, future building technologies and long-term planning.

INCENTIVES, DISINCENTIVES, AND A PORTFOLIO APPROACH

The current approach to development of the nation's civil infrastructure is infused with several dis-incentives to effective windstorm mitigation. First costs[15] typically control the value engineering process

[15] Up-front expenditures by builders and developers are usually referred to as first costs.

and result in reduced expenditures for inspections during construction, and reduced expenditures for code-plus design or in features or product choices that will provide less windstorm vulnerability. The desire for an expanding tax base and the threat of litigation frequently over-ride attempts to dissuade development in some of the riskiest areas of a community. Regulatory controls may also impede a market-based assumption of the true risks of developing certain areas. Some communities and states have initiated or mandated a variety of incentives to promote retrofitting of residential buildings and keeping development out of high-risk areas. In addition to building codes and standards there are a host of complementary mitigation programs and approaches available. These include land use and development regulations, natural resources protection promoting ecosystem mitigation services, financial tools such as lower tax rates, special tax assessments, and impact fees, and an array incentive based programs and policies that are being utilized, promoted, and explored at federal, state, and local levels. Research is needed to understand factors shaping the adoption, implementation and effectiveness of these approaches for risk reduction and the particular problems that can arise when dis-incentives and/or incentives push development and construction decisions in opposite directions.

OBJECTIVES AND PRIORITIES OF THE PROGRAM'S STRATEGIC PLAN

GENERAL ASSESSMENT

The consensus of the Committee is that the Strategic Plan developed by the NWIRP Interagency Coordinating Committee, Windstorm Working Group, NIST Staff and NIST Contractors is well thought out, well developed and clearly written. Except for a recommendation to add an eighth Strategic Priority addressing windstorm related vulnerabilities of existing buildings and other structures, the Committee considers the Strategic Priorities to be appropriate and agrees that they should not be offered in any type of priority order. Together, these Strategic Priorities provide a broad array of important endeavors and allow each federal agency and their partners to engage in a meaningful way as their missions and funding allow. The recommendations and suggestions included below offer additional objectives, tasks, and changes in language or emphasis to be considered as the Strategic Plan is finalized.

RECOMMENDATIONS

1. New Strategic Priority: Add an 8th Strategic Priority that focuses on improving the windstorm resistance of existing buildings and other structures. Buildings designed and built to modern engineering based high-wind codes and standards represent a small fraction of the current building stock. Most of the existing buildings subject to high-wind risks have been designed and built to codes and standards lacking advances in engineering and experience based provisions that enhance windstorm performance. Furthermore, many older buildings have not been adequately maintained and components and systems critical for windstorm resistance have degraded due to age and exposure. Unfortunately, the most vulnerable individuals and groups within our society, those least able to recover from an event, frequently live and/or work in these buildings. New tools and methodologies are needed that can be used in the field for evaluating the windstorm vulnerability of these buildings including assessing the structural resistance as well as the resistance of the building envelope to damage and to water intrusion. Creative cost-effective solutions are needed to reduce damage to these buildings as well as loss of use. Tools for evaluating benefit/cost ratios for retrofitting and mitigation efforts will be important resources for establishing priorities, rationalizing expenditures, and justifying building code changes addressing existing buildings.

2. Objective 7: Language in Objective 7 be modified to recognize:

    a. There is a need for research on compliance issues related to building codes and standards. This would include the range of possibilities from "do it yourself" (DIY) through permit based construction and building. The overarching goal is to foster a culture of compliance and safety.

    b. It is important to target research on the socio-economic factors that may shape differential impacts in windstorm events. Therefore, Objective 7 should include research focusing on the complex interplay between individual and broader socio-cultural and socio-economic factors shaping differential impacts. Examples might be how socio-economic factors shape investment and reinvestment in the built environment, deferred maintenance, variations in infrastructure differences, differential access to resources and information regarding mitigation, etc. These areas are important for understanding of broad based windstorm resiliency within U.S. communities. Additionally, research should focus on the creation of more granular and refined social vulnerability analysis and mapping tools and products for use by the scientific and practitioner communities.

c. Objective 7 should be broadened to include research on understanding processes shaping jurisdictional adoption, implementation, and enforcement of a broad range of policies related to mitigation. These topic areas might include factors and processes that shape the adoption and implementation of building codes, land-use planning, incentive programs, warning and communication strategies, etc.

d. There are a multitude of different actors shaping the built environment including homeowners, developers, builders, civil organizations, municipal agencies, private-public partnerships, private concerns, planners, etc. Therefore, research is needed to address the social, economic, and political constraints that influence response to and proactive adoption of windstorm hazard mitigation policies and strategies. Again, these policies and strategies should not be limited to building codes related to new construction and retrofits, but also other forms of land-use policies, incentive programs, develop regulations, out-reach and education programs, etc.

3. Objective 8: Manufactured HUD Code housing units need to be specifically addressed by this objective.

   In many states with significant windstorm risks, HUD Code manufactured housing represents a large portion of the housing stock as well as new housing starts, especially for vulnerable populations. Death and injury statistics demonstrate that a large portion of windstorm related deaths and injuries occur in HUD Code manufactured homes[16, 17]. While several objectives identified under goals B and C relate to manufactured housing windstorm performance issues, the strategic plan should more explicitly address this segment of the housing market. Objective 8 dealing with data collection, analysis and archival should include data elements specific to manufactured housing construction and anchorage. Objectives 10, 11 and 12 should also include consideration of manufactured housing issues.

   Given federal, state and local building and installation requirements for manufactured housing, the National Windstorm Reduction Program needs to include/engage the Department of Housing and Urban Development as a partner agency.

4. Objective 8: Data collection should also include more information about deaths, injuries and survival rates.

   The strategic plan requires baseline data on injuries and fatalities to determine if the Program is to meet the challenge of reducing these first-order impacts from wind-related hazards. Currently,

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[16] Ashley, W. S., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880-2005. American Meteorological Society - Journals Online: *Weather and Forecasting*, **22**, 1214-1228. http://journals.ametsoc.org/doi/abs/10.1175/2007WAF2007004.1

[17] Sutter, D., and K. M. Simmons, 2010: Tornado fatalities and mobile homes in the United States. *Natural Hazards*, **53**, 125-137. https://link.springer.com/article/10.1007/s11069-009-9416-x

these baseline casualty data are generated from NCEI's Storm Event Database/Storm Data. While weather-related fatality data include some limited victim information such as age and gender, injury data are largely based on media estimates and wholly inadequate as an assessment tool. An effort to gather more robust information on all casualties and their circumstances should be a primary focus of the NOAA and other related agencies (e.g., the Centers for Disease Control (CDC)). For instance, all reports of tornado and wind-related fatalities in buildings should include more information on the specific building type, age, geolocation, and EF-Scale rating where the death occurred – also, was death caused by windborne debris or crushing caused by collapse of a wall or roof structure. Such data could be used to prioritize efforts to reduce impacts in the most vulnerable residential or commercial buildings.

Conversely, new efforts, using pre- and post-event assessments and qualitative research, should focus on determining rates of survivability in tornado and other wind-related hazards, discovering specifically what factors increase survivability for those directly impacted by these hazards. That is, a focus should be on *successes* of the warning system during an event, rather than failures, as measured by death and injury. There is currently little understanding of survivability in these events, and how specific proactive mitigation efforts for those in the path of these events reduced vulnerabilities, death and injury rates, and economic impacts. Uncovering and focusing on these successes will promote more effective and salient mitigation activities compared to focusing solely on factors that enhanced the probability of death and injury.

5. Objective 9: Expand this objective to include development of benefit/cost modeling, the need for better wind-driven flood modeling, and amplification of the outcome statement.

    a. Add the development of robust benefit/cost assessment tools that build off the developments that are included in Objectives 6 through 9. There are many potential uses of robust benefit/cost tools including: 1.) ranking, selection and promotion of retrofit and mitigation elements; 2.) ranking, selection and promotion of new code provisions; 3.) ranking of states and jurisdictions as targets for mitigation; 4.) estimating the potential benefits of new technologies applied to various aspects and goals of the Program; and 5.) helping to select program elements for particular focus and investment.

    b. Address the fact that advanced risk assessment and loss estimation tools for wind-driven flooding are still in a fairly primitive state of development. Much work is needed to advance this area of work, which is somewhat different than the tools used for wind forces on buildings and other structures. Most probabilistic wind hazards are relatively smoothly varying over large areas; whereas, risk related to water hazards can vary very substantially over short distances. Also, terrain characteristics including elevation and natural barriers such as dunes can change significantly over time due to long-term effects such as subsidence and storm related erosion. Thus, the long-term risks often depend more on where you build than on how you build for these hazards and developments in coastal areas need to account for these long-term effects.

    c. Objective 9 covers a lot of activities, but the outcome statement is quite brief. The outcome statement should be amplified.

6. Objective 10: There is a critical need to develop technologies for assessing the vulnerability of existing buildings.

7. Objective 11: Wind-driven flooding risks need to be considered and it needs to be addressed by a combination of where to build and building codes that depend on the location of the building or other structure. Research is needed to develop the kinds of maps and/or rules needed to codify these location dependencies.

8. Objective 12: This objective discusses mitigation and "encourages communities to adopt modern building codes and standards as a basis for design and construction..." This relates to new building construction. Over 50% of the commercial building stock in the United States was constructed prior to 1980 and with the increase in design life and repurposing, mitigation of these buildings to resist wind loading needs to be addressed.

   A mitigation standard for wind loading on buildings similar to the American Society of Civil Engineers Standard No. 41 (ASCE/SEI 41) *Seismic Evaluation and Retrofit of Existing Building* needs to be developed. Furthermore, engineering based reference standards to address roof and wall components, cladding attachments, and securement of ancillary features need to be developed and made available to designers. Currently, these types of standards have been developed by individual manufactures for new installations based on design of their specific products.

   These standards should then be referenced in the Codes for both new and existing construction. Specific language relating to requisite thresholds of renovations which would trigger implementation of wind mitigation measures for existing buildings should be developed.

9. Objective 13: This objective calls for the integration of "next generation radar", replacing the WSR-88D system that has been in service since the early to mid-1990s. The Strategic Plan should call for the deployment of Multi-function Phased Array Radar (MPAR; http://www.nssl.noaa.gov/tools/radar/mpar/) with a target operation date near the end of the medium time frame (years 12-15). This will require continued design and testing, as well as development and deployment by contractors, during the short and medium time frames. MPAR's ability to provide more rapid and precise data will significantly improve detection and near-term forecasting of weather hazards, delivering a fundamental tool for meeting NWIRP's Mission of reducing casualties and protecting property.

10. Objective 14 should address optimization of storm warnings for best possible outcomes, support efforts to enhance search and rescue, and support optimization of decision making.

    a. While continued focus on improving warning lead times should be a priority, additional efforts should be placed on improving detection of hazards, optimizing storm warnings for best possible outcomes, and, most importantly, reducing false alarms (e.g., a tornado warning issued with no report of the hazard). Research and NOAA assessment reports (e.g., https://www.weather.gov/media/publications/assessments/Joplin_tornado.pdf) provide evidence that reducing false alarms is required to improve warning credibility and decrease complacency among the public.

b. This objective should include efforts to deal with issues affecting the ability of local jurisdictions and search and rescue teams to access and use new technologies as they become available.

c. Objective 14 should also address optimization of choices for decision-makers across four different time scales: 1) pre-storm preparation, 2) in-storm activities, and 3) rapid, cost-effective post-storm recovery and 4) long-term planning. Logically these four scales should be recognized as a circular system, with long-term planning also at the beginning of the sequence. Considerable work has been accomplished by FEMA in terms of information on hazards for long-term planning; however, the remaining actions in the sequence remain under-developed. To extend the hazard information into risk estimates, it will be essential to consider many additional factors such as estimated loss of life, potential economic and ecologic damages, and impact on communities. In such calculations, it will be also extremely important to recognize the impact of damage to critical infrastructure.

11. Add new Objective 15: ***Improved understanding of the portfolio of policy approaches for promoting windstorm mitigation***

Despite the clear recognition by the engineering and scientific community of the importance of building codes and standards for addressing windstorm risk, it is still surprising to find that many municipalities and counties have not or cannot adopt and/or enforce building codes and standards. Furthermore, many states have yet to adopt or enforce statewide building codes. However, a number of states, municipalities and counties have not only adopted building codes; but, are also employing a variety of additional policies, mandates, incentive and education programs to promote mitigation. These polices include Land use and development regulations, shoreline regulations, natural resource protection, information dissemination and awareness programs, financial tools, and incentive based programs. The NWIRP Strategic Plan should include an objective promoting research that address factors shaping the adoption, implementation, and enforcement of building codes and standards as well as the adoption, implementation and assessment of the effectiveness of additional mitigation policies for reducing windstorm risks.

SUGGESTIONS

1. Objective 4: suggest adding the following on page 21 after line 15. “It should be noted that structural overloading is typically not the most widespread damage mechanism in coastal or inland flooding events. In these events, water entering buildings (i.e. water level) is the most pervasive hazard affecting the built environment. Forces in water-related hazards typically have greater impacts on infrastructure such as destruction of bridges and even well-constructed buildings through the action of breaking waves and erosion.”

2. Objective 5: Suggested modifications.

   Page 22, line 10 – add -- wastewater treatment facilities and infrastructure interdependencies.

   Page 22, first paragraph, suggest mentioning research on creating refined mapping of physical vulnerability related to the built environment.

   Also on Page 22, after line 34 suggest adding the following:

"*Flooding*. Many areas within the U.S. are subject to flooding from large-scale and small-scale weather events. In coastal areas, these are usually associated with tropical storms, while inland flooding is typically associated with extratropical cyclones. In both areas, water levels and velocities, along with debris within the water column constitute the major damage factors. The interaction of hydrologic flooding and coastal surges has been substantially neglected in past studies and research. Such flooding now occurs frequently in many coastal areas even during relatively small rain events occurring during a high tide. A better understanding of flooding hazards in coastal and inland areas is critically needed. This should include the development of coupled hydrologic-oceanic (surge) models for coastal applications and improved flood probabilities which are locally specified over an entire study area rather than a reliance on a small set of hazard annual exceedance probabilities.

Erosion. Coastal erosion during large storms and over years of exposure to waves, often compounded by land subsidence, is a major hazard facing most coastal communities today. Dune and coastal levee/structure breaching must be understood on an event-by-event basis, while larger-scale coastal evolution must be examined on a longer time scale. This introduces a time factor in hazards which is critical to understand and to quantify. This time factor is still neglected in most coastal areas of the US.

Waves, Wave Run-up and Currents. Waves and currents are a major hazard to buildings and structures built near a coast and are usually driven by tropical or extratropical cyclones. Today, the methodology for dealing with these hazards remains quite simplistic. There is a Natural Hazards Engineering Research Infrastructure (NHERI)[18] experimental facility capable of addressing these issues and effort is now underway to improve the understanding and ability to quantify of these hazards; however, this problem is complicated by the variability of the coast itself, as noted under "erosion," and by the large amount of debris in the water during intense storms."

3. Objective 6: The current narrative implies that the computational models are to replace physical tests that pertain to loads. The Committee suggests the narrative be expanded to clarify that it also includes development of computational tools that can replace physical tests to evaluate resistance.

4. Objective 11: There is a need to simplify codes and standards for use by building designers and contractors in the long term. An expert system should be developed to assist designers, contractors, and installers to aid in effective construction design which incorporates the proper use of all the various and abundant choices of construction materials and systems.

[18] For further information about NHERI, see https://www.designsafe-ci.org/

PROGRAM COORDINATION AND COOPERATION

The Committee believes that the reorganization of the NWIRP, where NIST has been assigned lead agency function is a positive move for the Program. Unfortunately, Congress has not appropriated any new funding to support any of the agency activities assigned in the original 2004 authorization or the 2015 re-authorization. Nevertheless, the agencies are moving ahead as allowed by their existing resources and are identifying and coordinating activities directly related to the Program objectives. Furthermore, given its lead agency responsibilities, NIST has committed funds to support its functions and has increased funding allocated to specific Program-related activities. If Congress had appropriated new funding in line with the modest budgets authorized, the agencies would be in a much stronger position to create and implement a well-coordinated program.

STRUCTURE

An Interagency Coordinating Committee (ICC) composed of directors or their designees of NIST, FEMA, NOAA, NSF, the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) oversee the planning and coordination of NWIRP as required by the authorizing legislation. At the working level, the primary structure supporting day-to-day coordination of the NWIRP is the Windstorm Working Group (WWG) which was reconstituted by NIST following the re-authorization. A similar working group was formed by OSTP to coordinate activities following the 2004 initial authorization. This reconstituted group includes representative from the four Program Agencies (NSF, NOAA, NIST, and FEMA) identified by Congress in the authorizing legislation and has been expanded to include representatives from the U.S. Department of Energy (DOE), Federal Highway Administration (FHWA), U.S. Department of Housing and Urban Development (HUD), National Aeronautics and Space Administration (NASA), OSTP, and the U.S. Army Corps of Engineers (USACE).

This structure appears to be providing a successful level of planning and coordination between the agencies as demonstrated by:

- Creation of a credible and well-written Strategic Plan for NWIRP that has been released for public comment and is the subject of the third section of this report.
- Progress, through individual projects and programs, towards meeting objectives outlined in the 2006 Windstorm Impact Reduction Implementation Plan.
- A history of collaboration and coordination on individual programs and projects.
- Progress towards meeting some of the strategic objectives identified in the draft Strategic Plan for NWIRP.

However, specific collaboration examples such as those between DOE and NIST, NOAA and NSF, NIST and NOAA, were generally described as originating from personal relationships developed between program managers involved in the WWG and in interagency meetings. To promote greater cooperation and partnering, the WWG needs to foster expansion of agency staff engagement beyond those participating in the WWG.

Another barrier to collaboration is the tendency for agencies to seek comparable funding levels from each agency co-sponsoring a project. With large disparities in available funding within different agencies, it is difficult for agencies with smaller resources to reach the threshold required for co-sponsorship and cooperation on specific projects. The Committee recommends that agencies explore the possibility of creating smaller budget add-on project targeting implementation of results as appropriate for the missions of different agencies.

NIST

The NIST reconstituted WWG has attracted representatives of a number of agencies beyond the four agencies specifically identified in the reauthorization legislation as described above. Under NIST's leadership they have worked to produce a credible well written draft Strategic Plan that also included input from a broad stakeholder workshop. The Plan was subjected to a public comment period. Of note is a public response from the National Association of Home Builders indicating their interest in partnering in efforts to improve windstorm resilience. NIST provided briefings to the Committee on Environment, Natural Resources, and Sustainability Subcommittee on Disaster Reduction (SDR) that resulted in NASA and USACE joining the WWG.

On the project side of its efforts, NIST has demonstrated its commitment to partnerships and coordination by hosting two stakeholder workshops on its project to develop new tornado hazard maps for the United States. One workshop was a broad stakeholder meeting and the second was for federal stakeholders. As a result of these meetings and subsequent discussions, the Nuclear Regulatory Commission is co-funding a part of the mapping project that will better define uncertainty in the wind speeds. NIST has also been exploring possible collaboration with NOAA and USACE on development of enhanced tools for engineering design and risk assessment that accounts for joint probabilities of hurricane wind, surge and waves.

Since NSF does not fund research-to-application nor does it fund creation of databases needed to refine, develop, or enhance codes and standards, NIST is the most logical core agency to fund those efforts. NIST should carefully review the research projects being funded by NSF and seek ways to support research-to-application add-on efforts for projects that have the potential to improve building codes and standards or lead to development of effective mitigation measures. NIST should assess capabilities of NSF funded facilities as well as other national resource facilities available for simulation of windstorms and their effects. It should seek to facilitate the use of these facilities to provide data and insights of practical value in improving codes, standards, and mitigation measures.

NIST worked with a consultant to produce wind field maps showing estimated over-land maximum 3-second gust wind speeds for Hurricanes Harvey, Irma, and Maria. These maps, which were made available as preliminary estimates shortly after the events (in the case of Irma map estimates for the southern part of Florida were made available while the storm was still moving over the northern part of Florida), were shared with other federal agencies as well as with researchers and proved invaluable for both groups in the days following these hurricanes. While NOAA provides warning products and estimates of maximum wind speeds over water as the storm approaches, there is a critical need for reliable estimates of wind speeds experienced by buildings and other infrastructure located on land. These estimates provide an underpinning for assessing the impacts of building codes and standards in reducing damage and help focus recovery efforts. The process and responsibility for developing and making available these types of maps should be formalized and supported for future storms where winds approach or exceed design wind speeds for the areas impacted. The Committee recommends making these maps available on both the NIST NWIRP web site and on the NSF NHERI Rapid website in both print and geo-referenced data layers. In addition, the modeling technology can produce time histories of wind speed and direction at grid points throughout the impacted area. This kind of detailed information would be useful for a variety of applications including damage assessments and correlation with social media postings of damage observations.

NSF

While NSF is not a mission agency like the other three core members of the ICC and WWG, a review of grants funded over the past five years demonstrates its broad impact in funding research projects with goals and objectives that are aligned with the 2006 Implementation Plan and the draft NWIRP Strategic plan. Within the framework of its commitment to funding projects based on their intellectual merit and potential for broader impacts, NSF has funded multi-year research projects and the creation of research facilities critical to the NWIRP mission. These include:

- Natural Hazards Engineering Research Infrastructure (NHERI) facilities/sites specifically dedicated to storm hazards (two specializing in wind loads and wind effects and one specializing in surge modeling) at about $2.0M per year.
- Additional shared NHERI resources (network coordination office, cyberinfrastructure, computational modeling and simulation center, and post-disaster rapid response facility) with at least $1.0M per year potential benefit to NWIRP objectives.
- Origins and characteristics of extreme windstorms including tornadoes and hurricanes at about $1.8 per year
- Physical and computational surge modeling research at about $0.4M per year.
- Tornado damage studies, physical model simulations, assessments of internal pressure effects, and studies of uncertainty at about $1.0M per year.
- Hurricane related research on loads, effects, and resistance at about $1.0M per year.
- Computer simulation related to computational fluid dynamics modeling of wind loads, surface wind modeling in complex terrain transitions, and cyber-physical optimization of structural design for wind hazards at about $0.5M per year.
- Social science research related to issues such as human response to tornado and hurricane risks, stage-based evacuation, and post disaster response, recovery and resilience at about $1.4M per year.
- Storm effects and response of lifelines at about $0.6M per year.
- Performance based design at about $0.4M per year.

Unless Congress provides NSF with funds for a special initiative, it is expected that NSF will continue to apportion some of its overall budget to fund research on NWIRP related issues when the proposals show intellectual merit and the potential for broader impacts. A key challenge has been the collection and dissemination of information on NSF funded projects including their outcomes. NSF is making progress in this area by requiring a list of publications for NSF grants awarded after January 2016 and has been working with publishers to create and populate a public access repository. NHERI projects are required to archive data and metadata and the committee would like to see this happen more broadly, including in social science studies.

The Committee specifically encourages NSF as well as other agencies to provide broad based support for combined physical, engineering and social science research. Social science research is valuable for contributing independent direction for research projects or programs. Furthermore, social science researchers are valuable assets as integrated team members with physical science and engineering researchers. This will help assure that the results are palatable to stakeholders and have a better chance of being implemented. Recovery and mitigation case studies include numerous examples of failed efforts because the solutions offered were not culturally or socially acceptable. Broad-based research that includes a social science focus is critical for understanding and addressing social vulnerability aspects of disasters. Support for venues that bring together government (local, state, and federal), practitioner, and research communities, such as the Natural Hazards Research and Applications Workshop, to facilitate the exchange of research findings and stakeholder insights, needs, and concerns related to windstorm and associated hazards should be enhanced.

NOAA

NOAA is clearly improving its forecast and warning abilities and systems. It is very close to meeting its five-year goal for improving hurricane track forecasts. Nevertheless, additional track forecast accuracy remains an area where improvements would help to reduce uncertainty and the costs and impacts associated with mass evacuations. Hurricane intensity forecasting is an area where significant improvement is needed. Beyond the advances already achieved, new radar technologies offer the potential for significant improvements in tornado and severe local windstorm detection as these systems are deployed and their supporting analysis tools are refined against ground truth data. Coordination and cooperation has also been demonstrated through OAR supplements to three different NSF awards dealing with hazards communication and the effectiveness of warnings and warning systems.

From a NWIRP standpoint, there is a bit of a disconnect between the stated agency goal, "support atmospheric sciences research to improve understanding of behavior of windstorms and their impact on buildings, structures, and lifelines," and the goals stated for its coordinated budget, namely:

- Hurricanes – This includes funding for hurricane forecast improvement, hurricane research-to-operations (R2O) integration, and operationally-focused hurricane research.
- Local severe weather, including tornadoes, derechos, and severe thunderstorms – This includes R&D and R2O activities related to these areas, including hazardous weather and aviation weather forecast improvement.

While the Committee does not want to indicate in any way that forecast improvements are not critical and it strongly supports deployment of new technologies and atmospheric sciences research to understand the behavior of windstorms, what has not been adequately supported are efforts to understand characteristics of extreme windstorm winds close to the earth's surface, where buildings, structures and lifelines are located. Automated weather stations are notorious for their failures to collect wind data during severe wind storms and the data that they do collect before losing power does not provide information on the gust structure of the winds. Studies to determine wind loading using either physical models in wind tunnels or computational model simulations require high-fidelity data that describes the approach-flow structure.

Years ago, there was a push for a pilot program to provide backup power and the ability to collect and retain high-fidelity (high sampling rate) data when winds exceeded a certain threshold at key automated weather station sites along the hurricane prone coastline. That type of program would provide important data for the engineering community as it works to improve methods for determining design loads for buildings, structures, and lifelines.

Since Hurricane Georges struck Louisiana in 1998, there have been several University based teams deploying meteorological instruments in advance of land-falling hurricanes. Some deployments have also benefitted from deployment of the Doppler-on-Wheels that was developed using NOAA and NSF funds and used successfully in well-developed and well executed tornado related field research programs that are continuing. However, for hurricane deployments, these teams and researchers continue to operate on a shoestring with coordination and collaboration being dependent of individual researchers or teams reaching out to each other. Adequately resourcing and coordinating these teams and equipping them with the ability to uniformly and consistently feed data to NOAA in real-time would provide tremendous benefits to emergency managers and the weather enterprise. The near surface data obtained from broad and coordinated coverage of the impacted areas would provide ground truth data for post event damage surveys and could help answer key questions about near surface extreme windstorm winds and changes in flow characteristics as surface roughness transitions or varies. Correlations between single and multi-point near surface wind time histories with simultaneous low-angle close-proximity Doppler records could provide valuable insights into flow structures that, in combination with deployed meteorological instruments, could have an important influence on wind loading.

In the days following Hurricane Harvey’s impact on the coast of Texas and Hurricane Irma’s impact on the Florida Keys and the Florida peninsula, NOAA acquired aerial imagery of the hardest hit areas and made them available on the web. This imagery has been extremely useful to research teams from academic institutions as well as federal agencies as they have weighed the benefits of ground based damage surveys and developed plans for target areas to be studied. Frequently, it is difficult to get teams into the area in the immediate aftermath of a hurricane and this type of imagery is extremely useful to many agencies and stakeholders. The imagery also proved useful to homeowner who had evacuated as it allowed them to take a bird’s eye look at their property to see if it was still standing and to get some idea of damage to roofs.

The Committee strongly encourages formalization of this process as part of NWIRP coordination. Imagery should be geocoded so that it can be easily correlated with surface evaluations using available technology. Geocoded lidar data which could be used to compare pre-storm and post-storm data would be useful for evaluating storm effects on coastal landforms and wave, surge and wind effects on structures. As technology and analysis tools improve, hyperspectral imagery is also becoming more important and useful.

FEMA

FEMA continues to make available information on best practices for coastal construction, safe room (storm shelter) design and construction, rebuilding and retrofitting existing buildings. While several reports, such as its widely referenced and procured safe room design guides, have been updated over the course of the past few years, much valuable work and promotional efforts have been stymied by a lack of funding. This is clearly reflected in the NWIRP coordinated budget communicated to the

Committee. In a number of cases, FEMA had to depend on use of post-disaster funding in cooperation with local agencies that needed documents or guidance updated in order to create the documents.

FEMA is uniquely positioned at the federal level to disseminate information and best practices to those who have been impacted and are most receptive to guidance as they restore or rebuild. FEMA has developed a suite of recovery guides that deal with specific issues related to specific events and the unique character of the infrastructure affected. For example, after Super Storm Sandy FEMA worked with a group of national experts to develop several guides for mitigating the types of issues raised by flooding of basements of high-rise residential towers in New York City.

FEMA is also uniquely positioned as a primary source for response and recovery funding for state and local jurisdictions, businesses, households, and individuals in the aftermath of windstorm and related disasters. As such, it is also the depository of data on response, recovery, and mitigation funding critical for resilience and risk-reduction research. Institutional Review Board processes and secure Federal Statistical Research Data Centers (https://www.census.gov/fsrdc) can protect personal information and ensure confidentiality. Results of research employing these data can assess the effectiveness of response and recovery programs, help FEMA and other governmental agencies, and non-government organizations (NGO) optimize and better coordinate response and recovery efforts, and ultimately provide evidence based guidance toward a more windstorm resilient future.

OTHER AGENCIES

It is encouraging to see agencies other than the four specifically listed in the authorizing legislation stepping up and participating in the WWG. It is even more impressive that at least one NIST project is receiving cooperative funding from DOE.

HUD provides, subject to congressional appropriation, Community Development Block Grants – Disaster Recovery (CDBG-DR) funding for infrastructure and housing recovery from flooding and windstorm hazards. Research community access to HUD data would also be a valuable asset for the social science and engineering research community. Such research could help improve the targeting and optimization of HUD programs and the coordination federal, state, local, and tribal priorities for infrastructure and housing recovery and mitigation to reduce windstorm vulnerabilities and enhance resilience.

COOPERATION WITH OTHER GROUPS

NIST and the WWG have worked in cooperation with the American Society of Civil Engineers (ASCE) and the Applied Technology Council (ATC) to host a workshop that provided an early roadmap exercise to identify gaps in knowledge and directions for a windstorm hazard mitigation program. Subsequently, the WWG hosted a stakeholder community workshop at NSF. NIST hosted two stakeholder workshops related to its tornado map development project. NIST staff regularly participate in the ASCE committee that is working towards development of guidance for performance based design for windstorms.

There are several private and not-for-profit organizations as well as several state programs that are working to promote and enable windstorm mitigation efforts. The federal agencies participating in the WWG should seek to work with these organizations to determine their needs and to foster opportunities for federally sponsored research and programs to enhance these organizations efforts.

PROGRAM EFFECTIVENESS

"Achieving major measurable reductions in the loss of life and property from windstorms," the stated goal of the reauthorization language is an extremely heavy lift for the United States with its expanding population, increasing concentration of development and value in vulnerable areas, large quantity of buildings constructed to inadequate building codes or in areas where no codes had been adopted, and increasing social vulnerability. Achieving "major measurable reductions" will require significant long-term funding for research, research-to-application, and implementation programs. It will require engaging the scientific, architectural, engineering, social science, construction, and development communities together with state and local government agencies and elected officials, and an array of other stakeholders in efforts to actually build more windstorm resistant buildings and other infrastructure and to implement mitigation measures that improve the windstorm resistance of existing buildings and other infrastructure.

If Congress had appropriated new funding in line with the modest budgets included in the authorizing legislation, the agencies would be in a stronger position to create and implement a stronger and more effective program. NIST would be able to conduct or fund research-to-application add-on projects to NSF research grantees and would be better positioned to fund projects that provide data needed to answer key questions facing committees working to improve windstorm related building codes and standards. NSF would be able to fund an initiative that targets research needed to improve the understanding of the influence of windstorm characteristics on wind loading and wind effects for buildings and other structures. NOAA would be able to focus some resources on assuring that key National Weather Service measurement platforms are better suited to collect and archive high-fidelity wind data during severe windstorms and to adequately fund efforts to deploy rugged instrumentation in the face of land falling hurricanes. FEMA would be able to become a real partner in the dissemination of information and guidance being developed by NWIRP. In the meantime, the agencies do what they can with the resources made available to them and they are clearly working hard and working together to make the kind of difference the United States needs to address its windstorm related risks. Unfortunately, current funding is insufficient to materially affect a reduction in the rate of loss increases being experienced because of all the factors outlined in the earlier sections of this report. Even greater funding, than the amounts authorized, will be needed to reduce future losses below levels experienced in recent years.

From a big-picture standpoint, loss of life in windstorms has been dramatically reduced due to NOAA's successes in using technology and modeling to significantly improving warning times, refinements in geographic targeting of those warnings, and implementation of social science research which has improved the effectiveness of the warnings. Nevertheless, population growth in areas with limited evacuation capacity means that there may be a tipping point where mass evacuation from a hurricane may create greater life safety risk than sheltering in place, provided the flood risk is properly assessed and areas at greatest risk of storm surge and flooding are evacuated. As noted earlier in the report, there are indications that simply increasing warning times may not be the most effective solution for some types of storms and it is becoming important to focus on optimizing warnings in terms of outcomes rather than simply in terms of increasing time. FEMA guidance for design and construction of safe rooms has also proven effective with no deaths occurring in safe rooms constructed to their requirements. Both the individual and community safe room guidance documents have been reviewed and updated within the past few years and these requirements have formed the basis for International

Code Council Standard 500 (ICC 500) which is now referenced in the model building code used throughout the United States. The most frequent causes of loss of life by far in storms remain storm surge and flooding related deaths. As noted in the Strategic Plan review, storm surge modeling needs to be refined and improved to account for local factors.

When it comes to property protection and the spiraling costs of windstorms and windstorm related events, the United States is not doing as well, as illustrated again with Hurricanes Harvey and Irma. As noted in this report, the strategic plan needs to tackle a variety of needs from better understanding the windstorms and their impacts on buildings and other infrastructure to providing tools to communities and government agencies that will help them determine how best to accomplish enhanced windstorm resistance and resilience within their communities. While building code adoption and enforcement is well ingrained as a states/local rights issue, the federal government is being called on more and more to be the "insurer" of last resort and there is a federal role in helping communities to find their own way towards reducing their risks and dependence on the taxpayer's check book.

The standard for the effectiveness of any recommendation to improve resilience must eventually be framed within the context of actual reduced risks. In areas affected primarily by wind and seismic hazards, the clear dominant mechanism influencing economic losses within the built environment is the damage to buildings and other structures caused by forces acting on them. If no element of the building is broken or damaged, the economic loss to that building is substantially reduced. In areas subject to flooding and in buildings suffering significant wind-driven rain intrusion, however, a totally different scenario emerges. The intrusion of water into a building is, of itself, a major destructive process; thus, a building need not have any of its structural components damaged by forces and yet the entire building can be essentially destroyed or require major rehabilitation by water entering the building during a flooding event or when it suffers significant wind-driven water intrusion. In fact, most private homes that are damaged by moving water (waves or high currents) could very possibly be unusable or in need of major repair simply due to flooding, even if they emerged structurally undamaged. By themselves, analyses of potential structural responses to wave and current forces cannot capture the devastation associated with major flooding events in the United States. Effects on transportation infrastructure and other critical infrastructure components, such as oil refineries, major pipelines and major manufacturing plants have all been jeopardized by flooding that occurred in Hurricanes Katrina, Sandy and Harvey and accentuate both the complexity and need for accurate measures of effectiveness in these areas. The nature of these hazards transcends those related to only structural forces and require consideration of other building options (mold- and mildew-resistant building materials; new raised-foundation concepts, innovative planning for improved flood routing, etc., as well as some innovative thinking by good architects, engineers and scientists).

To build an effective path forward in this complex area, it will be essential to develop clear, objective metrics that consider all hazards potentially falling within these recommendations. The Nation's approach to coastal resilience should even consider long-term erosion of the coasts and sea-level rise in recommendations for these areas. Research recommendations should reflect the relative needs for improving quantification of wind and other wind-related phenomena in a clear fashion that ensures prioritization of the work that will have the most impacts on resilience (risk reduction).

The nation needs a well-coordinated and cooperative NWIRP that not only addresses the effects of windstorms on buildings and other infrastructure, identifies weaknesses, proposes cost effective ways to strengthen existing and new buildings and other infrastructure, and addresses the human factors that enable proactive mitigation of windstorm related hazards; and it needs it now. Amid numerous catastrophic events, it is extremely disheartening to see NSF cut base funding leading to the dissolution of a small, but tremendously effective, social, behavioral and economic science group. This is a solid group of scientists that have done a great deal of work in reducing wind-related hazard impacts over the last decade or so. Wind hazards are real and Harvey, Irma, and Maria show how much we need to learn and apply on the human factors side of hazards, losses and disruptions.

RECOMMENDED REVISIONS

During the course of its meetings and deliberations, the Committee developed several recommendations that would shift or broaden the focus of the NWIRP. These have been presented in some detail in the earlier section dealing with Objectives and Priorities of the Strategic Plan. Three overarching recommendations for revisions are listed below:

1. The Program needs to place a greater emphasis on developing tools for evaluating the windstorm resistance of existing buildings and other infrastructure and for providing practical cost-effective guidance on retrofitting these buildings and other infrastructure to improve their windstorm resistance. The Committee recommends adding an 8^{th} Strategic Priority that focuses on the issues of improving the wind resistance of existing buildings and other structures.
2. The Program needs to conduct and promote social science research that provides a greater understanding of the portfolio of public policy approaches for promoting windstorm mitigation. This should include research into triggers and options communities can use to promote adoption and enforcement of building codes and standards as well as enhancing community planning and land use management. The Committee recommended adding a 15^{th} Objective that addresses these research needs.
3. To better address all the risks associated with land falling hurricanes, the Program should be expanded to consider all effects of these storms including water intrusion and water induced forces from waves, surge, and flooding, including rainfall related flooding, near the coast. Currently, surge modeling and rain induced flooding are considered separately and there is a critical need to build a bridge between the two modeling communities so that all combined effects are adequately addressed near the coast. A similar need was recognized by the Committee in terms of needed improvements for modeling waves and wave-surge interactions in near-coast areas. The Committee noted that significant work is needed to adequately model local effects of wave, surge and rain induced flooding and recommended that improved modeling be developed. However, this potential expansion of the Program should not dilute existing efforts and should only be undertaken if Congress appropriates adequate funding for the existing Program priorities plus this additional area of model development.