Examples of...

SHM on Cultural Heritage Structures

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Introduction

- Department of Civil Engineering Mechanics as a part of Faculty of Civil Engineering in Zagreb is carrying structural health monitoring on the structures of cultural heritage located in Republic of Croatia for many years. As part of this presentation studies conducted on some of these structures will be shown.


Rector's Palace, Dubrovnik

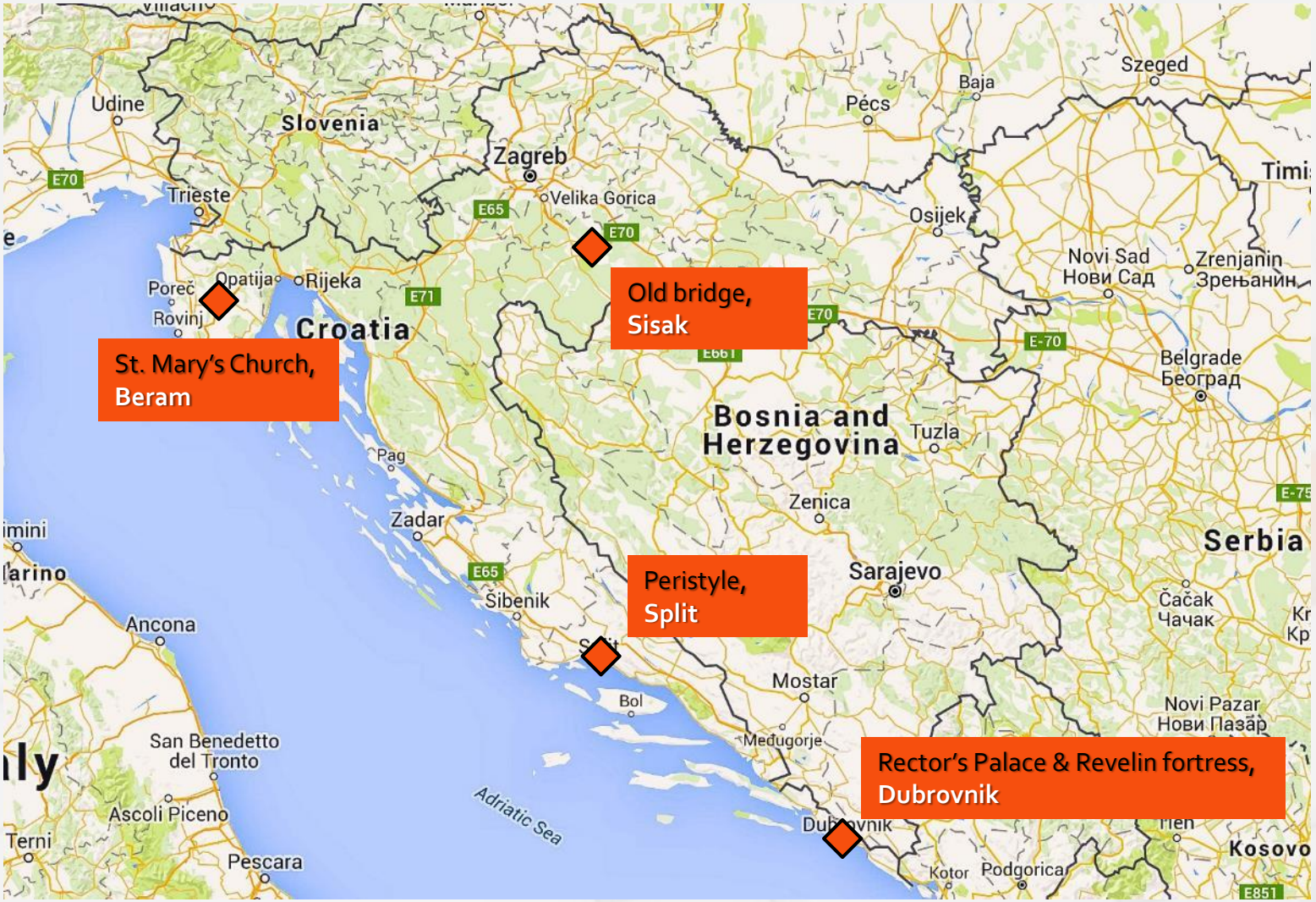

Peristyle, Split


St. Mary's Church, Beram

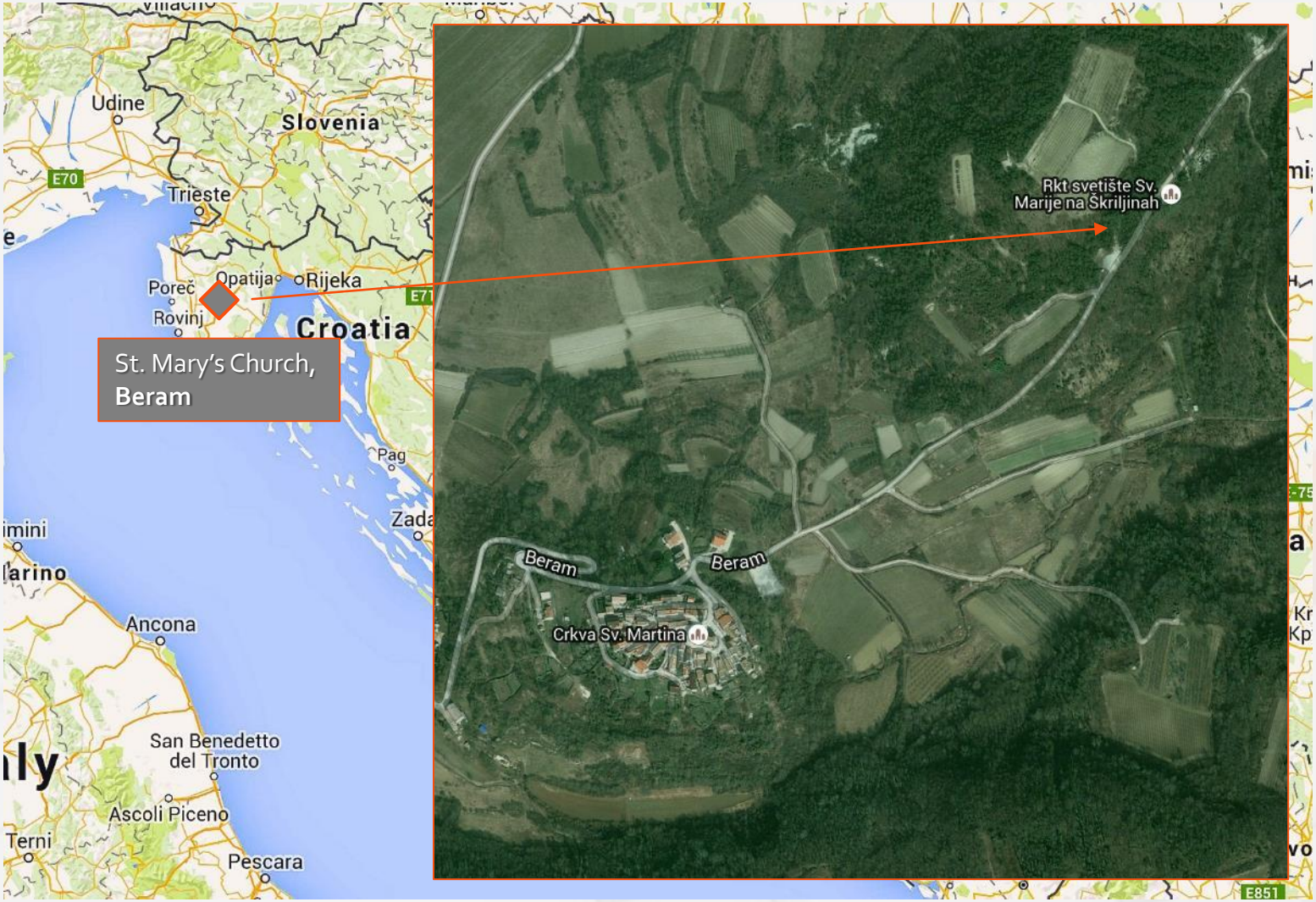

Old bridge, Sisak


Revelin fortress, Dubrovnik

Locations of investigated structures



Locations of investigated structures



Investigated structures

1] St. Mary's Church in Beram, Istria

The **St. Mary's Church** is a small chapel in the woods outside **Beram** in Istria. The interior of the church is covered in frescoes, including a portrait of Saint Martin, the Triumphal Entry into Jerusalem, the Last Supper, and other conventional subjects. The frescoes were commissioned by Beram Confraternity of St. Mary, so most are dedicated to the lives of Mary and Jesus. But the star of the show is a "**dance of death**" painted by Vincent de Kastav in 1474. In this version of the *dance macabre*, Skeletons walk in procession from right to left, led by a skeleton playing bagpipe.

St. Mary's Church, Beram

Dance of Death by Vincent de Kastav

Investigated structures

1] St. Mary's Church in Beram, Istria

PROBLEM

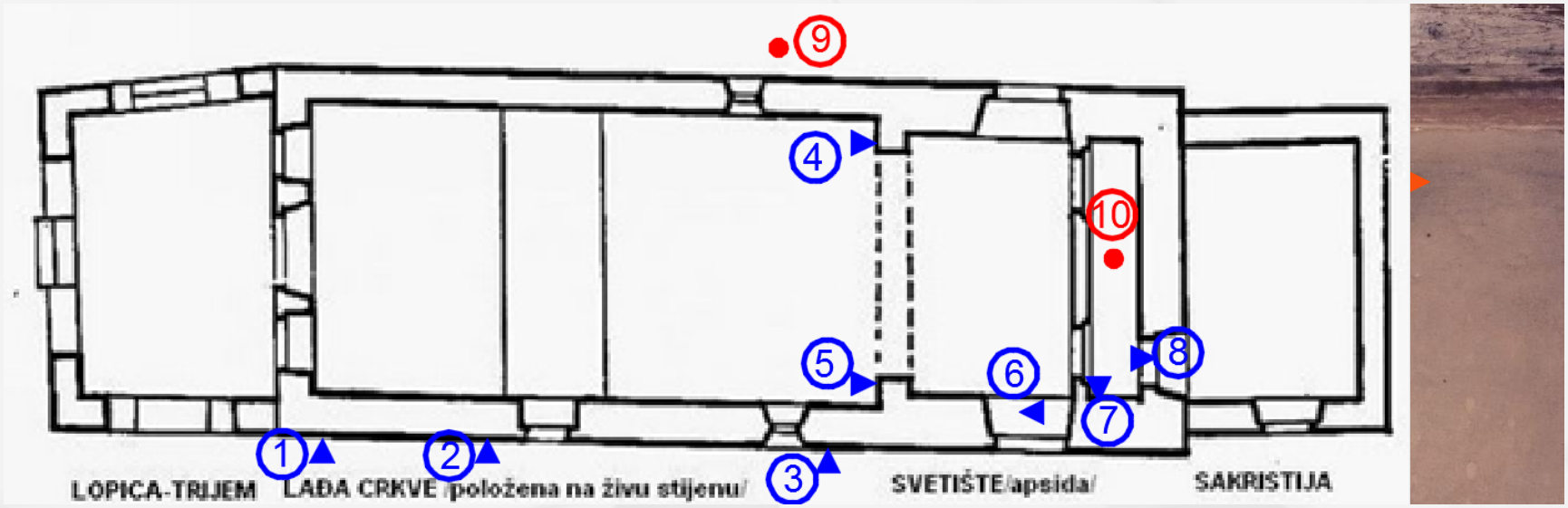
As a result of subsidence of foundations, the cracks od the main load bearing wall appeared.

Investigated structures

1] St. Mary's Church in Beram, Istria

PROBLEM → **MEASUREMENTS**

Eight inductive transducers were installed which measured expansion and contraction of cracks on load bearing elements.



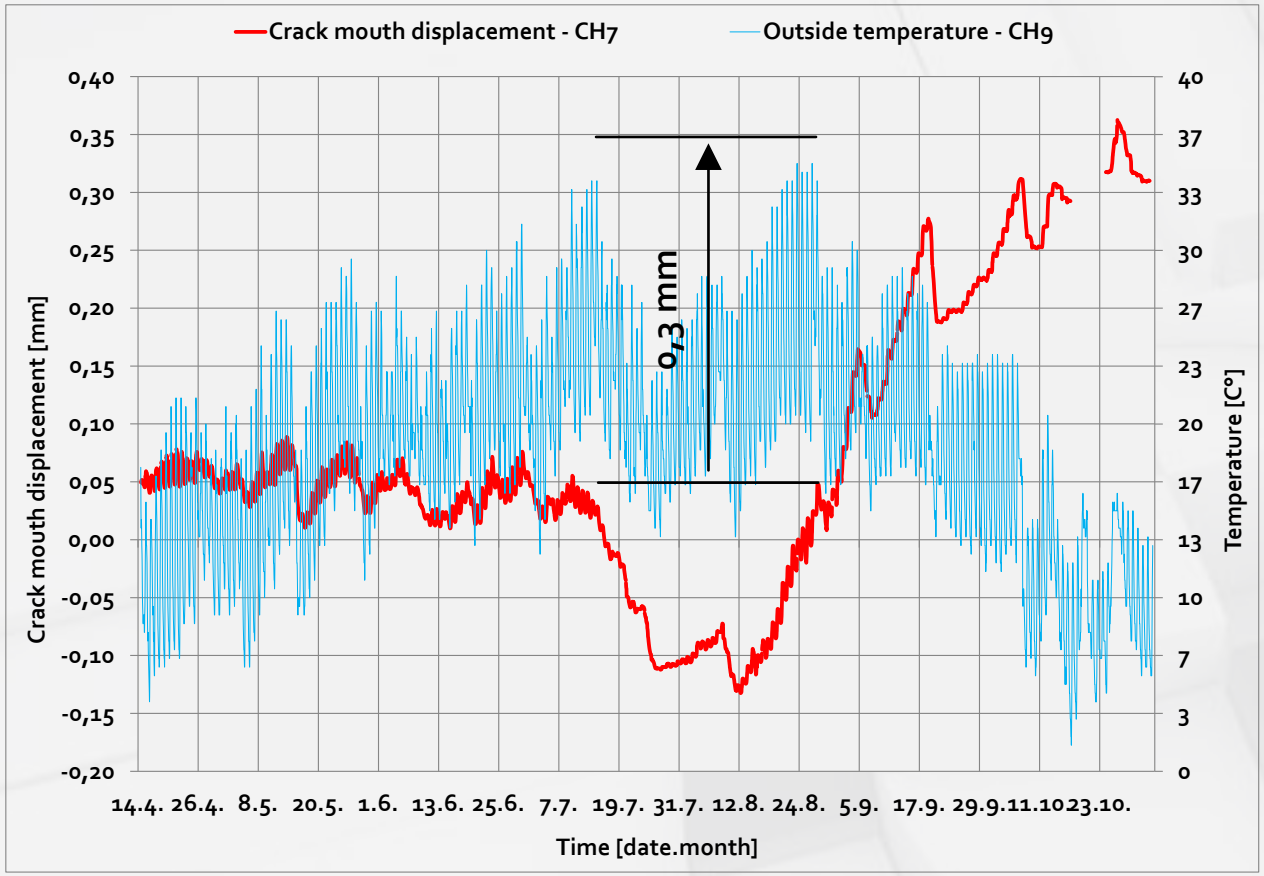
In addition, inner and outer temperature was recorded during measurements.

Investigated structures

1] St. Mary's Church in Beram, Istria

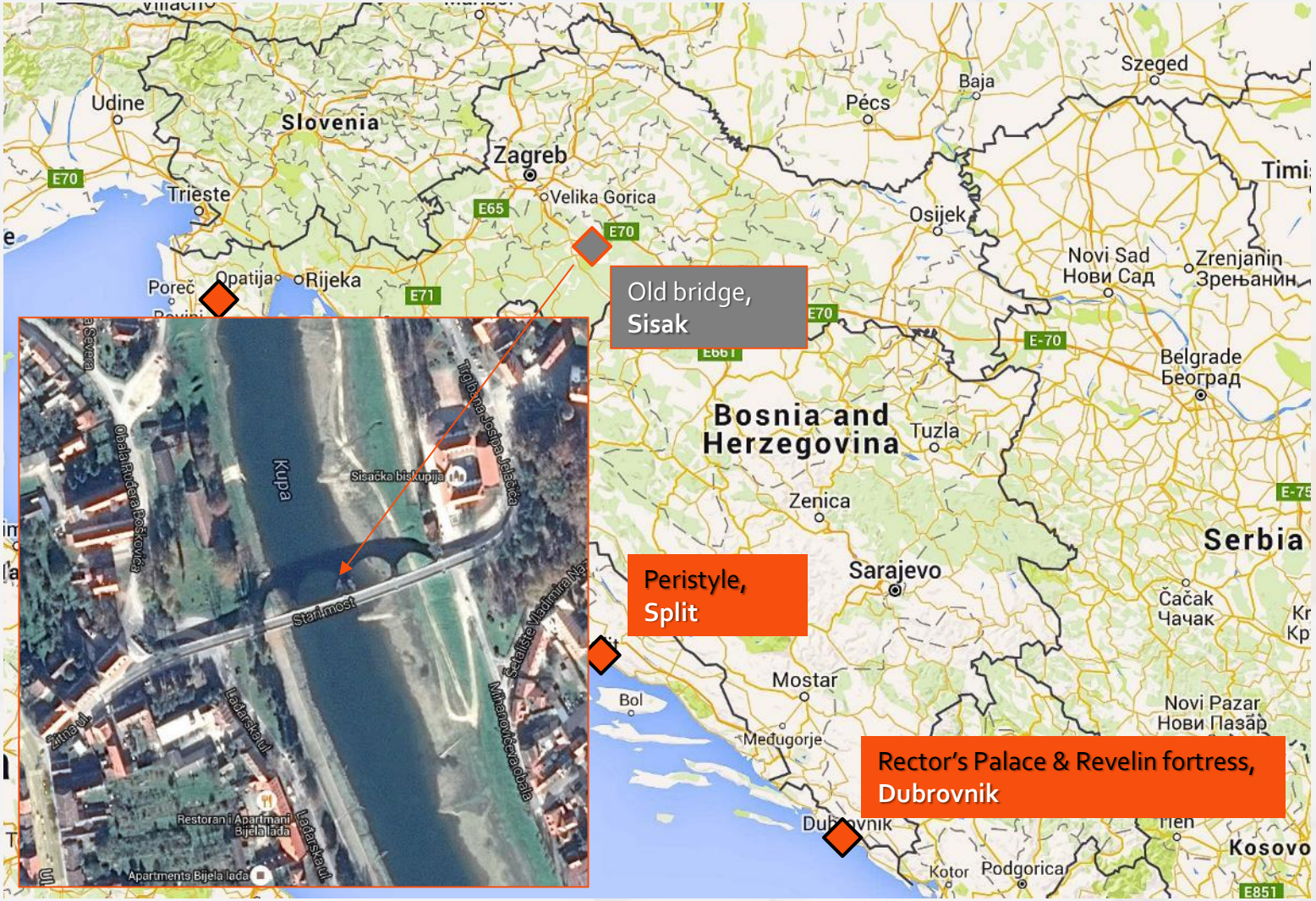
PROBLEM → **MEASUREMENTS** → **RESULTS**

CONCLUSIONS



Increasing of the crack mouth displacement on south load bearing wall was detected.

Locations of investigated structures



Investigated structures

2] Old bridge, Sisak

The bridge was built in 1934. as a replacement to an older wooden bridge dating from 1862. At a time when the concrete was already in widespread use, this bridge was built from traditional materials, stone and brick, which highlight its graceful forms. The citizens spontaneously named it „Stari most" (Old bridge), eventually the name became official and the bridge became one of the symbols of the city of Sisak.

Old bridge in Sisak

Investigated structures

2] Old bridge, Sisak

PROBLEM

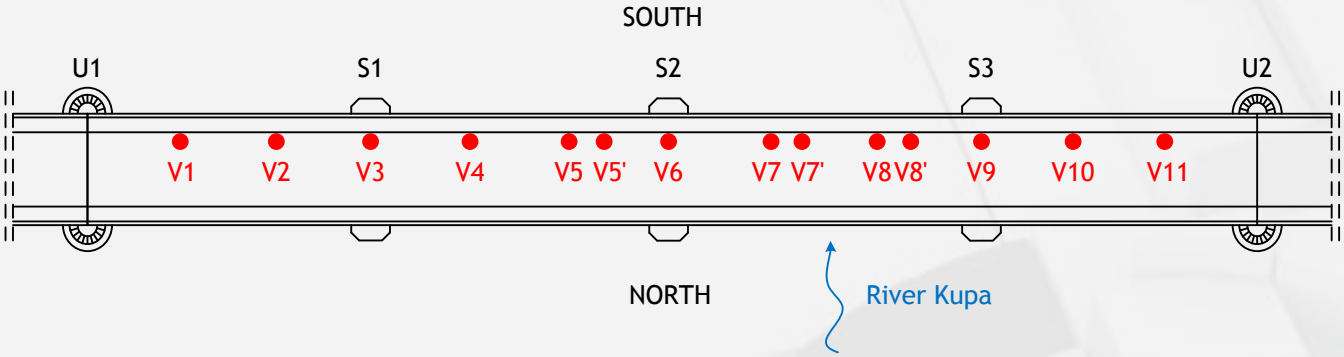
Extensive damage of non load bearing elements were observed especially visible on the heads of the columns and on the edge of the arch. Stability and durability of the structure were threatened with the direct penetration of precipitation from the road surface into the interior structure of the bridge. Another important phenomenon that threatened the sustainability and stability of the structure was condensation in the form of droplets of water on the surfaces of load bearing elements of the bridge structure.

Investigated structures

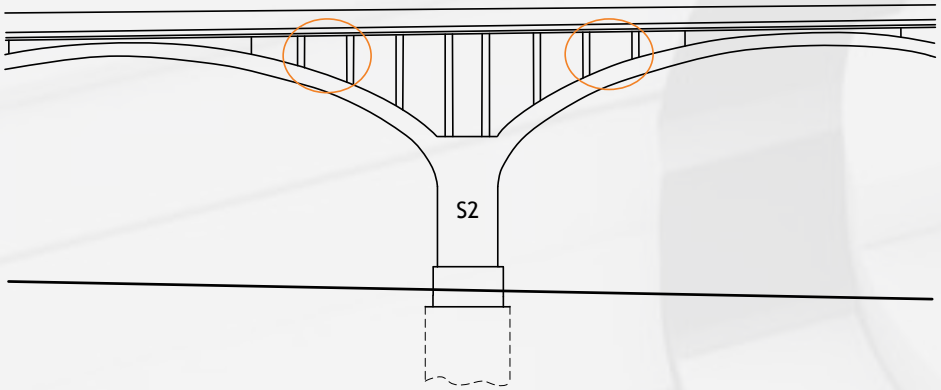
2] Old bridge, Sisak

PROBLEM → **MEASUREMENTS**

1] Compressive strength of concrete slab was determined on 14 test specimens taken on the field.



2] Compressive strength of masonry and stone elements was also determined on 14 test specimens.

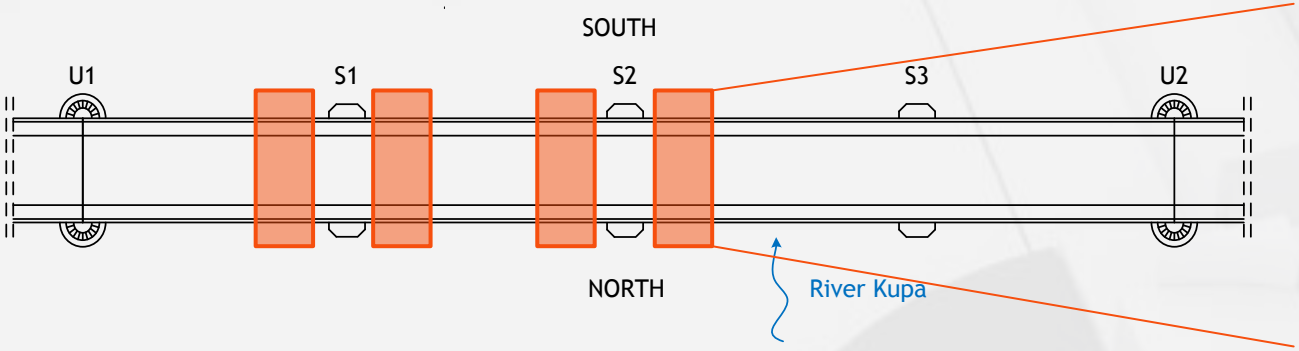


Investigated structures

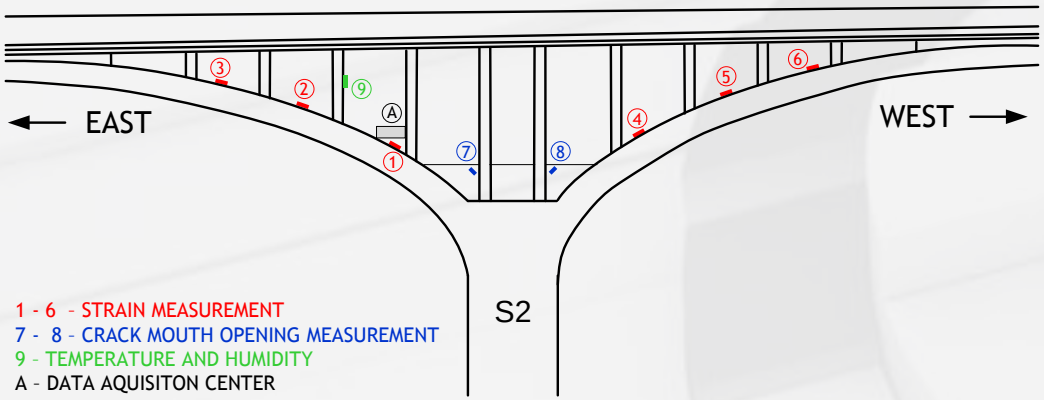
2] Old bridge, Sisak

PROBLEM → **MEASUREMENTS**

3] Corrosion parameters of structural elements of the bridge were measured.



4] Structural health monitoring was installed.

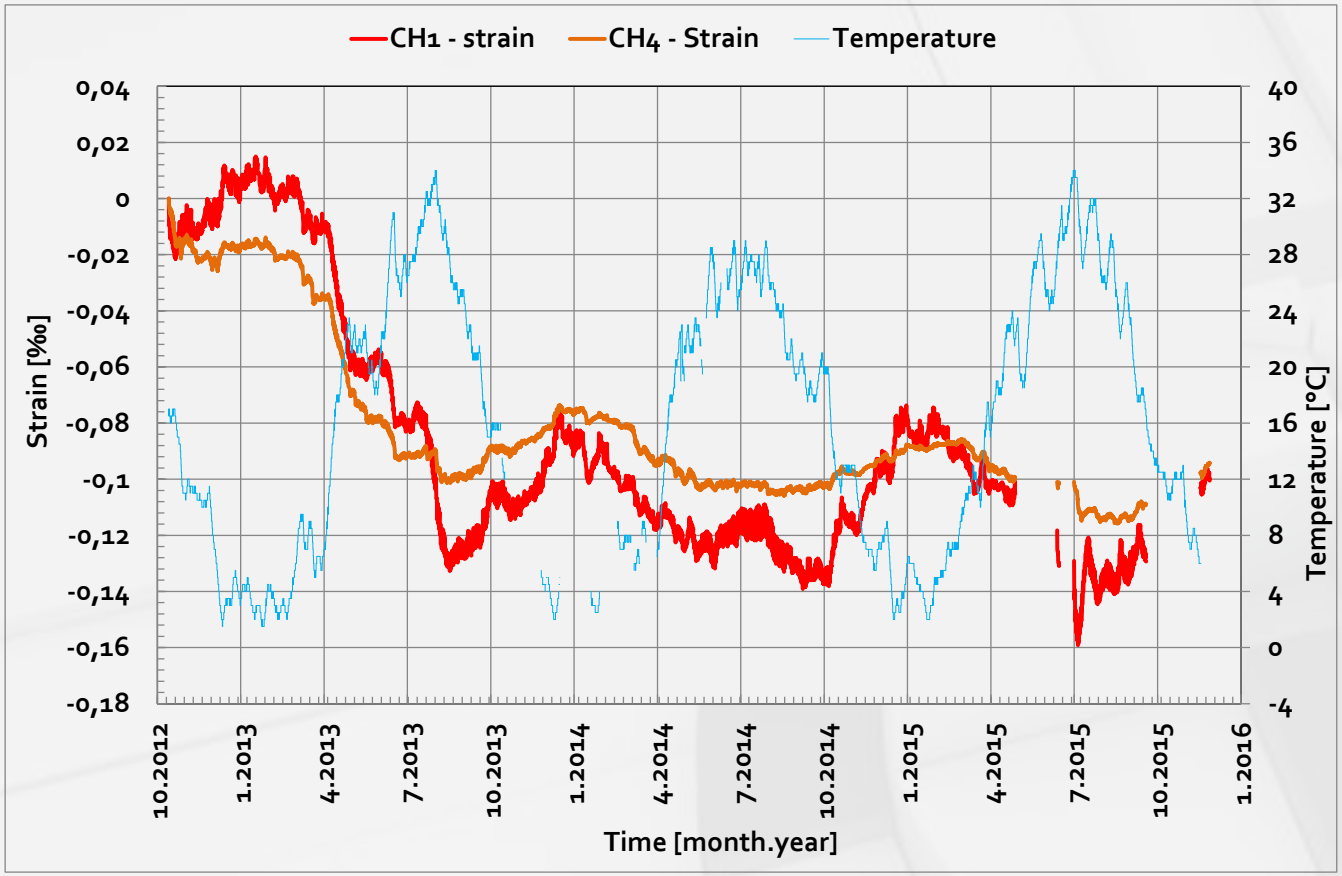


Measured parameters:
displacements
strains
cracks opening
temperature
and relative humidity

Investigated structures

2] Old bridge, Sisak

PROBLEM → **MEASUREMENTS** → **RESULTS** **CONCLUSIONS**



Measured strain values are low.

Monitoring is still active!

Locations of investigated structures

Investigated structures

3] Peristyle of Diocletian's Palace, Split

Peristyle, as the central square of the Diocletian's Palace, intended for the Emperor Diocletian celebrated as the living son of Jupiter, finds its place among many temples. In November 1979 **UNESCO**, in line with the international convention on cultural and natural heritage, adopted a proposal that the historic city of Split built around the Palace should be included in the register of World Cultural Heritage.

Peristyle, Split

Reconstruction of Diocletian's palace by Hebrard

Investigated structures

3] Peristyle of Diocletian's Palace, Split

PROBLEM

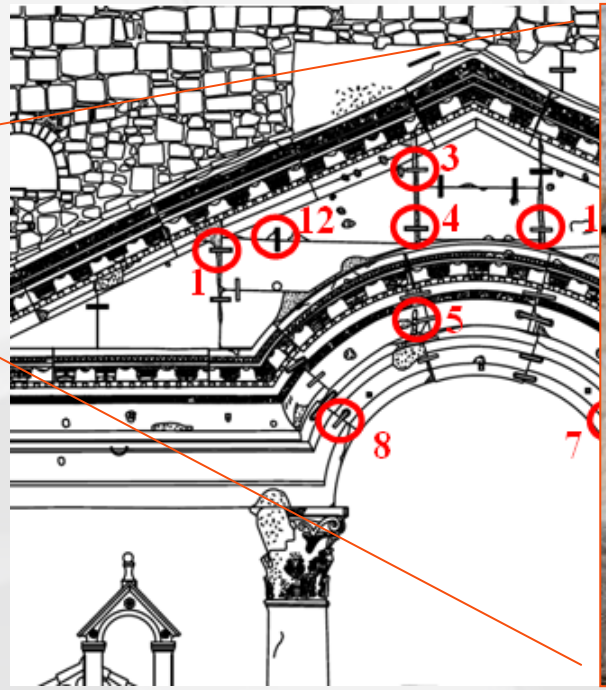
The damages on masonry structures mainly relate to cracks, foundation settlements, material degradation and structural deformations. There are many techniques which are capable to detect and locate damages even if they are not visible on the surface of the structure. These limitations can be overcome by implementing monitoring system for measuring behaviour of the structure.

Investigated structures

3] Peristyle of Diocletian's Palace, Split

PROBLEM → **MEASUREMENTS**

1] The hole drilling method was used to measure the magnitudes of residual stresses. The residual strain measurement was performed in order to determine the actual force in the copper clamp (12 measuring points).



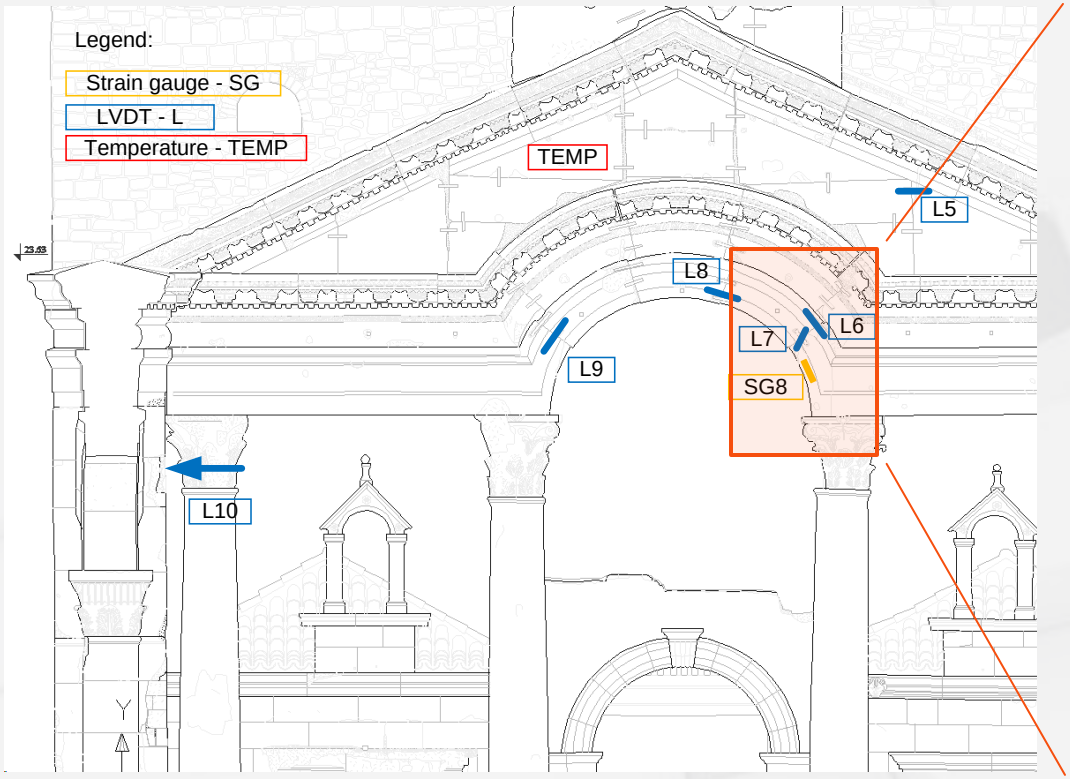
In addition, mechanical properties of the copper clamp were determined using tensile test.

Investigated structures

3] Peristyle of Diocletian's Palace, Split

PROBLEM ⟶ **MEASUREMENTS**

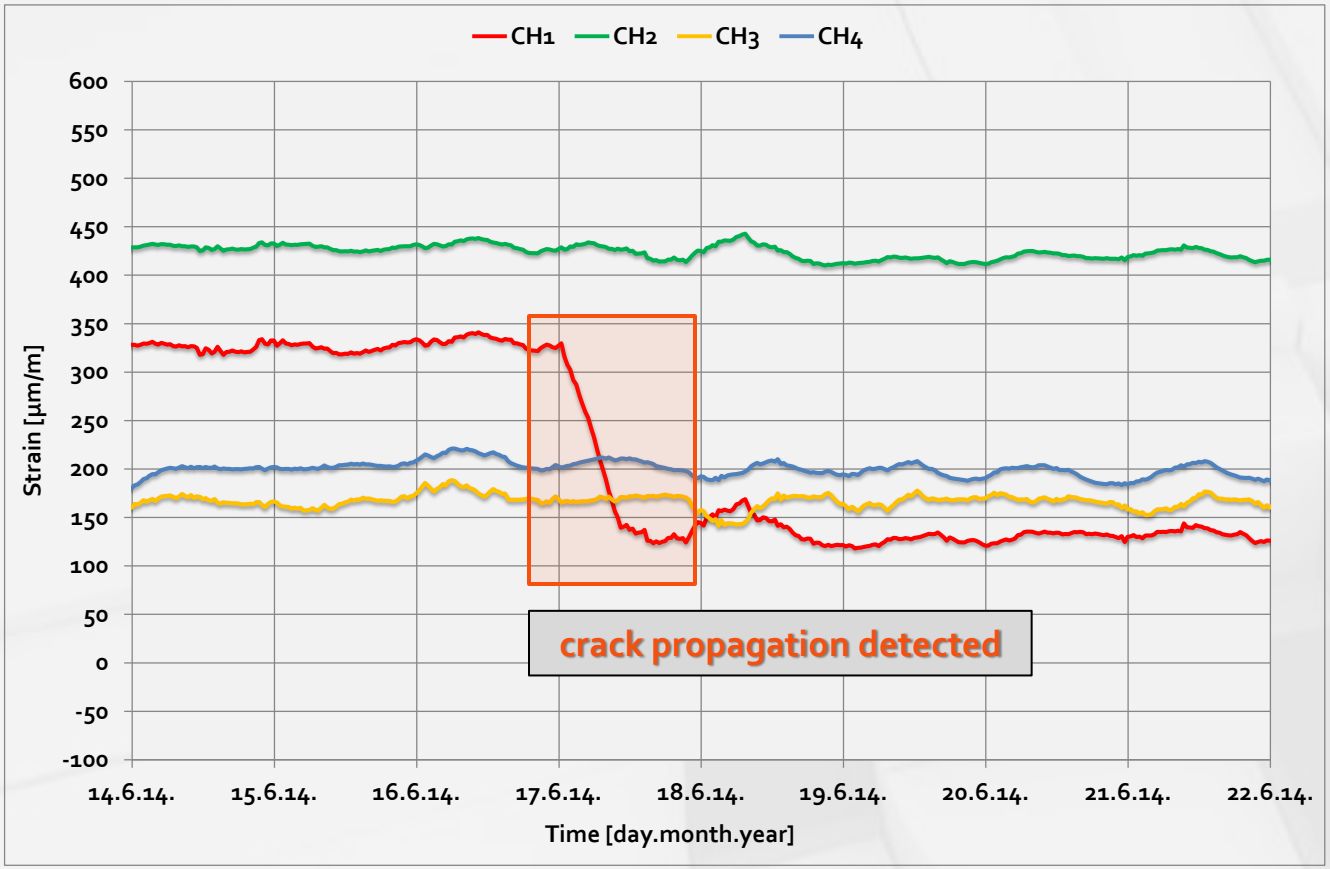
2] Continuous static structural monitoring based on LabVIEW and CopmaqDAQ designed to capture the displacements, strains and temperature at discrete nodes of a structure was installed.



Investigated structures

3] Peristyle of Diocletian's Palace, Split

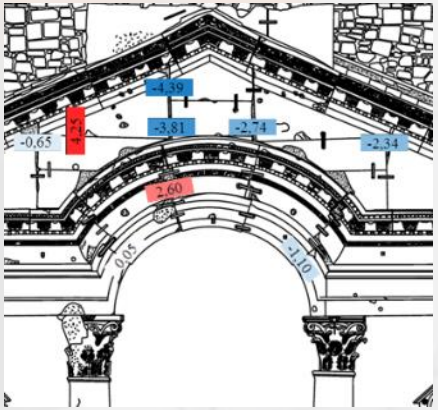
PROBLEM → **MEASUREMENTS** → **RESULTS** | **CONCLUSIONS**



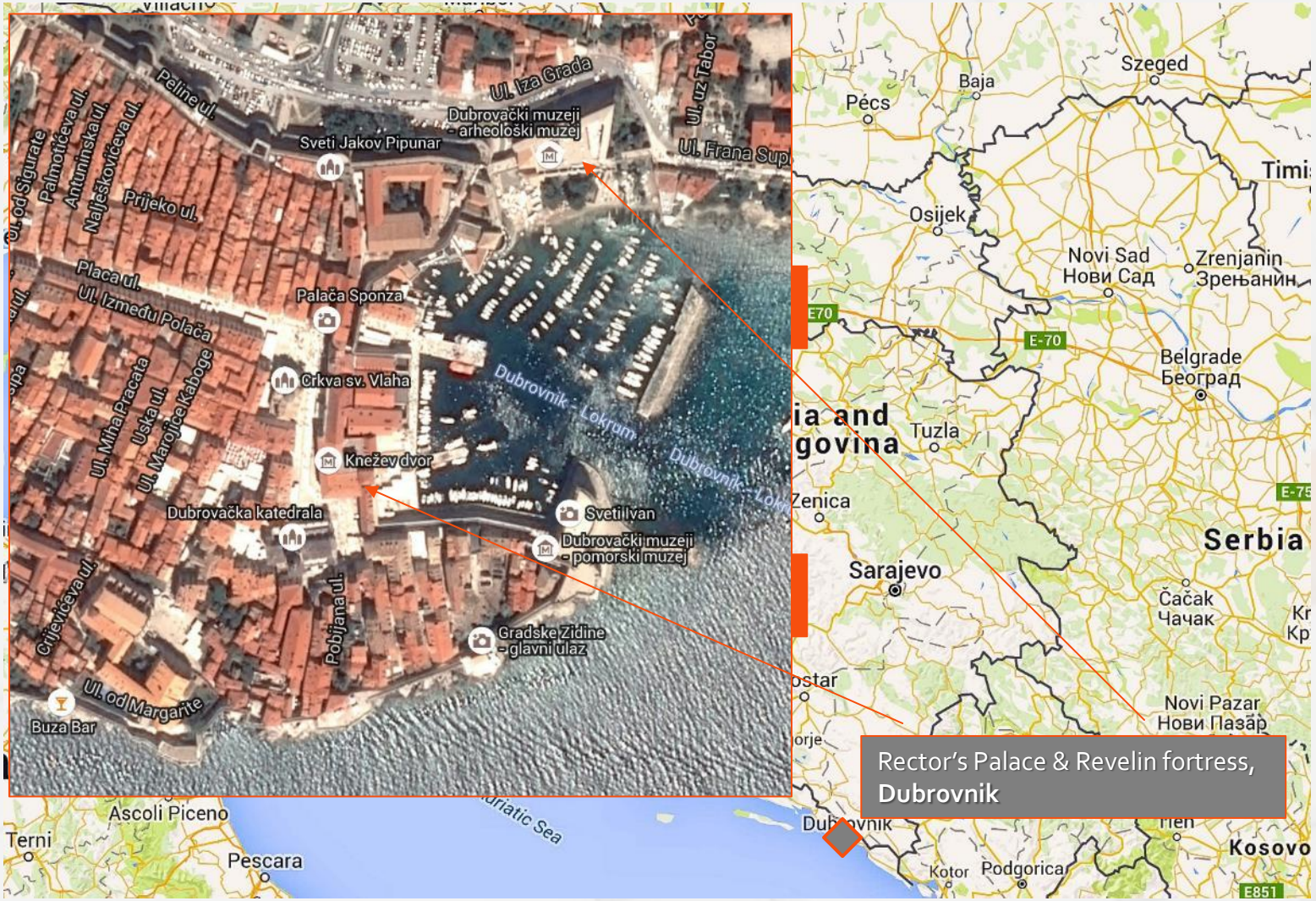
Current state of the structure is stable.

Monitoring is still active!

Measured residual force [kN]



Locations of investigated structures



Rector's Palace & Revelin fortress, **Dubrovnik**

Investigated structures

4] Rector's Palace, Dubrovnik

According to records dating from the 13th century, a castellum surrounded by four corner towers was once located on the site on which the Rector's Palace is to be found today. The reconstruction of the fortress into the palace took place in the 14th century. After the demolition of the old Rector's Palace in the gunpowder explosion of 1435 the new palace was built in the late-Gothic style by Onofrio de la Cava. That is when the palace received its present form (a single - storey building with four wings closing the courtyard - a portico with a small mezzanine floor gallery and a large floor gallery).

Interior of the Rector's Palace

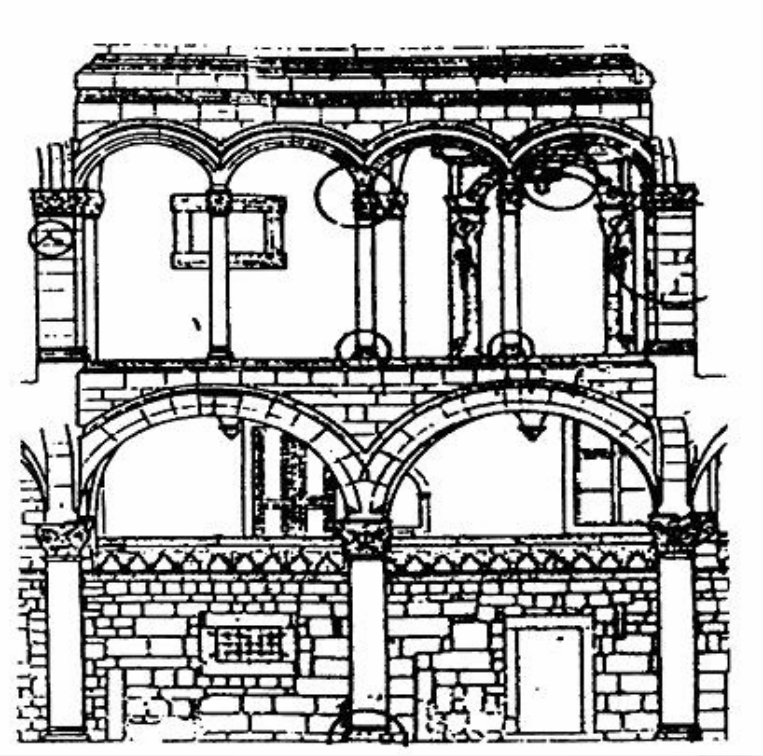
Rector's Palace, Dubrovnik

Investigated structures

4] Rector's Palace, Dubrovnik

PROBLEM

Disastrous earthquake of 1667 damaged the building's interior (columns and archer of the courtyard and the galleries). Last reconstruction took place in 1982/84 following the earthquake of 1979.

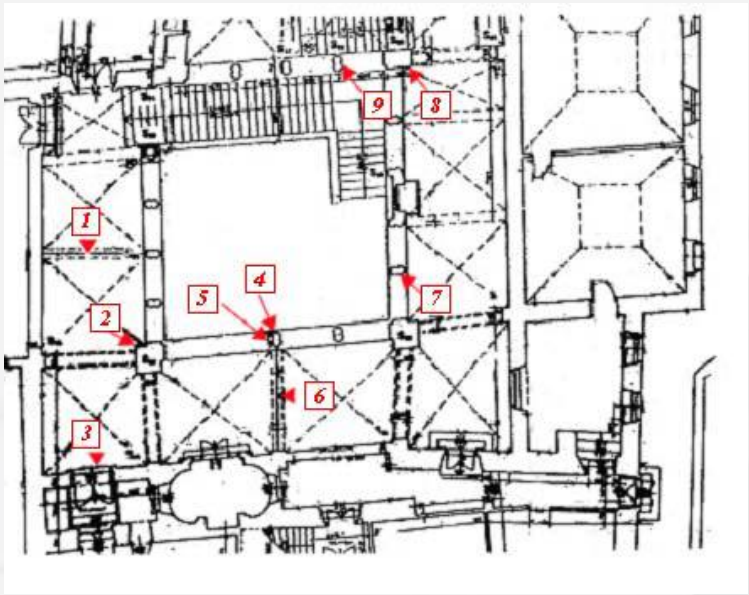


Investigated structures

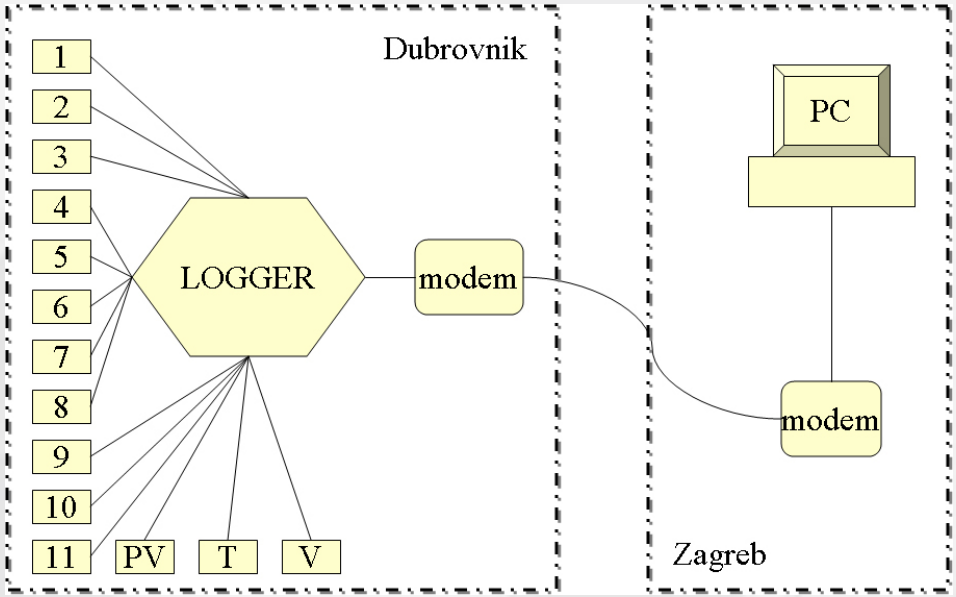
4] Rector's Palace, Dubrovnik

PROBLEM → **MEASUREMENTS**

At nine representative and characteristic cracks sensors for monitoring of crack opening were installed. As the majority of sustained damages and cracks were located at the atrium area in the center of the palace, and further more at the small twin columns, that is where the most of the measuring points were located and most of the sensors installed. Two sensors (1st and 6th) were installed at the steel tie rods of the first floor in perpendicular directions.



Measuring points

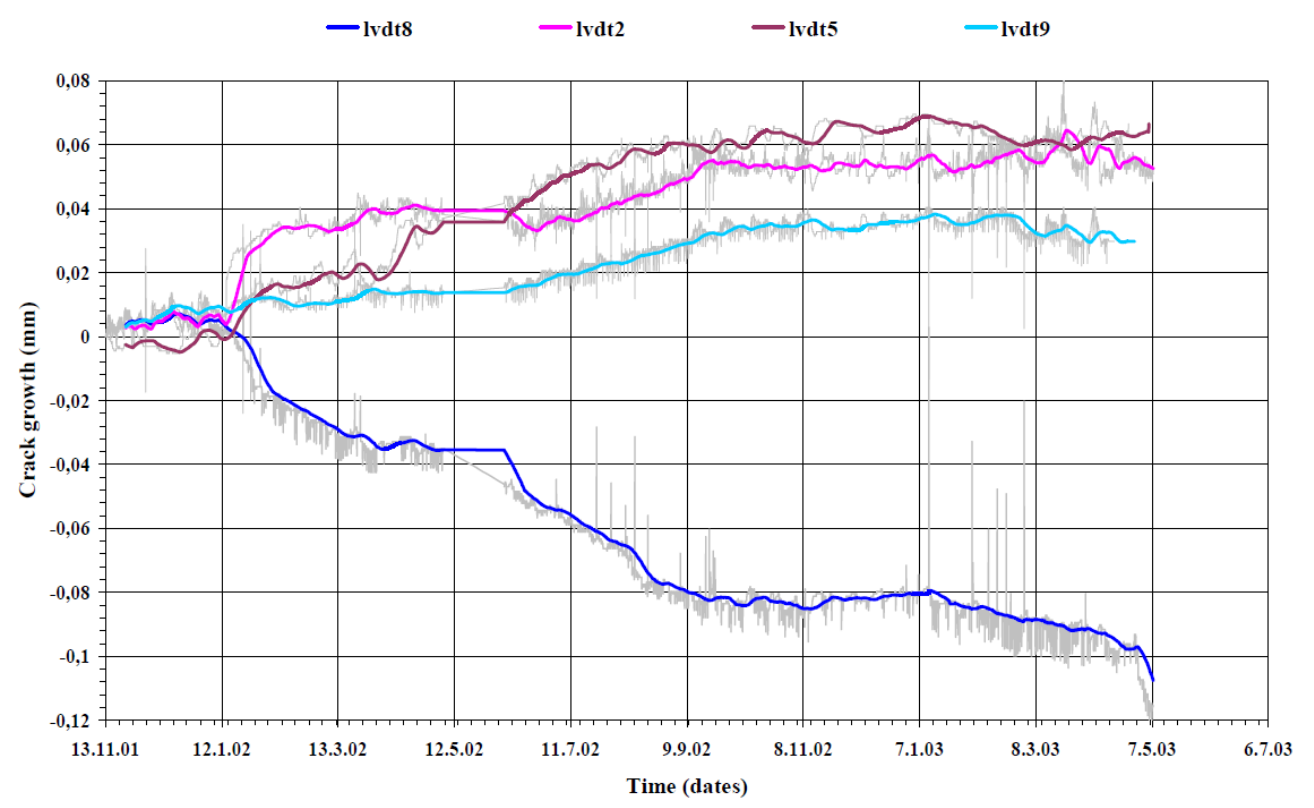


Block diagram of the monitoring

Investigated structures

4] Rector's Palace, Dubrovnik

PROBLEM → **MEASUREMENTS** → **RESULTS** **CONCLUSIONS**



Diagrams of crack growth for sensors 2, 5, 8 and 9

The aim of continuous long period monitoring of Rector's Palace structure behavior is to determine boundary conditions in order to create reliable numerical model of the structure for analysis which will define construction works needed to preserve stability of the structure.

Investigated structures

5] Revelin fortress, Dubrovnik

On the eastern part of the City, outside Ploče City Gate, the massive fortress of Revelin is located. The initial fort was built in 1463, in the period of unmistakable Ottoman empire (Turk) threat, who have conquered Constantinople in 1453 and were about to occupy nearby Bosnia (occupied in 1463). Revelin was built as a detached fortress providing additional protection to the eastern City Gate. In 1538 the Senate approved Ferramolino's drawings of the new, much stronger Revelin. It took 11 years to build it, and during that time all other construction work in Dubrovnik had stopped in order to finish this fortress as soon as possible. The new Revelin became the strongest fortress of Dubrovnik, safeguarding the eastern land approach to the city. Revelin was finally completed in 1549.

Revelin fortress in Dubrovnik

Investigated structures

5] Revelin fortress, Dubrovnik

PROBLEM

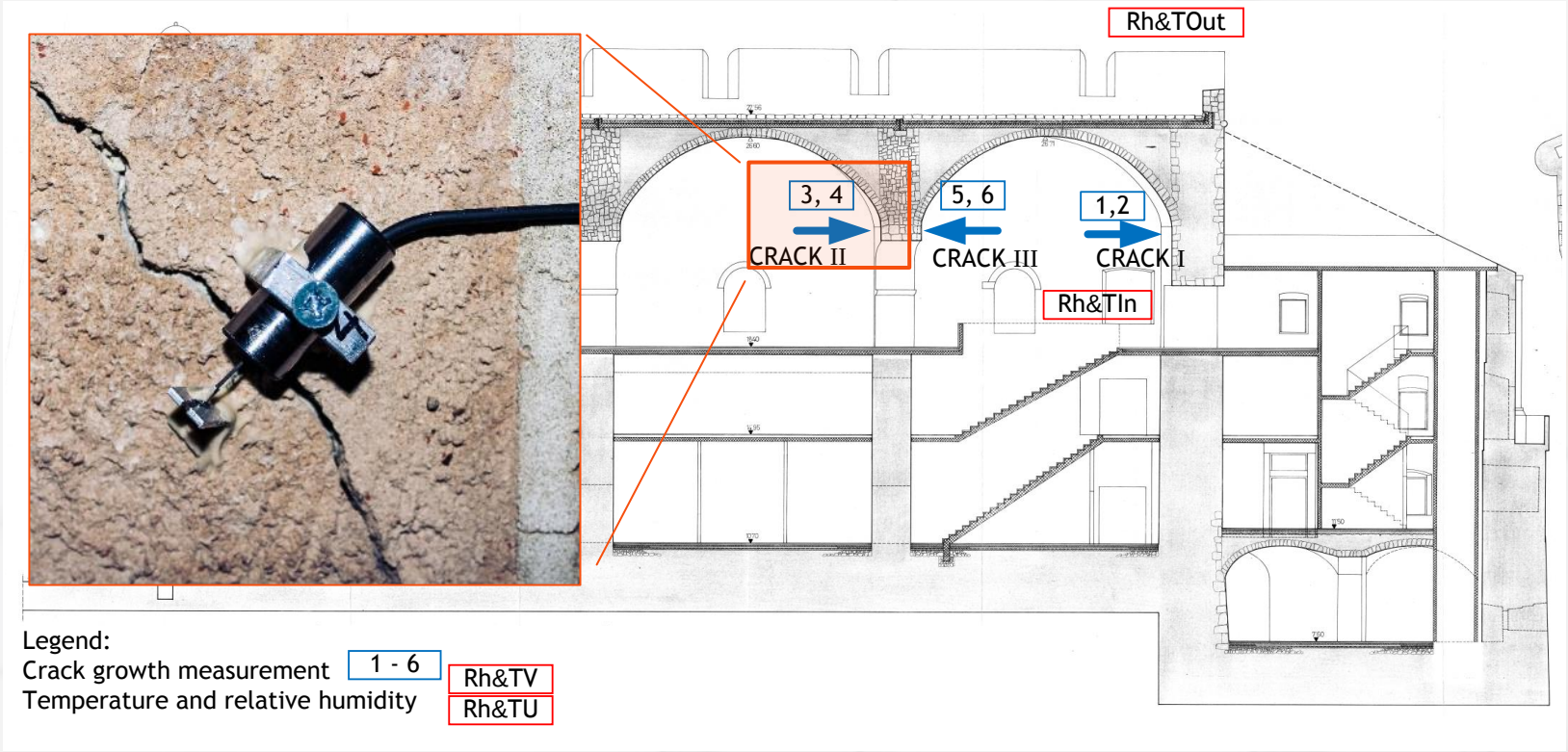
On the vaults of the hall of Revelin fortress cracks appeared, time and cause of crack appearance is unknown.

Investigated structures

5] Revelin fortress, Dubrovnik

PROBLEM → **MEASUREMENTS**

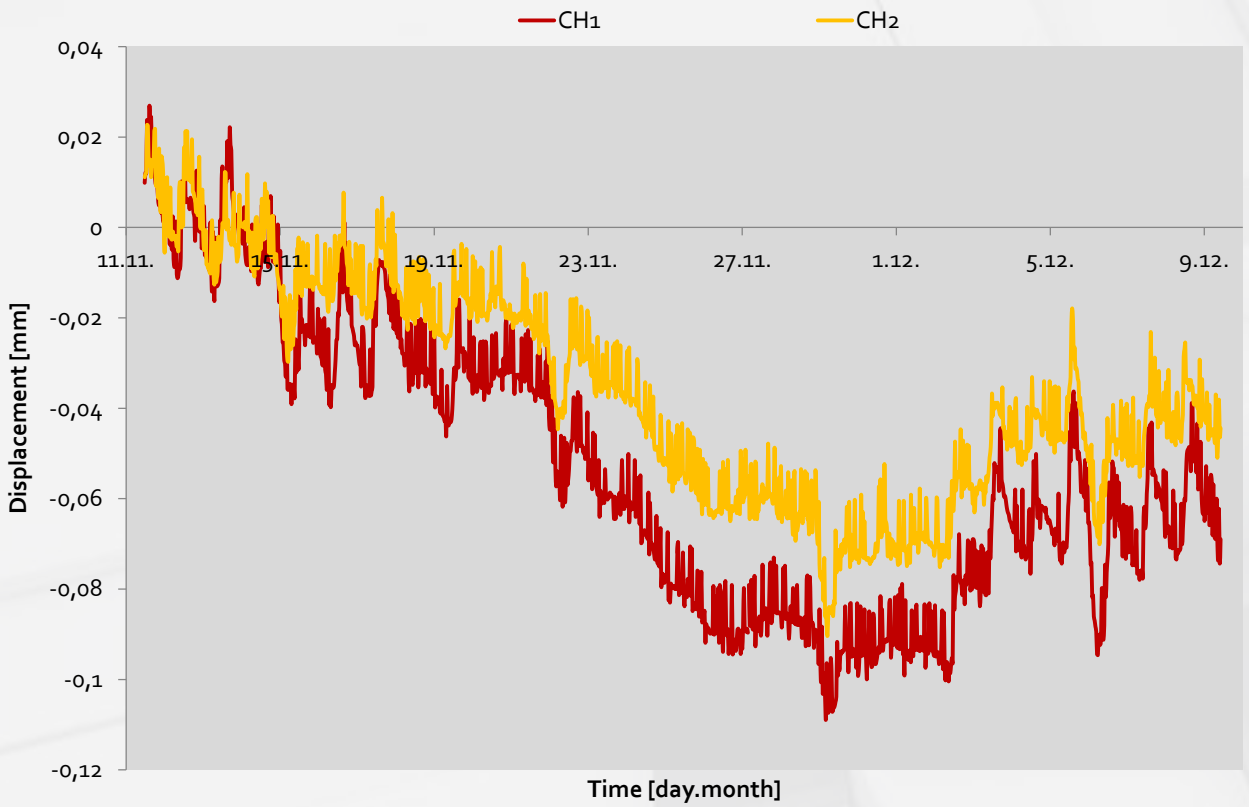
Eight inductive transducers were installed which are measuring growth and contraction of cracks on the vaults.



Investigated structures

5] Revelin fortress, Dubrovnik

PROBLEM → **MEASUREMENTS** → **RESULTS** | **CONCLUSIONS**



Monitoring was installed at the end of 2015. and no conclusions are shown in this presentation.

Monitoring is still active!