EXPERIENCES IN THE STRUCTURAL ANALYSIS AND SAFETY ASSESSMENT OF HERITAGE BUILDINGS IN CROATIA

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1.  **INTRODUCTION**

**structural aspects**
protection of cultural heritage buildings from natural and man-made disasters
stone masonry (traditional material, lack of concern and local expertise)

**multidisciplinary team**
...

**difficulties, uncertainties,**
interacting challenges, inadequate interventions,
engineering decisions influencing the final outcome

**numerical models**
indispensable tools, frequently very complex, ineffective if they are not adequately exploited,
adapt the model to the problem, understanding of the fundamental nature of the structural behaviour,
1. INTRODUCTION

DIFFICULTIES IN ANALYSIS AND VERIFICATION:

appreciation of the construction process
(doubts related to originally assumed concepts, construction techniques, consequent structural deformations and possible associated deficiencies)

understanding of complex geometry
(in plan and elevation, including vaults, arches, traditional pillars, multi-leaf walls, ties, etc.)

interpretation of combined structural elements
(internal wall leafs, connections, support on foundations, including uncertainties related to structural components, etc.)

implementation of architectural adaptations
(interventions due to modifications of use or upgrades, replacement of materials etc.)

consideration of time-dependent structural transformations
(including progressive deformations due to permanent loads, cyclic temperature changes, creep, foundation settlements, local relaxations etc.)
1. INTRODUCTION

DIFFICULTIES IN ANALYSIS AND VERIFICATION:

consideration of extraordinary structural transformations
(including consequences of environmental impacts, such as earthquakes, hurricane wind and fire, as well as war destructions)

clarification of the material degradation process
(both physical and chemical)

assumption of relevant material constitutive models
(uncertainties related to material properties and existing damage)

application of current code provisions
(codes are rather general, often uncomplete or not appropriate and mainly focused on measures for the reduction of damage)

missing education (in Croatia)
(specialised education, training in the field, small circles of experienced teams)

etc.
1. INTRODUCTION

DIFFICULTIES IN ANALYSIS AND VERIFICATION:

- geometry (structural system)
- material
- loads
- straightforward task
- perfect results
- numerical models (adapt to the problem with understanding of the fundamental nature of the structural behaviour)

extraordinary importance of CULTURAL HERITAGE buildings

wide knowledge (multidisciplinary team)
1. INTRODUCTION

The role of structural engineers in decision making and limiting unfavourable choices.

Example structures:
- The Martinušić Palace
- The Đorđić Palace
- Monastery Sv. Jakov
- Rector’s Palace in Dubrovnik

Knowledge, experience, clinical eye.
2. The Monastery Sv. Jakov

- established in 1222, constructed between the 13th and the 16th century, reconstructed 1667
- follows the terrain configuration through a cascading, maximum height difference of 7.0 m
- divided into several levels with story heights between 3.0 and 4.0 m
- first basement, the second basement, the ground floor, the first and the second floor
- plan the building is organized in four wings positioned around the central atrium, including a church, a bell tower and a fortified tower
- approximate plan dimensions 25.0 × 29.0 m
- maximum elevation equals to 16.5 m, corresponding to the height of the bell tower
- wall thickness varies between 25 and 170 cm
- floor structures are primary composed of wooden elements or classical limestone vaults, while the church is roofed by a 15.0 m long barrel vault over an 8.0 m wide span
2. The Monastery Sv. Jakov

DIFFICULTIES IN ANALYSIS AND VERIFICATION:

- structure had been upgraded in five phases (not adequately documented, construction joints?)
- many previous interventions (due to the need for the construction of an access road, a buttress had been removed, causing significant deformations)
- material properties were related to significant uncertainties
- boundary conditions had to be assumed (joints of walls and their support on the foundations)
- large out-of-plane deflections of the walls (significant geometric imperfections)
- significant damage of the stone arches
- numerous considerable fractures (through the entire wall, along the entire barrel vault, on the bell tower
- etc.

who made decision?

SEISMIC LOADS
2. *The Monastery Sv. Jakov*

**DIFFICULTIES IN ANALYSIS AND VERIFICATION**

- modifications in the structural layout and *changes in loading conditions*
- discontinuities present in the structural walls could activate *unexpected force transfer mechanisms* and cause sliding of disconnected parts of structural components
- *geotechnical problems* may occur, in particular due to the sloped terrain
- *construction joints of insufficient width* were provided during previous structural and non-structural interventions, eventually causing dynamic effects due to *pounding*
- Additional *displacements of the vault supports* may be caused
- inappropriate *wall connections* may cause *discontinuities in the transfer of forces*
2. The Monastery Sv. Jakov

Knowledge, Experience, Intuition (clinical eye)

- **numerical model** (accounting for the numerous significant parameters and uncertainties of the available data)
- utilised to identify the **most critical points** of the load-bearing system as well as to assess the principal seismic resistance
- according to the results, a plan for the **structural rehabilitation process** has been proposed, that today still may be considered appropriate
- application of **internal steel ties** within the walls (restoration of an equilibrated flow of forces, prevented the further propagation of cracks, seismic resistance)
3. The Martinušić Palace

- common renessaince building placed in the old town of Dubrovnik
- constructed **before 1667**, registered as one of the structures that survived the historic Dubrovnik earthquake
- occupies a **quarter of an urban block** with plan dimensions of 16.3 × 7.7 m and a total height of 15.8 m (four stories)
- load-bearing **walls** have a thickness of 50 to 85 cm, structural walls are shared with the neighbouring buildings, relatively large number of openings
- **ceiling** above the groundfloor is supported on limestone cross vaults, maining vaults are constructed entirely of wood
- **roof** is also made of wooden material, covered with heavy grooved tiles
3. The Martinušić Palace

DIFFICULTIES IN ANALYSIS AND VERIFICATION:

- due to the 1979 **earthquake** the structure has suffered substantial damage
- during the Homeland War in Croatia, in 1991, the palace has been set on **fire**
- series of **interventions** were applied to the structure without adequate documentation
- exposed to strong **atmospheric influences**
- geometry of the **foundations** was not known,
- **connection** between walls and supports had to be assumed
- definition of the **load-bearing system** due to the interaction with the surrounding buildings within the street block
- etc.
3. The Martinušić Palace

- relatively **simple geometry**
- **experimental analyses** of mechanical properties
- **geotechnical** investigations
- retrofit techniques (**injection**)

- **numerical model** (accounted for properties of the stone blocks, the mortar and the rubble, etc.)
- results pointed to **critical regions** of the structure, allowing the estimation of the structural capacity and a comparison against the demand at different levels of seismic action
- but **soil conditions** have been found particularly critical, since the load-bearing capacity of the soil may be unsatisfactory and in the case of stronger earthquakes the occurrence of liquefaction may be expected (all urban block?)
4. The Đorđić Palace

- **typical** historical building in central part of the old town of Dubrovnik
- consisting of **four storeys**, (plan dimensions $15.0 \times 16.0$ m, total height of about $18.0$ m)
- floor and roof structures were constructed of wooden elements

- **structural walls** have a thickness of 40-85 cm and are favourably distributed
- **disconnected** from the neighbouring blocks through about $1.0$ m wide passages, while the two walls on the southeastern side of the structure are **shared** with adjacent objects
4. The Đorđić Palace

DIFFICULTIES IN ANALYSIS AND VERIFICATION:

- poor overall conditions since it was damaged due to war destruction, seismic activity and inadequate maintenance
- northeastern part of the building was found to be completely burnt and only the load-bearing stone masonry walls were preserved (including roof)
- southeastern walls were in bad conditions, including pronounced cracks and a distorted geometry
- most structural walls were strongly cracked, major damage was caused due to previous earthquakes inducing torsional structural response

- eastern façade wall was inclined out-of-plane (about 40 cm)
- vaulted ceiling above the stairway had cracked and displaced notably
- conditions of the foundation system were completely unknown
4. The Đorđić Palace

- existing **previous studies** related to the rehabilitation and seismic resistance
- **geotechnical** investigations
- study of the structural **material**

- **numerical model** (anisotropy of the stone masonry elements, identified weakened points of the structural system, the varying stiffness properties for walls, floors and connecting elements, different boundary conditions)

- based on the safety assessment for the existing building the most **critical issues** have been identified and measures for the retrofit of the structure have been proposed (renovation of the floor structures, connections through steel studs, strengthening of all masonry vaults, application of ties, injection of the structural walls, restoration of the foundation system).

- **seismic load-bearing capacity** was increased substantially with respect to available results of previous analyses. Bearing in mind that original concepts of heritage buildings may not have been focused on the resistance against earthquake
5. The Rector’s Palace Atrium

- most outstanding monuments of Gothic and Renaissance architecture (UNESCO)
- Written history of the palace dates from the 13th century
- massive stone walls of the palace surround the inner opened structure, known as the atrium
- it consists of two storeys; each constructed by quadripartite stone masonry vaults
  - back side of the vaults is supported by masonry walls, while the front side lies on the stone columns
  - first floor columns are coupled and have smaller diameters (d = 23-25 cm) than those in the ground floor (d = 50 cm)
5. The Rector’s Palace Atrium

DIFFICULTIES IN ANALYSIS AND VERIFICATION:

- The palace was seriously damaged during the earthquakes in 1520 [16], 1667 [10] and 1979 [13], exposed to gunpowder explosions in 1463, and caught fire several times.
- Throughout history the building went repeatedly through modifications (major in 1981), including repair works, geometrical rearrangements, removal of structural elements etc.
- The foundation system, that most likely comprised wooden piles, was poorly documented.
- Only incomplete data related to the mechanical properties of the adopted materials was available and in some parts significant material deterioration could be identified.
- Difficulties in the clear definition of the global load-bearing system, arising due to the connection of some walls to adjacent buildings.
- Specific critical issue, characteristic fractures that have been identified on the bases and capitals of many columns.
5. The Rector’s Palace Atrium

- different types of stones, various styles of column shapes and capitals, stirrups around columns, stone insets and gaps
- very local in nature as the body of the column away from connections experiences only moderate uniform compression stresses and a large safety factor is maintained, possibly inducing misleading conclusions

- column connections were loaded mostly eccentrically or vertically inclined and such deviations could not be compensated due to the low rotational stiffness

- resulting stress concentrations may exceed the compression strength or deviations of compression trajectories may generate unwanted tensile forces, unavoidably resulting in fractures
5. The Rector’s Palace Atrium

- series of numerical models has been adopted: from simple frame and shell models to complex solid models, including also traditional calculations by thrust lines
5. The Rector’s Palace Atrium

- A series of laboratory tests was programmed with the aim to capture the actual conditions in the structure as closely as possible and to propose optimised solutions for the rehabilitation.

- According to both numerical and experimental results, it has to be emphasised that ignoring or not fully appreciating the real nature of connections may result in considerably misleading stress distributions for the entire structure, and even endanger both the local as well as the global stability of the structure.
If following the placement of the last stone, when through the removal of a wedge the final thrust line is established, the structure stands up for five minutes, it will stand up forever.

... from the structural point of view, this specific and responsible task should always be cautiously approached, on the clinical eye of the expert, accompanied by scientific knowledge and experience, rather than on generalised procedures!!!