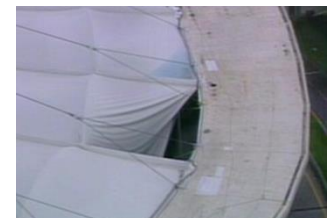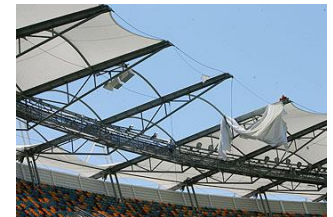# Wind Effects in Tensile Membrane Structures

Pedro Gil Marques de Queirós Ferreira

Elsa de Sá Caetano

2016

Wind Effects in Tensile Membrane Structures

- Motivation

  - Growing use of tensile membranes in special structures has brought increased demand in the assessment of their structural behavior

  - Membrane structures are characterized by: high flexibility, leading to strong geometric nonlinear behavior; complex shapes; slight prestress; orthotropic materials; and construction methods

  - Recent damages due to aerodynamic and ponding effects of these lightweight structures and lack of standards motivated this work

Wind Effects in Tensile Membrane Structures

- Objectives & Tasks
  - The work focused two main aspects
    - Form-finding
    - Characterization of the wind effects in membranes
  - Two types of examples
    - Roof of a multisport arena
      - Role of prestress & orthotropy on structural behavior
      - Wind effects considering generation of stochastic wind loads and numerical evaluation of membrane response through a simplified model, characterizing the aerodynamic mass, stiffness and damping
    - 470 Sailboat
      - Develop and validate a methodology of form-finding of a boat sail in real-time based on strain measurements

- Case studies
  - Roof

  - Sailboat

Wind Effects in Tensile Membrane Structures

– Structural form-finding and optimization methods

- Force Density Method (*FDM*): [1]*lFDM* and [2]*nlFDM*

  – Independent of the material properties and linearize the Equilibrium equations using a force density coefficient $q = t/l$ for the truss elements

  $$[C_s \, X_f \; q \; F]^{1,2} + Q_z^2 \implies X \, t \, l$$
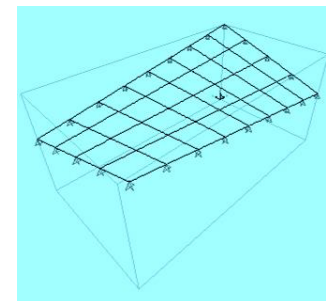
- Surface Stress Density Method
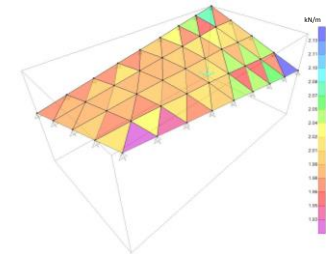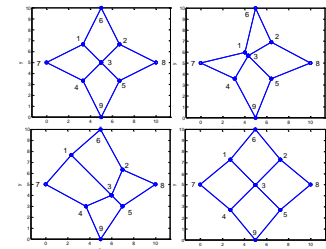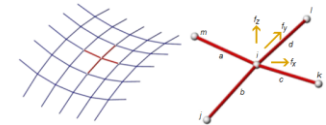
  – Analogous to *FDM* setting a surface stress density coefficient q_s for the constant strain triangle elements

  $$C_s \, X_f X_{ini} \, q_s F \implies X_{end} \, t \, l \, S \; \sigma = 4q_s S$$
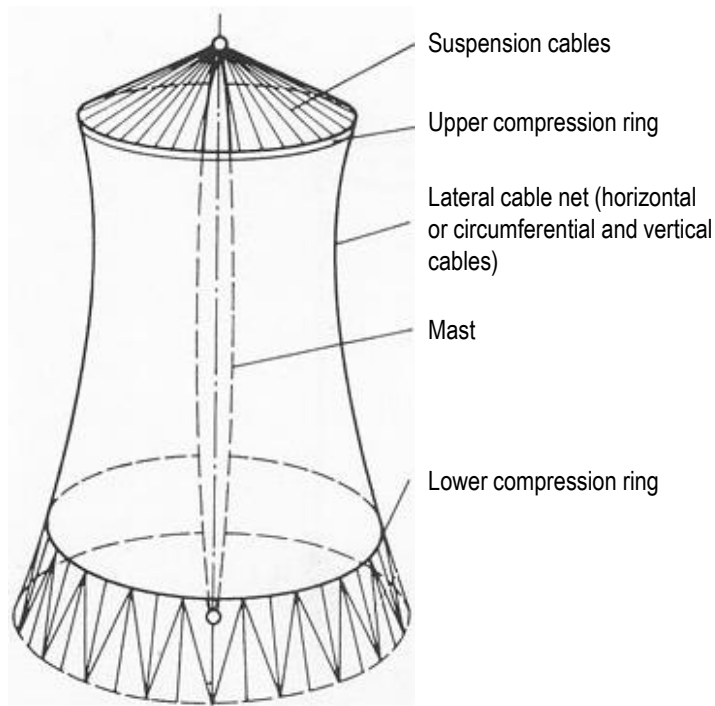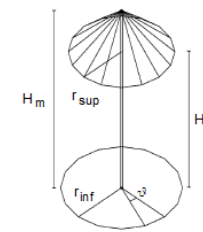
- Dynamic Relaxation Method: Viscous & Kinetic model

  – Explicit direct time-integration of the dynamic Equilibrium equations using central finite differences.

  $$C_s \, X_f \, X_{ini} \, F \, (E \, A \, t_i)_{truss \; el.} \implies X_{end} \, t \, l$$
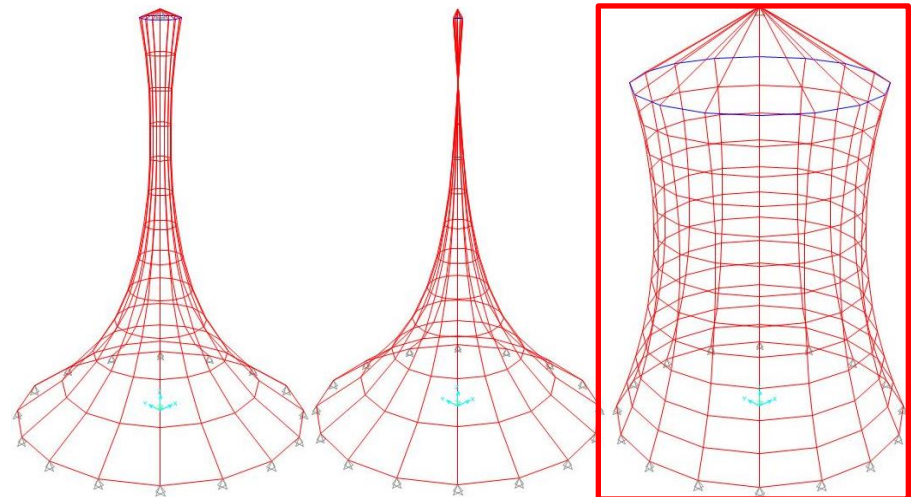
Wind Effects in Tensile Membrane Structures

- Linear Force Density Method (*IFDM*)
  - Example of a cooling tower
    - Solution is obtained iteratively: $r_{inf} \approx 9$ m, $r_{sup} \approx 7$ m, $H_c \approx 21$ m e $H_m \approx 25$ m

Suspension cables

Upper compression ring

Lateral cable net (horizontal or circumferential and vertical cables)

Mast

Lower compression ring

Configuração	a)	b)	c)
q_s (N/m)	400	400	400
q_{comp} (N/m)	-2800	-3000	-3000
$q_{c,v}$ (N/m)	100	100	1000
$q_{c,h}$ (N/m)	100	100	100

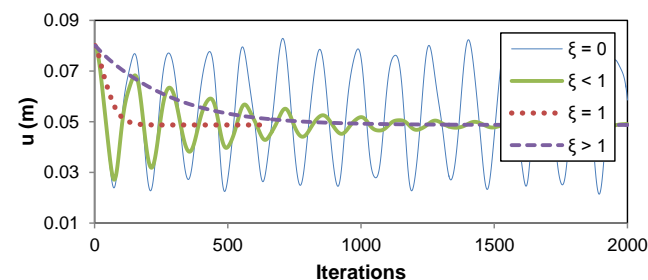# Wind Effects in Tensile Membrane Structures

- Viscous Dynamic Relaxation Method

  - 1 – Evaluation of the critical damping:

    $$f = \frac{1}{N\Delta t}$$

    $$c_{crit} = 4\pi mf$$

  - 2 – Evaluation of the static equilibrium response

$$\xi = \frac{c}{c_c} \Rightarrow \xi \begin{cases} = 0 & undamped\ vibration \\ < 1 & underdamped\ vibration \\ = 1 & critically\ damped\ vibration \\ > 1 & overdamped\ vibration \end{cases}$$

- Kinetic Dynamic Relaxation Method

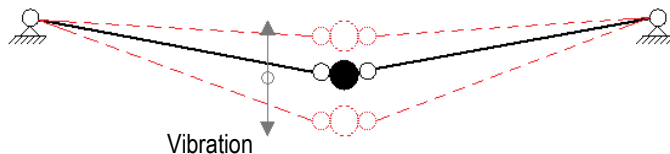$$U_k = \frac{1}{2}\left[(M\dot{U}_x)^T \dot{U}_x + (M\dot{U}_y)^T \dot{U}_y + (M\dot{U}_z)^T \dot{U}_z \right]$$

Equilibrium position:
$\dot{u}_{máx} \rightarrow$ Máx. kinetic energy
$\ddot{u} = 0$

Instable position:
$\dot{u} = 0$
$\ddot{u}_{máx}$

F

Vibration
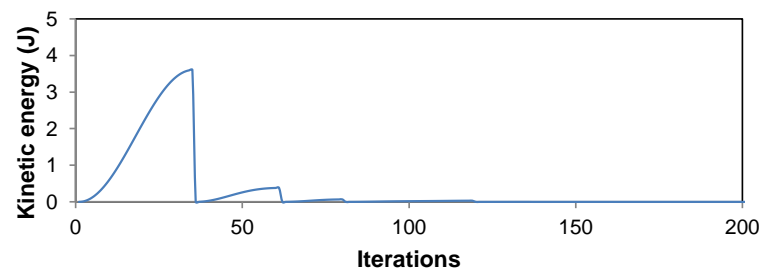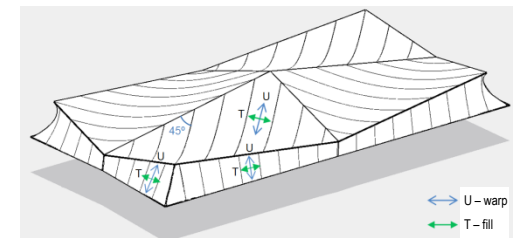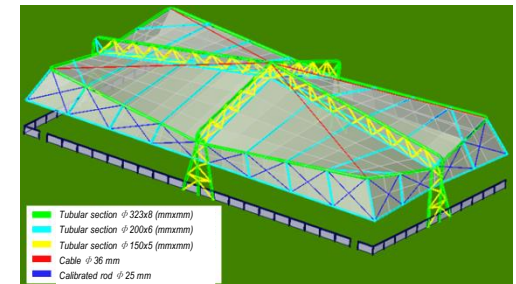
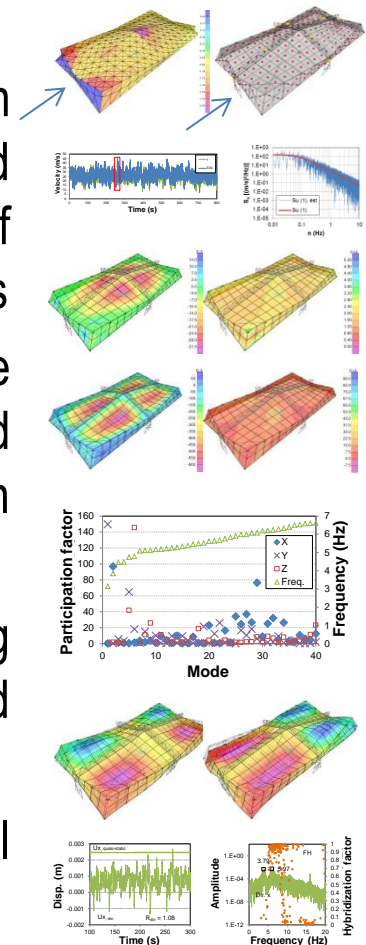# Wind Effects in Tensile Membrane Structures

– Roof of a multisport arena

- Tensile membrane roof structure located in Cartuja Island, Seville

- Doubly symmetric tubular metallic structure in plan, nearly rectangular in plan 24 x 46 m^2, including suspended cables and calibrated rods

- Tensile membrane made of PES/PVC, comprised by 4-top (hip. parab.) and 4-lateral modules (flat)

# Wind Effects in Tensile Membrane Structures

— Roof of a multisport arena

- Form-finding of the membrane with prestress of 2 kN/m through all implemented methods and specialized software, and comparing the same premises of orthotropic orientations, showed slightly different results

- Numerical simulation studies of the influence of the prestress, orientation of orthotropic directions, and Poisson coefficient evidenced significant differences on the static and dynamic responses of the membrane

- Nonlinear dynamic analysis in time domain considering geometric nonlinearity and large displacements showed dynamic amplification coefficients R_{dyn} of about 0,8

- Identification of wrinkles on the corners of the lateral modules due to non-economic shapes

Wind Effects in Tensile Membrane Structures

– Form-finding of a boat sail in real-time

- This work describes a monitoring system based on fiber optic strain gauge sensors used to reconstruct in real time the form of a sail

- The installation of FBG sensors on a beam allows to obtain curvatures in specific cross-sections, and evaluate, by interpolation, the coordinates of the deformed beam and consequently the most significant parameters of the sail shape

- Uncertainties related to optical technology, require the calibration and validation of the results through an alternative system.

- Since large amplitudes of deformations are measured, the fiber optic monitoring system was validated based on a imaging based system
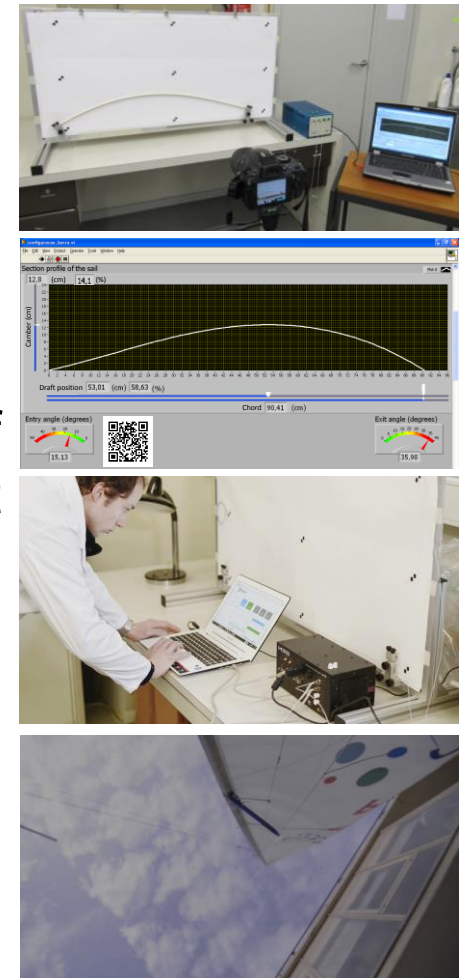
Conclusions

- Implementation of form-finding routines

- Application to a tensile membrane roof

- Identification of more relevant aspects of the behavior through parametric analysis

- Wind action and effects assessment

- Sail case: development, implementation and validation of an algorithm already patented for real-time assessment of sail shape. This methodology can be used for SHM of other engineering applications