Structural analysis of an outstanding historical building: New insight into its construction history

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The development of the constructional concept and details was a slow, step-by-step process — until the modern era of fast technical progress. In the past master-builders learned their skills from their predecessors. As the forms, spans and structural solutions changed slowly, they were able to apply their knowledge, acquired by observing pre-existing structures, to the structures they were actually building.

But there are some outstanding buildings, which made a giant leap in the history of construction with their original constructional and structural concept. These buildings, if their innovative concept proved to be structurally sound, became the origin of a new tradition — or remained isolated examples.

One of these isolated, unique structures is the cathedral of Šibenik, Croatia (began 1431 - completed 1536). The construction was carried out by unexceptional Venetian masters, when in 1441 a major structural problem appeared. Only in 1443 the construction was resumed, guided by a new protomagister, George the Dalmatian. He solved the structural problem and constructed the eastern part of the church in a new way. While the walls of the western part of the cathedral, built before George the Dalmatian, are constructed of stone blocks masonry, the apsidal part is built using specific technique of assembling large stone slabs into the stone «frames».

Nicholas the Florentine, protomagister of the Šibenik cathedral 1477–1505 (after George the Dalmatian's death), adopted the specific constructional method of the apsidal part and applied it to the barrel and semi-barrel vaults of the church. Thus he created an original vault system: the webs are assembled of long, thin stone slabs, wedged into slender stone arches. These vaults are much lighter than usual massive barrel vaults, and, unlike masonry vaults, transfer their load mostly to the arches. As the arches are tightened with iron tie-rods, their horizontal thrust does not affect their slender substructure.

This structural system is unique. Precise and original details, rediscovered only ten years ago, during the disassembling of the dome (damaged during the war in 1991), prove high skill of Dalmatian stonemasons in the time of Renaissance.

We researched the mechanical behaviour of this original, daring structure. In order to research the construction history of the cathedral of Šibenik, we analysed both historical documents and mechanical response of the structure in several building phases. This approach provided interesting insight into the mechanical characteristics of the building and into its behaviour during the construction, and inspired new hypotheses about its construction history.

Development of structural systems in history: Tradition and innovation

The history of architecture is inextricably connected with the history of construction. The architects’ idea of space and form cannot be materialised but through
the construction of a structure. Development of structural concepts, and not the changing of fashion in decorative forms, is the driving force of the history of architecture.

**Tradition**

In the pre-industrial, traditionalist societies, the generally adopted concepts of architecture, considered both as a spatial art and as a technique of building, were also an element of the identification of the society’s traditional values. Of course, only the architectural concepts that justified and proved their structural logic by a simple fact of existing for a long period of time, resisting all the usual and even unexpected impacts (such as earthquakes, strong winds, extreme temperature variations), were commonly adopted as good and reliable.

Following the common sense, the constructors of the traditionalist societies applied good old «time-proof» solutions to the new constructions that they were actually building. Indeed, why change the solutions that already proved their qualities?

Of course, in spite of this conservative, but logical approach, every building imposed specific requirements: larger spans, bigger openings, a new building material, specific requirements due to the gradual social change which resulted in a different way of life . . .

Thus, the structural and constructional solutions did change in time, but very slowly. Due to this fact, the master-builders of the past were able to apply the skills and knowledge acquired from their predecessors to their specific problems.

It is well known that the ancient masters did not know the theoretical laws of mechanics. The theoretical concept of mechanical force was not developed until Sir Isaac Newton’s axioms, which built a basis of a new, consistent theory of physics (17th century).

Nevertheless, the structures that great architects constructed throughout history —daring, logical and resistant— testify that they understood perfectly the mechanical behaviour of their structures. Their thorough insight and understanding of structures was based on the empirical knowledge, gathered in centuries-long tradition of building in the same or very similar manner. In fact, their knowledge was truly experimental —they observed existing buildings, their mechanical behaviour, possible weaknesses or occurrence of cracks, and applied this experience to the structures that they were actually building. And more, as the construction process was relatively slow (mediaeval cathedrals were being constructed for centuries), they were able to observe their own buildings, their behaviour and weak points, and to intervene if necessary. Thus, the real, existing buildings were their full-scale models (Mark 1982, 9).

**Exceptions**

The slow, step-by-step development process, in which new structures only slightly differed from the existing, time proved paradigms, was a usual way of development of structures and methods of construction in the past.

On the other hand, there are also some outstanding structures, with amazingly new and radically different solutions of technical and formal problems —the outcome of an ingenious concept and skilful craftsmanship, supported by an enlightened investor.

Such outstanding buildings, if their innovative constructional and structural concept proved to be structurally sound (which is simply empirically proved by their resistance to all the impacts that they were exposed to during their life-cycle), became the origin of a new tradition —or remained isolated examples.

**The cathedral of Šibenik**

One of these isolated, unique structures is the cathedral of St James in Šibenik, Croatia. In the year 2000 this masterwork of the Quattrocento architecture was inscribed into the UNESCO World Heritage list, primarily because of its « . . . structural characteristics . . . which . . . make it a unique and outstanding building . . . The Cathedral of St James is the fruitful outcome of considerable interchanges of influences between the three culturally different regions of Northern Italy, Dalmatia, and Tuscany in the 15th and 16th centuries. These interchanges created the conditions for unique and outstanding solutions to the technical and structural problems of constructing the cathedral vaulting and dome». (UNESCO 2000, 43)
Structural analysis of an outstanding historical building

The citizens of the small Dalmatian town of Šibenik, on the Croatian Adriatic coast, decided to build a new cathedral at the beginning of the 15th century, in a difficult period of dynastic wars between Ladislaus d'Anjou and Sigismund von Luxemburg. After Ladislaus d'Anjou sold Dalmatia to Venice, Šibenik resisted the Venetian siege for three years and then was forced to surrender. In spite of the new threatening force — the Ottoman empire (the border of which was not more than a few kilometres away from the town of Šibenik at the end of the 15th century) (Grubišić 1974, 34-65), in 1431 the citizens of Šibenik began the building of their cathedral (Fosco 1893, 61).

The construction was started probably after the design of the Lombard master Bonino da Milano (Stošić 1950, 130). Although Bonino died in 1429, i.e. two years before the construction started (Kolendire 1924b, 467), he is probably the author of the first project of the Cathedral, as in a document from ca 1430 he is mentioned as «primus magister ecclesie nove sancti Jacobi» (Stošić 1950, 130).

After «Franciscus quondam Jacobi de Venetiis» (Francesco di Jacopo da Venezia), who was in charge of the construction for one year only (1431), the cathedral did not have a protomagister at all. The construction was carried out by two unexceptional Venetian masters, Antonio Busato and Lorenzo Pincino (Kolendire 1924a, 174) who began to build the perimetral walls of the western part of the cathedral. They constructed at least the western part of the northern façade and northern part of the western façade up to the height of the Lombard frieze, which should have been the upper cornice of the northern wall of the aisle. Lorenzo Pincino was in charge of the construction also of the first bay of the northern aisle. (Frey 1913, 129–130.)

Then, in 1441, a sudden break of construction: the document of the City Council mentions «multi errores et defectus» (many mistakes and flaws), which caused «magna expense . . . quoniam aedificia et partimenta ipsius Ecclesiae non fuerunt dibitis modis composita et fabricata . . . » (Fosco 1891, 9). In such critical moment the citizens of Šibenik decided to employ a new, skilful and well-trained protomagister: they invited from Venice, a flourishing political and artistic capital, master «Georgius quondam Mathei de Jadra habitator Venetiarium» who called himself Dalmaticus (Fosco 1891, 10–11; Frey 1913, 131–132). Indeed, Georgius Mathei was by origin from Zadar («de Jadra»), another Dalmatian town not far away from Šibenik. He obviously solved successfully the serious structural problem mentioned in the document from 1441, and in 1443 he began with the construction of
the eastern part of the church—in a radically new way of building. While the walls of the western part of the Cathedral, built before, are constructed of ashlar (stone blocks masonry), the apsidal part is built using specific techniques of assembling large stone slabs into the stone «frames» (Ivančević 1997, 29). Georgius Dalmaticus (George the Dalmatian) changed also the spatial concept of the church, extending it into east and introducing a transept crowned with a dome. He also worked in the interior, constructing aisles and the nave wall up to the frieze of leaves (Montani 1967, 16–17).

«Nicolaus Johannis florentinus» (Nicholas the Florentine), protomagister who conducted the construction of the Šibenik cathedral 1477–1505 (Fosco 1891, 25–26; Frey 1913, 40, 164), adopted the specific constructional method of the apsidal part and applied it to the barrel and semi-barrel vaults of the church, and even to its dome. Thus he created an original vaulting system, assembling large elements, cut of the high-quality stone.

The following protomagistri of the Šibenik cathedral, «Bartolomeus quon. magistri Jacobi de Mestre» (Bartolomeo di Jacopo from Mestre), and later on his son Jacopo (Frey 1913, 44), completed the cathedral (the upper vaults of the aisles and nave) by using the same form (semicircular barrel vault for the nave and semi-barrel, less-than-a-quarter-circle vaults for the aisles) and the same constructive and structural system. In 1536 the construction of cathedral was completed by putting the key-stone on the western trefoil façade and simultaneously the «key-slab» of the first western bay of the nave vault (Fosco 1893, 61).

THE UNIQUE CONSTRUCTIVE AND STRUCTURAL SYSTEM OF THE UPPER VAULTS

Unique way of construction

The unique upper stone vaults of the cathedral of Šibenik are constructed in the original way: their webs are assembled of large thin monolithic slabs (their spans vary from 3.00 to 4.20 m, while their thickness varies from 15 cm to 25 cm—due to roof-tile-like overlapping). These stone slabs are wedged into slender stone arches, monolithic in cross-section (80 cm wide, 55 cm high in cross-section), which span 7.75 m (Šimunić 1989).

Figure 2
The cross-section through the nave and the aisles of the cathedral

The principle of assembling, applied also in the construction of the walls of the apsidal part of the Cathedral (where the large thin stone slabs are fixed into stone «frames» —vertical and horizontal stone bars— was probably inspired by timber constructions. Indeed, not only had many churches in Venice wooden vaults «a carena di nave» (Ivančević 1985, 29), but also other cities in Northern Italy (Verona, Aquileia . . . ) as well. It seems that also the ancient cathedral of St Anastasia in Zadar, native town of Georgius Dalmaticus, had a wooden vault «a carena di nave» (Petricioli 1983, 62–63).

The method of building in one material (wood) was «translated» into the constructing in another material (stone), with essentially different characteristics—in an ingenious, outstanding way. Wood is a traditional material that is able to assume both compressive and tensile stresses. Therefore it has been used for millennia for flat floor structures, where bending occurs, i.e. both compressive and tensile stresses appear.

On the other hand, stone is extremely resistant to compressive stresses, while its tensile strength is much lower. Therefore, when used for covering spaces, it was applied as massive masonry vaults,
which had a shape adjusted to the pressure line, in order to avoid tensile stress. Masonry structures have even lower tensile strength than stone as a material, because the joints between stone elements (usually mortar) have a negligible tensile strength (Di Pasquale 1984).

The way in which the constructors of the cathedral of Šibenik used stone for building vaults is unique. In fact, the method of erecting the vaults of the Cathedral had been a mystery—until the recent disassembling of the dome, damaged during the war in 1991. It was impossible to be sure how the details of the vaults were actually made, although the vaults were visible from the interior and the exterior (since they have never been roofed). Many art-historians (e.g. Josef Durm - 19th-20th century) assumed that the vault rib elements were made of two parts tightened together.

Figure 3
Dome rib during disassembling (photograph by M. Škugor)

Only ten years ago, during the partial disassembling of the dome, precise and original constructional details were rediscovered. Surprisingly, the arches of the dome are monolithic in cross section, with grooves in which the precisely cut slabs are fixed. Because of the intricate spatial geometry of the dome, stone wedges (lateral and frontal) were put into the arch grooves, to fix the slabs tightly and precisely (Škugor 1997, 138–139). It showed how the dome had been built: in horizontal rings, with slab layers and arch elements shifted by ca half a height. It was proved that the dome was stable at any stage of the construction, and that it could have been erected without scaffolding. In fact, every horizontal ring, when closed, is assured against overturning, and elements of the existing ring, (e.g. arch elements) stretching upwards, provide secure support for the elements (e.g. slabs) of the next horizontal layer (Škugor 1997, 139).

This ingenious structure with its precise details proves that in the time of Renaissance Dalmatia had high-skilled stonecutters, able to realise original, daring, new structural concept of the creators of the cathedral.

Unique structural behaviour

The unique stone vaults of the cathedral of Šibenik, assembled of thin large monolithic slabs, wedged into slender stone vaults, are much lighter than usual massive barrel vaults. And, what is even more important, unlike masonry barrel vaults, they transfer their load mostly in the longitudinal direction, to the arches, as the computational analysis proved. (Šimunić 1989, 84–93).

Thus, the vault loads—and consequently their horizontal thrusts—are concentrated onto a limited number of points—the supports of the arches. As the arches are tightened with iron tie-rods, their horizontal thrust does not affect their slender substructure (Šimunić 1989, 185).

In contrast to this, the usual massive masonry barrel vaults load their substructure with considerable horizontal forces along the whole length of the walls—which is a very unfavourable influence on their masonry substructure.

Structural behaviour of the Šibenik cathedral during construction

Method of research

In order to understand the construction history of the cathedral of Šibenik from the structural point of view, we explored the mechanical behaviour of its structure in several building phases. On the basis of the
historical sources (previously analysed by numerous art-historians who researched documents from the time of construction, preserved in the Šibenik archives, as well as other historical sources — e.g. coats of arms, incised in the walls of the cathedral), we tried to establish up to which extension and height the Cathedral was built in several crucial periods.

While art-historians concentrated on attributing several parts and elements of the Cathedral (especially sculptures) to certain authors, we considered the Cathedral as a building, the structure being its essential feature.

We built 3D models of the whole structure in order to check if the assumptions made by art-historians (established mostly through the analysis of stylistic details) can stand the examination of the structural logic of the building as a whole.

Then we analysed the mechanical response of the structure in several building phases that we had established. We used the experimental finite element method programme CALPA developed in the early nineties at the University of Florence for the analysis of masonry structures (Smars 1992). This programme is based on the theory of masonry mechanics developed by Prof. Dr. S. Di Pasquale (Di Pasquale 1984): low tensile strength of masonry is presumed negligible, and regions where tensile stress would appear are considered deactivated, fractured. Thus, the real, resisting structure is reduced (Di Pasquale 1992, 175), and the programme iterates calculations with a new stiffness matrix (Smars 1992).

Due to the limited possibilities of the programme used (only 2D analysis, limited number of finite elements), we analysed a characteristic cross section through the nave and aisles, actually through their primary structural elements — vault arches, pilasters and columns.

**Structure completed by 1441**

First, we analysed the structure as it was presumably completed by 1441, when serious structural problems appeared. From the documents and coats of arms incised on the walls, it is certain that at least the northern pilaster of the western façade was completed up to the height of the Lombard frieze (Frey 1913, 7), which should have been the upper cornice of the building.

Thus, at least the northern part of the western façade and the western part of the northern façade were also built up to this height. The Gothic Lombard frieze (blind arches cornice) was also begun in this period, but it was probably not built in its full length. The art-historians have proved that the northern portal of the church, known as «porta dei leoni», begun before 1434 (Frey 1913, 8), was completed only in 1453–1454 (Folnesics 1914, 47). As the ninth bay of the northern façade has decorative elements belonging to a later period, and as it is built in another way, completely different from the usual ashlar masonry, applied in the firstly built parts of the church, it is certain that the eighth bay of the northern façade is the ultimate limit to which the first builders — Francesco di Giacomo in the first year, and Antonio Busato and Lorenzo Pincino later on— could have carried out the construction.

Documents testify that in this period also at least one bay of the northern aisle vault was completed: its first western bay. It is vaulted with a usual Gothic ribbed groin vault. As the lower part of the northern façade (outer wall of the northern aisle) has a row of pilasters, which do not exist in its upper part, we assumed that the first constructors of the Cathedral built these pilasters as shallow buttresses intended to assume the horizontal thrust of groin vaults.

Therefore, we supposed that the structure was
originally designed as Gothic vaulted structure, buttressed by façade pilasters, i.e. without iron ties, which are present in the structure now.

The computational analysis of a 2D model of such structure, built up to the groin vault and the Lombard frieze, showed that even at that early stage of construction serious structural problems would have appeared if the structure had not have additional elements for assuming the thrust of the groin vaults. In fact, the pilasters proved to be insufficient for that purpose, because tensile stress in the vault and its diaphragm would have appeared, causing significant relative displacements of the nave wall and aisle façade. The large continuous fractured region in the midspan of groin vault arch and in its diaphragm would have caused a discontinuity in the structure.

caused the suspension of construction and urgent invitation of a new, experienced protomagister. Until now, the art-historians assumed that these mistakes occurred in the apsidal part of the building (Frey 1913, 16), because it was the first part to be built by the new protomagister, Georgius Dalmaticus (even though the construction of the eastern part began only in 1443).

This hypothesis can be confirmed with the fact that all the capitals of the nave arcades and all the wall capitals of the aisle walls of the groin vaults have the stylistic characteristics of the first (Gothic) period—all but the third capital of the southern nave arcade and the first wall capital of the southern aisle wall (Frey 1913, 12).

Therefore, it seems plausible that the damage occurred in the southern part of the building. Indeed, the Cathedral is built on the steep slope, and while its northern side was founded on the rock, its southern side was founded on a less rigid support. Moreover, the episcopal palace is leaned on the southern wall of the Cathedral, and acts as a buttress, while the first three bays of the southern aisle do not have such «buttressing system».

Knowing this, we formulated the hypothesis that the damage, mentioned in historic documents, occurred exactly here. Thus, the structural analysis of the Cathedral in the first construction phase, when serious damage occurred, inspired a new hypothesis on the nature of that damage. To control our hypothesis, we analysed also the building in the next phase.

This would have transformed the more stable two-support (two-wall) structure, connected with a vault, into two independent vertical cantilevers—much less stable against horizontal forces.

But even if such a structure was loaded only with dead vertical loads, the cracks and significant relative horizontal displacements could have caused significant damages, and a fractured vault would have been a warning. This state of stresses and displacement could have caused even a real collapse of the vault bays, constructed until 1441.

This consideration inspired us to formulate a new hypothesis of the possible «errores et defectus» which
Construction completed by protomagister Georgius Dalmaticus

Protomagister Georgius Mathei Dalmaticus obviously solved the construction problem (whatever it was—the cracks in the vaults, due to insufficient thrust-assuming system, or any other problem) and built the eastern part of the church using specific assembling method, unusual in stone construction. (Ivančević 1997, 29). It is certain that he used iron ties for assuming the horizontal thrust of the groin vaults, and that he completed these vaults following the model of the first northern aisle bay, built by Pincino. According to our hypothesis, he adopted the same shape for the new vault bays, but he changed the structural system of the vault, introducing iron ties to prevent the structural problems that had already endangered the structure. There are no proofs that the first builders of the Cathedral did not use the tie-rods. However, there are proofs that Georgius Mathei did use them. In the contract for building the sacristy adjoining the Cathedral, they are explicitly mentioned: «duas catenas ferreas largas . . . pro archivolto dicte Sacristie» (Frey 1913, 153).

Construction completed up to the semi-barrel vault of the aisle

To research the structural behaviour of the structure in the next stage of construction, we analysed the structure when also the upper vaults of the aisles were built. First bays of these vaults, next to the dome, were built probably before the construction of the dome, i.e. before 1499, under the protomagister Nicholus Florentinus.

The thin semi-barrel vaults and their slender substructure testify that the architect built-in iron ties, as we can still see. The part of the northern façade (northern aisle wall) above the Lombard frieze does not have pilasters—the façade surface is plain. It proves that the architect did not rely at all on pilasters as buttressing elements, that he entrusted the role of assuming horizontal thrust completely to the iron ties. This solution was successful, for no structural problems have ever been mentioned since 1441.

The computational analysis of the structure in this phase of construction confirmed the historical data. In spite of bigger height and consequently bigger dead load, in spite of another vault, placed higher in the structure, which therefore could have influenced the vertical substructure even more unfavourably, the state of stress is much more convenient than in the first analysed case. Due to the tie-rods, which assume almost the entire horizontal thrust of both vaults (the upper and the lower one), the vertical substructure is

Figure 7
Construction completed by protomagister Georgius Dalmaticus

Figure 8
Compressive stresses in the structure completed up to the semi-barrel aisle vault
slender. Nevertheless, the critical, fractured areas are reduced to a minimum. There is no dangerous fractured region in the midspan of the groin vault and its diaphragm. Small deactivated areas appear due to the local influences, such as the concentrated force of the tie-rod, which causes fractures in a small area (a point, really) at the tie-rod anchoring. Another critical point is the support of the arch of the semi-barrel aisle vault on the nave wall — due to the vault thrust, which at that point is not assumed by a tie-rod, nor contrasted by a load of the nave vault above (not constructed yet, in this phase).

But these deactivated areas are neither large nor continuous; they do not occur at the vital points of the structure and do not spread through the whole section of structural elements. Therefore, they do not endanger the structure.

**CONCLUSION**

The history of architecture is the history of construction, the history of structural concepts and systems, rather than the history of decorative forms and stylistic conventions. Structure is an intrinsic component of architecture.

Throughout the history, traditional empirical knowledge of «res aedificatoria» (the art of building), based on direct observation of existing structures, allowed only slow, gradual changes of structural concepts. Therefore, the examples of radically new, original constructive and structural concepts, which broke with the tradition, are extremely rare. Of course, many «experimental» buildings have not survived the environmental forces and impacts.

The original, innovative structures that resisted all the impacts for centuries proved their structural qualities ipso facto. One of these outstanding buildings is the cathedral of Šibenik, with its unique vaults, constructed in the original way, which, consequently, results in the specific structural behaviour.

The static analysis of several construction phases, reconstructed on the basis of historic documents and previous art-historical researches, proved that the structure, which was presumably begun without tie-rods, with shallow pilasters as buttressing elements, was not resistant enough to withstand the horizontal thrust of the groin vaults of the aisles — not even in the first phase of building (1431–1441).

The creation of fractures in the bays of the groin vaults, erected until 1441, may well have caused the suspension of construction. Indeed, when the building was stopped due to «errores et defectus» which caused heavy damage «quoniam aedificia et partimenta non fuerunt dibitis modis composita et fabricata» (Frey 1913, 130), there must have been serious structural flaws that endangered the construction.

Because of that serious structural problem, a new protomagister was invited: Georgius Mathei Dalmaticus. He managed to correct the «errores et defectus», to remove weaknesses and to continue the building, using iron tie-rods. He also developed a new, original construction system, erecting the walls of the apsidal part of the Cathedral by assembling large stone slabs, fixing them into stone frames.

His successor, Nicolaus Florentinus, applied the principle of assembling large stone slabs to the construction of the upper vaults of the Cathedral. The thin monolithic slabs are fixed into the slender stone arches, which are tightened with iron ties. Thus, an original vaulting system was developed, which differs substantially from the usual masonry barrel vaults.
Therefore, no massive substructure or buttressing system is necessary.

Indeed, the analysis of the next stage of the construction, when also the upper, semi-barrel aisle vault was completed (and assuming that both vault arches are tightened with iron tie-rods), displays clearly that this system has no structural weaknesses. Due to local influences (tie-rod force, e.g.) only small localised fractured regions appear, which do not endanger the structure as a whole.

The strength of the Cathedral structure, daring and apparently fragile, was proved in 1991, when it resisted even a direct bombshell shot.

«Virtual experiments» on the structure of the Šibenik cathedral (some of which are described here) gave a new insight into its mechanical behaviour during the construction, and into the possible reasons of the structural failure in the beginning of its building. Like the ancient masters, who made use of this failure to develop a new constructive and structural system, contemporary architects and architectural historians should be aware of such episodes in the construction history in order to better understand how the historic structures were designed and constructed. Thus, we would be able to grasp the very essence of our architectural heritage: its structure.

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