The idea of bridging the gap in Rion Antirion strait was first envisaged by the Greek Prime Minister Charilaos Trikoupis back in late 19th century.

Rion Antirion crossing time through ferries could exceed 45 min and significant traffic jams were experienced during:
- Peak season
- Bad weather conditions

Rion Antirion Bridge links the west motorway network of Greece connecting significant ports.

Crossing time through Bridge dropped to less than 5 min regardless of weather conditions.

Social and economic impact especially on local area.
**STRUCTURAL DESIGN:**

**ENVIRONMENTAL SITE CONDITIONS**

- **Weak Sea Bed up to 500m**
  No bedrock encountered in first 100 m during soil investigations, while geological studies indicated similar conditions for up to 500 m

- **Water depth up to 65 m**
  Uniform sea bed at depth of 60 m with steep slopes near coast

- **High Seismicity**
  Active normal faults on both sides of Corinthian gulf, at the vicinity of Bridge

- **Tectonic movements**
  Tectonic kinematic of area indicates separation of Peloponnese from mainland Greece with rate of ~20 mm/year

- **Strong Wind area**

- **Navigation channel**
  Significant marine traffic through Rion - Antirion strait
STRUCTURAL DESIGN:

MAIN DESIGN LOADS

- Seismic load (Spectrum: pga 0.48 g, max Sa 1.20 g for T=0.2 up to 1.0 sec) - EQ of 2000 years Return Period

- Tectonic movements up to 2m (between adjacent piers)

- Design Wind speed 50m/sec at deck height

- Aerodynamic stability up to 74m/sec

- Ship collision:
  - 85000 dwt bulk carrier (full laden) at 16 knots
  - 180000 dwt tanker (on ballast) at 16 knots
STRUCTURAL DESIGN:

MAIN CHARACTERISTICS OF STRUCTURE

- **4 DAMPERS ON EACH MAIN PIER & 2 ON EACH TRANSITION PIER (TP)**
  - In service: The deck is laterally supported by means of a restrainer (nominal load: ±10,5MN for main piers / ± 3,5MN for TP)
  - In ultimate conditions: It fuses allowing the dissipation system to absorb the induced energy (dampers stroke: 3,5 m for main piers / 5,2 m for TP)

- **2 EXPANSION JOINTS:**
  - +1,26/-1,15 m longitudinal expansion in service (max longitudinal expansion +2,81/-2,20 m)

- **SHALLOW FOUNDATION ON REINFORCED SOIL**

- **FOOTING DIAMETER**
- **TOTAL FOUNDATION DEPTH**
- **TOTAL HEIGHT**
  - 189 M TO 227 M
- **386 CABLE STAYS**
  - (TOTAL LENGTH 79 M UP TO 295 M)
Weak soil was reinforced with steel inclusions (steel pipes 2m diameter)

\[
\begin{array}{cccc}
M1 & M2 & M3 & M4 \\
112 & 194 & 156 & -
\end{array}
\]

Crushed gravel was laid on top to achieve required friction coefficient

Footing was floated and rested on top gravel layer – no connection with inclusions

Enlarged footing diameter to enhance stability and minimize soil stress (80/90m diameter M4/M1-M3)

Preloading of soil to accumulate settlements during construction
Dissipation system: absorbs earthquake energy, reducing the lateral movement during strong earthquakes

- To avoid transverse movements during normal operation conditions or small earthquakes, the deck is attached to the pylons (and rotating frames) through the fuses.
- Fuses on pylons are devices that release the deck when the force exceeds 10500kN in both directions.
- Fuses can be replaced after a strong earthquake easily by replacing the sacrificial thread.
- Dampers can absorb lateral deck motions up to ±1,65 m and loads up to 3500kN.
INSTRUMENTED MONITORING

STRUCTURAL HEALTH MONITORING (PERMANENT SYSTEM)

ASSUMPTIONS

ENGINEERING SYSTEM

KNOWLEDGE

EXPERIENCE

ENVIRONMENTAL ACTION

NATURAL SYSTEM

INPUT

SYSTEM

OUTPUT

MONITORING SYSTEM

SENSORS

DAQ

WIRING

NOISE

RAW DATA

SYSTEM RECORDS

DATA ANALYSIS

ENGINEERING INTERPRETATION

Operator

Rules

Thresholds
INSTRUMENTED MONITORING

Structural Health Monitoring (permanent system)

- **Assumptions**
  - Knowledge
  - Experience

- **Engineering System**
  - Input
  - System
  - Output

- **Natural System**
  - Environmental action
  - Structure
  - Response

- **Monitoring System**
  - Sensors
  - DAQ
  - Wiring
  - Raw data
  - Noise
  - System records

- Define natural system
- Verification of design assumptions
- Monitor structural health

- Operator
- Rules
- Thresholds
INSTRUMENTED MONITORING: STRUCTURAL HEALTH MONITORING ARCHITECTURE

- Switch/Hub
- Double optic fiber Network
- Power supply UPS/Generator
- Supervisor Computer
- Control Room

- DAQ/PXI
- DAQ/PXI
- DAQ/PXI
- DAQ/PXI

- Surge Arrestors
- Lightning protection
- LPDA
- Diodes

- DAQ System software
  - Sensor data acquisition
  - Sensor data processing
  - Threshold checking
  - History files record
  - Dynamic files record
  - Alert files record
  - PXI communication
  - Main software communication
  - Communication with SCADA

- Supervisor computer Software
  - Data files retrieving
  - Sensor data display (Real time)
  - Data files display (graphs)
  - Sensors parameters modification
  - Record parameter modification
  - PXI communication

- Control room communication via SCADA server
  - Record data regarding user safety/operation
    - Wind speed
    - Road temperature
    - Message display
      - Earthquake
      - Strong wind
      - Black ice risk
      - Fog

LEVEL 1: Sensors
LEVEL 2: Power supply & signal transfer
LEVEL 3: Digitalization, acquisition & signal processing
LEVEL 4: Communication network, data management
## INSTRUMENTED MONITORING: STRUCTURAL HEALTH MONITORING ARCHITECTURE

### LIGHTNING PROTECTION
- **SOUTH**
- **NORTH**
- **WEST**
- **EAST**

### LEVEL 1: Sensors
- **DISPLACEMENT METER**
- **STRAIN GAUGE ON FUSES**
- **ANEMOMETERS**
- **LOAD CELLS ON CABLES**
- **PYLON ACCELEROMETERS**

### LEVEL 2: Power supply & signal transfer

### LEVEL 3: Digitalization, acquisition & signal processing

### LEVEL 4: Communication network, data management

---

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Quantity</th>
<th>Expected range</th>
<th>Sensor range</th>
<th>Monitored phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D anemometers</td>
<td>2</td>
<td>0-50 m/sec</td>
<td>0-60 m/sec</td>
<td>Wind intensity</td>
</tr>
<tr>
<td>Temperature and Humidity sensor</td>
<td>2</td>
<td>50ºC to 100%RH</td>
<td>0-60%RH</td>
<td>Thermal loading</td>
</tr>
<tr>
<td>3D Pylon accelerometers</td>
<td>12</td>
<td>±5.7g (top) ±5.7g (base)</td>
<td>±5.7g (top) ±5.7g (base)</td>
<td>Pylon vibration (Earthquake/wind)</td>
</tr>
<tr>
<td>1D/3D Deck accelerometers</td>
<td>3/12</td>
<td>±2.7g</td>
<td>±2g</td>
<td>Deck vibration (Earthquake/wind)</td>
</tr>
<tr>
<td>3D Ground accelerometers</td>
<td>2</td>
<td>±0.48g</td>
<td>±0.4g</td>
<td>Earthquake</td>
</tr>
<tr>
<td>3D Cable accelerometers</td>
<td>13</td>
<td>±2g</td>
<td>±2g</td>
<td>Cable vibration/Wind</td>
</tr>
<tr>
<td>Monitored load of cables</td>
<td>16</td>
<td>0 up to 75% Fmax (199 KN)</td>
<td>0-320 KN</td>
<td>Cable load vs. (Wind/Earthquake/Balance)</td>
</tr>
<tr>
<td>Magneto, distance meter</td>
<td>2</td>
<td>±1200-1130 mm</td>
<td>±50 mm</td>
<td>Expansion joint opening (Earthquake/Balance/Thermal)</td>
</tr>
<tr>
<td>Strain gauges (full bridge)</td>
<td>4</td>
<td>±10500 με</td>
<td>±1500 με</td>
<td>Wind induced lateral load</td>
</tr>
<tr>
<td>Road temperature sensors</td>
<td>4</td>
<td>-</td>
<td>-50ºC to 50ºC</td>
<td>User safety (black ice risk)</td>
</tr>
<tr>
<td>Deck temperature sensors</td>
<td>5</td>
<td>-</td>
<td>-10ºC to 80ºC</td>
<td>Thermal loading</td>
</tr>
</tbody>
</table>
LEVEL 1: Sensors

LEVEL 2: Power supply & signal transfer
- Sensors more than 400 m away from DAQ unit
- AC/DC convertors (~230 V to 24 VDC)
- Signal conditioning (Amplifiers)

LEVEL 3: Digitalization, acquisition & signal processing
- 4 acquisition points (one per pylon)
- Low pass filtering at 10 kHz
- Digitalization at 500 Hz
- Signal conversion to engineering unit
- Alert checking and file creation & Real time data transmission
- Synchronization (SNTP)

LEVEL 4: Communication network, data management
- Optic fiber network in ring configuration for redundancy
- Communication with Supervisor Server (SE) for permanent file storage/visualization/parameter management
INSTRUMENTED MONITORING

STRUCTURAL HEALTH MONITORING (PERMANENT SYSTEM)

MONITORING SYSTEM OPERATION PROVIDES:

1. Dynamic characteristics of actual structure
2. Characterization of real actions
3. Design verification and feedback
4. Structural health status determination
5. Supports Operation

History Files analysis: Slow varying processes/statistical parameters of structural response

History files: 1 value every 30 sec

Dynamic Files analysis: Dynamic process/actual measurements of structural response

Dynamic files: High frequency (100hz) records of limited duration
AMBIENT CONDITIONS DATA ANALYSIS

DATA: History

Analysis output

Wind speed & direction
- Data exclusion algorithm on selected data
- Addition of Meteo Year data to global Meteo database
- Statistical properties calculation per month
- Distribution per wind direction
- Graphic representation
EXPANSION JOINT DATA ANALYSIS

DATA: History

Analysis output

- Data exclusion algorithm on selected data
- Dependence on Deck temperature
- Deck length calculation
- Estimation of creep & shrinkage
- Addition of EJ Year data to global EJ database
LOAD ON CABLE DATA ANALYSIS

DATA: History & Dynamic

Analysis output

- Data exclusion algorithm on selected data
- Statistical properties
- Distribution
- Addition of LoC Year data to global LoC database
- Comparison with equivalent LoC (frequency calculation)
DECK VIBRATION

DATA: Dynamic

Analysis output
- Data exclusion algorithm on selected data
- Calculation of vibration indexes
- Statistical properties calculation
- Dependence on Wind speed
- Identification of single mode vibration cases
- Modal identification
DECK VIBRATION

DATA: Dynamic

Analysis output

- Data exclusion algorithm on selected data
- Calculation of vibration indexes
- Dependence on Wind speed
- Identification of single mode vibration cases
- Modal identification*

*Synchronization algorithm is necessary
CABLE STAY VIBRATION

Cable stays are characterized by low intrinsic damping and are prone to large amplitude vibrations.
- Damping ratio to critical $\xi_s = -6 \times 10^{-4}\times L + 0.24$ (L in m)

Rion - Antirion cable system critical phenomenon for vibration is excitation due to deck combined with buffeting.
- Cable modal frequencies are within the range of torsional deck frequencies
- For moderate winds (16 m/sec) vibration amplitude of up to 800mm can occur for longer cables (L>200m)

Proper provisions were available in order to implement various mitigation measures.
- Cross ties installation at pre-installed steel collars on L/3 & 2L/3 of cable
- Installation of External Hydraulic Dampers (EHD) on longer cables and Internal Hydraulic Dampers (IHD) on shorter ones (#1 to #10)

Selection of optimum mitigation measures required actual structural data from SHM system
CABLE STAY VIBRATION

Event Characteristics
- Eastern winds ~120 ° from deck axis
- Maximum wind speed (2' average) 31.2 m/sec M1M2 28.3 m/sec M3M4
- Lower temperature 1.2 °C (ice formation on cables)

Deck Response
- Maximum deck vertical amplitude ±16 cm
- Frequency bandwidth 0.2 to 0.7 Hz

Cable Response
- Maximum vibration amplitude >2.0 m (cables L>200m)
CABLE STAY VIBRATION

CSTB Analysis on recorded data

Based on data records an envelope of deck response was calculated

\[ V(f) = 1 + \frac{3}{f^2} \cdot f \] (frequency) in Hz, \( V \) (amplitude) in mm

The envelope was used as input for parametric excitation analysis and calculation of necessary damping for mitigation of cable vibration amplitude to one (1) cable diameter

- No additional damping for short cables \( L < 100 \ m \)
- 1\% damping ratio for intermediate cables \( L = 100 – 250 \ m \)
- 1.5 % damping ratio for long cables \( L > 250 \ m \)

For above damping ratios, the cables were verified against ice and dry galloping

Mitigation measures by VCGP & FRE according to CSTB analysis

Solution adopted:

- No additional damping for short cables
- EHD on all intermediate and long cables #11 and above (with \( \delta > 4\% \))

Commissioning tests verified EHDs efficiency
CABLE STAY VIBRATION

Event Characteristics
• Eastern winds ~100° from deck axis
• Maximum wind speed (10’ average) 35.4 m/sec, M1M2 30.7 m/sec M3M4
• Lower temperature 6.5 °C

Deck Response
• Maximum deck vertical amplitude ±20 cm
• Frequency bandwidth 0.2 to 0.8 Hz

Cable Response
• Maximum vibration amplitude <0.5 m
DECK VORTEX SHEDDING

DECK VIBRATION EVENTS REPORTED

THRESHOLD PROCEDURES AND RULES FAILED TO DETECT

Low acceleration amplitudes (below thresholds)

DYNAMIC FILES TARGETED ANALYSIS (automatic files)

WS ~ 8.5 m/sec
WD ⊥ Deck
DispAmp < 20 cm
3rd mode excited
f = 0.216 Hz

Wind speed ~ 8.5 m/sec

Maximum observed amplitude < 20 cm (in dynamic files)

Excited mode determination (3rd Mode) f = 0.216 Hz [T = 4.6 sec]
**DECK VORTEX SHEDDING**

**DECK VIBRATION EVENTS REPORTED**
- Threshold procedures and rules failed to detect
  - Low acceleration amplitudes (below thresholds)

**DYNAMIC FILES TARGETED ANALYSIS**
- (automatic files)
  - $WS \approx 8.5 \text{ m/sec}$
  - $WD \perp \text{Deck}$
  - $\text{DispAmp} = 20 \text{cm}
  - 3rd mode excited
  - $f = 0.216 \text{ Hz}$

**WHAT ARE THE CONSEQUENCES OF THE EVENTS? ARE MITIGATION MEASURES NECESSARY?**
- If so, cost?
  - More information is necessary:
    1. Frequency of occurrence/Duration/Amplitude
    2. Nature of phenomenon (evolution?)
    3. Fatigue consequences on structural elements

**INVESTIGATION IN COOPERATION**
- GST (Data Processing)
- CSTB (Wind phenomena)
- VCGP (Fatigue)

**Development of data analysis procedure for History files (1)**

**History files:**
- 0.5 sec averaged values every 30 sec
- Capture all events

**Study of averaging and aliasing properties**

**STD index correlated with Dynamic analysis results (STDh ~ STDd)**
DECK VORTEX SHEDDING

WHAT ARE THE CONSEQUENCES OF THE EVENTS?
ARE MITIGATION MEASURES NECESSARY?
IF SO, COST?
More information is necessary:
1. Frequency of occurrence/Duration/Amplitude
2. Nature of phenomenon (evolution?)
3. Fatigue consequences on structural elements

INVESTIGATION IN COOPERATION

GST  
(Data Processing)

CSTB  
(Wind phenomena)

VCGP  
(Fatigue)

Development of data analysis procedure for History files (1)
Calculate load cycles & identify phenomenon (Vortex shedding) No Evolution (2)
Calculate fatigue of structural elements (gussets) No Risk (3)

Calculation of transverse loading of Gusset C3523W for maximum VS vibration events

Maximum transverse loading due to VS events is <20 % of cut off limit 0,5% Fcr

VS vibration amplitude is less than specified limit for tolerable comfort according to BD49/01

Vibration amplitude < ymax=214 mm

\[ K_D = f^2 + y_{max} \]

\[ K_D < 10 \text{ cm/sec}^2 \]
Measurements and evaluation of:

- tectonic movements
- Piers tilt & settlement
- Deck geometry
- TP settlement

The processed data are analyzed & compared with theoretical results

<table>
<thead>
<tr>
<th>SECTION DETAILS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECTION</strong></td>
</tr>
<tr>
<td>Global Network</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Main Bridge</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Rion Viaduct</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Antirion Viaduct</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Toll Plaza</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Measurements and evaluation of:

- Tectonic movements (T0-T5 opening rate ~2.2 mm/year)
- Piers tilt & settlement (max settlement <8 cm since 2004)
- Deck geometry
- TP settlement
Measurements and evaluation

- Tectonic movements
- Piers tilt & settlement
- Deck geometry
- TP settlement
INSTRUMENTED MONITORING

GEOMETRICAL MONITORING (NON-PERMANENT SYSTEM)

Measurements and evaluation of:

- Tectonic movements
- Piers tilt & settlement
- Deck geometry
- TP settlement (~13cm since 2004)
Thank you for your attention

CRL School 2018