THIRD BOSPORUS BRIDGE AERODYNAMICS: SECTIONAL AND FULL-AERIAL ELASTIC MODEL TESTING

A. Zasso, M. Bellotti, T. Argemini, O. Flamand, G. Knapp, G. Grillaud, J. F. Klein, M. Virlogeux, and V. de Ville
BB3 - Aeronautical Challenges

- Highest span length on innovative structural solution
- Widest 60m deck ➔ large aerodynamic derivatives expected
- Low-frequency bending and torsional modes in deck and towers
- Frequent strong lateral winds at the bridge site (higher than BB1)

- Great opportunity from aeronautical optimization:
  ➔ Improved structural wind interaction performances
  ➔ Improved safety on vehicles & train runability
BB3 – Deck Cross-Section

High slenderness steel deck
2 x 4 lanes of traffic
 Provision for future 2 rail track
Possible wind screens aeron. optimization:
Vehicles wind loads & VIV control

Slenderness = W / h = 11

5.5 m

58 m
3rd Bosporus Bridge: Project Team

Geotechnics

Railway Engineering

Wind Engineering

Local consultant E&M

Risk Management
CSTB Nantes (France)

Wind speed measurements
Large-scale high-speed wind tunnel
Numerical studies (CFD)
Atmospheric wind tunnels

Non-profit public body dedicated to construction safety and
Politecnico di Milano Wind Tunnel (Italy)

- POLIMI Wind Tunnel
- Academic environment of Politecnico di Milano Engineering University
- Operating since 2001

Two test sections:

<table>
<thead>
<tr>
<th>Tests Sections</th>
<th>Dimension [m]</th>
<th>Max Vel. [m/s]</th>
<th>( \Delta u /u ) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low speed / boundary layer</td>
<td>4 x 4</td>
<td>16</td>
<td>(&lt; \pm 2 %)</td>
</tr>
<tr>
<td>Low speed / low turbulence</td>
<td>4 x 4</td>
<td>55</td>
<td>(&lt; \pm 2 %)</td>
</tr>
</tbody>
</table>
Exposed site towards the northern end of the Bosphorus.
Stronger winds than Istanbul, BB1 and BB2
Complex terrain: Hills and mountains
Site monitoring and CFD modelling for regional wind speeds
C S T B – Wind Studies at BB3 Site

Met-Mast at the Bridge Site:

→ Detailed correlation allowed with Meteo Stations in the area
Prevailing Wind Direction Tested

- 58° Nord
- 45° → 347° NW
- 0° → 32° NE
- 90° → 122° SE
STEP 1: Deck Design Studies (CSTB)

**Deck (CSTB)**

- **Rigid section model**
  - scale 1:100
  - Static Coefficients
    - for different configurations
  - Validation of wind shields
    - (location, size, porosity)

- **Aeroelastic section model**
  - scale 1:100
  - 2 dofs (vertical/torsional)
  - VIV / aeroelastic stability
  - Flutter derivatives (free motion test)

**Tower (CSTB)**

- **Rigid model**
  - scale 1:150
  - Boundary Layer
  - High Reynolds Number
  - Static forces at foundation
  - Pressure distributions
• **Rigid model suspended on spring system**

• **Materials:** Carbon fibre, polyurethane, stiff foam, steel

• **Static and Dynamic Tests**

• **Reduced Velocity Scaling:**

  - **Length Scale:** \( \lambda_L = 1/100 \) (Model / Full Scale)
  - **Velocity Scale:** \( \lambda_V = 1/5 \)
  - **Frequency Scale:** \( \lambda_f = 20/1 \)
“No Wind Screens” Configuration

Optimum Drag / Not optimum VIV Response & Vehicles Wind Loads
C S T B  -  D e c k  S e c t i o n a l  M o d e l  (S c a l e  1 : 1 0 0)

- “2 W i n d  S c r e e n s ”  C o n f i g u r a t i o n
-  O p t i m u m  V I V  R e s p o n s e  &  V e h i c l e s  W i n d  L o a d s  r e d u c t i o n
- Low drag and favourable Lift and Moment Coefficients
- Almost linear trend (Lift & Moment).
- Positive derivatives (Lift & Moment).
- Very stable at High Wind Speed
- Optimum wind screens design for vehicle protection
C S T B - Tower Rigid Model

- Carbon fibre rigid model \(\rightarrow\) High Reynolds Tests
- Rigid base balance \(\rightarrow\) Mean and dynamic overall Wind Loads
- Pressure taps \(\rightarrow\) Unsteady pressures
CSTB - Tower Rigid Model (Scale 1:150)

- Pressure taps
- Unsteady pressures
time-space distribution

- Rigid base balance
- Mean and dynamic overall Wind Loads
STEP 2: Aeroelastic tests (POLIMI)

Aeroelastic tests (POLIMI)

**Full aeroelastic models**
- scale 1:180
- boundary layer wind tunnel

**In Service Bridge**
- full bridge with final configuration of deck

**Erection stages**
- tower stand alone
- tower + cantilever deck
- tower + cantilever deck + suspended deck

**Smooth flow tests**
- VIV
- stability

**Turbulent flow tests**
- Buffeting response and loads, wind different wind directions and turbulence characteristics
**POLIMI - Full Bridge Aeroelastic Model**

- **Materials**: Carbon fibre, polyurethane, stiff foam, steel
- **Dynamic Tests**: “In Service” & “Construction Stage” configurations
- **Reduced Velocity Scaling**:  
  - Length Scale: \( \lambda_L = 1/180 \)  
  - Velocity & Frequency Scale: \( \lambda_V = 1/\sqrt{180} \)  
  - Frequency Scale: \( \lambda_f = \sqrt{180} \)  

**Smooth & Turbulent Flow**
POLIMI - Full Bridge - Monitored Sections

European side

- s1. 1/4 span
- s2. 3/8 span
- s3. 1/2 span
- s4. 3/4 span
- s5. side span
- TE - h1. 1/2 tower height
- TE - h2. top tower

Asian side

- RE: r u a g balance, e u r. tower
- RA: r u a g balance, a s i a t o w e r

• 3 accel. 3 displ.
• 3 accel. 3 displ.
• 3 accel. 3 displ.
• 2 accel.
• 2 accel.
• 6 comp.
• 6 comp.
POLIMI – Free Standing Tower Aeroel. Model

Accelerations and Displacements (mean & dynamic) at two locations

Rigid base balance
Mean and dynamic

h1 = 150 m
h2 = 300 m
POLIMI – Free Standing Tower Aeroel. Model
• Aeroelastic Model CAE designed and manufactured
• Aeronautical Model CAE designed and manufactured
• Temporary stiffening connection simulated (very low structural damping)
POLIMI – Free Standing Tower Aeroelastic Model

- Free standing Aeroelastic Tower & Incoming Turbulent Wind
- Spires in the background generating the requested Boundary Layer
POLIMI - Full Bridge Aeroelastic Model

- Combined effects of exposure angle and upwind roughness considered
- e.g.: incoming turbulent wind Exposure 45° → 347° NW
POLIMI - Construction Stage Aerelastic Model

- Detailed representation of most relevant construction stages configurations
POLIMI - Full Bridge Aeroelastic Model

- Very effective aerodynamic performances:
  - Regular response to Turbulent Wind \( \rightarrow \) expected usual quadratic trend
  - No appreciable VIV excitation at low wind speed
  - No aerelastic instability up to wind speed well over design limit

![Graphs showing normalized rms of acceleration and normalized bending moment versus wind velocity.](image)

CSTB - le futur en construction
STEP 3: tests at large Reynolds number (POLIMI & CSTB)

STEP 3
Request for checking VIV and Wind Screens towards Reynolds Effect

Rigid Deck Section model (CSTB)
scale 1:25
- Vertical wind profiles
- Deck pressure distributions
- Wind loads on vehicles
- High Reynolds Number

Wind shields
OK

Aeroelastic multi-modal deck model (POLIMI)
scale 1:50
- Vertical wind profiles
- Deck pressure distributions
- VIV

No VIV

comparison of results for Re effect
Large Scale Rigid Model

- 1:25 Scale
- Up to 50 m/s → Re = 1.3E+7
- Measures: Unsteady pressure distribution on deck section
- Wind Screen aerodynamic characterization
- Wind velocity profiles on road & train lanes
- Aerodynamic forces on vehicles (trucks and trains)
Large Scale Aeroelastic Model 

- 1:50 Scale / Aeroelastic deformable / Very low damping → Low Scruton
- Up to 16 m/s → Re = 2.0E+6
- Measures: Aeroelastic response
  - Unsteady pressure distribution on deck and screens
  - Wind Screen aerodynamic characterization
  - Wind velocity profiles on road & train lanes
Wind Screens & Deck Aerodynamics: Optimum cross validation CSTB – POLIMI results on Mean pressure distribution

Reynolds Range:
CSTB $\Rightarrow$ Re = $1.3 \times 10^7$
POLIMI $\Rightarrow$ Re = $2.0 \times 10^6$
Mean velocity magnitude

Mean flow angle

Streamlines - Mean velocity magnitude coloured
POLIMI - CFD / Exp. Cross Validation

NACA 0006_uw_U_5_Ext_0 - U Magnitude

\[ \alpha = 0^\circ \]

NACA 0006_uw.PL_5_Ext_0 - Streamlines

\[ \alpha = 0^\circ \]

Streamlines - Mean velocity magnitude coloured

POLITECNICO DI MILANO
Conclusions

- **BB3 project proved to reach highest wind interaction performances:**
  - No appreciable VIV excitation at low wind speed
  - No aerelastic instability up to wind speed well over design limit
  - Improved safety on vehicles & train runability

- This was reached through:
  - **Successful partnership and cross-validation between two major European wind laboratories**, ensuring best practices
  - Robust solutions cross-validated in different Labs and wide Re range
  - Great effort from Aerodynamic Teams on Experimental vs Numerical
Polimi - Full Bridge Aerelastic Model

Full bridge - monitored sections

- s1. 1/4 span
- s2. 3/8 span
- s3. 1/2 span
- s4. 3/4 span
- s5. side span
- TE-h1. 1/2 tower height
- TE-h2. top tower
- RE: r u a g b a l a n c e, e u r. tower
  forces
- RA: r u a g b a l a n c e, a s i a t o w e r
  forces

3 accel. 3 disp.
3 accel.
3 disp.
3 accel.
2 accel.
2 accel.
6 comp.
6 comp.
POLIMI - Full Bridge Aerelastic Model

Monitored sections - deck accelerations

- s1, s2, s3, s4: three accelerometers for each sect
- s5: two accelerometers (z,z)
POLIMI - Full Bridge Aeroelastic Model

Monitored sections - deck displacements (laser)

- 2 sections monitored (s1 and s3), each with 3 lasers
The loads at the base of the towers are monitored by 2 six-components dynamometric balances
• RE: ruag balance, European tower
• RA: ruag balance, Asian tower
Two sections of the European tower are monitored by 4 accelerometers:

- TE-h1-x
- TE-h1-y
- TE-h2-x
- TE-h2-y
Large Scale Aerelastic Model → POLIMI

- 1:50 Scale
- Up to 15 m/s
- Pressure distribution around deck
- Aerelastic for VIV investigation