Structural analysis in the research of the construction history – A case study

M. Simunic Bursic
University of Zagreb, Faculty of Architecture, HR-10000 Zagreb, Kaciceva 26, Croatia
Tel: +385 1 4639388; E-mail: marinasimunic@yahoo.com

P. Ferschin
Vienna University of Technology, Institute for Computer Aided Architecture and Planning, Treitlstr. 3, A-1040 Vienna, Austria
Tel: +43 1 58801/27210; Fax: +43 1 58801/27299;
E-mail: ferschin@iemar.tuwien.ac.at; www: http://www.iemar.tuwien.ac.at/

Abstract
The cathedral of Sibenik is an outstanding Croatian Quattrocento building, inscribed to the UNESCO Heritage List in 2000. It is a stone structure, specific for the construction and structural behavior of its vaults. The thin stone vaults are constructed of monolithic stone slabs, wedged into slender stone arches, which are tightened with tie-rods. As structural analysis proved, these “large-panel” barrel and semi-barrel vaults do not behave like usual masonry vaults, but transfer the most of their loads to the arches.
To research how this original vault system was developed, the analysis of the building phases of the structure was carried out. The historic sources, examined by generations of art-historians, provided precious data for the reconstruction of the building phases. The 3D models helped to understand the progress of construction – as the three-dimensional virtual reconstruction enabled to understand the structure as a spatial entity.
The analysis of virtual models of the early stages of construction enabled to understand its construction history and its structural logic. It inspired a new hypothesis on the nature of problems that appeared in the first period of building, when the construction was suspended. It suggested that fractures, even collapse of the groin vault bays completed by then would have occurred if these vaults have had no tiers.
Thus, a contemporary researcher can observe on the models the problems that ancient builders coped with in reality. Besides the theoretical knowledge that it can provide, it can also be a useful tool for the research and for the appropriate maintenance and consolidation of the architectural heritage.

Keywords: architectural heritage, construction history, structural analysis, stone vault, cathedral of Sibenik

Aesthetic and technical analysis in the preservation of architectural heritage

In the attempt to preserve architectural heritage, restorers are often tempted to focus on the aesthetic value of ancient buildings, and to neglect their technical aspects: structure, material, technique of construction, etc. And yet, the architects of the past had to consider not only the aesthetic problems, but also to tackle such technical problems as economy of construction, durability of materials, stability of structure, etc. Indeed, the solution of technical, especially static problems, connected with the very essence of a building, often influences its structure and form.

Therefore, structural analysis of the historic building, which is frequently carried out *ad hoc*, to save the already endangered structures, can be very helpful for understanding the building structure. It might give an insight into the method of designing and constructing of the ancient builders.

The cathedral of St. James' in Sibenik (Croatia)
The cathedral of St. James' in Sibenik is the most important building of the Croatian Early Renaissance. Its construction began in 1431, its eastern part with a dome was completed by 1499, and its structure was completed by 1436, when the church was solemnly consecrated. The relatively small cathedral of the Mediterranean town of Sibenik is a part of the UNESCO World Heritage, primarily due to its original structure: *"The structural characteristics of the Cathedral of St James in Sibenik make it a unique and outstanding building in which Gothic and Renaissance forms have been successfully blended."* [1]

Specific stone vaults
In spite of its modest dimensions, the cathedral in Sibenik is important in the history of construction for the unique structure of its vaults. Its barrel and semi-barrel vaults, which span 7.75 m (nave and transept vaults), and 3.75 m (upper aisle vaults) are constructed of thin monolithic slabs (length 3.00-4.20 m, thickness 0.15-0.25 m), inserted into the grooves of the slender stone arches.

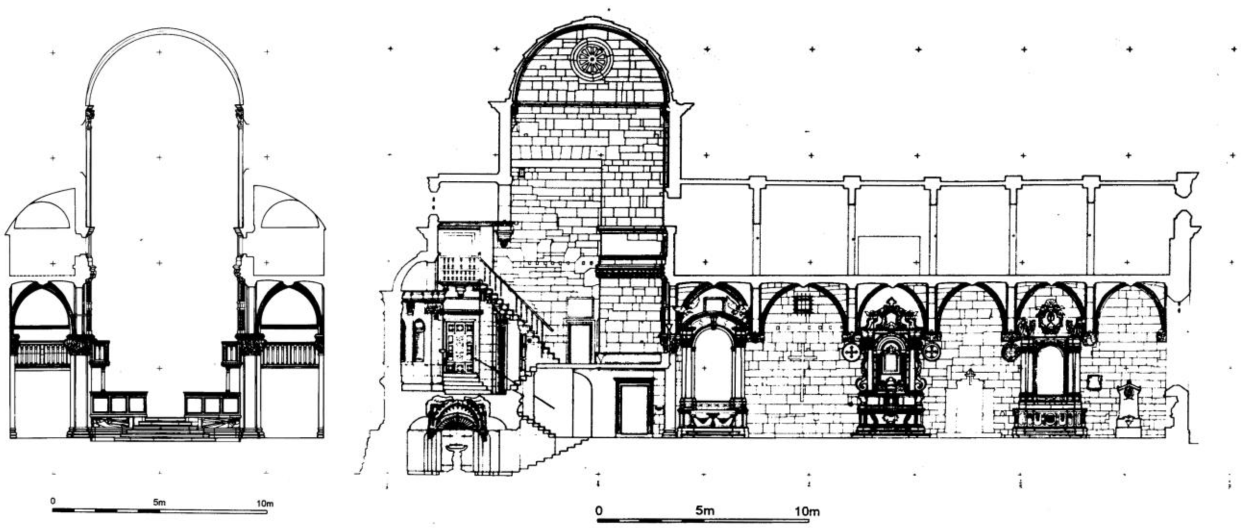

Figure 1: Cross section of the nave and aisles of the Sibenik cathedral

The details of connection of the stone elements were the object of speculation of experts until the recent repair of the dome. [2] In fact, only the dismantling of the upper part of the dome, damaged in the war in 1991, revealed the original solution of its details: stone slabs are inserted into the arch grooves and fixed precisely with stone wedges. [2]
The arches of the barrel and semi-barrel vaults, conceived with the analogous details, create together with thin stone slabs a "pre-fabricated system", designed to be "assembled" on the building site and thus to spare labor and material for scaffolding. Indeed, the construction of a real-scale model of the damaged dome proved that it was possible to assemble the dome without scaffolding. [3]
Due to the specific "assembling" method of construction, the stone barrel and semi-barrel vaults have thin webs, which span the inner space and provide also for the covering of the church.

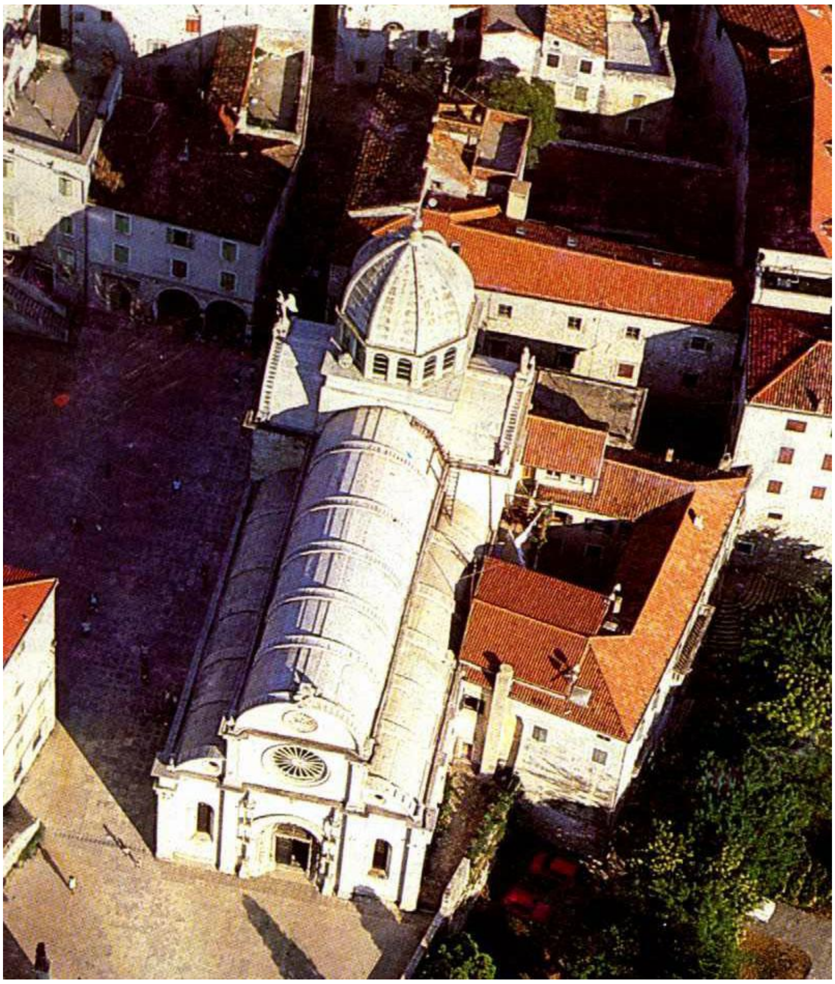

Figure 2: The cathedral of Sibenik – aerial view

The identity of the outer form and the inner space, which is clearly delineated on the trefoil façade, is exceptional in the Early Renaissance architecture: the trefoil façades of the contemporary aisled Venetian churches, e.g. S. Michele in Isola, S. Zaccaria… are "coulisse façades", while the western façade of the Sibenik cathedral is a true expression of the vaulted space of its interior. [4]
Therefore, we found it interesting to explore the constructive and structural system of its vaults, and its implication on the vault substructure.

Structural behaviour of the vaults

The innovative constructive system of the vaults, utterly different from the usual masonry construction (i.e. assembling large thin monolithic "panels" instead of building with small elements) resulted in the essentially different structural behavior of these vaults, and therefore into a different action of the vaults on their substructure. [5]
The usual massive masonry barrel vaults, constructed of stone blocks or bricks, connected with mortar, transfer the most of their loads in their transverse direction. They act as series of parallel transverse arches, and thus load their longitudinal walls with important force along their whole length, and consequently also with important horizontal thrust. [6]
Unlike them, the thin web slabs of the lightweight barrel and semi-barrel vaults of the Sibenik cathedral, being monolithic, enable the load transfer also in the longitudinal direction. Indeed, the computational finite element analysis of one characteristic slab (carried out in 1989 by

using ICES STRUDL program) shows that the most of the load is transferred in the longitudinal direction, to the transverse arches. [5]

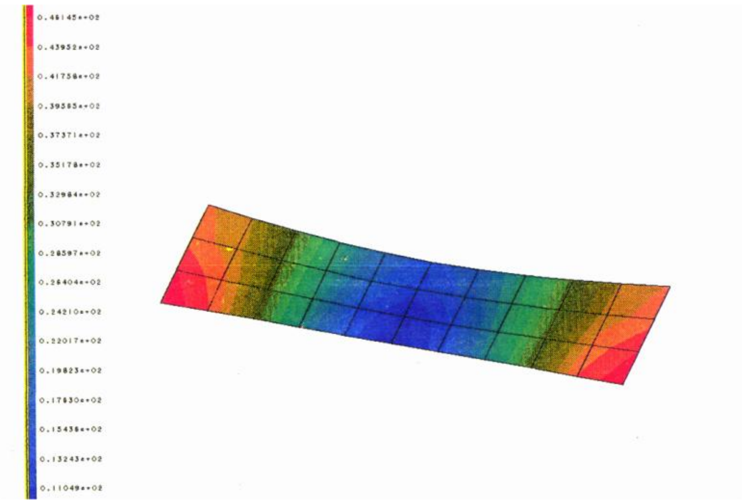

Figure 3: Finite element analysis of a barrel vault web slab

Thus, the major part of the vault load is taken over by these arches, and therefore the forces are concentrated in a few points – in the supports of transverse arches. The iron tiers, inserted at these points, take over the major part of the horizontal thrust, enabling a slender vertical substructure.

Structural analysis of the building phases

To investigate how this original vault system was developed, we carried out the analysis of the construction phases of the structure. The historic evidences (documents, coats of arms carved in the stone structure, etc), researched with scientific accuracy already at the begin of the 20th century, [7] enabled the virtual reconstruction of building phases, which then were analyzed structurally.

Figure 4: Construction of the dome model

The three-dimensional computational reconstruction enabled to observe the structure as a spatial entity, while the 3D models of the construction progress enabled us to examine the building as a 4D entity, within a time-space continuum.

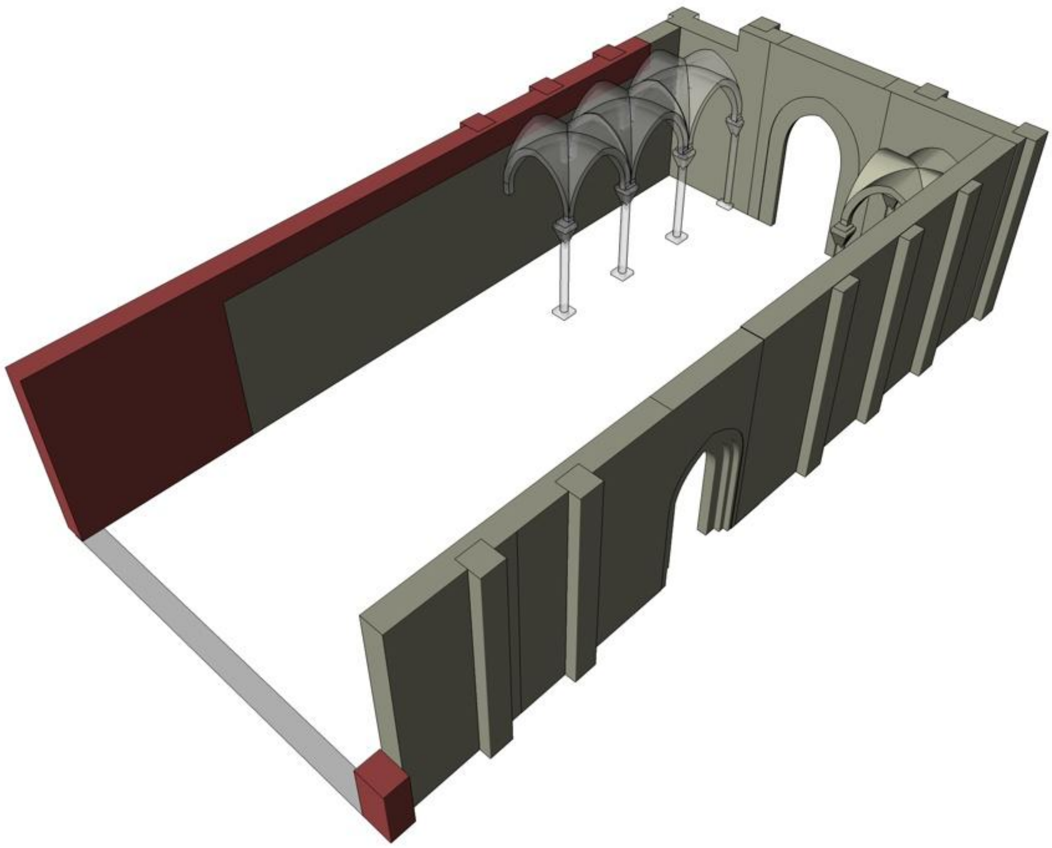

Figure 5: 3D model of the first building phase

The structural analysis of the early construction phases of the building was carried out with the CALPA computational program. This program, developed by P. Smars, [8] is based on the theory of masonry mechanics developed by Prof. Dr. S. Di Pasquale. According to it, masonry structure, which have a very low tensile strength, is simulated as a no-tension material. [9] Being one of the first finite element programs for the calculations of masonry structures (in the early nineties), it enabled only 2D analysis.

Therefore, we carried out the 2D analysis of certain construction phases of the building. In the case of the Sibenik cathedral, the 2D analysis may be considered as a satisfactorily good approximation of the real stress-strain state, due to the specific behavior of the thin vaults, which transfer the most of the load to the transverse arches support. [10]

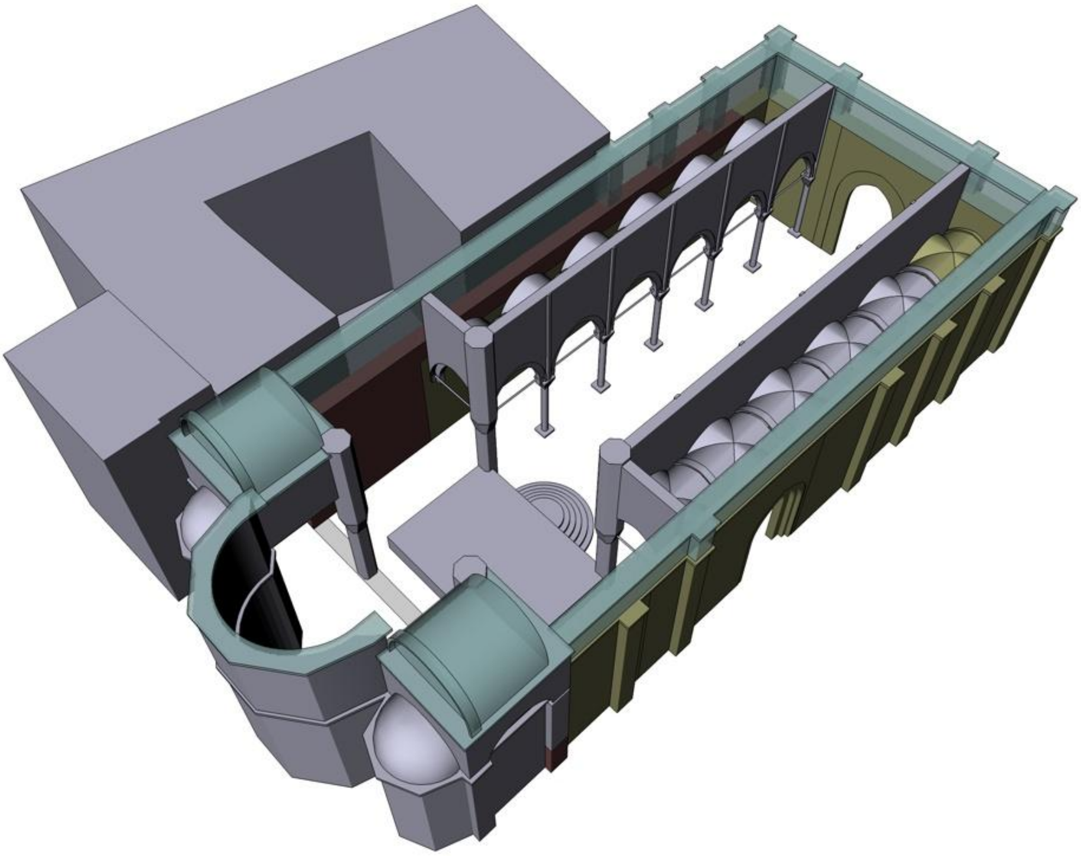

Figure 6: 3D model of the second building phase

Structural behavior in the early phases of building

The analysis of the cross-section across the nave and aisles in the two early stages of the building was carried out:

1) construction completed by 1441, when at least the first bay of the lower aisle vault (a common Gothic groin vault, built of stone blocks, and therefore acting as usual masonry) was constructed (Fig 5); and
2) construction completed by 1499, when at least one bay of the upper semi-barrel vault of the aisle (the bay next to the crossing) was constructed. (Fig 6)

Structure completed up to the groin vaults

The first building phase considered (Fig 5) is characterized by relatively massive stone structure with pilasters stiffening the façade walls. This allows us to assume that the builders entrusted to the wall pilasters the role of taking over the horizontal thrust of the groin vaults. Therefore we analyzed the structure completed by 1441 as a structure buttressed only with wall pilasters, without iron tie-rods which are to see still nowadays.

The computational analysis of the cross section of this hypothetical uncompleted structure revealed a large continuous deactivated region in the middle of the groin vault transverse arch. In this critical region the tensile stresses would have caused fractures, due to the low tensile strength of masonry structures. This is a result of the relative horizontal displacement of the two supports (nave column and wall pilaster), due to the vault thrust, which is not counteracted by strong enough buttressing elements.

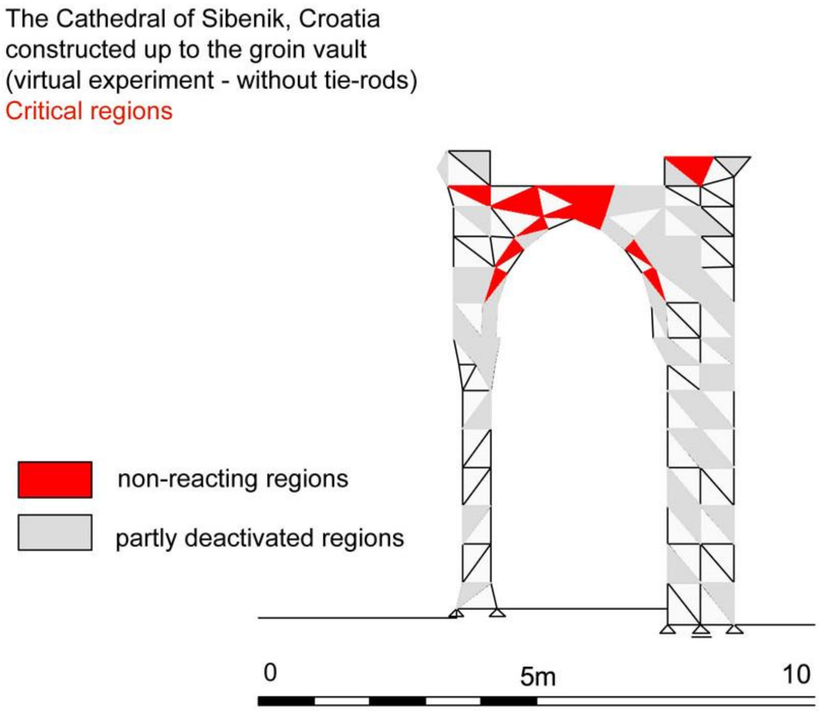

Figure 7: Critical regions in the structure completed up to the groin vaults (hypothetical structure without ties)

The structural continuity of the cross section is disrupted by continuous fractured region in the groin vault arch and its diaphragm: column and façade wall would not be structurally connected any more. Such a structural system (which, after the fracturing, consists in fact of two independent vertical cantilevers) is far less resistant than a frame structure connected with a vault. Therefore, the relative horizontal displacement increases, as well as the fractured region, and the structure becomes unstable.

The south aisle structure would have been particularly endangered, since it was founded on the artificially filled-up slope, inclined steeply towards the sea shore. [7] In its western part the south aisle was not buttressed by the adjoining bishop's palace. Maybe in this part of the structure the bays of the south aisle groin vaults fractured, and some of the bays completed perhaps already in the first period of construction might have collapsed. Indeed, the document of the City Council from 1441, preserved in the Sibenik archive, mentions "*errores et defectus… quoniam aedificia et partimenta ipsius Ecclesiae… non fuerunt dibitis modis composita et fabricata..."* [7]

It must have been a major error, probably concerning the structure, since the construction was interrupted and a new master was invited from Venice to continue the construction of the building. The new *protomagister* of the Sibenik cathedral, *Georgius Mathei Dalmaticus*, became the best and the most famous architect and sculptor of the Croatian Early Renaissance.

As he was an innovative constructor, who applied an original "assembling" constructive method on the walls of the apsidal part of the Sibenik cathedral, it can be assumed that he also managed to correct the structural mistakes of the first builders of the Sibenik cathedral. Since without tie-rods the structure would have been unstable even at that early stage of construction (as showed above), we proposed the hypothesis that *Georgius Dalmaticus* introduced tie-rods in the west part of the Cathedral. Indeed, the document, concerning the construction of the sacristy adjoining the Cathedral (supervised simultaneously by George the Dalmatian), mentions *“catenas ferreas longas et laboratas pro archivolto…”* [7]

Whether accepting this hypothesis or not, one fact is undeniable: the architect(s) who completed the northern façade wall relied completely on iron tie-rods as structural elements to resist the vault thrust. The shape of this exterior wall suggests it: its upper part does not have pilasters to buttress it.

Structure completed up to the semi-barrel vault of the aisles

The structural analysis of the next analyzed construction stage, which was completed certainly by 1499, proves this assumption. The structure constructed up to the height of the upper, semi-barrel vault of the aisle, was analyzed both with and without tie-rods. This is a kind of virtual experiment, in which the structure without ties has the role of a “control unit” in the experiment. The logical consideration, as well as our structural analysis of the previous stage of construction, show with great probability that the structure must have been tightened with tie-rods. Nevertheless, we made a comparative analysis of both structural cases, in order to explain and prove the role of the ties.

The comparison of the two hypothetical structures confirms our considerations stated above: the structure without ties, completed up to the semi-barrel vaults, has similar weak points as the previously analyzed stage without tie-rods.

Hypothetical structure without ties

The critical region is again the groin vault arch span, in which a large fractured area would have appeared, caused by horizontal thrust of the vaults, which are not satisfactorily buttressed by the shallow wall pilasters. This state of stress would have resulted in instability, which would eventually have caused the collapse of some bays of the groin vault.

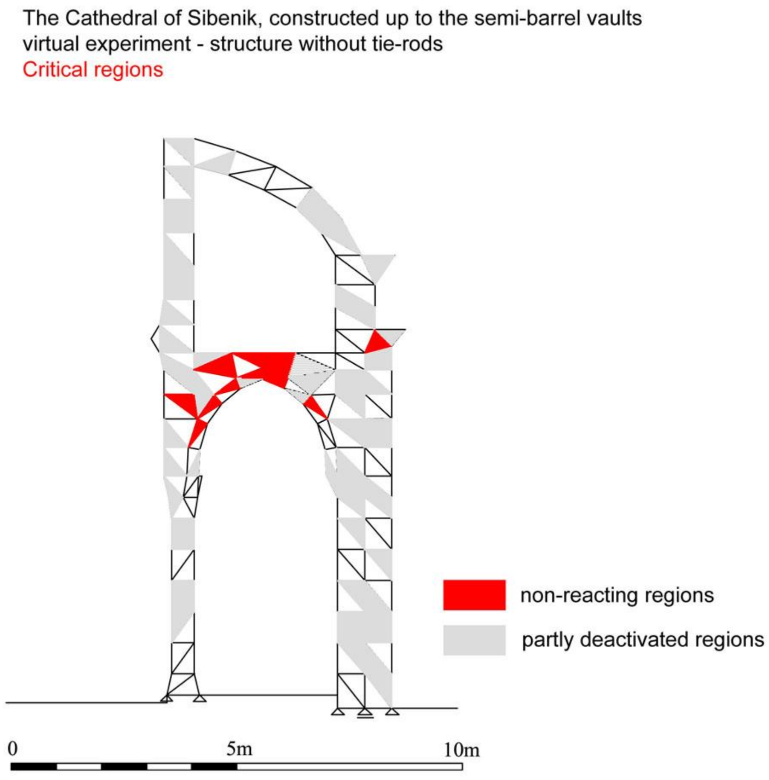

Figure 8: Critical regions in the structure completed up to the upper, semi-barrel vault of the aisles (hypothetical structure without ties)

Uncompleted structure with tie-rods

On the contrary, the structure tightened with iron ties at the level of the groin vault support and at the level of semi-barrel vault support is structurally much more resistant.

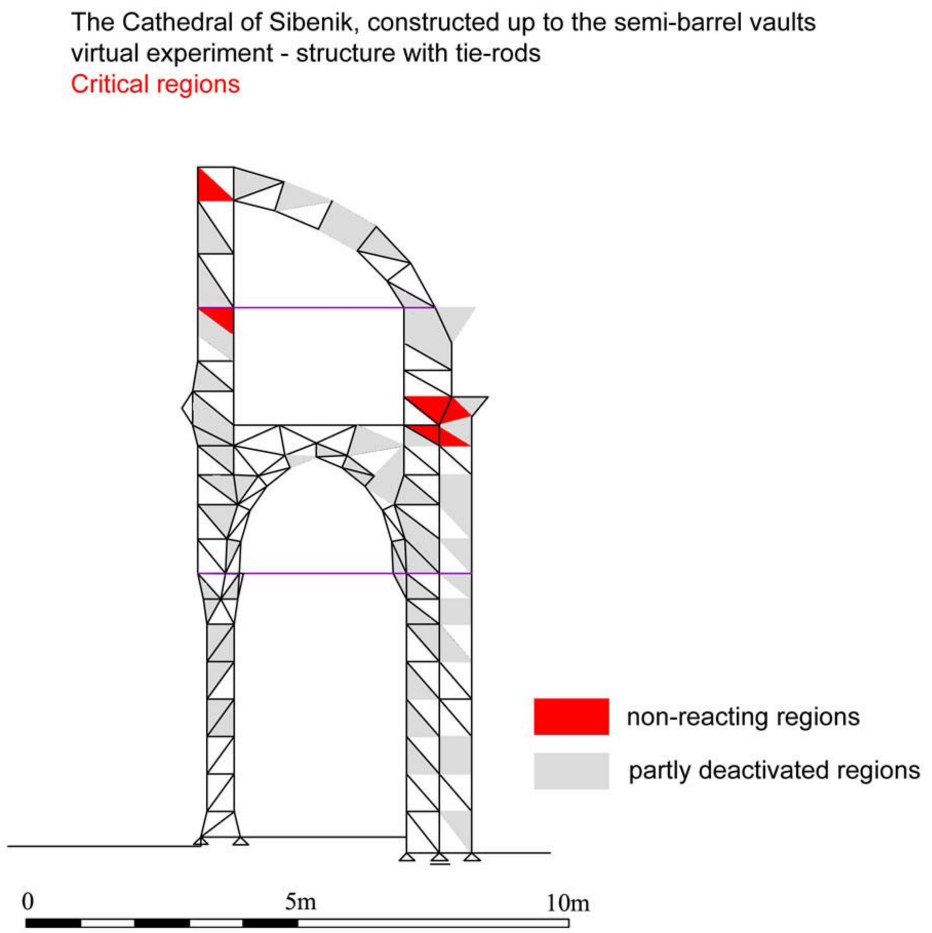

Figure 9: Critical regions in the structure completed up to the upper, semi-barrel vault of the aisles (structure tightened with tie-rods)

The inactivated zone is much smaller and it is not continuous, but it is limited only to several structurally unimportant points. There are no discontinuities of the active structure: it acts as a whole.

Thus, the structure, conceived and built by 1441, though more slender in its upper part than in its lower part, is stable and resistant. The purposeful, structurally logical concept proves that the constructor of the upper part of the northern façade planned the unique vault structure already when they were completing the aisles walls, the lower part of which was conceived by the first builders of the Sibenik cathedral. Whether the innovator was George the Dalmatian or his successor Nicholas the Florentine (*protomagister* since 1477), he designed an original and logical structure.

Conclusion: New hypothesis on the construction history of the Sibenik cathedral

The static analysis of the structure of the Sibenik cathedral during its construction inspired a new hypothesis on its construction history.

From the historic sources it has been known that in 1441, i.e. ten years after the construction started, it was interrupted because of the major "errors". But the documents do not specify the nature of these "errors".

The computational analysis of the early construction stages revealed important weaknesses of the hypothetical uncompleted structure, if it had not been tightened with tie-rods. Due to the large continuous fractured region in the groin vault arch span, the structure would not have been stable without tiers.

Since the lower part of the northern façade is strengthened with pilasters, while its upper part is flat, without pilasters, we suppose that in the first phase (1431-1441) the builders conceived the pilasters as the primary buttressing elements. Even if they had inserted the iron ties, they might have been too weak or not properly anchored.

This mistake would have caused horizontal displacements of the vertical substructure of the completed groin vault bays, their fracturing and even collapse. Perhaps some bays in the western part of the south aisle had been built, but collapsed due to the mentioned structural weakness. In fact, only one capital of the southern nave arcade, as well as one wall capital of the southern façade wall, have stylistic characteristics of the second construction period, while all other capitals and semi-capitals belong to the first building period. The hypothetical collapse of some groin vault bay(s) of the western part of the southern aisle would explain this fact. This hypothetical fracturing or even collapse could have been a reason for a sudden interruption of construction and the engagement of a new *protomagister*, who introduced the iron tie-rods. Thus he changed the structural system of the vaults. This could have been the inspiration for the development of a new constructional and structural system of the upper vaults.

The above considerations, based on combined historic and structural analyses, illustrates how this approach can be useful for the understanding of the structural logic of the architectural heritage, and thus for its appropriate maintain and repair.

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