NCST Technical Investigation of Hurricane Maria (Puerto Rico)

Performance of Critical Buildings Project

Project Leaders: Joseph Main and Marc Levitan

Background and Motivation

Engineered buildings with good structural performance suffered significant ***damage to building envelopes***, and penetration of rainwater resulted in extensive ***nonstructural damage*** and ***loss of function***:

- roof covering and rooftop equipment damage from wind and windborne debris;
- window and door damage caused by wind and windborne debris;
- rainfall ponding on the roof due to excessive rainfall rates and debris blocking drains; and
- wind-driven rain penetration through undamaged cladding, such as windows and doors.

Source: NIST (all photos)

Loss of power and failure of backup generators also disrupted the function of some critical buildings, including hospitals, schools and storm shelters.

Project Plan: Data Collection

Initial Data Collection: Coordinate with Puerto Rico government agencies, Federal partners, and others to identify and collect relevant existing data

Sample Selection: Select representative hospitals and shelters for detailed evaluation, considering characteristics of buildings, hazards, other factors

Facility Evaluations:

- **Phase 1:** initial document collection and review
- **Phase 2:** interviews, additional document collection, field investigation

Wind Tunnel Testing: Test scale models of two selected facilities

Project Plan: Data Analysis

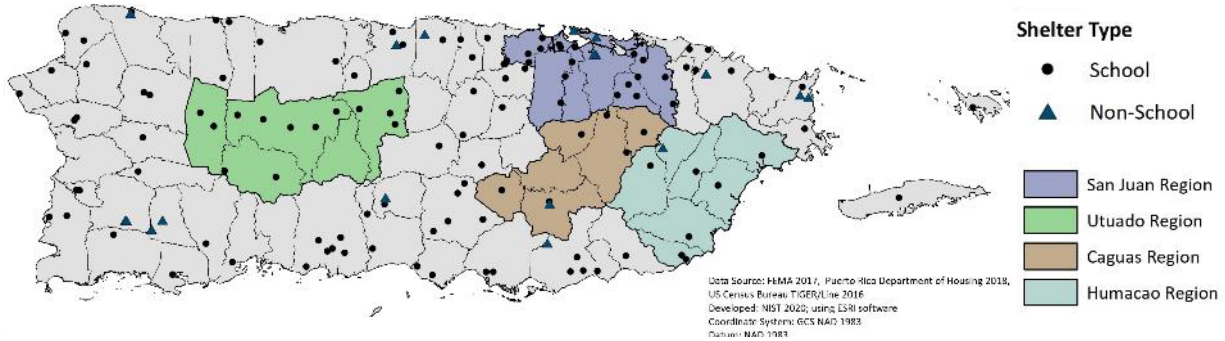
- Evaluate the performance of selected critical buildings with consideration of:
  - wind loads and other hazards encountered during Hurricane Maria
  - damage to buildings and impacts on building function and life safety
  - adequacy of existing codes, standards, and practices
- Evaluate shelter selection criteria, design criteria, and operational guidance for the larger population of shelters with consideration of:
  - hazard levels encountered at shelter sites and damage to shelter buildings
  - shelter population per site over time, including relocation of occupants
  - adequacy of existing selection criteria, design criteria, and operations plans
- Develop findings and recommendations, as appropriate, for specific improvements to building codes, standards, and practices

Recent Progress: Shelter Sample Selection

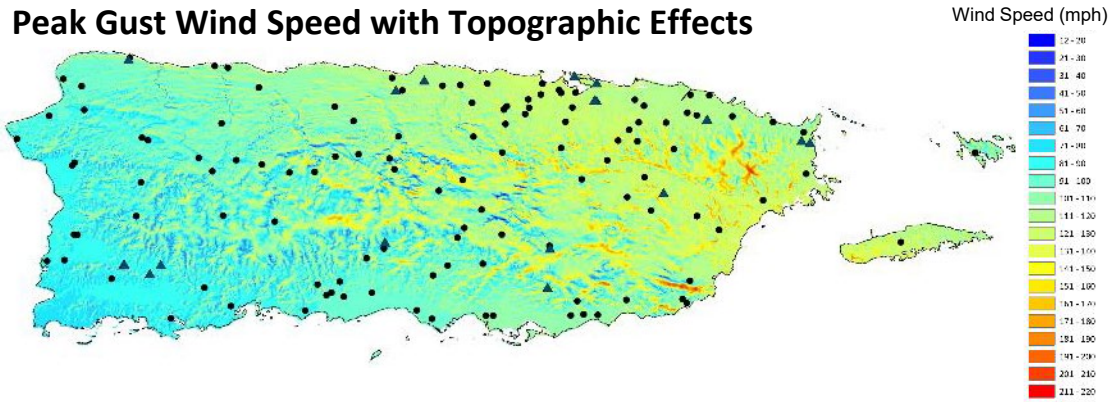
- Five shelter facilities selected for detailed evaluation:
  - 4 schools, 1 non-school shelter (all 5 used for sheltering during Hurricane Maria)
  - At least one shelter in each of the 4 study regions
- Selection methodology informed by extensive review of available information:
  - Facility characteristics
  - Hazard exposure
  - Damage assessments, pre- and post-storm imagery
  - Media reports
  - Screening calls

Aerial Imagery

Study Regions



Peak Gust Wind Speed with Topographic Effects



Recent Progress: Facility Evaluations (1/2)

Hospitals

- Reviewed information from Phase 1 evaluations of the 5 selected hospitals and selected a subset of buildings at each facility for further evaluation in Phase 2
- Conducted staff interview for first hospital facility using previously developed interview guide
- Identified and reviewed additional documentation on damages for 2 hospitals

Interview Guide Categories

1. Participant Background
2. Facility Description Prior to Hurricane Maria
3. Hazard Exposure and Impacts to the Facility
4. Damage to Buildings
5. Function and Operation of the Facility
6. Wrap-Up

Phase 1: Initial document collection and review

Phase 2: Interviews, additional document collection and review, field investigation

Recent Progress: Facility Evaluations (2/2)

Shelters

- Adapted project plan to incorporate staff interviews in conjunction with Phase 1 evaluations to improve efficiency
- Initiated Phase 1 evaluation tasks for all 5 of the selected shelters
- Conducted virtual meetings with administrators of two shelter facilities to introduce the project and the NIST/Stantec team
- Conducted staff interview for first shelter facility using previously developed interview guide

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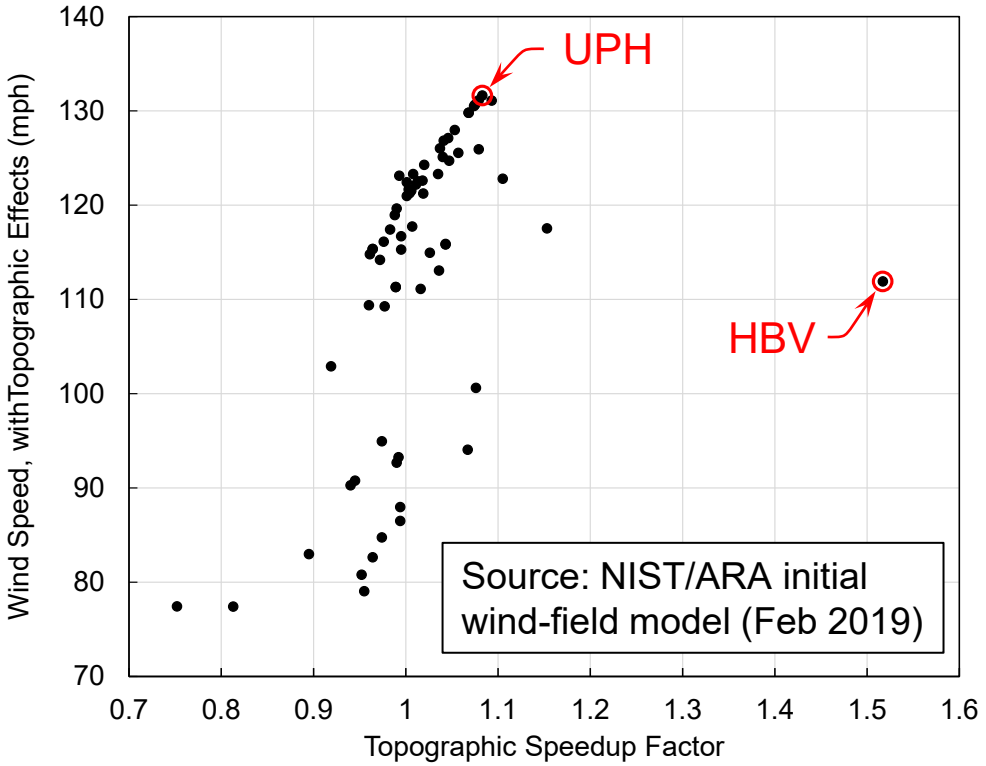
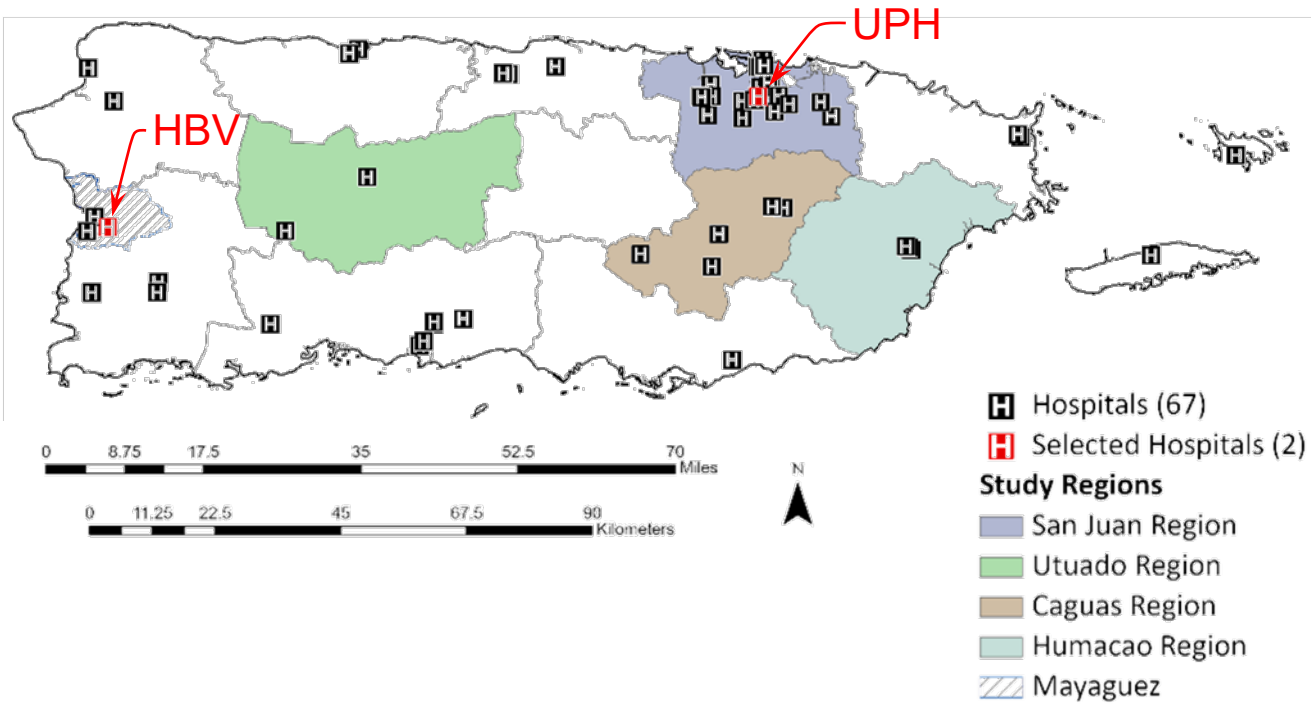
Objectives of Wind Tunnel Testing

Objectives for the two selected hospital facilities:

- **Hospital Bella Vista (HBV):** Evaluate effects of topography on wind loads for a site with significant topographic speedup of winds (Topographic Speedup Factor ~1.5)
- **University Pediatric Hospital (UPH):** Evaluate loads on components, cladding, and rooftop equipment, including effects of flow acceleration caused by adjacent buildings
- **Both facilities:** Evaluate adequacy of existing standard provisions (ASCE 7)

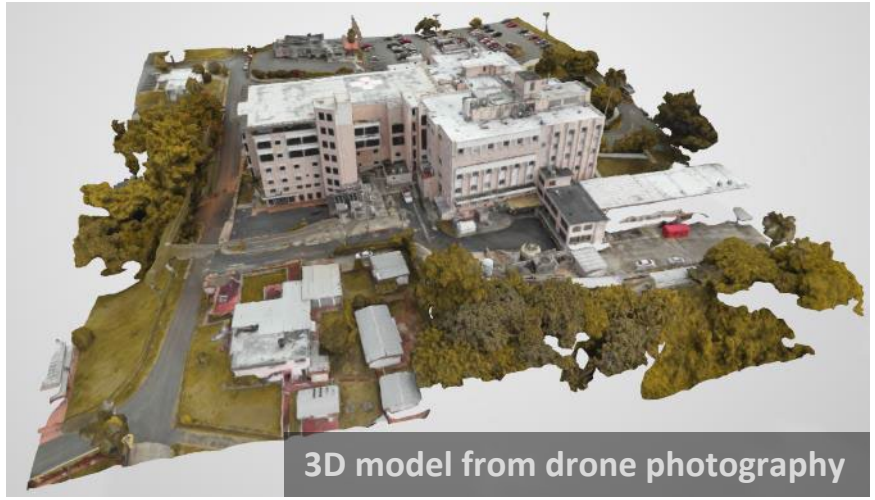




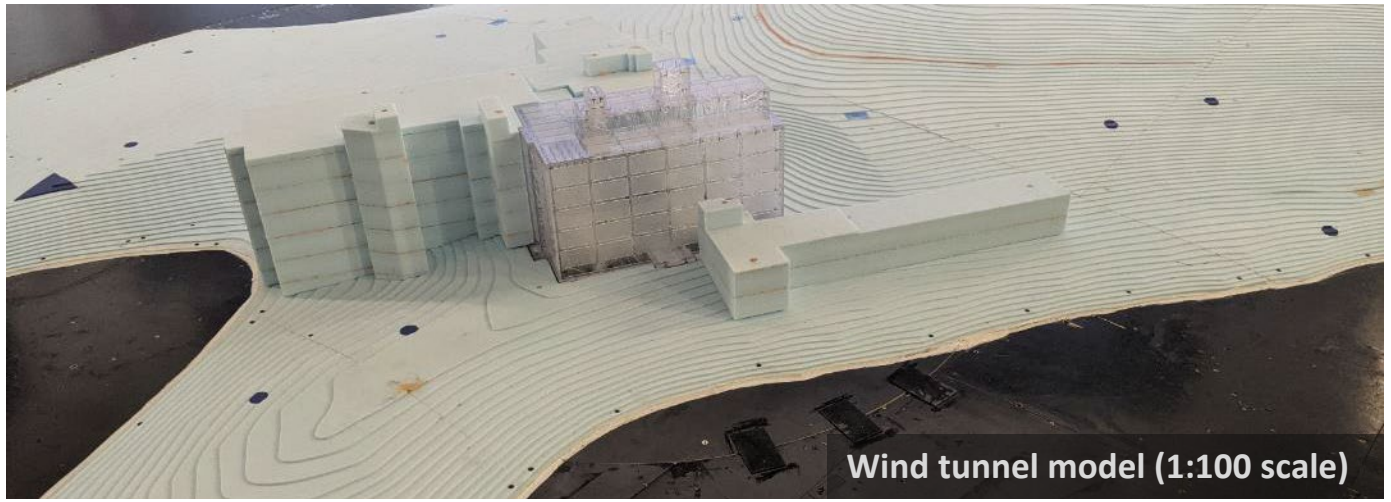
Recent Progress: Wind Tunnel Testing (1/8)

Completed model fabrication and wind tunnel testing for two hospital facilities

Hospital Bella Vista



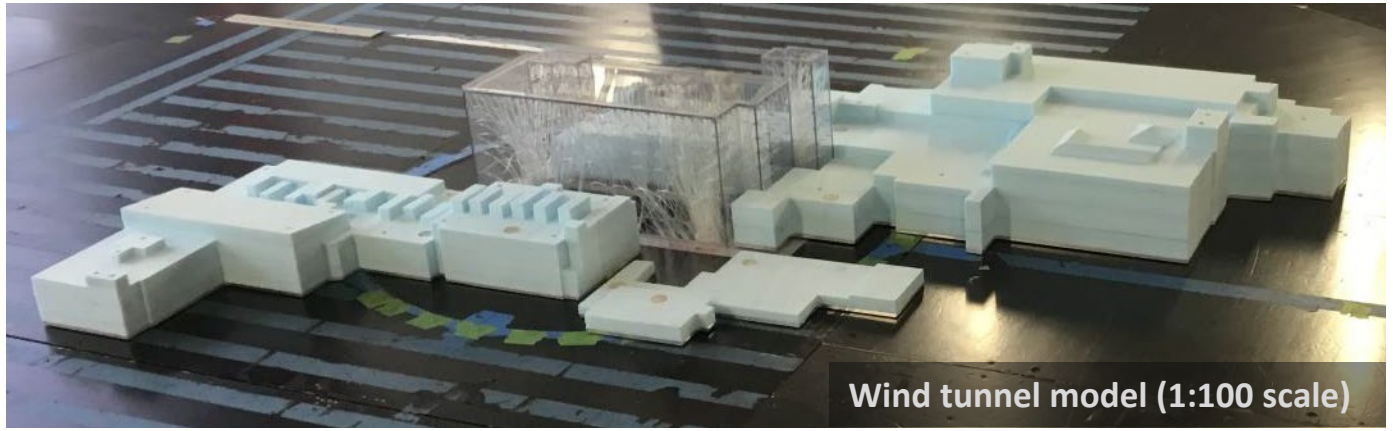
Source: Stantec (Contract 1333ND20PNB730117)



Source: University of Florida (Contract 1333ND19PNB730233)

University Pediatric Hospital

Source: Stantec (Contract 1333ND20PNB730117)

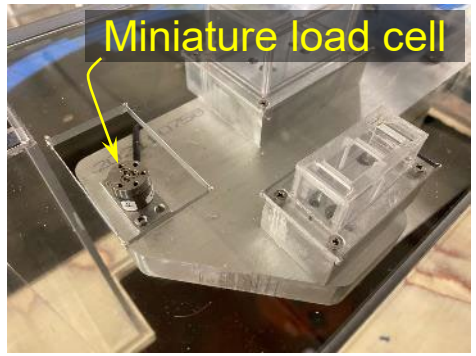


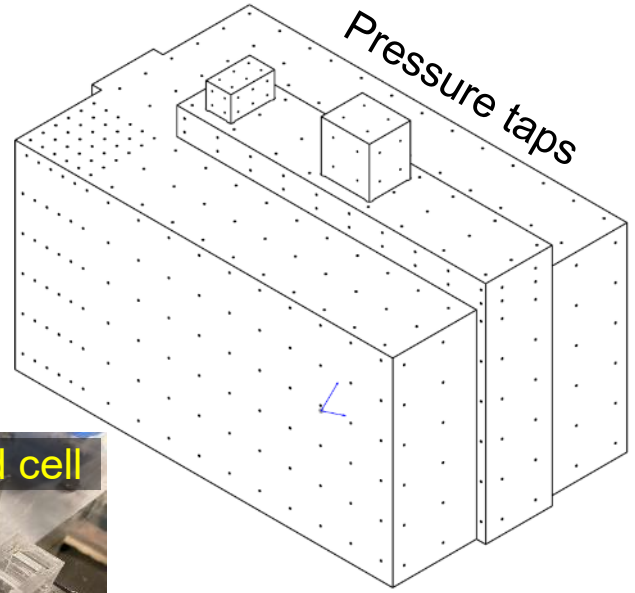
Source: University of Florida (Contract 1333ND19PNB730233)

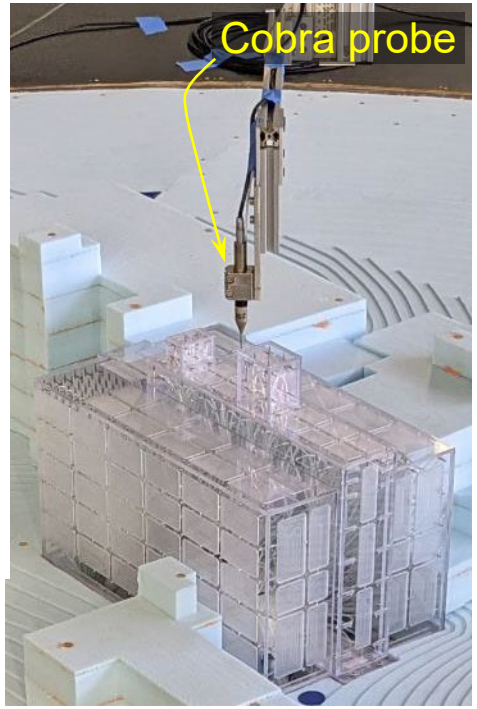
Recent Progress: Wind Tunnel Testing (2/8)

Instrumentation used for measurements:

- **Pressure taps:** measurement of surface pressures
- **Base force balance:** measurement of resultant forces and overturning moments (HBV)
- **Miniature load cell:** measurement of resultant forces on rooftop equipment (UPH)
- **Cobra probes:** measurement of wind velocities in approach flow and over buildings







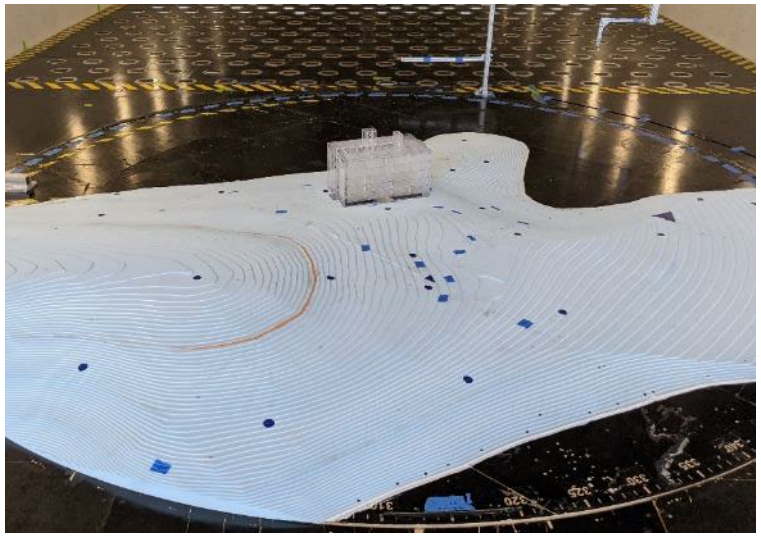
Source of photos: University of Florida (Contract 1333ND19PNB730233)

Recent Progress: Wind Tunnel Testing (3/8)

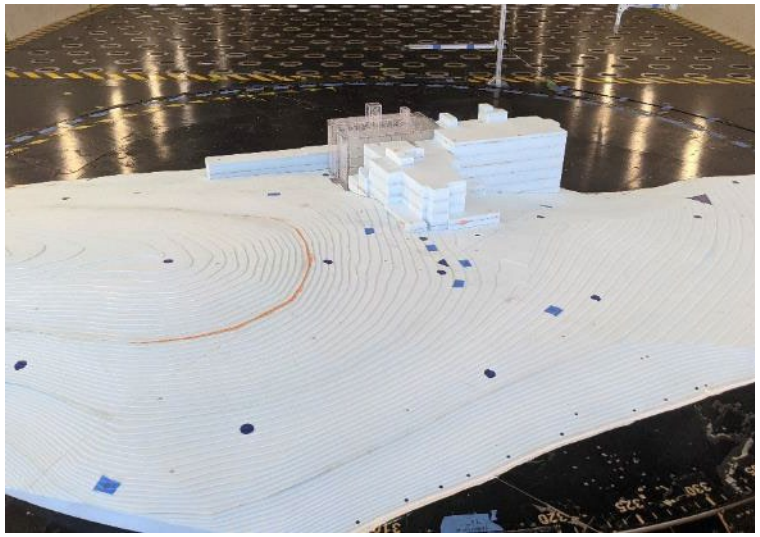
Test cases for Hospital Bella Vista:

- Performed testing over 180° range of wind angles in 10° increments, for cases with and without the area model and proximity buildings
- Tests conducted under different approach flow conditions:
  - Standard Exposure C ("open terrain") approach flow: considered for isolated building to facilitate comparisons with standard provisions
  - Simulation of topographic effects for each direction using Flow Field Modulator

Case 1: Isolated Building



Case 2: Building + Local Topography



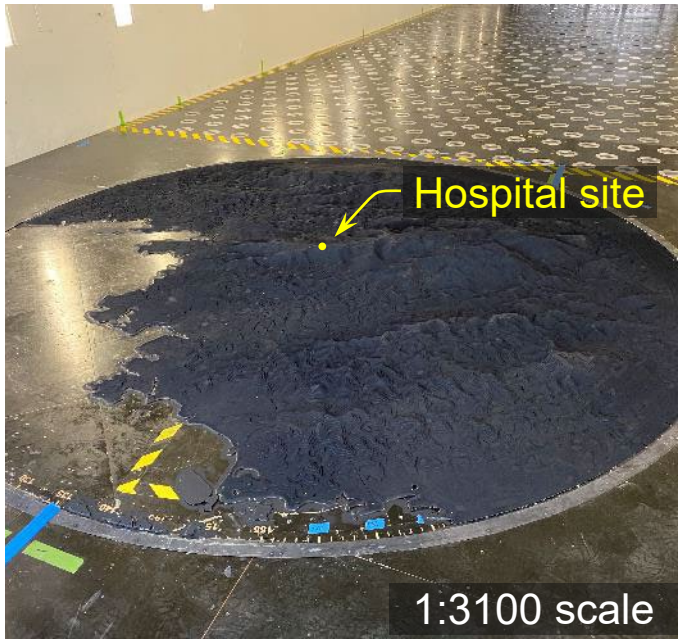
Case 3: Building + Local Topography + Proximity Buildings

Source of photos: University of Florida (Contract 1333ND19PNB730233)

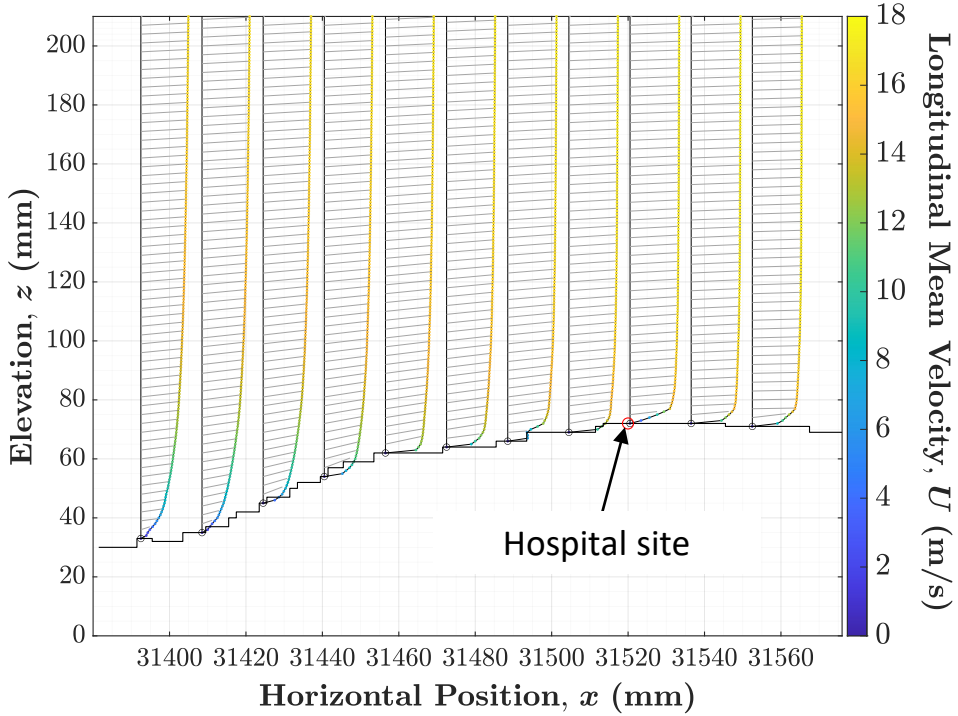
Recent Progress: Wind Tunnel Testing (4/8)

Multi-Scale flow simulation for Hospital Bella Vista:

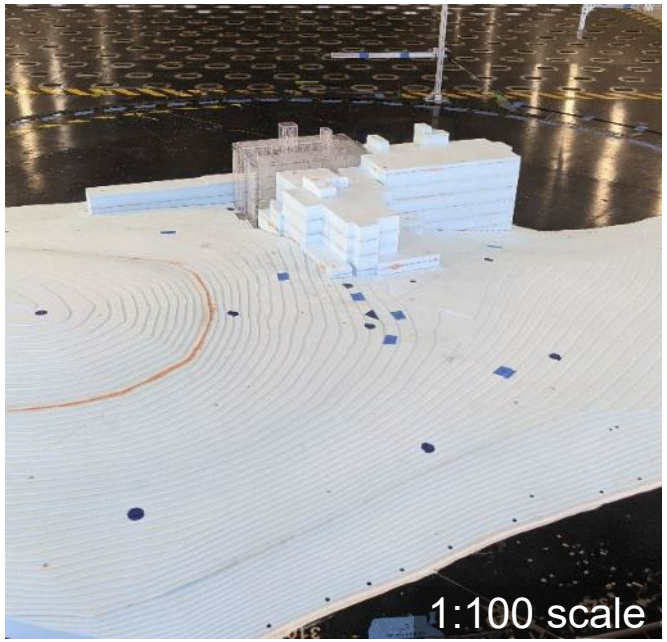
- Measurements of approach flow velocity profiles at hospital site obtained from Mayagüez topographic model (1:3100 scale) using Particle Image Velocimetry (PIV)
- Approach flow profiles at 1:100 scale simulated using Flow Field Modulator for wind tunnel testing of building and area model



Mayagüez Topographic Model



PIV Approach Flow Measurements



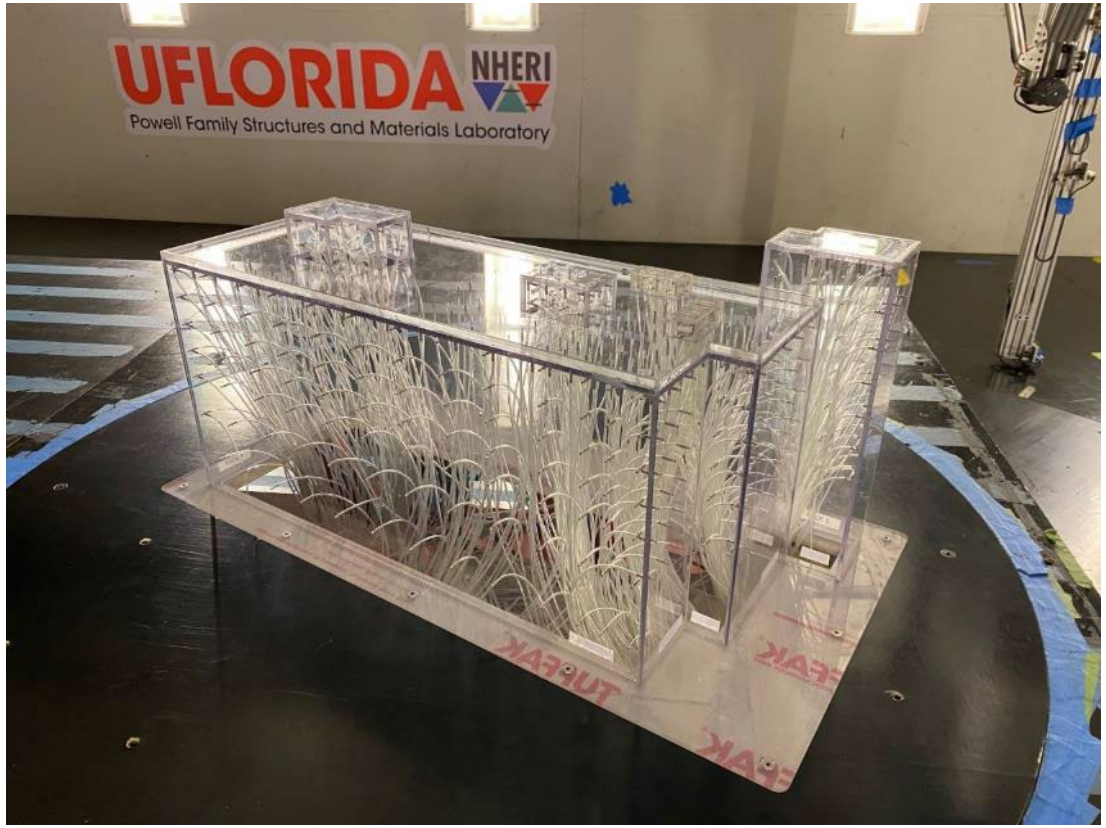
Hospital Building and Area Model

Source of photos: University of Florida (Contract 1333ND19PNB730233)

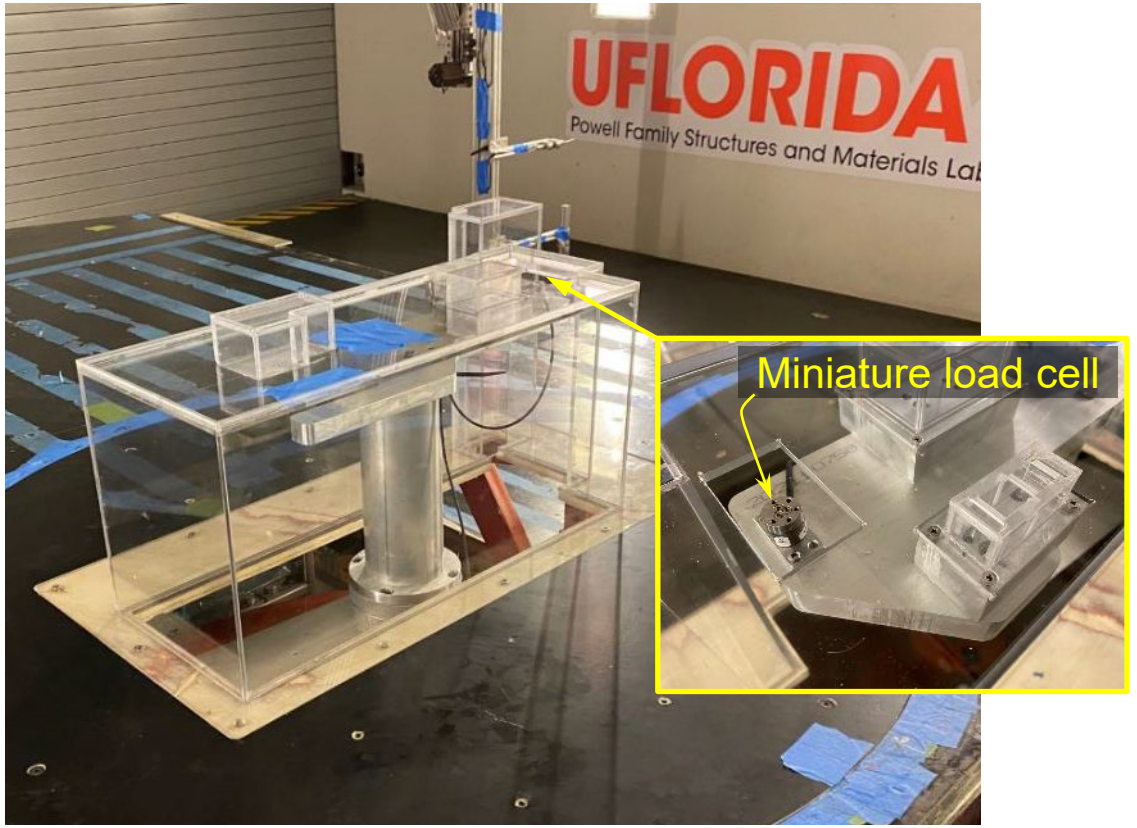
Recent Progress: Wind Tunnel Testing (5/8)

Two different models designed and fabricated for University Pediatric Hospital:

- **Pressure tap model:** used for measurement of surface pressures on components, cladding, and rooftop equipment
- **Load cell model:** used for measurement of resultant forces on rooftop equipment



Pressure Tap Model



Load Cell Model

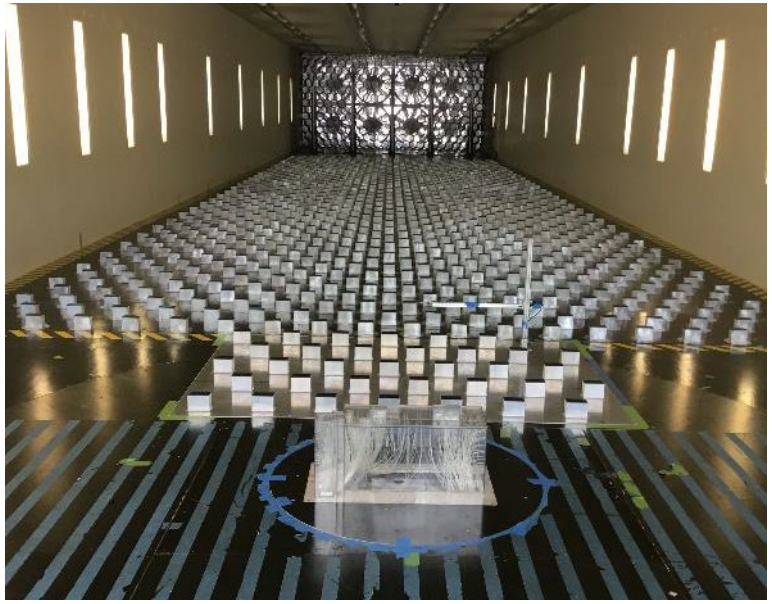
Source of photos: University of Florida (Contract 1333ND19PNB730233)

Recent Progress: Wind Tunnel Testing (6/8)

Test cases for University Pediatric Hospital:

- Two approaches used for simulation of wind angle:
  - Stationary testing with 10° increments of wind angle
  - Nonstationary testing with continuously varying wind angle
- Tests conducted under different approach flow conditions:
  - Standard Exposure C ("open terrain"): facilitates comparisons with standards
  - Exposure B+ ("suburban"): corresponds to estimated roughness at hospital site

Isolated Building, Exposure C



Isolated Building, Exposure B

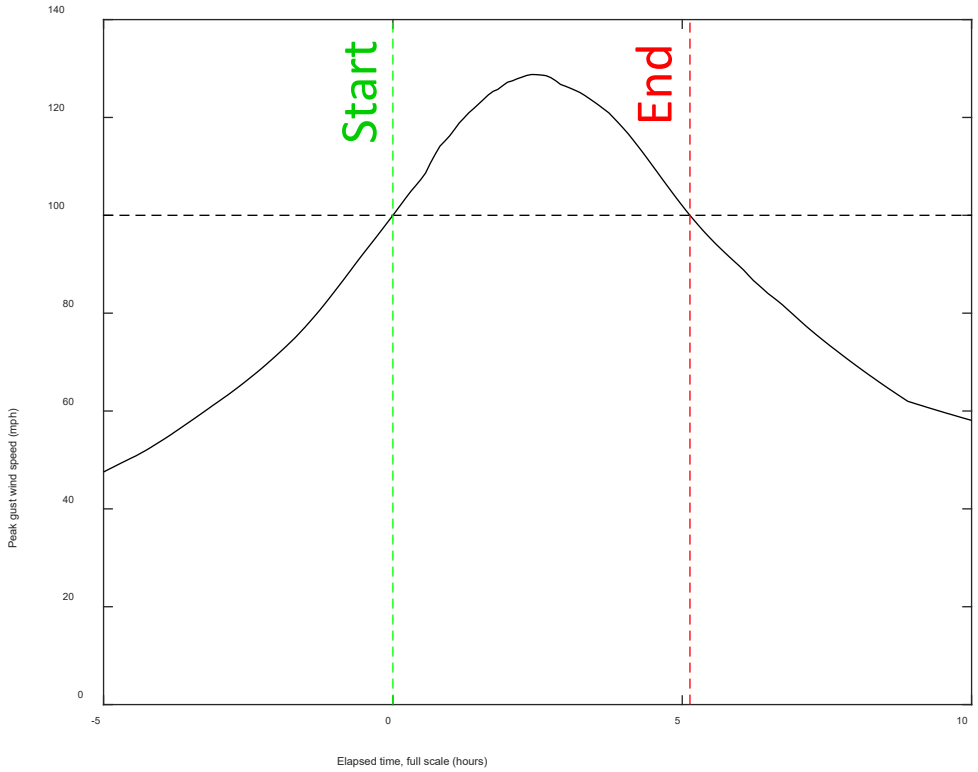
Building + Proximity Buildings, Exposure B

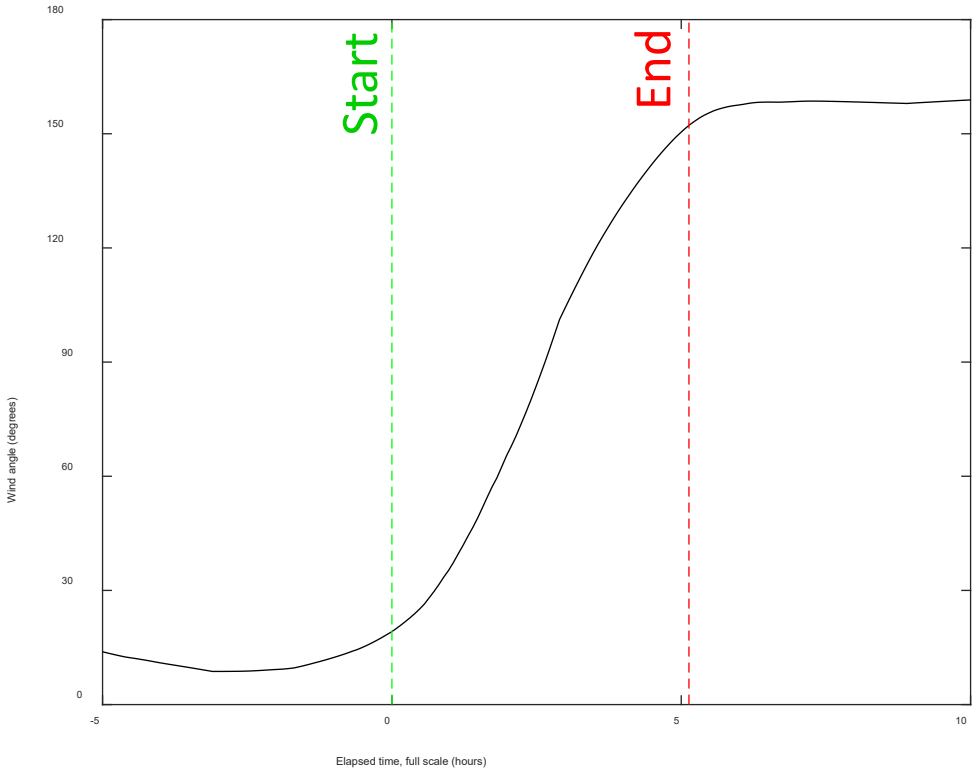
Source of photos: University of Florida (Contract 1333ND19PNB730233)

Recent Progress: Wind Tunnel Testing (7/8)

Nonstationary simulation of Hurricane Maria wind direction history

- Time histories of wind speed and wind direction obtained from wind-field model
- Portion of record with peak gust wind speeds exceeding 100 mph selected for testing
- Similitude relationships used to scale the wind direction history to model scale (1:100)
- Wind angle history simulated in wind tunnel by controlling rotation of turntable





Recent Progress: Wind Tunnel Testing (8/8)

Nonstationary simulation of Hurricane Maria wind direction history

Video is 32x actual speed at model scale

Source: University of Florida (Contract 1333ND19PNB730233)

Next Steps

Facility Evaluations

- Complete staff interviews for remaining 4 hospital facilities
- Complete Phase 1 evaluations and staff interviews for 5 selected shelters
- Conduct site visits and additional document review as needed to complete the Phase 2 evaluations for the 5 hospitals and 5 shelters

Wind Tunnel Testing

- Complete processing and curation of data from testing of the 2 building models, including quantification of uncertainty

Data Analysis

- Develop an integrated NIST/contractor database of information collected on hospitals and shelters and begin data analysis
- Integrate wind tunnel measurements from building models with time-dependent Hurricane Maria wind-field model to evaluate wind load histories

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Performance of Critical Buildings Project

Project Leaders: Joseph Main (NIST), Marc Levitan (NIST)
Project Team: Jazalyn Dukes (NIST), Cynthia Rivas (NIST), DongHun Yeo (NIST), Camila Young (NIST)
Contractor Teams: Stantec, University of Florida