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ARCHITECTONIC AND STRUCTURAL STUDY OF FORT SAN DIEGO AT ACAPULCO

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Abstract. *With reference to historical data the actual conditions of Fort San Diego at Acapulco are analyzed. This study encompasses the architectural features, the geometry details and the structural behavior. Results of field works are presented and discussed, mainly on topographical survey, architectural features, materials characterization, and hardness measurements of the main materials and survey of damages. Architectural aspects are related to classical treatise and antique books on military engineering. The recommendations for the preservation of the architectural values are made based on these. Geometrical characteristics are pointed out, and it is demonstrated that the plan follows three concentric circles almost perfectly. The circles have radii of 70 varas (58.45 m), 50 varas (41.75 m) and 40 varas (33.40 m) respectively. It is also noted that the outer picks form a quasi-perfect pentagon. With the data of field studies a probable construction sequence is proposed consisting of eight major steps that take several decades to be completed. The probable structural behavior was investigated mainly for the eventuality of the occurrence of intense earthquakes. According with historical data, the fort was practically destroyed in 1776 during a severe earthquake and it was rebuilt in later years to its actual general form. Thus, a particular interest in this study was the strength assessment of the fort for the case of the biggest earthquake expected in the zone. The vulnerability of the structure was investigated mainly because the fort is currently used as a museum with the possibility to be crowded. In order to do this, an analytical model was developed and damage and vulnerability indexes were calculated according to the method proposed by Lagomarsino. The analysis of the data shows that the probable structural behavior of the monument is safe for normal operating conditions but might have moderate to severe damages for the eventuality of the occurrence of an earthquake with the greatest intensity expected in the area. Some parts of this study will be proposed to form part of informative literature accessible to visitors of the fort.*

1 INTRODUCTION

The subject of this paper is the technology and design of Spanish fortifications in America. Remarkable examples of this kind of construction exist at the coast of Pacific Ocean, the Caribbean and the Golf of Mexico. One of the most important is San Diego Fort at Acapulco because the building represents definitive contributions to know the technology and construction materials which gave base to the design and architectural composition of the military fortress from that time. The photograph presented in Figure 1 show a partial view of San Diego Fort. Because its strategic position at that time, this fort transcended not only in New Spain (actual Mexico) but also in Europe, because Acapulco was the base of operation of *La Nao de China* (Philippine Galleon) which support the commerce between America and Europe with Orient. The forts of San Diego at Acapulco and San Juan de Ulúa at Veracruz were the main protection facilities for that commerce activity.

Figure 1. Partial View of San Diego Fort at Acapulco.

The objective of this paper is to analyze the main technical characteristics of the building in relation to architectonic and constructive aspects and to compare with the theory of fortifications by Christoval de Rojas [1] published in 1598. The methodology followed was based in the next steps:

1. The investigation of data directly on the site, in particular in regard to: a) composition and design formal aspects, b) geometric characteristics by means of architectural and topographical surveys, c) the basic properties of the materials with in situ observations and non destructive tests.

2. To compare the data obtained with other sources of information, mainly the Tratado de Fortificaciones (Fortification treaty) written during XVI Century by Christoval de Rojas [1] and to know at what deep the formal criteria was followed.

3. To propose the possible constructive sequence and to analyze the structural behavior expected.

2 ANTECEDENTS

In 1565 Fray Andrés de Urdaneta disembarked at Acapulco Port who came back from Philippines establishing in this way the route from Asia to America crossing the Pacific Ocean. Thanks to that circumstance that year starts the navigation of The Galleon which for more than 200 years maintains, with frequent and some times prolonged interruption, the Spanish commerce with Orient. This was the main reason to build a fortification at Acapulco.

By the year 1608 it is known that a first defensive construction was built consisting of some masonry walls and a timber building with tile roofs which can explain the presence of broken clay tiles in the mass of mortar of subsequent constructive stages. Because of the attack incursions of Holland warships to the port in 1615 the Spanish Crown decided to substitute the primitive defenses by a formal fortification. The design and construction of the new fort is attributed to Adrian Boot from 1615 to 1617. The basic characteristic of that fortification was an irregular pentagon with two *caballeros* (bastions) looking to the coast, this is known by a plan made by Ramón Panón published in 1772.

This building was destroyed during an intense earthquake in 1776, so another fort was constructed from 1778 to 1783 according with an initial project of Miguel Constanzó, by the way author of a remarkable geographic and ethnographic study on North California. The project of Constanzó was based again in an irregular pentagon; however the final construction results in a regular pentagon, modification attributed to Ramón Panón [2]. The construction of the fort was concluded until 1809 and is the one that exist to day; however some modifications and reparation were made in different years before.

3 ARCHITECTURE, TRACE, DESIGN AND COMPOSITION

The geometry of the actual fort in plan is a rectangular pentagon inscribed in an exterior circle with 140 *varas* (116.9 m) diameter, other concentric circle with diameter of 100 *varas* (83.5 m) defines the lateral folds of the five bastions. Other smaller concentric circle with diameter of 80 *varas* (66.8 m) define the point were the ends of the bastions intersect with the beginning of the curtains. It is assumed that the unit of measure of that time was the *vara castellana* equivalent to 835 mm. The angle of the vertices between two consecutive bastions is 70 degrees with small variations. The main geometrical characteristics of the fort are presented in Figure 2. It was demonstrated that Ramón Panón, the author of the regular pentagon, based his design on the rules established by Christoval de Rojas, as well as some influence of classical treaties of Vitruvius and Le Pestre.

The analysis of Figure 2 shows that the geometry follows, in a very direct and simple way, the rules according to the defensive criteria for the fortifications at that time. Considering the limitations of measure apparatus at that time (cords, chains and primitive levels or corobates) and the technical difficulties in a very irregular land, is amazing the level of accuracy attained, the deviation of the angles defining the picks of the five bastions is not more than 2 degrees

(2.3%), that is, the real plan is very accurate respect the theoretical project of a regular pentagon, this fact is represented in Figure 2 which sows the theoretical and actual traces, the last based in measurements taken in April 2007.

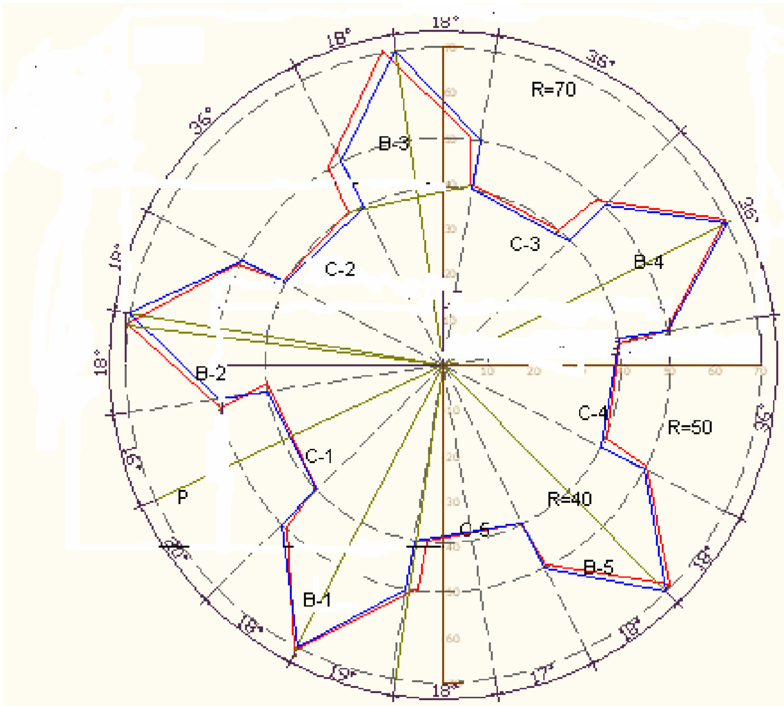

Figure 2. Geometrical characteristics of San Diego Fort at Acapulco

Figure 3 shows the distribution of rooms in the inner part of the fort and Figure 4 show the correspondent theoretical design proposed by Rojas in his treaty of 1598, so the military engineer Panón for sure based his design, trace and construction on that book. The pentagon shape according with Rojas was very useful in places with a face directed to the sea and the other directed to land, because permitted strategic movements for attack and defense strategies, as well for counteroffensive, vigilance and internal security. Before construction it was recommended to the builders to perform a paper scale drawing on a wood platform of "generous dimension" in order to verify dimensions and angles as well as geometric forms by means of architects square and compass. With this exercise the definitive trace on the land was facilitated using ropes and poles, as an extension of the experience on paper.

In general the architectonic program utilized in the construction of the fort included: five bastions with the names of La Concepción, Santa Bárbara, San Luis, San Antonio and San José; a chapel, bridge, the plaza or mall, habitation rooms, storage, defensive ditch and covered access.

Figure 3. Inner distribution of San Diego Fort at Acapulco

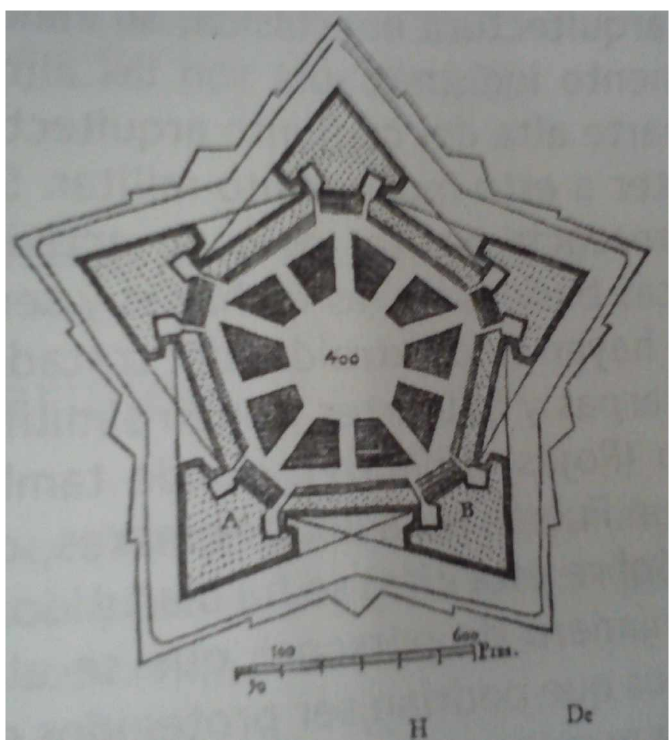

Figure 4. Geometrical idealization of pentagonal fort according with Rojas (1598)

4 MATERIALS

The accurate inspection of the building permitted the identification of the principal materials for the construction, a brief description is as follows:

Granitic stone in different shapes: a) slabs of irregular form as a cover of interior and exterior walls some with step slope with defensive purposes, b) as blocks with a carved face in the upper part of the walls, c) thin slabs supposedly as reparation elements after the construction was completed. Mean measured hardness was 61.9 with a rank (higher value minus lesser value) of 18.1 which means great variation from one zone to the other. Estimated probable strength was 50 MPa.

Limestone: of the type locally known as *piedra muca*, of coralline origin with fossil shells in the interior. This material was used in the edges of the bastions probably to get a cushioning effect to projectiles during attacks. Mean measured hardness was 30.8 with a rank of 14.0, the strength is approximately compared to that of a mean to low concrete of about 20 MPa.

Stone-cutting: soft stone of pink color used at the facades of the main accesses and in particular in arches and supports as well as architectonic details and ornaments. Mean measured hardness was 55.3 with a rank of 12.3, estimated strength of 30.0 MPa.

Bricks: prismatic pieces of burned clay with dimensions of 80, 200 and 400 mm, this material is very uniform in shape and hardness, probably of European origin, because it was used also as a ballast of the vessels in the returning trip from Europe. This material was used to construct the vaults to cover the inner rooms as well as the structural component of arches of the access bridge, the cistern and details of the sentry-boxes (garitones). Also was used as infill material in walls and foundations. Mean measured hardness was 28.5 with a rank of 5.2 with low variation and estimated strength of 25.0 MPa.

Mortar: material with a remarkable hardness which has resisted very well the effect of the salty environment. In several references it is mentioned that an admixture was added to obtain extra hardness and durability as crushed shells or clay, natural resins or egg whites. It was not possible to verify the presence of addition of that type, however in some parts, were the mortar is apparent, it is clear the addition of burned and pulverized clay, may be grind bricks or tiles, technique that at the time of colony was known as *picadiz*. Mean measured hardness was 26.7 and rank of 16.8 which are associated with a high variation. The probably strength considering the variation was estimated as 5.0 MPa.

Pulse velocity was measured in six representative point of mortar. The average in the horizontal direction was 4100 m/s and 3200 m/s in the vertical direction, the difference is attributed to the formation of micro-cracks in the vertical direction due to the effect of exposure to rain and other natural phenomenon. The strength of the mortar bases in this data is approximately 4.0 MPa which is compatible with the estimation in base of hardness data.

For the conjunction of the masonry using the data obtained and the criterion proposed by Meli [3] the properties for the main materials were proposed as follows: a) walls, compressive strength 20 MPa., shear strength 0.06 MPa, volumetric weight 21 kN/m³ (2150 kg/m³), b) vaults, compressive strength 1.5 MPa , shear strength 0.04 Mpa, volumetric weight 17.68 kN/m³ (1800 kg/m³). These estimated values were used as the base to analyze the structural behavior as will be treated later.

5 CONSTRUCTIVE PROCEDURE

The actual building was founded on the remains of the former, according with the observations on site, and data from Sáenz [4], the probable constructive process consist of:

1. General outlining and leveling of the trench and base platform. For this parts of the former construction were demolish an others incorporated to the walls of the new building.
2. Consolidation of the platform with irregular rocks embedded in thick layers of mortar, as a cyclopean concrete.
3. Erection of exterior walls with steep slope, the inner part of the walls constructed with granite irregular slabs with joints of lime and sand mortar of about 100 mm thick. Walls rose to a high of about 9.6 m from the lower level of the trench. This was done in several stages, at least two horizontal discontinuities were observed in the perimeter of the walls. The inclination of the escarpment is very close to 9 degrees respects the vertical; this inclination was decided in base of military concepts to minimize probable damage from cannon projectiles from war vessels.
4. Construction of the exterior cover with granite slabs with the plain side to the exterior.
5. Construction of the lower part of interior walls to form a reticular body to give confinement to the whole structure, according with the book of Rojas: "…as an exterior pressure equivalent to the force of the projectiles" The junction of the interior reticular body to the exterior walls was attained by superposition and interlocking between rocks.
6. Fill of the vain parts of the reticular body with gravel and construction waste except at the cistern that was covered with brick vaults. It seems that the fort was left some years al this level, 5.30 m approximately from the lower part of the trench, and then the function was as a plan fortification with some provisional construction on it.
7. Complete the interior rooms with the same procedures already described, and then the construction of the cover with brick vaults.
8. Construction of the interior finishing of the vaults with lime and sand mortar and a hardening material in the surface. In the upper part a flat roof was constructed with light mortar to attain a plane surface and finally a water proof finishing made of mortar, alum and soap as was common at that time.

6 STRUCTURAL BEHAVIOR

The site observations permitted to identify the principal causes of structural affectations as follows: a) the deterioration of the materials due to the saline environment, b) settlements of some heavy parts of the construction because of the irregular morphology of the zone which causes cracks in walls and vaults, c) the human activity which causes some modifications and the transit of visitors causing deterioration to floor and finishing materials.

With data obtained the procedure proposed by Lagomarsino [5] was applied to estimate the damage index (Id) and the vulnerability index (Iv) of historical buildings. For this macro-elements with a defined structural behavior were identified, composed by it self with walls, vaults and supports. In this way, as can be seen in Figure 2, eleven macro-elements were defined: the five bastions, the five intermediate rectangular blocks (curtains) and the access bridge.

Damage index (Id) is an estimation of the level of damage in a scale from cero to one, cero means total absence of damage and one is an upper limit meaning total damage. The vulnerability index (Iv) represents an estimation of the probability of damage during an intense earthquake as a function of the vulnerability of the components.

Calculations for the eleven macro-elements are summarized in Table 1, in which N is the number of components (walls, vaults, arches) of each macro-element, m is the number of components that is not possible to evaluate (difficult to inspect, for instance). The parameter Sk is the summation of the level of damage for each component from 0 to 3, the damage index is calculated as: Id = Sk/3N. The parameter Sv is the summation of the probable occurranse of damages for each component from 0 to 2, the vulnerability index is calculated as: Iv = Sv/2(N-m)

The calculated average for Id for all the macro-elements was 0.29 with a rank of 0.30. This indicates a remarkable variability. This can be interpreted that the damage of the building is of consideration, but the stability in general is not affected except at isolated parts

The calculated average of vulnerability index for all the macro-elements was 0.43 with a rank of 0.30, which means an estimated probability of 43% of damages during an intense earthquake. In the supposition of all the present damages were repaired with more or less effective techniques [6], it was estimated a reduction of the average of the damage index (Ida) to 0.15 and the average vulnerability index (Iva) to 0.24, that is a reduction of probability of damage of about half. It is concluded that very good safe condition can be attained with a relative low cost [7]. It is noticed that a level of intrinsic vulnerability is present which can not be avoided with only reparation. In the case of complete safe conditions were desired strengthening and partial re-structural techniques will be needed.

Table 1. Summary of damage index and vulnerability index.

Macro-element	N	m	Sk	Id	Ida	Sv	Iv	Iva
B1 (bastion)	16	2	20.2	0.42	0.24	12.1	0.45	0.28
B2 (bastion)	17	4	17.8	0.35	0.20	14.8	0.57	0.32
B3 (bastion)	17	3	12.0	0.24	0.14	12.8	0.46	0.23
B4 (bastion)	15	2	11.9	0.26	0.16	12.8	0.49	0.21
B5 (bastion)	15	2	12.9	0.29	0.14	7.1	0.27	0.19
C1 (block)	13	2	8.3	0.21	0.10	8.0	0.36	0.19
C2 (block)	16	3	10.1	0.21	0.11	13.1	0.50	0.26
C3 (block)	12	2	7.5	0.21	0.11	9.2	0.46	0.22
C4 (block)	13	3	8.5	0.22	0.11	10.3	0.52	0.34
C5 (block)	11	3	6.8	0.21	0.07	5.9	0.37	0.21
P (bridge)	7	0	10.9	0.52	0.29	4.7	0.34	0.16

7 CONCLUSIONS

There is enough evidence to set that the design, composition and construction of San Diego Fort were based in the Fortification treaty by Christoval de Rojas.

The principal materials used in the construction of the fort were: granitic stones of different shapes and origin, limestone of the kind known locally as piedra muca, bricks and mortar. With the data of non destructive tests it was possible to estimate the strength of the materials and masonry.

The mortar exhibits a remarkable hardness which has been resisted very well the effect of the salty environment this was attributed to the pozolanic effect of the addition of burned and pulverized clay, may be grind bricks or tiles, technique that at the time of colony was known as picadiz.

In relation to the structural behavior a diagnosis was elaborated which main aspect are: a) the damages in different parts of the building are of consideration however the stability in general is not affected except at isolated parts, b) the level of vulnerability in the case of a intense earthquake is important and in that case severe damages and local collapses may occur, c) in the supposition of all the present damages were repaired with more or less effective techniques a reduction of probability of damage of about half will be attained.

The reparation of damages is recommended, in that way a very good safe condition can be attained with a relative low cost.

A level of intrinsic vulnerability is present which can not be avoided with only reparation. In the case of complete safe conditions were desired strengthening and partial re-structural techniques will be needed.

REFERENCES

[1] Rojas, Christoval de (1598) *Teoría y práctica de la fortificación conforme las medidas y defensas de estos tiempos, repartida en tres partes*. Editor Luis Sánchez. Madrid, España.

[2] Moncada, José (1985) *Ingenieros Militares en Nueva España, inventario de su labor científica y espacial Siglos XVI a XVIII.* UNAM, México.

[3] Meli, Roberto (1998) *Ingeniería estructural de los edificios históricos. Fundación ICA*, México

[4] Sáenz, Sarah (2009) *Tres fortificaciones en Nueva España. Estudio arquitectónico-constructivo.* Tesis de doctorado. Universidad Politécnica de Cataluña. Barcelona España.

[5] Lagomarsino, S. (1998) *A new methodology for the post-earthquake investigation of ancient churches*. Proceedings of the European Conference on Earthquake Engineering. Paris, France

[6] Chanfón, Carlos (1996) F*undamentos teóricos de la restauración,* UNAM. México

[7] Binda, L. and Saisi, A. (2002) *State of the art of research on historic structures in Italy. Department of Structural Engineering.* Polytechnic of Milan, Italy .