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Computational Modeling, a Foundation for Understanding the Structural Make up of Historical Buildings Based on Principles, Theoretical Criteria and International Conservation and Restoration Recommendations

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Abstract. The ISCARSAH principles and guidelines encourage the structural analysis of historical buildings to be carried out using an analogy doctor-patient relationship. Given that this type of building carries intrinsic in their architecture and engineering the historical and technical knowledge of our ancestors, it becomes fundamental and necessary to understand them, so that they can continue to be preserved and thus inherit them to future generations. For that reason, at present, engineers dedicated to the structural analysis of heritage buildings require the support of technological tools that can reproduce numerically and graphically, the behavior of this type of buildings to understand them more accurately. This type of computational modeling is becoming more useful every day, since it is necessary to have instruments that speed up virtual modeling to deal with the effects of natural and/or accidental events, such as earthquakes and differential subsidence. With a proper understanding, it will be possible to choose for the best intervention on heritage objects around the world. In this chapter, some computational graphical models are described that can help students, professionals and researchers in the field.

Keywords. Computational structural models, conservation and restoration criteria, doctor-patient analogy, historical buildings, construction systems.

1 Introduction

The culture and history of any society have always been of utmost importance because of everything it has implied conceptually and contextually over time. Therefore, the conservation and restoration of its ancient buildings became essential due to the great tangible and intangible values of its heritage properties, which is why these types of buildings became the main attractions for residents and tourists around the world. Such conservation required the creation of structural models of historical buildings and involved the collection of information for their comprehensive development, since, as a virtual representation of physical reality, it entailed gathering material and immaterial characteristics to represent the real object. Different aspects were used to develop these models, such as history, geometry, construction systems, and mechanical properties, among others. The uniqueness of this work was based on the integration of the three essential pillars, which, in common structural engineering, were difficult to develop in an interrelated manner. Among the first structural studies that began to propose historical-technical systematization in the structural analysis of historical buildings, those proposed by [4, 5] stood out. However, it is important to mention that very few works have been published on the computational structural modeling of complete heritage building systems that have consciously, coherently, and objectively considered theoretical principles. One such work was recently published by [19], which was applied to modern heritage. This justified the need to write texts with objectives related to the generation of complete structural models of historical buildings by linking the three constituent aspects of restoration, which have

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been found implicit in international guidelines, theoretical principles, and criteria [12, 13] that have remained in force to this day.

2 Materials and Methods

The primary tools implemented in the models presented were based on qualitative theoretical-historical analyses, as well as quantitative graphical-numerical analyses. The models were based on the finite element method, whether continuous or discontinuous, using both structural and construction systems, representing deterioration and discontinuities in cracked areas. The materials used are based on national and international literature, mainly the mechanical properties of irregular masonry [2]. The integration of theoretical aspects into the models was considered in the morphological correlation of the structure with theoretical positions. The Structural Analysis Program (SAP2000) version v23 [7] software was used as a tool for analysis and mathematical modeling.

3 Correlation of Theoretical Conservation and Restoration Criteria with Structural Analysis of Historical Buildings

Before going into computational modeling, it is essential to deal with specific features concerning the main theoretical criteria of conservation and restoration, since the main objective of studying heritage objects is to conserve them to pass them on to future generations.

To exemplify the correlation of conservation and restoration criteria with the structural analysis of historical buildings, three known orthodox positions are described and their relationship with all that implies studying or analyzing from a structural engineering perspective:

One of the first theoretical approach in which the concern for the conservation of historical monuments is manifested, because of reconstruction works in St. Peter's Cathedral in the Vatican (1823-1829) is attributed to papa Leo XIII, who, in a text attributed to him, according to Susana Mora, mentions the following:

“No innovation should be introduced neither in the forms nor in the proportions, nor in the ornaments of the resulting building, if it is not to exclude those elements that at a later time than its construction was introduced at the whim of the following period.”

From these principles, there emerge the different approaches and criteria of restoration, in which the completion of the buildings will be contemplated by means of integration, as well as their consolidation for their structural stability.

One of the best examples of this theoretical approach is manifested in the intervention of the Colosseum or Flavian Amphitheater (1818-1821), in the city of Rome, carried out by the architects Raffael Stern and Giuseppe Valadier, incorporating new structural elements to stabilize the monument and the Arco de Tito in which both architects participated, incorporating a new criterion in the stylistic unity of the building, the architectural Anastylosis [20].

1. It is in the nineteenth century when it begins to try to systematize the restoration processes, it is Viollet-le Duc who puts into practice his systemic thinking in old buildings, however, such practice was carried out with very little rigor, in addition to the fact that scattered methods and processes were used [6]. Viollet-le Duc's thinking leads him to mention the following sentences:

“Restoring a building *does not mean preserving it, repairing it or remaking it, but obtaining its complete pristine form, even if it had never been so... It is necessary to put oneself in the place of the primitive architect and suppose what he would do if he returned to the world and had the same problem before him”.*

“If the architect rejects iron construction because the medieval masters had not used such a system, he would, in our opinion, be making a mistake, since this would avoid the terrible dangers of fire that have so often been fatal to our ancient buildings”.

“The architect must proceed like the skilled and experienced surgeon who does not touch an organ without first becoming aware of the function and without first foreseeing the immediate and future consequences of his operation. Before acting at random, it is better to do nothing. Better to let the patient die than to kill him”.

Table 1. Summary of principles ISCARSAH (1 of 2)

Principles
• *The conservation, consolidation and restoration of architectural heritage require a multidisciplinary approach.*
• *The value of a historic building lies not only in the appearance of its individual elements, but also in the integrity of all its components [...].*
• *Any intervention on a historic structure must be assessed in the context of the restoration and conservation of the whole building.*
• *Architectural heritage structures, due to their peculiarity and complex history, require organization of studies and analyses in the various steps, like those carried out in medicine.*
• *No action should be undertaken without having evaluated the benefits and damage that may be caused to the architectural heritage.*
• *A multidisciplinary team should work together from the first phase of the study.*
• *It is necessary to analyze the available data to develop a plan of activities appropriate to the problems of the structure.*
• *Any restoration and conservation project requires a full understanding of the structural behavior and characteristics of the materials. It is essential to have information on the structure in its original state and in the stages prior to the intervention, as well as on the techniques that were used for its construction, in addition to knowing the current state.*
• *The structural solutions needed to stabilize the structure while excavation is in progress must not endanger the building.*
• *The diagnosis should be based on historical information, qualitative and quantitative analysis. Qualitative analysis is based on direct observation of structural damage and deterioration of materials, as well as historical and archaeological research. On the other hand, qualitative analysis requires structural analysis, material testing and monitoring.*
• *The assessment of the level of safety (a post-diagnostic step) is the phase in which the decision to intervene is made and must unite the qualitative and quantitative analyses.*
• *All the information derived from the diagnosis and the decisions on the intervention should be reflected in an explanatory report or memory.*
• *Therapy should be directed at the root of the problem and not at the symptoms.*
• *Conservation and consolidation measures should be based on the level of safety and an understanding of the historical and cultural significance of the building.*
• *No action should be taken unless it has been shown to be indispensable.*
• *Interventions should be proportional to safety objectives and should be kept to the minimum level of intervention that guarantees safety and durability, causing the least damage to the heritage values.*
• *The design of the intervention must be based on a full understanding of the type of actions that have caused damage and deterioration, as well as those that will act in the future.*
• *The choice between techniques (innovative and traditional) must be weighed, preference should be given to those that are less invasive and more compatible with heritage values.*
• *The difficulty in assessing the safety levels and benefits of intervention may suggest an observational approach with the possible adoption of subsequent supplementary or corrective measures.*

Table 1. Summary of principles ISCARSAH (cont., 2 of 2)

• Whenever possible, the measures adopted should be reversible. If interventions are not fully reversible, they should not preclude subsequent interventions.
• The characteristics of the materials to be used in the restoration work and their compatibility with existing materials must be fully understood. This knowledge must include the long-term effects.
• Any intervention should respect, as far as possible, the design, construction techniques and historical value of the structure.
• The intervention should result from a comprehensive plan that gives adequate importance to the different aspects of the architecture, structure, installations and functionality of the building.
• The removal or alteration of any historic material or any distinctive architectural feature should be avoided.
• Repair is preferred to replacement.
• Alterations and imperfections should be retained when they have become part of the history of the structure, if safety is not compromised.
• Any proposed intervention must be accompanied by a monitoring program that will be carried out as far as possible during the execution of the work.
• All control and monitoring activities should be documented and preserved as part of the history of the structure. functionality of the building.
• Removal or alteration of any historic materials or any distinctive architectural features should be avoided.
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• Alterations and imperfections should be retained when they have become part of the history of the structure, if safety is not compromised.
• Any proposed intervention should be accompanied by a monitoring program, which as far as possible should be carried out during the execution of the work.
• All control and monitoring activities should be documented and retained as part of the history of the structure.

Therefore, it is essential to review and analyze the criteria of the restorer regarding the intervention of the building, in order to evaluate the feasibility regarding the adequate structural behavior, in addition to the history and theory, it is necessary to study the technical aspect: the shape, materials, type of soil, compositional systems, acting loads, possible previous interventions: releases, integrations, among others [22]:

"The noblest building will be the one in which an intelligent eye discovers the great secrets of the infrastructure, as any animal form always reveals them, even if only an attentive observer can discover them".

2. On the other hand, the moral, romantic and literary conscience of John Ruskin could be labeled as a criterion contrary to that of Viollet-le Duc, who promotes not to intervene the heritage object, since it should not be restored and preserve the historical and authentic, he prefers the building to be ruined if there are no other options other than its reconstruction, even the building would have to die, similar to the human being, once it has

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completed its life cycle [1, 6, 26]. Ruskin's thinking leads him to quote the following sentences:

“[…] it is impossible, as impossible as raising the dead, to restore anything that was once great or beautiful in architecture […]”

“[…] The first result of a restoration is to reduce the old work to nothing; the second is to present the most vile copy, or at best, however careful and laborious it may be, a cold imitation, a model for the parts that should be so according to a hypothetical completion.”

“Let us not speak, then, of restoration. The thing itself is, in short, nothing more than a deception.”

“Destroy the building, throw its stones into the most remote corners, and rebuild it with mortar to your liking. But do it honestly; do not replace it with a lie.”

With Ruskin's phrases, it would seem that the structural engineer would be disabled, since it would be better to let the building die, however, in today's society, many of the historical buildings that contain strong deterioration or even damage in its structure, are still being used by humans, which, by letting the building die structurally speaking, would also be putting at risk the lives of the population, including the adjacent buildings.

That is why it is recommended at least its consolidation to be able to conserve, and as this has to do with the structural area, it is vital the previous analysis with quantitative data.

On the other hand, when analyzing buildings that are unfortunately in ruin today, they become, from a medical patient perspective, organisms that expose their compositional physics, which is essential for their study and structural modeling with new computational technological tools.

For Ruskin, to restore is equivalent to destroying the building in a forceful way, to falsify the monument that is destroyed. He criticizes the rational way of restorers and qualifies them as insecure and lacking all scientific rigor [20].

3. In the late nineteenth century, the Italian approach of Camilo Boito is presented, who argues to reuse the monuments and reflects on the discipline of restoration, moreover, treats it as something serious.

Boito is considered not as a restorer based on his thinking and his own understanding, but rather, a scientific restorer who intervenes works with great rigor in science. Whenever feasible, he respects the materials of such work, however, if intervention is required, one can proceed modernly [20]. Camilo Boito's thought leads him to quote the following sentences:

“[…] when the need to restore a monument is demonstrated, it should be consolidated before repaired, repaired before restored, avoiding renovations and additions.”

“[…] the oldest part, even if it is the most venerable and important, should not always prevail over the added part, which may have intrinsic and absolute beauty. In such cases, beauty can surpass antiquity.”

Historical buildings, besides being analyzed historically and theoretically, the technical part is essential, hence methods and procedures for information gathering and structural analysis are constantly being developed to conserve and restore their structures. Garcia's [8] thinking leads her to quote the following sentence:

"In order to find appropriate solutions to conservation problems, it is necessary to contribute from various disciplines whose solutions may conflict with each other.

One of these is structural engineering, which seeks to preserve the stability and safety of buildings while affecting their historical and architectural values as little as possible.

Preserving the safety of these buildings requires adequate information to assess the actual condition of the construction, so it is essential to have an in-depth understanding of how the structure works and to understand the basis of its original structural solution. It is also important to understand the sociocultural context in which they were built."

Trough numerical analysis based on computational mathematical models, it is possible to simulate the behavior of the structure, which requires information such as geometry, mechanical properties of the materials, including those of the soil, connections between elements, among others.

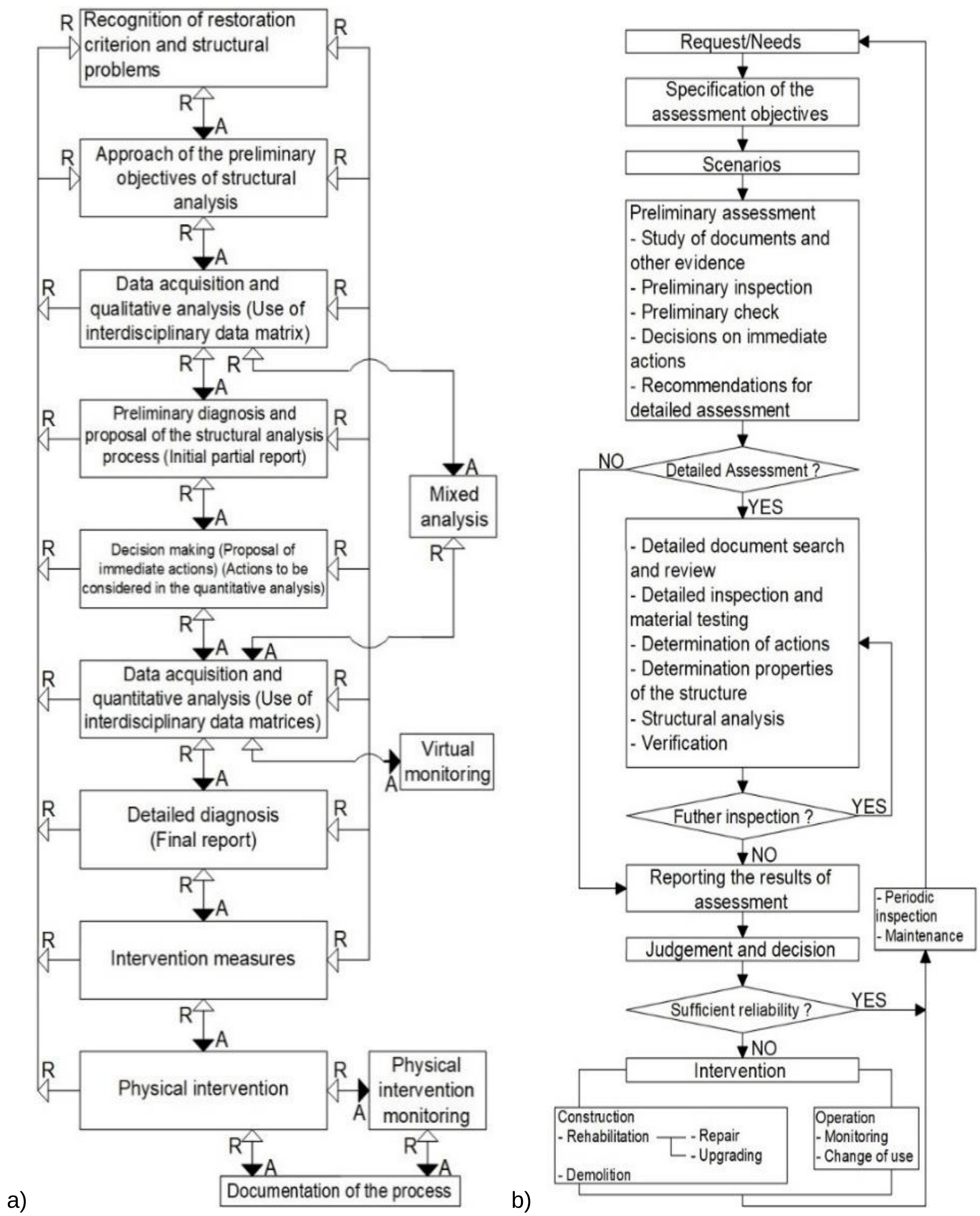

Fig. 1. Structural analysis procedures for historical buildings, a) systemic-interdisciplinary approach, where A= Advance, R= Return [26], b) flow chart for the general evaluation of existing structures [14]

4 Principles and Guidelines (ISCARSAH): International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage, (ICOMOS): International Council on Monuments and Sites

There are currently international recommendations that bring together principles and guidelines for analyzing historic building structures.

For example, the following lines present the criteria and recommendations issued by the International Scientific Committee for Analysis and Restoration of Architectural Heritage Structures [13].

The principles are divided into three parts: general criteria, investigation and diagnosis, and corrective and control measures.

Table 1 summarizes the main points; it is worth mentioning that, for a broader view of these principles, it is recommended to consult the original source [13].

It also has guidelines, which have the following sections: general criteria, data collection (information and research), structural behavior, diagnosis and evaluation of the safety level, structural damage, deterioration of materials, and therapeutic measures

On the other hand, the Guidelines for Evaluating and Mitigation of Seismic Risk to Cultural Heritage, developed by the Italian Government Ministry of Cultural Heritage and Activities in 1997 [9], are an important set of protocols aimed at protecting cultural heritage from seismic events.

They have a series of steps to determine their structural status, such as risk assessment, mitigation measures, emergency preparedness, documentation and monitoring, enforcement, collaboration and consultation.

These guidelines aim to balance the preservation of cultural heritage with the need to protect these assets from seismic risks.

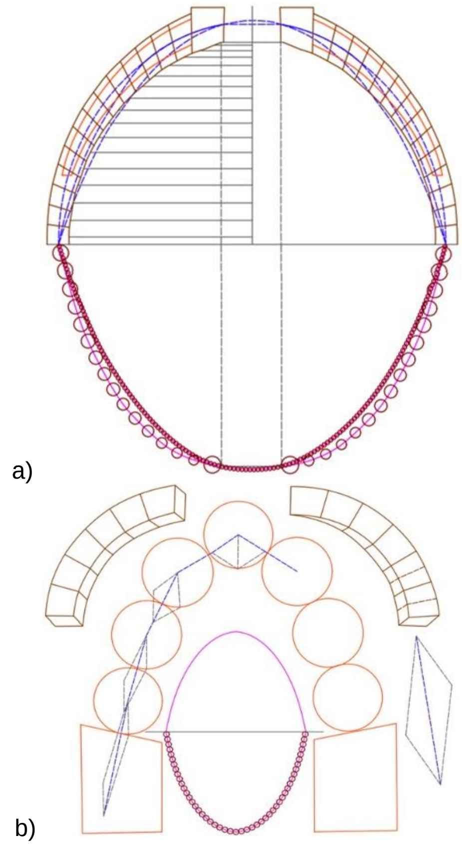

Fig. 2. It is shown that the St. Peters Dome was stable even in the cracked state, a) inverted reflection of the Dome in the form of a catenary, b) calculation of the arc in slices considering concentrated loads. Images taken from [10]

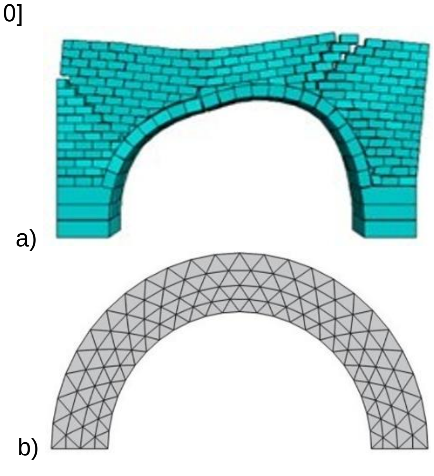

Fig. 3. Models with finite elements, a) discrete elements, images taken from [23], b) continuous finite elements. Images taken from [16].

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5 Doctor-patient Analogy in Computational Models for the Structural Analysis of Historical Buildings

Minimally invasive, non-invasive and laboratory tests on the materials that make up the historical buildings, such as: magnetic resonance imaging, ultrasound, core extractions, vibration tests, etc., can be similar to those carried out on humans, for example, when an echocardiogram or echocardiography is performed, when a sample of epithelial tissue is extracted, tissue composed of red blood cells, white blood cells and other substances contained in that liquid which is called plasma. It is known that a scientifically proven vaccine is usually, most of the times, a great protection for the human being, if compared with the fatality that a virus or a bacterium that invades the organism of living beings can entail. In the same way, the information and data extracted from the tests carried out in historical buildings can be great protection to avoid deterioration, partial or total loss of the built object, if they are properly processed and used in the structural analysis.

It is worth mentioning that in the XXI century and despite scientific and technological advances, there are still people who practice self-medication or homemade recipes to try to cure conditions of the human body, such recipes or self-medication may have worked at some time under certain conditions of the ecosystem in which the daily activities of mankind were developed, However, today there are many technological tools and encapsulated substances that help the human body to heal quickly, commonly called medicines or controlled drugs, even if emergency surgery is required, in many parts of the world, there are hospitals equipped with doctors, trained personnel and the relevant infrastructure. Similarly, in structural engineering, despite the fact that humanity has great technological and computational advances, with powerful numerical tools and sophisticated laboratories to obtain physical, mechanical and equilibrium properties regarding the behavior of materials and construction systems of the structures of heritage buildings, old rituals and recipes continue to be applied to intervene in buildings classified as

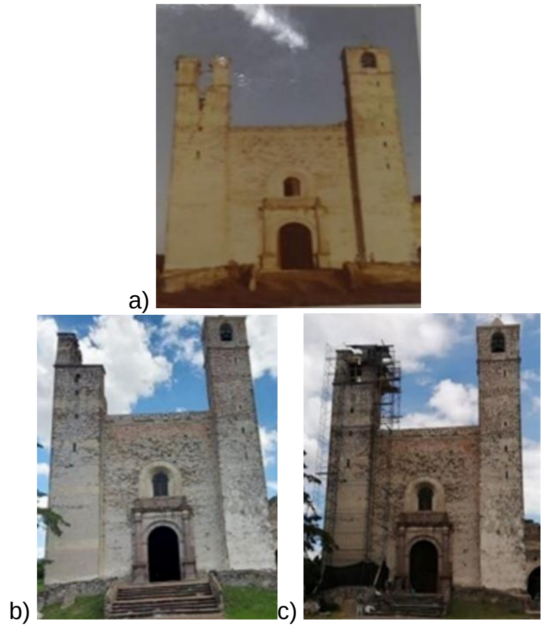

Fig. 4. Photographs of the Ex-convent from Cuauhtinchán, Puebla Mexico, a) facade in 1986, b) partial collapse of the upper part of the left tower (photograph taken in 2022), c) scaffolding for intervention in the upper part of the left tower in October 2023. Images taken from [21]

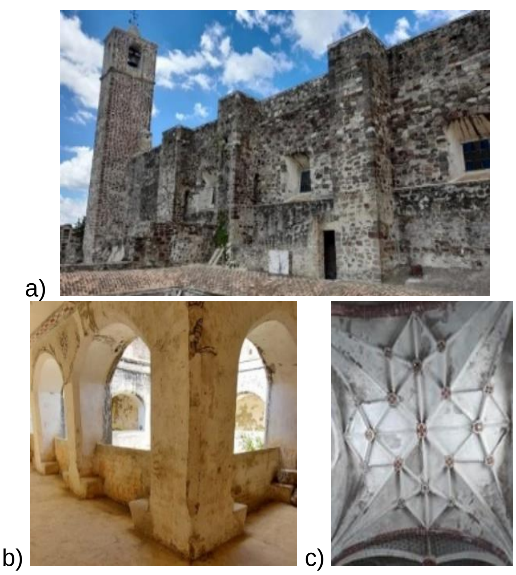

Fig. 5. Photographs of the heritage building, a) right lateral view, b) interior view from the cloister arches, c) lower view of the vaults of the main nave. Images taken from [21]

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historic or artistic, which, in most cases, present boundary conditions and induced or accidental actions completely different from those for which they were conceived, in addition to the fact that many of the materials used in historic buildings currently present subsidence, degradation, corrosion, humidity, cracks, stress concentration, alterations in the construction systems, non-compatible integrations, among other conditions accumulated with the passage of time.

For this reason, today wanting to intervene or restore a historic building only considering what is still taught in some universities around the world: to intervene heritage buildings by feeling, is no longer an option for serious scientific restoration procedures, it is like wanting to cure an acute appendicitis or even severe peritonitis, just by placing cold water compresses on the abdomen. Computational models offer virtual simulations of an endless number of scenarios of structural behavior that historic buildings could have under different boundary conditions and loads, thus being able to predict the benefits and/or damages that they could have under different criteria and intervention or restoration postures. Therefore, the analysis of heritage buildings cannot be merely qualitative and observational processes; it requires a systematic and interdisciplinary procedure of anamnesis, auscultation and diagnosis with scientific support. To this end, it is proposed, at least, to carry out each of the phases indicated in Figure 1.

6 Background for Structural Modeling of Historical Buildings

Natural stone has been one of the main materials chosen by mankind to create the masonry construction systems that have survived to the present day. The masonry construction that initially supported wooden roofs evolved to support masonry decks, with the aim of ensuring that the buildings would remain as long as possible, which is why arched elements were created. Hence, the traditional equilibrium calculation with graphical methods is reliable for elements with adequate dimensions [11].

On the other hand, Yvon Villarceau suggests three hypotheses for structural analysis of historical masonry buildings: 1) masonry has no tensile strength, 2) compressive stresses are so low that the resistance is practically infinite, 3) failure by sliding cannot occur [10].

Structural models of historical buildings are not completely new tools and can be totally attributed to current times and computational technologies, since the term model is defined by the dictionary of the Real Academia Española [18] as:

“Archetype or reference point to imitate or reproduce,” “Small representation of something,” “Theoretical outline, usually in mathematical form, of a complex system or reality, ... developed to facilitate understanding and study of its behavior.”

Likewise, Gaudí used the parabolic curve to obtain the line of thrust within the material, also called catenary, like the one shown in Figure 2, to check the equilibrium of the masonry structures.

This type of procedure was done to check the structural equilibrium, and in some countries, it is still practiced with physical models where forces are simulated by means of weights made with different materials such as sacks filled with soil, pieces of metal, among others.

With the passage of time and the invention of computers, software based on discrete element and continuous element method programming has been developed.

In the paper [23], it is shown a wide variety of methods that are being used both in research and in the modeling of practical cases around the world (see Figure 3a).

Likewise [16] present several finite element-based procedures, either discrete or continuous, for analyzing historical buildings (see Figure 3b).

The paper [2] presents a compendium of courses and readings that fill a large gap that existed regarding fundamental topics to be considered in the analysis of heritage buildings, to mention a few: behavior and modeling of masonry, limit analysis, constituent materials and their equations, practical applications for masonry equilibrium, simplified models, refined models, experimental results, modeling of friction in masonry without mortar, blocks with mortar, homogenization of masonry, among others.

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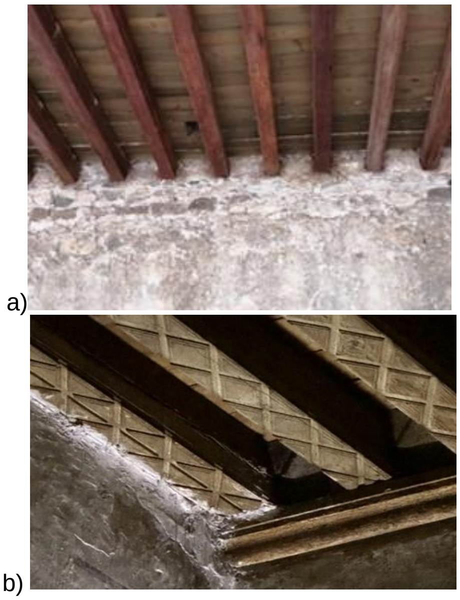

Fig. 6. Timber joist mezzanine system, a) beams supported directly on the masonry wall, b) beams supported on a trailing beam in the chancel area. Images taken from [21]

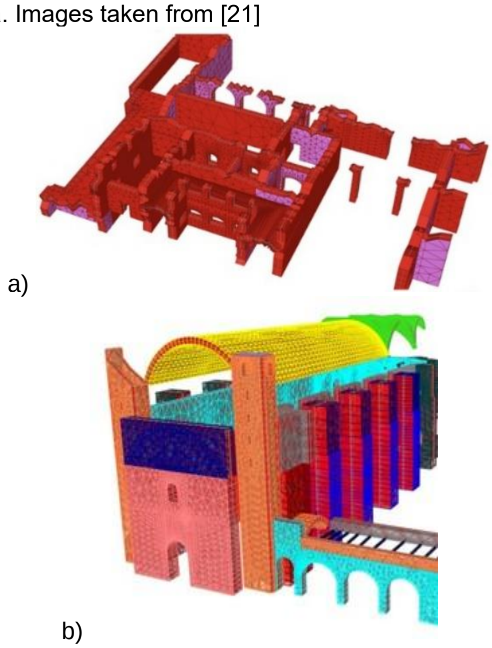

Fig. 7. Structural modeling of the heritage building, a) aerial view of the initial construction of the shell finite element model, b) geometric-constructive breakdown of the main nave of the church: vaults, buttresses, arches, walls and wooden beams, to understand the construction system. Images taken from [21]

7 Physical Knowledge and Understanding of the Historical Buildings

Historical buildings contain a greater complexity in their structural system, compared to modern buildings, this is reflected in the shape, the materials implemented, their very particular construction systems and how they behave mechanically and by equilibrium due to the actions to which they are exposed. All these components are essential for computational virtual modeling.

Currently, sophisticated technological tools are available to help in the acquisition of accurate knowledge, such as laser scanners, high precision photogrammetric cameras, presses to obtain mechanical properties, among others. In addition, it is necessary to know the historical aspect, to support the type of continuity or discontinuities of the different structural elements. A thorough and detailed auscultation of all the elements that make up the structural system is required.

7.1 Materials, Construction Systems, Mechanical Properties, Geometry and Actions

Historical constructions can be considered as a complex system, whereby one action or event affects the whole system. The systemic components can be summarized as follows, which are also mentioned by [13]:

Knowing the materials is fundamental, since they are susceptible to a certain level of affectation, deterioration or damage before any harmful action, which can compromise the structural system. The mechanical properties of certain materials tend to vary over time, causing less resistance or imbalance.

The construction systems are essential, since the architectural-structural composition and boundary conditions of each element [25] that make up these buildings are directly related to the structural behavior.

The mechanical properties also affect the behavior, since, depending on the mechanical characteristics of each of the elements, a certain structural behavior will result. It is worth mentioning

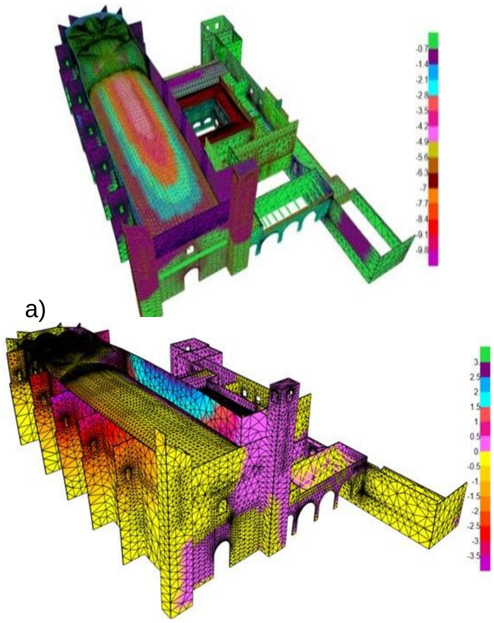

Fig. 8. Deformations due to combined effects of gravity loading and seismic actions a) displacements (cm), due to self-weight of materials in gravity direction, b) displacements in cm, in the X direction. Images taken from [21].

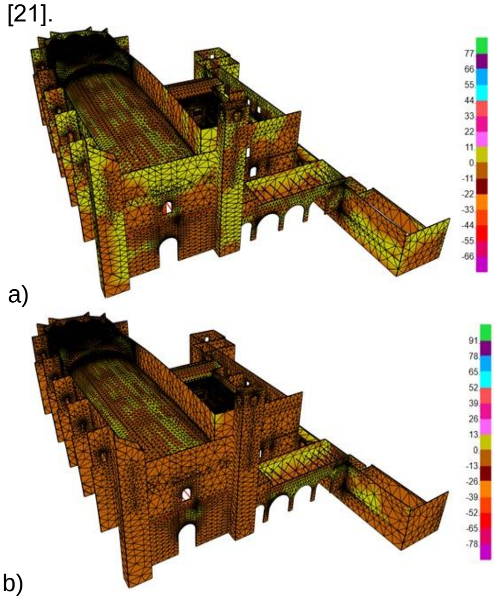

Fig. 9. Stresses (kg/cm^2) due to gravity and seismic actions, a) stresses in “X” direction due to “X” actions, b) stresses in “Y” direction due to “Y” actions. Images taken from [21].

that the same element tends to have different mechanical properties, given the generally heterogeneous and orthotropic conditions.

Geometry is an important aspect. Shapes dictate behavior, so it is necessary to have a full understanding of the shape of the system and of each element, as well as its connections.

External and internal actions impact the structural performance of buildings causing stresses and deformations. The most common actions are dead and live loads, soil settlements, seismic actions, hurricanes, vehicular vibrations, among others.

8 Application of Computational Modeling in Two Case Studies

To exemplify the application of computational models to understand the structural behavior of historical buildings, two case studies of real buildings in Mexico are presented. These cases are taken from scientific research works and theses developed in the Escuela Superior de Ingeniería y Arquitectura (ESIA), Unidad Tecamachalco (UT), from the Instituto Politécnico Nacional (IPN).

8.1 Case Study 1: Ex-convent of Cuautinchán, Puebla, Mexico

The Ex-convent from Cuautinchán is presented; in this case study, modeling tactics proposed by [27] were considered. Likewise, figures 4 to 10 show images of the building and the analysis of the complete system under gravity and seismic loads, elaborated by [21].

Images 11 and 12 show the initial partial construction of the mathematical computational model that represents the structure by means of shell-type finite elements with their respective meshing.

With this type of image cut at a certain level measured from the base of the slab, it is possible to check the correct intersection between nodes. This type of computational modeling allows us to observe the virtual thickness and configuration of the elements that compose the system.

Fig. 10. Cracks and fissures treated, a) vault of the main nave seen from the choir, b) vaults seen from inside the cloister. Images taken from [21].

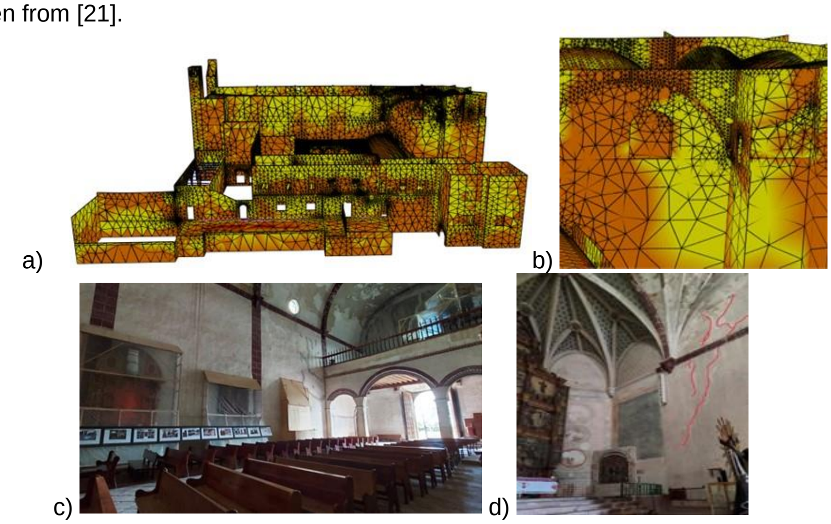

Fig. 11. Cracks and fissures detected with the models, a) cracks detected with the modeling of the structural system, b) physical cracks located in the wall near the presbytery, c) approach in cracked area in wall, d) cracks detected adjacent to the chancel. Images taken from [21].

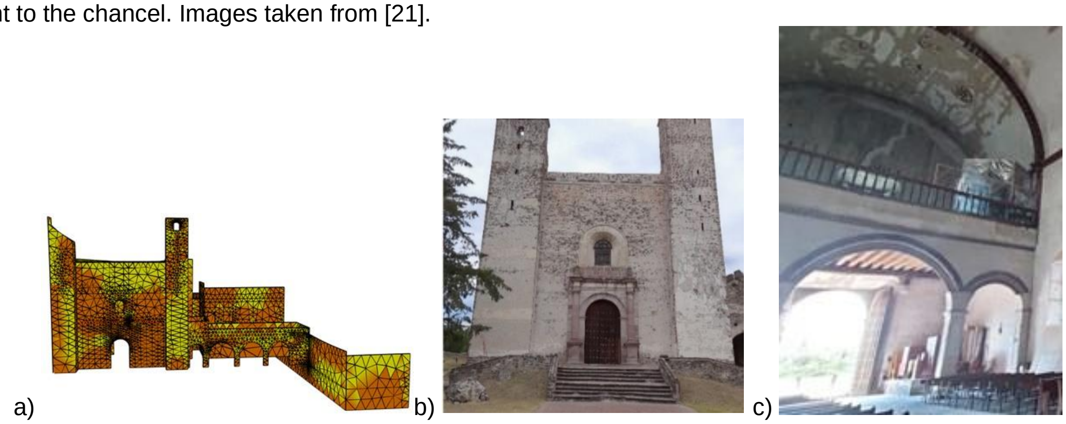

Fig. 12. Cracks and fissures treated, a) vault of the main nave seen from the choir, b) vaults seen from inside the cloister. Images taken from [21].

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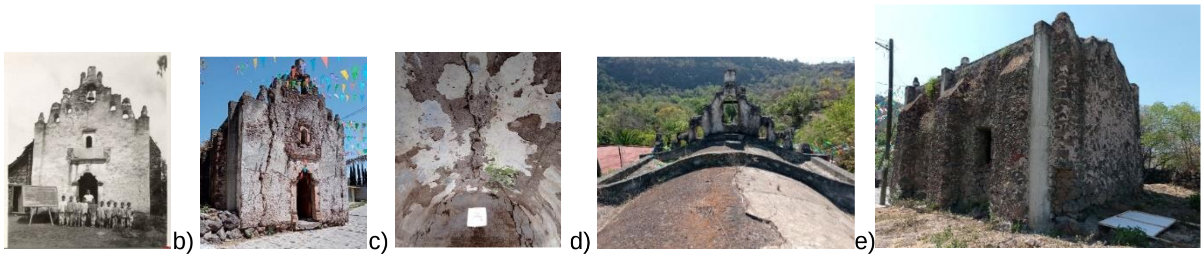


a) b) c) d) e)

Fig. 13. Chapel of Santa Catarina, a) facade preserved in the 20th century, b) present state of the facade, c) current condition of the interior of the vault, d) side wall and buttresses, e) present state of the exterior of the vault. Images taken from [3,24].

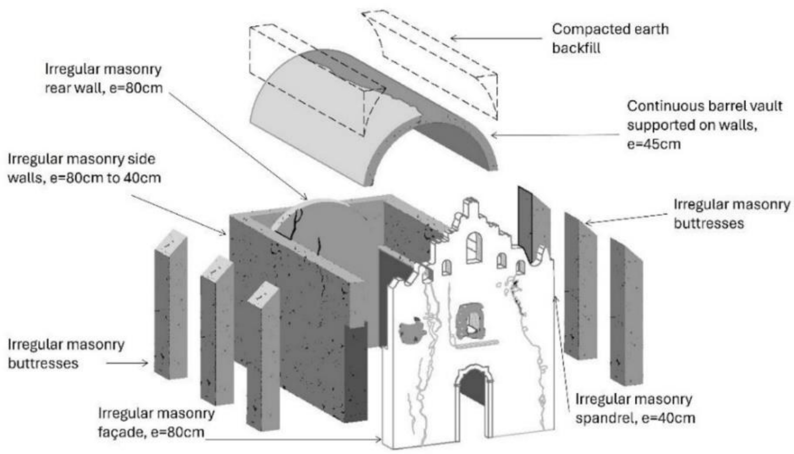
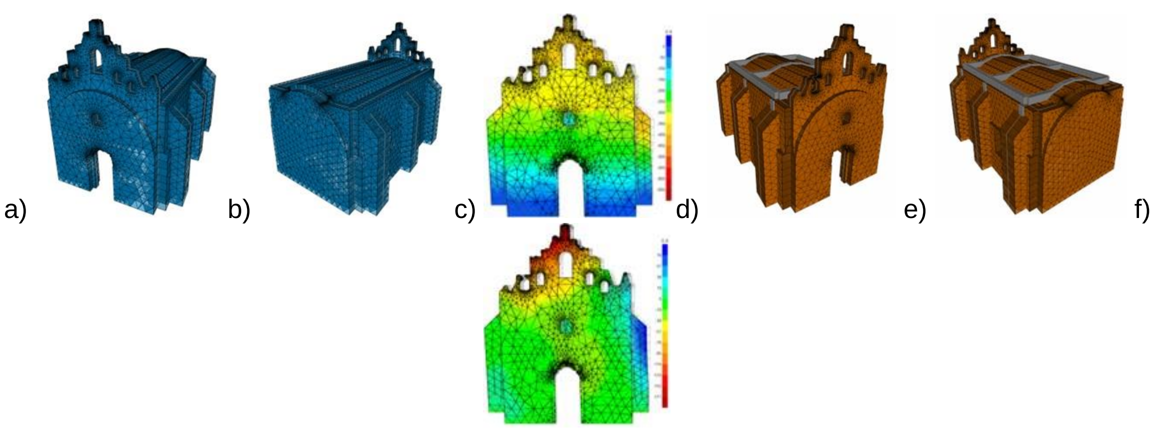


Fig. 14. Disaggregation of the system's compositional structural elements: vault, buttresses, walls, facade and earth fillings. Where: e = thickness. Image taken and adapted from [24,28].



a) b) c) d) e) f)

Fig. 15. Structural models with shell-type finite elements with homogeneous mechanical properties, a) and b) model without integration of reinforced concrete elements, c) Vibration mode in the “X” direction d) y e) model with integrated reinforced concrete frame-type structural elements, f) Vibration mode in the “Y” direction. Models taken and adapted from [24].

8.2 Case Study 2: Chapel of Santa Catarina, Hidalgo, Mexico

The Santa Catarina church is presented; this case was taken from [28] and [24]. Figures 13 to 14 show this temple, its digital model and its physical-geometric specifications and structural composition.

Figures 15 and 16 show the computational models with continuous finite element and graphical methods, respectively, to contrast and complement the results. 9 Results and discussion

Over time, various scientific articles have been written on the conservation and restoration of heritage buildings. This text exemplified the combination of the three pillars for the conservation and structural restoration of historical buildings: history, theory, and technique, as it brings together, synthesizes, and exemplifies the application of these essential aspects [1, 6, 20, 22] through computational structural models. From the earliest approaches to restoration, there have been fundamental principles that have remained in force to this day. First and foremost, they have served to contribute to and guarantee the structural stability of the monument and its consolidation [12, 13, 14, 26]. Digitization, modeling, and structural calculation tools have made it possible to carry out virtual interventions without having to physically touch the building or to intervene in a more accurate way in accordance with its history, as well as to predict future scenarios in the building for monitoring and structural behavior [2, 8, 10, 11, 12, 13, 14, 15, 30], thus avoiding the partial or total loss of the building. Digitization, modeling, and structural calculation tools have made it possible to carry out virtual interventions without having to physically touch the building or to intervene in a more accurate way in accordance with its history, as well as to predict future scenarios in the building for monitoring and structural behavior, thus avoiding partial or total loss of the building. The incorporation of new technological tools and equipment in the recording and practice of restoration has enriched the possibilities for implementing theoretical approaches in conservation and restoration, offering an encouraging outlook for the conservation of built heritage [16, 23]. The implementation of computational technology tools in the field of conservation and restoration has been fundamental in carrying out analyses with greater certainty and efficiency. However, it has required the knowledge, understanding, and simultaneous application of three fundamental aspects, even though this may seem as impossible as mixing oil and water [21, 24, 27, 28, 29]. Although all three aspects were implicitly considered in this text, the technical aspect of computational modeling of historical structures was generally emphasized, as the possible behavior of heritage objects were visualized graphically.

Currently, the implementation of computational technological tools in the field of conservation and restoration is essential to carry out analyses with greater certainty and efficiency; however, knowledge of three fundamental aspects is required: theory, history and technique. Although all of them were implicitly considered in the text, the technique of computational modeling of historical structures is highlighted in general, with the aim of representing as closely as possible the behavior of the real heritage object. It can be concluded that with the development of computational models it is feasible to experiment virtually with different scenarios of the real object in order to observe possible behaviors and thus foresee possible solutions without interfering with reality in an arbitrary manner.

From the first positions of Restoration, there are fundamental principles that remain until today, in the first term, to guarantee the structural stability of the monument and its consolidation, to subsequently standardize the unity of the building, from its spatial and aesthetic ambivalence. Today's digitization, modeling and structural calculation tools make it possible to practice virtual interventions without having to physically touch the building or to intervene in a more adequate way, as well as to foresee future scenarios in the building for its monitoring and structural behavior, thus avoiding the partial or total loss of the building. The incorporation of new tools and technological equipment in the recording and practice of Restoration enriches the possibilities of current and future theoretical positions in Conservation and Restoration, glimpsing an encouraging outlook in the conservation of the Built Heritage.

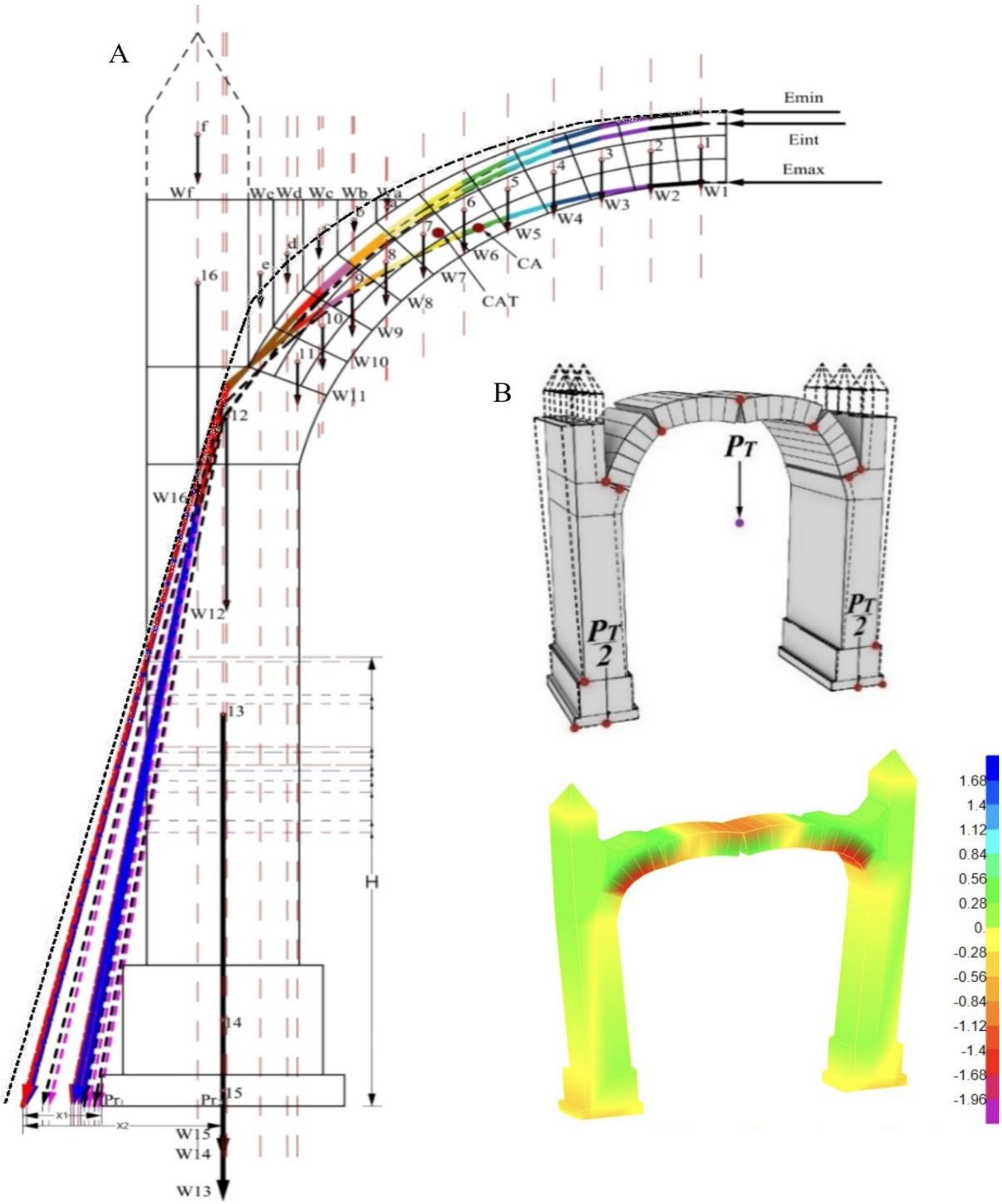


Fig. 16. Simulation of the hinge opening and gravity load distribution (Graphical and Finite Elements Methods "FEM"), a) vector analysis of a symmetric half of the arch system, b) digital computational models simulating the arch opening by means of hinges. Image taken and adapted from [17, 29].

From a technical perspective, the systemic understanding of materials, construction systems, mechanical properties, geometry and actions, as well as the appropriate selection and use of technological tools, allows the configuration of computational structural models that best represent real heritage buildings.

10 Conclusions

It was concluded that with the development of computational models, it is and has been feasible to virtually experiment with different structural scenarios for these buildings in order to observe their behavior and thus anticipate possible solutions without arbitrarily interfering with reality.

From a systemic perspective that interrelated historical, theoretical, and technical aspects—materials, construction systems, mechanical properties, geometry, and actions, as well as the appropriate selection and use of technological tools—it was possible to configure computational structural models that more accurately represented heritage buildings.

Computational tools and software worked effectively to streamline and refine structural analyses of complete systems, as well as the location of stress concentrations, displacements, vibration periods, modal shapes, compression thrust lines and hinge formation, which validated the areas of structural deterioration and cracking determined digitally in contrast to those detected in actual physical buildings.

Important note

This paper is derived from the analysis, synthesis, and integration of research works (projects: 20171664, 20181461, 20195419) of the Secretaría de Investigación y Posgrado (SIP) and from the theses and research carried out by students of the Sección de Estudios de Posgrado e Investigación (SEPI) de la Escuela Superior de Ingeniería y Arquitectura (ESIA) Unidad Tecamachalco (UT) del Instituto Politécnico Nacional (IPN), México.

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