2009 BFRL Project Description

Project Title: Wind Engineering and Multi-hazard Failure Analysis

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BFRL Program: Structural Performance under Multi-Hazards

Objective: To develop the measurement science methods and tools that will enable performance-based standards for designing structures to resist wind and storm surge in a multi-hazard context.

Problem:

What is the problem? Disasters due to hurricanes and other windstorms cause about $6B/yr average annual costs. Obsolete codes, standard provisions, and practices (CSP) are major contributors to the losses and to unnecessarily large construction costs. The link between basic research and CSP is weak. Limitations of current measurement science capabilities include (1) problems in estimation of extreme wind speed, aerodynamic and dynamic effects, and uncertainties inherent therein, (2) the lack of a science-based methodology for characterizing the hazards posed by the combined effect of hurricane wind, storm surge, and waves, and (3) the lack of a probabilistic assessment, design, and failure analysis approach to assuring safety and cost effectiveness in single- and multi-hazard conditions, including validated tools to estimate system-level reserve capacity of structures subjected to multiple hazards. These limitations have been shown to result in: (1) under- or over-estimation of wind effects by up to 40 % for tall buildings and 80 % for low-rise buildings; (2) the significant underestimation of the storm surge hazard for design of coastal structures; and (3) the underestimation by up to 100 % of the probability of exceedance of design limit states in multi-hazard environments. Critical measurement science needs have been identified to correct this state of affairs.[1]

[1] *Design of Buildings ... for Wind*,Wiley, 2006; *Hurricane Warning:…*, Nat'l Sc. Board, 2007; *…Investigation ..World Trade Center..*, NIST NCSTAR 1-2A, 2005; .. *Challenges on Disaster Reduction* …,Nat'l Sc. Tech. Council, 2005; "NIST-NOAA Resilient Communities.. " *J. Marine Tech.*, 2007; "Wind speeds in ASCE 7.… Map…," *J. Struct. Eng.*, 2003; "Internat. Comparison ..Wind Tunnel Estimates…," *J. Struct. Eng.* (2008); "Low-rise structures under directional winds: mean recurrence interval of failure," *J. Struct. Eng.,* 2008; "Assessment of ASCE 7 Standard Wind Load Factors for Tall Buildings, *J. Struct. Eng.,* 2008; "New generation of tools for design of tall buildings under wind loads, *Proc*., Eng. Systems Design and Analysis, 2008;*... Joint Hurricane Wind Speeds and Storm Surge Events*; NIST TN 1482, 2007; *Performance of Physical Structures in Hurricane Katrina and Hurricane Rita: A Reconnaissance Report,* NIST TN 1476, 2006; "Safety of Structures Exposed to Strong Winds and Earthquakes: Multi-hazard Considerations," *Proc.*, NIST/UJNR, 2007.

Why is it hard to solve? Difficulties in wind engineering are due to the complex and inextricable interaction of probabilistic, extreme value statistics, atmospheric fluid dynamics, dynamics, and structural analysis approaches. Simplifying approaches that disregard the complexity of wind phenomenology, wind-structure interaction, and uncertainty effects have been shown to result in grossly inadequate metrics and models. For storm surge, difficulties are associated with: accounting for wave effects on total inundation in hydrodynamic simulations; the lack of hurricane databases for regions outside Florida; the lack of comparisons/validations of competing hydrodynamic models; and the constantly changing coastal bathymetry and topography. For multi-hazard failure analysis, developing methodologies for achieving designs that satisfy, *in a cost-effective manner*, strength and serviceability constraints inherent in multi-hazard exposure, particularly near ultimate limit states, requires novel and imaginative solutions that presently do not exist.

How is it solved today, and by whom? The problem has not been solved. Contributions to relevant measurement science with potential application to performance-based codification are made mainly by NIST, Florida Internat. Univ., Univ. of Florida, Notre Dame Univ., Texas Tech Univ., Univ. of Western Ontario, Tongji Univ., Tokyo Polytechnic Inst., NOAA, FEMA, USACE, and FHWA. Existing work in storm surge funded by FEMA considers only a semi-probabilistic approach to hurricane selection for hydrodynamic simulations; therefore, joint probabilities of different wind speed/surge height combinations cannot be estimated for design purposes. Whether attempts reported in a 2007 MCEER/ASCE workshop on approaches to multi-hazard design will be successful is unclear. BFRL is focusing on measurement science issues not addressed by these and other institutions, including innovative syntheses of probabilistic, hydrodynamic, nonlinear structural analysis, reliability of dynamic systems with multi-directional response, and structural optimization approaches.

Why NIST? BFRL has an influential record of seminal and creative contributions to wind engineering, known worldwide for their scope, integrity, and effectiveness. The contributions to this field have been numerous, especially through widely cited publications and ASCE 7 Standard developments. BFRL's experience in interdisciplinary wind engineering research is unique, and provides it with the measurement science basis for performing research consistent with BFRL's mission and vision, serving the public in an area of national concern. Storm surge, on which BFRL has worked with NOAA, and multi-hazard design research are natural extensions of those capabilities. This project is aligned with BFRL's current strategic priority on Measurement Science for Disaster-Resilient Structures and Communities.

Approach:

What is the new technical idea? The fundamental new technical idea is to use the unprecedented capabilities of numerical computation and existing data to develop new procedures and standard provisions that describe far more accurately wind and storm-surge loads than is now the case. An improved description of those loads will provide the basis for the development of performance-based design approaches, that will reduce losses and achieve more efficient structures under wind and/or storm-surge hazards. This goal requires developing: (1) realistic wind maps to replace the current, statistically incorrect, ASCE 7 Standard maps, via (a) the mining and use of NOAA ASOS wind data, and (b) innovative multi-hazard modeling of wind

speed extremes in mixed wind climates (e.g., climates with thunderstorm and synoptic winds, or tropical and extratropical storms); (2) science-based methodologies for aerodynamic simulation and measurements to eliminate the gross errors inherent in oversimplified standard tables and plots as well as those revealed by international comparisons of wind tunnel estimates; (3) estimates of safety margins, and performance prediction tools, to assure the safe performance of low-, mid-, and high-rise structures under multiple hazards. Probabilistic concepts applied to extreme wind and seismic effects, structural optimization under multi-hazard constraints, and nonlinear structural analysis tools will be employed to develop a coherent basis for multi-hazard engineering. For storm surge, an integrative, interdisciplinary methodology will be developed that (a) utilizes a probabilistic approach to storm track selection for hydrodynamic simulation thereby allowing for calculation of site-dependent mean recurrence intervals (MRIs) of any joint wind speed/surge height events; (b) enables incorporation of the wave model (SWAN, **S**imulating **WA**ves **N**earshore) into SLOSH model (**S**ea, **L**ake, and **O**verland **S**urges from **H**urricanes) to account for wave action in addition to total inundation; (c) allows for comparison of competing hydrodynamic simulation models; and (d) provides the data/validation necessary for use as the basis for design criteria for structures in coastal regions.

Why can we succeed now? BFRL can use its unique competence and capabilities; its interactions with universities (e.g., Notre Dame U., Florida International U., University of Florida), industry (e.g., Metal Buildings Manufacturers' Association), and other agencies (NOAA, NRC); and its proactive role in standards development to create the measurement science tools needed to achieve this project's objectives and contribute to the improvement of the ASCE 7 Standard and the draft ASCE standard on wind tunnels.

What is the research plan? Major research activities will use NIST's and stakeholders' resources in wind, multi-hazard, and storm surge engineering to achieve outcomes that result in tools to better estimate wind and storm-surge hazards and provide the technical basis for development of new design approaches aimed at reducing the potential for losses due to wind and storm surge in a multi-hazard context. The tools and design approaches developed within this project will lead to the development of new sets of guidelines and performance-based pre-standards for designing structures to resist wind and storm surge in a multi-hazard context as outlined below. This project will produce:

1. Tools:

    - Methodology for accurate estimation of wind effects on structures using Database- Assisted Design (DAD), including:

      (a) intelligent compression of aerodynamic pressure databases

      (b) estimation of tall building member demands with specified mean recurrence intervals and DAD-based optimization of tall building design in wind under strength, drift, and acceleration constraints

    - New methodologies on wind speed estimation and simulation for ASCE 7 Wind Tunnel Method and a new wind map for ASCE 7-15 Standard

- Tools for estimating ultimate capacities and safety margins of structures under multi-hazard conditions
- Methodology for hydrodynamic simulation with consideration of waves
- Digital map-based software for computing site-dependent MRIs of joint hurricane wind speed/surge height events for coastal regions of Florida

2. Guidelines:

- Guidelines on integrated methodology for estimating ultimate capacities and safety margins of structures under wind
- Best Practices Guide on multi-hazard design for wind and other hazards Guidelines for development of design criteria for the combined effects of wind speed/storm surge events

3. Pre-Standards:

- New wind map for ASCE 7-15 Standard
- Performance-based multi-hazard design for wind and other hazards

Specifically, the tools, guidelines, and pre-standards will be developed as follows:

For wind research: **(1)** For *aerodynamic and dynamic components of DAD*, develop: (a) data compression techniques to massively reduce storage demands on public servers (tool); (b) DAD time-domain methodology for rigorous demand estimates for tall buildings in wind (tool; **(2)** For *climatological component of DAD*, develop: (a) novel prediction methods for extreme speeds in mixed climates (multi-wind-hazard) regions, where homogenizing the wind data sets produces load predictions differing by up to 35 % from statistically correct predictions (tool); (b) full capability for mining relevant NOAA data (tool); (c) feasibility study on super-station approach to reducing sampling errors in estimation of extreme speeds in thunderstorm regions; (d) *non-directional wind map for ASCE Standard* (pre-standard,), based on (a)-(c); (e) simulation tools for creating large directional wind speed databases from ASOS data sets for ASCE wind tunnel method (tool); **(3)** Perform pilot Computational Wind Engineering (CWE) calculations and check against available DAD datasets, to assess CWE potential for creating valid aerodynamic datasets. **(4)** *DAD-based reliability:* develop DAD-based methods for assessing annual probabilities of failure under wind loads for selected types of structure, accounting for wind directionality and post-elastic strength reserves .

For Multi-hazard research: (**5**) *Multi-hazard design and failure analysis:* (a) use probabilistic, statistical, and experiment design tools to achieve risk consistency between structures subjected to single hazards and structures subjected to wind and earthquake hazards (tools and guidelines,); (b) develop procedure for structural optimization under multi-hazard constraints (strength, acceleration, drift) to achieve safe and cost-effective designs (tool); (c) develop wind map that accounts for dependence of the extreme wind estimates on multi-hazard nature of windstorms (see item 2a above) (pre-standard); (d) Perform ultimate failure analyses to evaluate synergy between design for wind and design for other hazards (pilot study, guidelines).

For Storm Surge Research: (**6**) *Storm Surge:* (a) develop methodology for hydrodynamic simulation (without incorporation of waves) and methodology for derivation of design criteria for three representative basins in Florida (tools); (b) develop methodology for incorporation of wave model (SWAN) into SLOSH model and pilot hydrodynamic simulation (with wave) of one representative basin that is sensitive to wave effects (tool); (c) hold joint NIST-NOAA public workshop to discuss methodology with stakeholders and other relevant agencies; (d) complete report on sensitivity study on effects of waves for different regions in Florida with consideration for shielding and local bathymetry; (e) complete report on comparison of applicable NIST results and the updated FEMA's DFIRM map; (f) develop draft design criteria for the combined effects of wind speed and storm surge using the NIST-developed methodology (pre-standard).

Recent Results:

These publications document recent NIST work on improved understanding of wind loads on structures, failure of structures exposed to wind loads, and development of design criteria for joint hurricane wind speed and storm surge.

Archival Journal Publications (published or in press)

- Fritz, W.P., Bienkiewicz, B., Cui, B., Flamand, O., Ho, T.C.E., Kikitsu, H., Letchford, C.W., and Simiu, E. (2008), "International Comparison of Wind Tunnel Estimates of Wind Effects on Low-Rise Buildings: Test-Related Uncertainties," *J. Struct. Eng.*, Dec. (*Finding*: discrepancies among test results by various leading wind tunnels can be as high as 100%; relates to safety and cost-effectiveness of structural design)
- Simiu, E. (2008), "A comparison of methods of extreme wind speed estimation," *Discussion, J. Wind Eng. Ind. Aerodyn.* (in press; relates to problems in the estimation of extreme wind speeds).
- Duthinh, D., Main, J.A., Wright, A. and Simiu, E. (2008) "Mean Recurrence Intervals of Failure Wind Loads." *J. Struct. Eng.*, Aug. (*Result*: For low-rise industrial portal frames, estimated mean recurrence interval of failure under wind loads; relates to safety and cost-effectiveness of structural design).
- R. D. Gabbai, W. P. Fritz, A. P. Wright and E. Simiu (2008), "Assessment of ASCE 7 Standard wind load factors for tall building response estimates" *J. Struct. Eng.*, May, 842-845 (*Finding*: failure to account for uncertainties in dynamic parameters can result in significantly larger risks for tall than for low-rise buildings; relates to safety and cost-effectiveness of structural design).
- R. D. Gabbai (2008), "The influence of structural design on the aerodynamic stability of Brancusi's endless column," *J. Eng. Mech.*, June, 462-465 (relates to safety and cost-effectiveness of structural design).
- Duthinh, D., and Fritz, W.P. (2007), "Safety evaluation of low-rise steel structures under wind loads by non-linear database-assisted technique," *J. Struct. Eng.*, April, 587-594 (relates to safety and cost-effectivenss of structural design).
- Simiu, E. (2007), "Relation between Saffir-Simpson hurricane scale winds and peak 3-s gust speeds over open terrain," *J. Struct. Eng.*, July, 1043-1045. (*Finding:* ASCE 7 relation is incorrect; change was accepted by ASCE 7 wind loads subcommittee; relates to safety and cost-effectivenss of structural design).

- Simiu, E. (2007), "Generalized Pareto methods for wind extremes. Useful tool or mirage?" *Discussion, J. Wind Eng. Ind. Aerodyn.* 133-136 (relates to problems in the estimation of extreme wind speeds).
- Gaynor, J. and Simiu, E. (2007), "The NIST-NOAA Resilient Communities Initiative and Its Contribution to Coastal Community Resilience, *Marine Technology Soc. J.*, 26-32 (relates to safety and cost-effectivenss of structural design).
- Simiu, E. (2007), "Peak Wind Load Comparison: Theoretical Estimates and ASCE 7," *Discussion, J. Struct. Eng.*, Oct., 1484-1485 (relates to safety and cost-effectivenss of structural design).
- Simiu, E. (2007), "Errors in GEV analysis of wind epoch maxima from Weibull parents," *Discussion, Wind and Structures*, 399-400; relates to problems in the estimation of extreme wind speeds).

Archival Journals (in review)

- Coffman, B.,Main, J., Duthinh, D., and Simiu, E., "Wind Effects on Low-Rise Buildings: Database-Assisted Design vs. ASCE 7-05 Standard Estimates," *J. Struct. Eng.* (submitted April 2008) (*Finding:* discrepancies of up to 90% between database-assisted design estimated pressures and ASCE 7 specified design pressures; relates to problems in the estimation of extreme wind speeds.)
- Lombardo, F.T., Main, J.A., and Simiu, E., "Automated extraction and classification of thunderstorm and non-thunderstrom wind data for extreme-value analysis," *J. Wind Eng. Ind. Aerodyn.* (submitted July 2007; relates to problems in the estimation of extreme wind speeds).
- Filliben, J.J., and Simiu, E., "Tall building response parameters: Sensitivity study based on orthogonal factorial experiment design techniques," *J. Eng. Mech.* (submitted June 2008; relates to safety and cost-effectivenss of structural design).
- Phan, L.T.; Simiu, E.; McInerney, M.A.; Taylor, A.A.; Glahn, B.; and Powell, M.D. "Development of Design Criteria for Joint Hurricane Wind Speed and Storm Surge Events," *ASCE J. Struct. Eng.* (submitted March 2008; relates to characterization of multihazard environment and design).

In addition, NISTIR and papers were submitted and presented at conference proceedings as follows: NISTIR: 1; papers: 6 in FY08; 10 in FY07.

PI is scheduled keynote speaker, Americas Conf. Wind Eng., June 2009, keynote speaker, Europe-Africa Conf. on Wind Eng., July 2009.

Standards and Codes: ASCE 7-98 allows application of database-assisted design within framework of wind tunnel method. It now also has methods for estimating wind speeds in non-homogeneous terrain based on the logarithmic law, long advocated by NIST. NIST research will result in significant changes in the ASCE 7 Standard. Proposals based on NIST research developed in the last few years have been approved by ASCE 7-10 Wind Load Subcommittee on: relation between Saffir-Simpson hurricane scale and design speeds; database-assisted design; wind directionality effects (per WTC Report Recommendation). The PI will monitor responses to the NIST appeal concerning draft ASCE standard on wind tunnels response, with a view to implementing WTC Investigation recommendations on wind effects on tall buildings. PI is Distinguished Member, ASCE 7 Loads Committee; Member, ASCE 7 Subcommittee, Wind

Loads; contributor to public assessment of ASCE Draft Standard on Wind Tunnels. PI work was incorporated into *DG-114, Design-basis tornado and tornado missiles for nuclear power plants* (2006). The Structures Group currently has a voting position on the ASCE 7 Main Committee (McAllister) and will consider options for back up to membership on the ASCE 7 Subcommittee on Wind Loads.