STRUCTURAL MONITORING OF CASTILLO DE SAN MARCOS NATIONAL MONUMENT
by National Park Service, Southeast Cultural Resources Preservation Center

Interdisciplinary Research Team:
Dr. Dennis B. Fenn (NPS, Texas A & M); Eng. Todd Rutenbeck (Bureau of Reclamation); Dr. Lawrence I. Knab and Dr. James R. Clifton (National Bureau of Standards); and, Dr. Benjamin B.G. Nistal-Moret (NPS, Southeast Preservation Center)

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Introduction

Castillo de San Marcos is located in St. Agustine, Florida, on the shore of Matanzas Bay, about a mile from the Atlantic Ocean. The Castillo is the oldest existing masonry fortress constructed of coquina stone. Its construction was started in 1672 and many modifications were made until its final deactivation as a fort in 1900. The walls were once plastered with lime stucco, most of which has been completely eroded. Gradually, the exposed surfaces of the exterior stone have weathered and some of the most severely deteriorated stone has been replaced. The Fort is exposed to seasonallyheavy thunderstones and sea-water spray. Coquina is a porous stone which can be easily penetrated by water and, as a consequence, the walls appear damp and in some areas efflorescence is observed.

The Castillo shows a series of cracks running through the bastions, casemates and scarps along the west elevation which rests on a wet moat subject to sea tidal action. The terreplein is detached from the west wall in many sections. Historic records indicate these problems have existed for many years, but the matter is of serious concern for the National Park Service (NPS) which plans to have Castillo structurally stabilized by 1992.

The Director of NPS instructed the Southeast Preservation Center to develop a low-cost and intensive monitoring program for the monument to determine pathological conditions of building materials, causes of deterioration, structural conditions, and causes of possible structural movements. The collection of data was to be accomplished within a year of installation (1986-7) to have results ready for analysis and preservation planning by 1988-9, and interventions by 1989-90.

The monitoring program was designed as a four-stage interdisciplinary plan to be conducted concurrently: (1) structural crack monitoring to measure vertical, horizontal, settlement and tilting movements; (2) moisture and temperature study of environmental air, surface of building materials and substrate of building materials; (3) coquina stone study to determine compressive strength, absorption, bulk specific gravity, and flexural strength; and (4) geotechnical study to establish subgrade characteristics and composition, compressive strength, load bearing capacities, and porosity.

Monitoring structural movements (Eng. Todd Rutenbeck)

The purpose of the study is to determine if progressive structural movements are taking place which could lead to collapse along the western half of the Fort. The cracking is evidence of past structural movement, but it is possible that current movements are only seasonal fluctuations.

Structural movement monitoring data will be correlated with other data to locate any serious structural defects and to develop guidelines for stabilization. Monitoring is also viewed as a management tool for the best use of funding and prevention of uneeded modern intrusions. Vertical cracking of exterior walls, cracks between the walls and non-historic firing steps, and cracks between vaults of casemates and the exterior wall combined with the effects of varying water levels in the wet moat above the foundation suggest serious structural problems that would be very expensive to correct.

To measure changes in cracks width, it was necessary to have an accurate system that could resist corrosion in a humid, salt-spray environment and not to succumb to vandalism. As eight of the gages were to be mounted high on the scarp above the moat, it was also desirable to be able to read the gages without erecting a ladder in the moat for each reading. LVDT electronic gages would provide the needed remote readout but were rejected for two reasons: (1) wires leading to the LVDT may be used as roped by vandals scalating the walls, and (2) it would cost several hundred dollars per gage to replace units damaged by vandals or by corrosion. It was decided to use waterproof mechanical dial gages and to read inaccessible gages using a tripod-mounted telescope. Replacement costs for these gages is about $60.00 each.

Eight vertical cracks in exterior walls were instrumented. At each location a gage with a range of 5mm and an accuracy of 0.01mm was installed across the crack about three-fourths of the way up the wall. Cracks between the firing steps on the terreplein and the exterior walls were instrumented at five different locations. Gages were installed by bolting a dial indicator to a length of 1" x 1" x 3/16" aluminium angle stock. A small area on the wall was cleaned with a wire brush and heated with a propane torch to evaporate moisture from the bonding surface. The aluminium surface was cleaned and scratched with an awl to produce a rough surface. An epoxy putty with a setting time of five minutes was used to bond the gage assembly to the wall. On the other side of the crack, a bracket made by bending a length of 1" x 1/4" aluminium stock 90° was installed as the bearing surface for the gage indicator plunger. Gages installed on the firing steps used a small flat plate on the perpendicular adjacent wall surface as a bearing surface. All gages are read monthly by park staff. Approximately every three months, the gages are inspected for proper operation and any signs of water leakage or internal corrosion.

During the first six months of monitoring, many of the cracks continued to get wider. That trend is now moderating and could possible reverse. At least one full year's data will be needed to separate seasonal fluctuations from progressive movements. At least one year of overlap with wall moisture and temperature data will be needed to correlate trends. There are many factors that can cause seasonal changes in gage readings. The dimensions of the dial indicator and the gage brackets change with temperature both during the day and from season to season. While changes in temperature during the day can also affect the structure, the largest effects on the structure come from gradual changes from one season to the next. Both temperature and moisture changes can change the dimension of the wall sections and thus change the width of the cracks. Changes in moisture content of the soil at the foundation can also cause seasonal movements under some conditions. Such seasonal movements can be separated from the more dangerous progressive movements by studying a plot of movement versus time.

This simple but accurate monitoring system has, thus far, shown itself to be effective and trouble free. Should one or two years of monitoring reveal only seasonal movements, the monitoring will be discontinued. If progressive movements are taking place, additional instrumentation to measure wall tilt and foundation settlement will be installed to determine exact locations for needed structural and foundation modifications.

Wall moisture and temperature study (Dr. Dennis B. Fenn)

The goal of this portion of the monitoring program is to determine the moisture content and temperature on and within the coquina stone of the west wall of the

Fort which required the drilling of holes through historic material to provide access to the interior of the walls. To minimize the number of such holes it was desirable to find a moisture probe that could also measure temperature. This was a difficult task since few marketed probes possess that capability. One tested was the AGWA-II soil matric potential sensor by Agwatronics Inc. of Merced, California. The probe was tested in a sample of coquina stone and performed very well, for which reason it was selected for use at Castillo de San Marcos.

The measurement of matric potential, a property directly related to moisture content below saturation in a given porous medium can be a labor intensive effort when numerous probes are involved. In order to provide continous record for all 16 probes implanted in the west wall a data acquisition and recording system was installed which automatically records moisture/temperature readings every 24 hours per day. Each probe is read every 6 hours on the hour and the data is stored on magnetic tape and printed in tape paper. This system will yield a full year of data gathering with sub-minimum labor effort. The data recording system is composed of anHP41CV programmable calculator, an HP3421 data acquisition system,an HPIL printer, an HPIL cassette drive,an A10220 AGWA-SIPS unit and other minor electronic components.

A total of seven holes were drilled into the west wall, six into an elevation (interior of a casemate) andone into the foundation. An attempt was made to drill all holes at a slight downward angle to facilitate placement of repacking material around the implanted probes. Holes were made using a 1 1/4" diameter masonry bit and four especially constructed 24" long extension steel rods. Power was supplied by a 3/4horsepower Stanley impact electric drill.

Each probe was implanted by carefully inserting it to the desired depth in the wall (ranging from 8' to 1' deep) using a length of 3/4" PVC pipe. The probes' electrical leads were fed through the pipe and pulled tight to maintain the probe in proper position against the end of the pipe. A small amount of sieved coquina sand was mixed with water to form a slurry and blown by air pressure into the hole. The probe was inserted and gently pushed into the slurry. Additional slurry was then blown into the hole and packed around the probe by tamping with the end of the 3/4 PVC pipe that had been stuffed with a rag. Then, about four inches of the hole was filled with slightly moist coquina sand using air pressure. The sand was then tightly packed in the hole as above. This process was repeated in approximately four inch intervals until the hole was backfilled to the desired depth for the implantation of the next probe. Slurry was again blown in and the subsequent probe was implanted by the same procedure as already described.

For two holes the first four feet of wall was coquina and the remaining depth was fill dirt that the historic records named "marsh mud" used to fill over the casemates vaults and the interior of the bastions at the time of construction. A sample of this material was taken for laboratory analyses (% sand, silt and clay, electric conductivity -salinity measurement- pH, organic matter content and X-ray difraction of clay minerals component).

Each probe implanted at depth in the wall was aligned parallel to the access hole with the ceramic tip pinpointed away from the interior room where the hole was located. Each probe implanted near the surface was reversed and the ceramic tip was pointed back toward the interior wall surface. This allowed the probe to measure conditions very near the surface while still being implanted in the wall.

The data recording and computing station was installed in the climate controlled artifact storage room constructed within a casemate. Multi-channel telephone cable wire was installed to connect the probes in two rooms with the data storage center. The climate controlled room will protect the computer and data logging equipment from the humidity, condensation and salt-air conditions which prevail at Castillo de San Marcos.

In addition to the automatic data recording system and network of 16 AGWA-II moisture/temperature probes, seven day recording hygrothermographs were placed in the rooms where the probes were placed to record atmospheric humidity and temperature. Dial gage surface temperature gageswere attached to the walls adjacent to four holes to measure the temperature at the wall/air interface. Finally, a rain gage was placed on the terreplein of the northwest bastion to measure precipitation.

Mechanical and physical properties of coquina stone from Castillo de San Marcos (by Dr. Lawrence I. Knab and Dr. James R. Clifton)

It is the purpose of this section to characterize some of the important mechanical and physical properties of coquina such as compressive and flexural strengths, dry density, and water absorption.

Coquina stone was formed from cemented sea shells and shell fragments. In the coquina stone samples investigated, the shells were incorporated into the stone in a fairly uniform bedding plane pattern. This pattern resulted in the formation of a highly porous stone with high water absorption, low dry density, and low compressive strength.

The coquina stone samples tested, one was not from Castillo but from the vecinity of St, Agustine. The other was from the Fort. It was retrieved from the southwest bastion scarp approximately 3' from the corner and 4' from mean water line. The sample was extracted from an already structurally disturbed area where one of the cracks runs north-south between the bastions.One section of the stone was cracked while in situ which clearly suggested strong distresses prior to removal.

From the large non-historic sample, 32 cubes were cut and tested in compression and 3 beams were cut and tested in flexure; from the historic sample, 24 cubes were cut and tested in compression and 2 beams were cut and tested in flexure. A diamond saw blade was used for cutting. The cubes were approximately 2" in one side and the beams were approximately 2" x 2" x 6". The cubes were cut such that the bedding planes were approximately perpendicular to four of the cube faces and parallel to the other two faces. The beams were cut so that the bedding planes were approximately parallel to the top and bottom of the beam as tested -i.e. during flexural testing, the load was applied to the midspan of the beam and the direction of loading was perpendicular to the bedding planes. The cubes tested included two cubes cut from the two ends of each beam after the beam had been tested in flexure. (i.e. there were 6 cubes taken from 3 non-historic beams and 4 cubes taken from the 2 historic beams tested). Where possible, the compressive strengths were determined according to ASTM C170. Because of the friable and somewhat crumbly nature of the coquina stone, it was not possible to saw the opposite faces of cubes and beams to be parallel and flat -rather the cut faces were only approximately parallel and flat; the surfaces as sawn were used as bearing surfaces for compressive testing- no sanding or grinding were performed. The cubes were selected at random from the historic and non-historic samples. For the compression cubes, the following test conditions were investigated (a) loaded perpendicular to the bedding planes (this loading condition was considered by the NPS to be the typical loading direction of the coquina stone at the Fort), (b) loaded parallel to the bedding planes, (c) dry, (d) wet -after immersion in distilled water and sea water-.

All beams were tested dry at or near room temperature after they had been dried at 105-108°C for 22-24 hrs.

Water absorption, bulk specific gravity, compression, and flexural tests were

performed as follows. The cubes and beams were dried at 105-108°C for 24-26 hrs., soaked in distilled water for 48-50 hrs. at room temperature, then the absorption and bulk specific gravity values were measured according to ASTM C974. The cubes and beams were further treated as follows: (a) cubes to be tested after immersion in distilled water were kept immersed in distilled water until just prior the testing in compression (total immersion time was 51-52 hrs) just prior to compression testing, the cubes were removed from the water and their surface water removed; (b) cubes and beams to be tested dry were dried at 105-108°C for 22-24 hrs. and tested in compression or flexure in their dry condition; (c) cubes to be tested after immersion in sea water were dried at 105-108°C for 22-24 hrs., immersed for 51hrs. in sea water at room temperature, then removed from the water and their surface water removed just prior to test in compression; (d) cubes which were cut from both ends of each beam after beam was tested, were dried an additional 23-24 hr period at 105-108°C prior to testing to remove any water absorbed during cutting the cubes from the beams.
All compression cubes were tested at or near room temperature using approximately load rates of either 1000-1200lbf/min or 1600lbf/min.
In addition to the bulk specific gravity measurements, approximate dry density determinations were made by dividing the oven dry weight of the cube by the approximate volume of the cube (based on the measured length x width x height of each cube).
From these tests some important mechanical and physical properties of coquina stone were determined to aid in the condition assessment of the monument. Mechanical properties determined were the compressive strength under several different testing conditions, including testing wet as compared to dry, and the direction of the applied load relative to the bedding plane orientation. Physical properties determined were water absorption and dry density. The results indicate that the coquina stone has a very low compressive strength relative to the common building stone. The low compressive strength was believed to be caused, at least in part, by the friable and very porous nature of the coquina.

Geotechnical study (Dr. Benjamin B.G. Nistal-Moret and Dr. Dennis B. Fenn)
The hypothesis being tested is that the apparent structural dislocation of the west wall of the Fort is the result of several interacting destructive forces which might be entering into a critical stage (or interface). The moat surrounding the north, west, and south walls is subject to constant tidal effect while the east wall is free from such sea-action although internal moisture is as severe as the other sections. That is, the most serious dislocations are located in an area whichfoundations are constantly wet and weathered by sea erosion. Approximately fifty years ago the Fort was completely surrounded by a dry moat. The excavation lowered the ground level approximately 3' to 4' and exposed the toe and footing of the walls.
The geotechnical study is geared to identify the nature of subsoil conditions: the types of soils and their stratification (composition, density, and consistency). Of primary importance is to fully assess the shear strength, compressibility, and classification of soil to understand the bearing capacity of the ground around and underneath the Fort and particularly the structurally disturbed areas. This ~~is being~~ accomplished through seven borings in the west section of the moat and five borings in the east section of the moat. The borings will reach a preliminary depth of 50' and will go deeper if materials retrieved indicate such determination is required.
Three of the borings in the west moat will be done 45° underneath the founda-

tion. Their locations are at the center of the west wall of the northwest bastion, at the center of the scarp, and at the center of the southwest bastion The other four borings are perpendicular to the ground and their locations are north of the northwest bastion, two west of the west boring at the center of the west wall, and the seventh is located south of the southwest bastion. The dispositions of the borings will permit seven "readings" and a minimum of four interelated "readings" along the west wall. The last four "readings" will constitute ground sections of sub-soil conditions perpendicularly located under the critically disturbed west wall. The borings are directly related to the crack pattern which runs north-south along the west wall and bastions.
As a control, the same pattern and locations of the borings in the east wall will approximately resemble that of the west.

Total cost of monitoring program (funding by NPS, Southeast Regional Office
The approximate cost is $75,000.00 which includes equipment.

Technical and scientific group

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ABSTRACT

Castillo de San Marcos is located in St. Agustine, Florida, on the shore of Matanzas Bay, about a mile from the Atlantic Ocean. The Castillo is the oldest existing masonry fortress constructed of coquina stone. Its construction was started in 1672 and many modifications were made until its final deactivation as a Fort in 1900. The walls were once plastered with lime stucco, most of which has been completely eroded. Gradually, the exposed surfaces of the extetior stone have weathered and some of the most severely deteriorated stone has been replaced. The Fort is exposed to seasonally heavy thunderstorms and seawater spray. Coquina is a porous stone which can be easily penetrated by water and, as a consequence, the walls appear damp and in some areas efflorescence is observed.

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The monitoring program is being accomplished through the installation of 13 waterproof mechanical dial gages with a range each of 5mm and an accuracy of 0.01mm to measure crack width and wall movement; the insertion in the west wall of 16 ceramic probes which simultaneously read moisture and temperature, two hygrothermographs, four dial gage surface temperature meters, and a rain gage; a complete petrographic analysis of coquina stone to determine the stones mechanical and physical properties; and, 13 borings around and under the Fort with a minimun depth of 50' to establish a complete wall section of substrate conditions directly under the dislocated area of the Fort.

OBSERVACION ANALITICO-ESTRUCTURAL DEL CASTILLO DE SAN MARCOS (MONUMENTO NACIONAL)

por el Servicio de Parques Nacionales, Centro de Preservacion de Recursos Culturales del Sureste

Grupo Interdisciplinario de Investigacion
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El Castillo de San Marcos se encuentra enclavado en las orillas de la Bahia de Matanzas a una milla del Oceano Atlantico en la ciudad de San Agustin de la Florida. El Fuerte es la estructura mas antigua construida de manposteria de piedra de coquina. Su construccion comenzo en 1672 la cual tardo unos veinte anos en concluirse. Sufrio considerables alteraciones a lo largo de 200 anos siendo la presente estructura aquella que quedo despues del Fuerte dejara de ser bastion militar en 1900. Originalmente el Castillo estuvo enlucido con una capa protectora compuesta de arena y cal brunida la cual se deterioro sin ser repuesta. El deterioro del enlucido dejo expuesta la piedra de coquina lo cual provoco el inicio de un lento proceso de descomposicion del substrato. Acelerado este por la proximidad del Fuerte a los embates atmosfericos marinos y las violentas y torrenciales tempestades tipicas de la zona. La piedra de coquina es un agregado semi-arenisco compuesto de pequenas conchas, restos de moluscos,fragmentos marinos y arena cimentado por carbonatos de calcio altamente solubles. Su constitucion es altamente porosa y fragil lo cual la hace susceptible a la penetracion de agua y desgaste interno.
A lo largo de la seccion occidental del Fuerte una grieta corre de norte a sur atraves de dos bastiones, las bovedas de las casamatas, escarpa y terraplen. La seccion norte, oeste, y sur del Fuerte estan rodeadas por un foso humedo mientras que la seccion este tiene el foso desaguado. La evidencia historica indica que las grietas han sido objeto de cierta preocupacion pero no se tiene evidencia que las grietas hayan sido debidamente estudiadas para determinar las implicaciones que pueden tener en la estructura.
Por estas razones, el Director General del Servicio de Parques Nacionales instruyo al Centro de Preservacion del Sureste el inicio y ejecucion de un plan de observacion analitico-estructural del Castillo. El estudio deberia ser de bajo costo pero con el mayor rendimiento posible. La instruccion pidio una clara determinacion sobre las condiciones patologicas de la estructura, sus causas, la condicion de los materiales y sus causas y la determinacion final sobre la estabilidad estructural del monumento. La informacion deberia estar recogida para 1986-87, los analisis terminados para 1987-8, los planes de intervencion para 1988-9, y la intervencion ejecutada para 1989-90.
El plan desarrollado y en ejecucion consiste en un estudio interdisciplinario que abarca los siguientes extremos: (1) estudio y mensura de las grietas por espacio de un ano para determinar movimientos horizontales, verticales, desplazamiento e inclinacio; (2) estudio y mensura de la humedad y temperatura en la superficie e interior de las parades compuestas de piedra de coquina por espacio de un ano; (3) estudio petrografico exhaustivo de la piedra de coquina con el fin de determinar sus caracteristicas mecanicas y fisicas; y (4) un estudio geotecnico para determinar la composicion, porosidad, resistencia a la compresion y la capacidad de carga.