Técnicas de avanzada en el diagnóstico patológico de edificaciones: “El Templete” de la Habana Vieja

Advanced techniques in building pathology diagnosis: “El Templete” of Old Habana

José Armando Chávez Hernández*, Jorge Luis Broche Lorenzo*, Carlos A. Recarey Morfa*, Fernando Sánchez García¹*, Miguel Ángel Maestre Mesa**, Noel Pérez Martínez***

* Universidad Central “Marta Abreu” de Las Villas. CUBA

** Empresa Nacional de Investigaciones Aplicadas (ENIA). Ministerio de la Construcción (MICONS). CUBA

*** Empresa Nacional de Investigaciones Aplicadas (ENIA). Ministerio de la Construcción (MICONS). Instituto Superior Politécnico “José Antonio Echavarría”. La Habana. CUBA

Fecha de Recepción: 28/11/2011

Fecha de Aceptación: 01/05/2012

PAG 19 - 33

Resumen

En el lugar exacto donde se fundó la Villa de San Cristóbal de La Habana, se levanta un monumento que semeja un pequeño templo de la Grecia antigua: El Templete. Esta importante edificación de la ciudad ha estado sufriendo de lesiones estructurales poco comunes para un inmueble de estas características: pequeña, de una estructura robusta, materiales adecuados, buena ejecución, y por tanto de una excelente estabilidad estructural. Varias intervenciones no han podido evitar que vuelvan a aparecer estas lesiones estructurales, por lo que se hizo necesario un estudio de mayor complejidad y utilizando técnicas más avanzadas, que permitieran llegar a conocer las verdaderas causas de los daños. En este trabajo se expone el procedimiento que se ha seguido para llegar a un diagnóstico sobre bases científicas, que es el soporte para realizar el proyecto de intervención y recuperación del inmueble.

Palabras Clave: Diagnóstico, Instrumentación, Edificaciones Patrimoniales, Modelación, Técnicas Avanzadas.

Abstract

Exactly in the same place where the Villa of San Cristóbal of Havana was founded, a monument that look like a small temple from Ancient Greece rises: The Templete. This important building of the city has been suffering unusual structural lesions for a construction with those characteristics: small, robust construction, suitable materials, proper execution, and therefore an excellent structural stability. Several interventions have failed to prevent reappearance of structural lesions, that is why it became necessary a more complex study and the use of more advanced techniques, which allow to get to know the true causes of the damage. This paper outlines the procedure to be followed to arrive at a diagnosis on a scientific basis, which is the main support for the proposed intervention and recovery project of the property.

Keywords: Advanced Techniques, Diagnosis, Instrumentation, Modelling, Patrimonial Buildings.

1. Introduction

The Templete is one of the most peculiar structures among Cuban architecture, well connected to the history and customs of La Habana City inhabitants. On November 16, 1519 a mess was celebrated in this place to found the Village. Figure 1 shows a picture of the building present condition, which has a Ceiba tree at the front, where habana inhabitants attend every November 16th to commemorate the village foundation and to make a wish.

On 1827 the Captain General of the island, Francisco Dionisio Vives ordered the construction of this building on the very same place, which today we recognize as the Templete. The building was inaugurated on 1828.

Over almost two hundred years the building has endure the regular deterioration caused by ageing. At a lower extent operation conditions have also affected this building, since it has been restored in several occasions, so as to eliminate main injuries taking place throughout time. However, injuries reappeared and some of them are even severer.

¹ Autor de correspondencia / Corresponding author:
E-mail: fsanchez@uclv.edu.cu

Figura 1. Imagen del Templete en la actualidad

Figure 1. Picture of the Templete at present time

That is the reason why the Historian Department of La Habana City has requested to The Counseling and Advisory Department for Modelling and Instrumentation of Structures and Ground, created by CIDEM¹ and ENIA², permission to develop studies of high theoretical complexity and practice on structure restoration. This Department was working at this time at the Palacio of Capitanes Generales³ in the very same Old Habana, which is quite close to the Templete. The requested research intended to study the reason why injuries reappeared after different restorations developed on this building and to provide recommendations for long-lasting treatments.

It was observed during the first visit to this building, and after performing a detailed injuries survey, that the main injuries were vertical crackings going from the roof down to each column on the pediment. There were vertical crackings at the sides, from the roof down to the walls base and, assumingly they also reached the foundation. It looked like the building has been vertically "cut". Through those crackings, which are primary injuries, the rain felt down and new pathological processes took place, thus affecting other areas and the pictorial patrimony in the building inside.

The researchers proposed the hypothesis that vertical crackings could be the result of differential settlements due to the ground characteristic where the building was constructed or, due to external factors such as affectations caused by the vigorous roots of the tree growing in front of the building.

¹ CIDEM (Research and Development Center for Structures and Materials). Research Center attached to the Construction Faculty of Universidad Central "Marta Abreu" de Las Villas. Cuba.

² ENIA (National Company of Applied Research). Company attached to the Ministry of Construction (MICOMS) of Cuba.

³ Palacio de los Capitanes Generales is one of the most ancient icons in Colonial Cuban Architecture placed at Plaza de Armas in the Old Habana, it is also a City Museum.

2. Development

The applied methodology is the “Procedure of pathological diagnosis for high complexity patrimonial buildings by means of computer techniques” (Chavez, 2005). This procedure not only uses computer techniques but it also employs all the tools that contribute to its utilization and development, such as mathematical modelling and the use of instrumentation.

The methodology considers four stages, including a series of specific tasks (Figure 2). It works as a systemic procedure, where obtained data will feed the following step. It is possible to go back and reformulate or complete contents with new findings any time it is needed.

Figura 2. Procedimiento utilizado en el estudio patológico llevado a cabo en el Templo

Figure 2. Procedure employed by the pathological research developed at the Temple

2.1 Stage I. Preliminary Inspection

The Temple has a rectangular floor plan inspired on Greek-roman architecture. It is composed of an architrave of six Doric column caps and baseboards, as well as four additional pilasters at the sides. The simple pediment is ornamented with Doric triglyphs alternating with heraldic figures. The columns are arranged in a symmetric but irregular way, as they are grouped in a peculiar sequence, and they show a clear drum quartering (Figures 3 and 4).

Figura 3. Destalle del capitel en las columnas

Figure 3. Details of column caps

Figura 4. Detalles del frontón

Figure 4. Details of pediment

Most elements were constructed from limestone aggregates of sedimentary type, well known as “conchiferous” due to the amount of shell and mollusks fossils contained in it. The stylobate is made of Carrara marble.

From a structural point of view, this is a load bearing wall building. Loads are transmitted from the roof down to the walls, by means of timber beams placed over the walls. Loads are transferred from the walls down to the foundation and then to the ground. The six columns in front area transmit a load portion from the roof and pediment down to the foundation.

The most affected areas of this building are the pediment and columns, as well as load bearing walls. Inspections carried out lead to the conclusion that it was not necessary to develop emerging actions such as shoring or evacuating the building, however it was necessary to protect works of art, since moisture could damage them.

At this stage it was proven that the application of an Identification and pathological diagnosis intelligent system (Charniak & McDermott, 1985) and (Bello, 2002) was not necessary; because injuries were well identified as from the first inspection in site. However, the injuries causes were unknown, and such System - employing artificial intelligence - is applied on injuries or injury families of complex identification and treatment.

During the dimensional survey study of the building and the structural components it is made of, laser devices were employed, which enabled the elaboration of floor drawings, storey heights and other details with great accuracy. Afterwards a 3D model was developed for the building including geometry data. Results indicated that it is a stable structure lacking of design or construction failures (Figure 5).

Figura 5. Modelo en 3D de la Edificación (GiD)

Figure 5. 3D model of the building (GiD)

2.2 Stage II. Previous Studies

Specialists, such as Álvarez (2003), agree on the fact that it is necessary to develop a correct diagnosis of the structure by studying the fundamental parameters that characterize the materials composing the structure. Such parameters enable the achievement of a building numerical model quite similar to its actual behavior, as long as an adequate numeric model calibration is carried out. In this stage, the working methodology shown on Figure 6 was employed, which became quite useful for obtaining the structure properties.

Figura 6. Trabajos realizados para la caracterización de los materiales

Figure 6. Research for materials characterization

Timber beams characteristics are shown on Table 1.

Tabla 1. Características mecánicas de la madera empleada en El Templete. Fuente: (Galabru, 1964), (Autores, 1978)

Table 1. Mechanical characteristics of timber beams employed in the Templete Source: (Galabru, 1964), (Authors, 1978)

Clase de Madera Timber type	Tracción (MPa) Tensile strength (Mpa)	Compresión Compression strength		Flexión en la fibra extrema (MPa) Flexure strength on the ultimate fiber (MPa)	Cortante paralelo a las fibras (MPa) Shear strength parallel to the fibers (MPa)	Módulo de elasticidad (MPa) Elasticity modulus (MPa)	Peso Especifico (kN/m ³) Specific weight (kN/m ³)	Coef. de POISSON Poisson Coefficient	Coef. de dilatación térmica Coefficient of thermal expansion
		Paralelas a las fibras (MPa) Parallel to the fibers (MPa)	Perpendicular a las fibras. (MPa) Perpendicular to the fibers (MPa)						
Dura/ Hard	218	81	47	120	7	17 360	11.25	0.18	5x10-6

In the case of walls composed of limestone and mortar, the homogenization theory is employed for material characterization. In the first place limestone and mortar are mechanically characterized, then, virtual tests are applied (micro and macro numerical modelling describing the behavior of the limestone-mortar compound), in order to obtain the mechanical characteristics of such compound material. For the determination of mechanical characteristics of load bearing walls (deformation modulus E and Poisson Coefficient of composed material - μ - and their corresponding ultimate strength parameters), the following actions were taken.

- Characterization of compound material and the properties of each single material (limestone and mortar).
- Test virtual modelling to determinate the influence of rock on the set.

- Definition of physical parameters of load bearing walls.

These parameters are relevant for structural modelling of the building, taking into account that load bearing walls are the bearing structure in this building. Detailed explanations of these actions are described below.

2.3 Organic-rich limestone ashlar masonry

A pressuremeter test and a plate bearing test were applied on limestone blocks, on different massifs, because taking walls cores was not allowed due to the protection restrictions on this building. From these curves modulus values can be obtained from expressions on Table 2. (Jiménez Salas y L. de Justo Alpañés, 1975). Additionally, cores were taken from rocky massifs from the place limestone used on the walls was originally extracted and, three-axial compression tests were also applied, which enabled achieving constituent parameters (elastic and plastic) that characterize such material.

Tabla 2. Ecuaciones para determinar los valores de módulo de deformación general

Table 2. Equations used to determine values of general deformation modulus

Tipo de Ensayo/ Type of test	Ecuación/ Equation	Términos/ Terms
Prueba de Placa Plate bearing test	$E = \frac{\Delta q}{S} \cdot \frac{\pi}{8} \cdot (1 - \nu) \cdot f_z \cdot B$	<p>B- Diámetro o ancho de la placa/ Diameter of plate width</p> <p>Δq- Incremento de presión para el cual se la va a calcular el valor del módulo/ Increased pressure from which modulus values will be calculated</p> <p>S- Variación en la deformación para ese incremento de tensión/ Deformation variation for such tensile strength increase</p> <p>f_z- Coeficiente de corrección que vale 1 si la placa está en la superficie y 0.85 si se encuentra en el fondo de una excavación/ Correction coefficient, which value is 1 if the plate is located on the surface and 0.85 if the plate is on the excavation base</p> <p>ν-Módulo de Poisson/ Poisson modulus</p>
Presiometría Pressuremeter test	$E = (1 + \nu) \cdot \frac{(r_1 + r_2)}{2} \cdot \frac{(p_2 - p_1)}{(r_2 - r_1)}$	

2.4 Modelling of ashlar masonry and mortar compound

In order to estimate the parameters of compound material several methods are employed (such as in-situ real tests, laboratory-scale, non-destructive and virtual, micro and macro-modelling tests), so as to accurately define the physical-mechanical properties for a correct structural modeling.

Each test is developed to determine physical-mechanical parameters of the compound and, to asses which is the influence the limestone block has on load bearing walls. By considering the initial hypothesis that because of the block structure and dimensions regarding the mortar, the parameters characterizing the wall shall be defined by the contribution of ashlar masonry block. Figures 7 and 8 depict some virtual modelling schemes for an ashlar masonry wall.

Figura 7. Modelación virtual del ensayo a compresión diagonal
Figure 7. Virtual modelling of the diagonal compression test

Figura 8 Modelación virtual del ensayo a compresión simple
Figure 8. Virtual modelling of simple compression test

It was confirmed that limestone ashlar masonry corresponds to a massive stratification of organic-rich limestone, with high levels of porosity and water absorption, which favor density and steady loads increases.

Besides the effects of building expansion/contraction and abrupt changes of existing stiffness, caused due to different elements dimensions comprised by the structure are considered. Such characteristics are influencing the injuries appearance.

The soil was also studied by using a pole-pole electric tomography, to recreate in a three dimensional way the soil underneath the building and to incorporate this recreation into the building modelling. For the first time this type of test was carried out in the country. Four drilling points were selected (Figure 9) and soil samples were extracted by introducing electric radiation probes. Drilling procedure was made with tungsten crowns and simple bearing cores, by casing down to 7.40 m depth (Figure 10).

Figura 9. Ubicación de las calas
Figure 9. Test holes arrangement

Figura 10. Operarios en la máquina perforadora Mark V
Figure 10. Workers operating drilling machine Mark V

This paper obviates a detailed explanation of test procedure by means of electric tomography. The value employed to identify images tallies with drillings number and their sequence order. For instance image T12 is the image between test hole 1 and test hole 2. The image will be always seen from the perimeter outside. Quadrupole measurements sequences were developed by means of the "Electre" software, which is also used to transfer the automatic measurements method into the measuring equipment. Six tomographic sections were measured by using the pole-pole variable and tomographic images ρ_a were created for each of them.

Figure 11 shows some examples of soil tomograms

Figura 11. Imágenes reales del equipo de geoelectricidad

Figure 11. Real images of the geo-electricity device

Once these sections are obtained the three-dimensional model was developed as shown on Figure 12

Figura 12. Representación esquemática de la compleja geometría de los diferentes estratos de terreno detectados debajo de la cimentación del Templo
Figure 12. Scheme representation for the complex geometry of different soil strata detected underneath the Temple foundation

After reaching the soil three-dimensional model, the building was placed on it to develop the modelling later (Figure 13).

Figura 13. Estratos de terreno detectados debajo de la cimentación del Templo
Figure 13. ground strata detected underneath the Temple foundation

The great diversity of strata existing underneath the building was confirmed as well as its irregular distribution.

The “pocket” found exactly beneath the building draw special attention. As a result of such analyses, four engineering-geological elements were defined, which fully characterize different studied profiles (Maestre, 2008). It was proven that this is a quite heterogeneous, poorly resistant soil, with high water content due to its proximity to the seaside and groundwater (Figure 14 and Table 3)

Figura 14. Muestra del elemento ingeniero- geológico No. 4
Figure 14. Sample of engineering-geological element Nr. 4

Tabla 3. Propiedades de las rocas y el suelo
Table 3. Properties of rocks and soil

	Y (Kn/m ³)	E (Mpa)	μ
Roca Calcarenitas/ Calcarenite	19.8	210	0.3
Caliza/ Limestone	22	350	0.32
Suelo Residual/ Residual soil	18	40	0.26
Arcilla/ Clay	16	15	0.38

Data obtained so far (building loads and soil properties) are added to the initial model, which is calibrated later. This methodology phase is called Modelling (Phase 2). At this research point, the initial hypothesis was already proven: that the Temple was “sliding” together with the soil where it was constructed. Differential settlements were the cause of crackings taking place in the structure.

2.5 Stage III. Pathological diagnosis

In this stage all pathologies survey is completed, as well as structural pathologies already under study (Pentón, 2007).

This separate group included pathologies related to moisture, dirtiness, actions of plants and some other mechanical actions among others (Coscollano, 2000). (Figures 15 and 16)

Figura 15. Manchas de humedad por filtraciones en la cubierta
Figure 15. Moisture spots due to leakage on the roof

Figura 16. Grietas y partiduras en las losas de mármol del piso
Figure 16. Crackings and fissures on the floor marble flagstones

All these information from pathological processes was used to develop a graphical visualization system, by means of ArcView software. A knowledgebase (Peña 2006), (Galvez, 2006) from the data management system was delivered to the Historian Department.

Besides injuries caused by differential settlements, the building stone elements have also been affected by marine breeze, since the Temple is located 200 meters from the seaside. High relative humidity, wind, heavy rains and preservation system deficiencies have also affected the structure (Pérez, 2000).

Due to the type and extent of injuries, the following diagnosis was reached:

- 1. As far as recommended intervention level is concerned: (Table 4)*
- 2. The general technical condition of this building can be classified as a regular condition, not only due to present injuries but also by new potential ones, especially those related to differential settlements and moisture.*
- 3. Before conducting an intervention project, it would be convenient to develop some waterproofing test holes in order to achieve the layer height and being able to rectify slopes.*

4. *In the building south-eastern corner, where injuries are likely caused by a settlement turn on the foundation base, it is convenient to develop a prospection enabling the determination of settlement extent. In this case, it is convenient to use geo-technical and structural instrumentation so as to determine whether the differential settlement is active or not. In this way the need to develop an earth-fill or not is decided, so as to limit the probable progress of differential settlements.*
5. *Due to the fact that ever since there has been a big tree in front of the Temple, roots have affected its floors, pavements and other elements, which gets even worse due to the soil stratification existing underneath the building.*

Tabla 4. Recomendaciones según los procesos patológicos
Table 4. Recommendations according to pathological processes

MANIFESTACIÓN MANIFESTATION	AFECTA A AFFECTS	NIVEL DE INTERVENCIÓN RECOMENDADO RECOMMENDED INTERVENTION LEVEL
Fisuras/ Fissures	Seguridad y durabilidad/ Safety and durability	Imprescindible/ Essential
Humedades/ Moistures	Durabilidad/ Durability	Imprescindible/ Essential
Otras lesiones/ Other injuries	Estética y confort/ Aesthetics and comfort	Recomendado/ Recommended

2.6 Stage IV: Proposed actions

In this stage a set of recommendations to be considered for the intervention project were elaborated. Since the main tests were developed to achieve crackings causes, and these causes were already known, it was recommended to study which would be the most adequate treatment for intervening stone, considering its peculiar characteristics and damages it has suffered so far. In this case, some researches like the one developed by Juan Monjo (Monjo, 1998) were considered, as much for cleaning and reinforcement of natural stone walls. The designation of an interdisciplinary team was recommended to deal with damages caused on the building pictorial and sculptural assets. A desalination process was proposed among the actions to be taken when the report on the salt type and its effects is available. Other aspects to deal with are metal elements, especially those in contact with stones, due to damages caused by fractures during their corrosion process. Furthermore, mortars to be used shall be studied, which in all cases must be similar to the original ones, as far as dosage and composition are concerned.

Regarding the most relevant subject, that is the soil condition and its structural behavior, we shall refer to results provided by modelling because such process elaborated two models: one considering soil stiffness underneath foundation and the other that considers soil as a rigid solid. The results obtained from the model considering the soil as a rigid solid enabled the determination of causes that provoke structural pathologies existing in the building, as well as focusing the efforts towards a soil-structure interaction analysis, in order to asses the influence of soil deformation on crackings appearance.

The analysis facilitated the comparison among tensile stress concentration zones with the respective structural pathologies allocation inside the building; thus demonstrating that crackings appearance is caused by differential settlements. The fracture of masonry stone is produced by the action of vertical loads, which act on the complex geometrical shape of the strata, thus provoking a differential settlement and a turn in the building simultaneously.

For these kinds of injuries, the project team recommended to develop some earth-filling to stop differential settlements progress, especially in the building south-eastern corner that contains the highest volume of plastic clay pocket. This solution was modeled proving that settlements as well as crackings were eliminated. Therefore, the problem is overcome.

3. Conclusions

Without the applications of advanced techniques as the ones used in this research job, it would have been too difficult - if not impossible - to achieve the true cause of main injuries and, the whole intervention project would have been a failure, thus pathologies would intermittently reappear. In high-value patrimonial and highly-protected buildings, the use of instrumentation and modelling are the best choice to conduct a correct diagnosis avoiding the application of traumatic techniques on the structure.

The procedure applied happened to be quite useful, in spite of the fact that some techniques such as the Identification and Pathological Diagnosis Intelligent System and Graphical Visualization System did not play a prominent role as the building is quite small, they contributed to establish the actions to be taken and they enabled the complementation between each research stage.

Finally, the most complete and scientifically documented report ever made on the Templete was elaborated, which guarantees that future interventions will be supplied with high level scientific data.

4. Referencias/ References

- Autores C. (1978)**, Madera. Normas Cubanas. NC 053-036-78. La Habana.: Oficina Nacional de Normalización.
- Bello R. (2002)**, Aplicaciones de la Inteligencia Artificial. Guadalajara: Universidad de Guadalajara.
- Coscollano Rodríguez J. (2000)**, Tratamiento de las Humedades en los Edificios. Madrid, España: International Thompson.
- Charniak E. y McDermott D. (1985)**, Introduction to Artificial Intelligence.: Addison Wesley.
- Chávez Hernández J.A. (2005)**, Procedimiento para el diagnóstico patológico de edificaciones patrimoniales de alta complejidad a través de técnicas computacionales. Editorial Samuel Feijoó. Universidad Central "Marta Abreu" de Las Villas., Santa Clara. Villa Clara.
- Galabru P. (1964)**, Obras de Fábricas y Metálicas. TRATADO DE PROCEDIMIENTOS GENERALES DE CONSTRUCCION - Ilustrado. Barcelona.: Editorial Reverté.
- Gálvez Lio D. (2006)**, Sistemas basados en conocimiento. Santa Clara: Universidad Central "Marta Abreu" de Las Villas.
- Jiménez Salas J.A. y L. de Justo Alpañés J. (1975)**, Geotecnia y Cimientos I. Propiedades de los suelos y de las rocas.: Editorial Rueda.
- Maestre Mesa M.A. (2008)**, Proyecto de Investigación Patológico, edificación: El Templete. Informe de Perforación y Muestreo. Oficina de Consultoría y Asesoría de Modelación e Instrumentación de las Estructuras y el Terreno. (ENIA-CIDEM). La Habana. Cuba.
- Monjo Carrió J. (1998)**, Tratado de Rehabilitación (Munilla-Leira ed. Vol. 3). Madrid, España: Universidad Politécnica de Madrid.
- Pentón Piña E. (2007)**, Patologías y Tratamiento de los materiales pétreos naturales utilizados en la construcción de edificaciones. Diploma, Universidad Central "Marta Abreu" de Las Villas, Villa Clara, Santa Clara, Cuba.
- Peña Ayala A. (2006)**, Sistemas basados en Conocimiento: Una Base para su Concepción y Desarrollo. Mexico.
- Pérez Echazábal L. (2000)**, Influencia del medio ambiente en la patología de los monumentos de alto valor histórico construidos con materiales pétreos naturales. Doctoral, Instituto Superior Politécnico "José Antonio Echevarría", La Habana, Cuba.