Modeling of Historic Structures

Simulation-Based Structural Analysis of Fort Sumter Considering Foundation Settlement

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With the invention of mid-19th century naval weaponry, coastal fortifications in the United States were rendered obsolete as they lost their functional use of defense. More than 100 coastal forts, now over a century old, are considered national heritage structures to be preserved for future generations. Many of these brick masonry forts have incurred structural damage during bombardments, and further accumulated damage due to the harsh environments in which they were constructed.

There exist no guidelines, however, to assist stewards in the safeguarding of these historically significant masonry fortifications. Therefore, a structural engineer must either rely on modern rules of material strength and structural behavior, or try to understand the failure mechanisms of the unreinforced masonry on a more fundamental level. An understanding of unreinforced masonry can be achieved through a combination of experimental and numerical studies by gaining insights into macro-level strength-deformation behavior and micro-level defects and crack growth of masonry structures. While uncertainties and errors inevitably arise in the development of such numerical models, experiments can ultimately reduce such uncertainties and errors in predictions.

Figure 1: The current state of Fort Sumter National Monument: (a) aerial view, (b) barrel vaulted casemates, and (c) degradation of brick and mortar piers.

Fort Sumter National Monument

Fort Sumter, in Charleston harbor, SC, is a 19th century brick masonry coastal fortification. Declared a national monument in 1948, it is best known as the site where the first shots of the American Civil War were fired in 1861. According to archival documents, construction began in 1829 with the foundation, a man-made island filled with nearly ten thousand tons of granite and over sixty thousand tons of assorted rocks and aggregate. By 1860, the pentagonal-shaped structure (*Figure 1a*) rose nearly 50 feet high, with three tiers built with locally made bricks and Rosendale mortar. After several devastating bombardments between 1861 and 1865 and reconstruction efforts lasting into the early 20th century, only the lower first tier of the original fort stands with major portions reconstructed. The walls are made up of barrel vaulted casemates (*Figures 1b* and *1c*) that once held guns and artillery. Each casemate has a gun embrasure opening in the exterior scarp wall allowing artillery to fire from the fort in all directions. The scarp wall, is adjacent to the casemate piers and vault, but the masonry is not continuous at the interface, thus forming a cold joint. This design is typical of Third System coastal fortifications in North America, as it served as a method of isolating the impact damage from enemy artillery on the outer walls.

In this article, we investigate the behavior of this structure under various foundation settlement scenarios.

Finite Element Model Development

Finite element (FE) analysis is a widely accepted method for analyzing historic masonry structures due to its ability to model complex geometric 3-dimensional shapes and resolve nonlinear and anisotropic material behavior.

In the nonlinear analysis of masonry behavior, to represent an appropriate failure criterion for masonry, the elastic modulus, cracking strength and crushing strength of the homogenized assembly must be defined. This modeling step is typically when the majority of uncertainties are introduced, due in part to our lack of knowledge (known as epistemic uncertainty) and in part to the natural variability of the material (known as aleatory uncertainty). Any laboratory tests or on site evaluations of material characteristics would help reduce the epistemic uncertainties, while the aleatoric uncertainty (such as the spatial variability of masonry) inevitably remains in the model predictions.

During our studies on Fort Sumter, a prism sample along with 2.5-inch diameter cored samples were obtained on site (*Figure 2, page 28*). The compressive strength and modulus of elasticity were determined according to ASTM standard tests parallel and perpendicular to the mortar bed joints. The tensile strengths of the brick and mortar samples are determined via three-point flexural tests. The tensile capacity

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Figure 2: *Coring of material samples revealed that although the construction drawings indicate a brick wall across the width, the construction of the fort is composite with tabby concrete infill.*

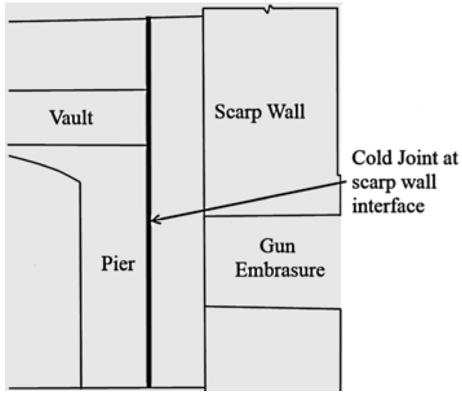

Figure 3: The discontinuity between the scarp wall and barrel vaulted casemate isolates the structural damage to the scarp wall to prevent the casemate from collapsing in the event of an attack.

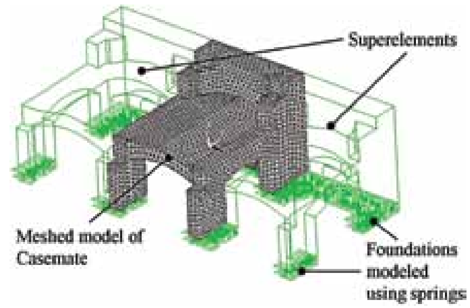

Figure 4: The finite element model of the casemate is built recognizing the elastic constraints of the adjacent casemates as well as the unmodeled foundation.

of the brick-mortar assembly is taken as the volumetric average of a representative cell. The properties of the tabby concrete infill are determined via diametral tests on the cored samples. Lastly, the densities of the materials are measured by taking a ratio of weight to volume of the specimen.

Historic masonry monuments are typically a complex network of curved elements such as arches, vaults, domes, and buttresses with straight elements such as piers and walls. Some structural elements may also contain decorative moldings, surface texture or damage such as minor chipping, etc., making it difficult to reproduce the geometry in a numerical model. Such details can unnecessarily increase the model complexity and, thus, the computational demand. The fundamental principle in geometric modeling must be preserving the structurally important geometric features, such as cross sectional area, center of gravity, moment of inertia, etc.

Over the past 150 years, Fort Sumter's infrastructure has undergone significant and permanent deformations, material degradation, and discontinuities due to crack formations. In our study, terrestrial 3-D laser scanning with a Trimble CX scanner was implemented to digitally reproduce the fort's geometry.

A 3-D non-linear FE solid model of one of the casemates was developed using ANSYS 13.0. The model geometry was constructed from the wireframe models developed using the laser scan, and initial material properties were assigned according to the material tests. In analyzing masonry with the finite element approach, the geometric model was meshed with specialized elements designed for brittle materials accounting for cracking and crushing according to a predefined failure criterion. The size of the mesh was determined based on the trade-off between numerical accuracy and run times. A mesh size of 0.2 meters typically yields a numerical uncertainty below the variability in the structure's expected response due to environmental factors (5-6%).

In our study, the discontinuous interface between the scarp wall and vaulted portion of the casemate (*Figure 3*) was treated as a contact surface and approximated by a friction coefficient. The coefficient was calibrated according to an experimentally measured ratio of displacements on the two sides of the interface when an instrumented hammer was used to impact one side.

The casemate foundation was modeled assuming a linear relationship between the pressure on the foundation and the deflection, i.e. a Winkler type foundation. Thus, a series of vertical and horizontal linear springs was distributed throughout the base of the casemate. The stiffness of the springs represented the foundation stiffness, which required calibration to the experimental data.

When developing finite element models of large masonry monuments, it is often necessary to isolate a portion of the structure. Such an approach, although necessary to keep the problem to a manageable size, results in unknown restraining forces between the structure of interest and components that are excluded from the model. To account for these unknown forces, the most computationally efficient approach is substructuring, which entails approximating the force-displacement relationship of the adjacent components through a small number of elements located at the interface. These elements are known as superelements, and they significantly reduce computational demands. While modeling one of the casemates of Fort Sumter, the adjacent casemates are represented with superelements, effectively reducing the problem to one third (*Figure 4*).

Calibration of Material Properties

Calibration refers to the systematic adjustment of model input parameters to match the solution with experimental observations. Non-destructive vibration tests were performed to extract the natural frequencies of the casemate, such that the model input parameters can be fine-tuned by comparing the predicted natural frequencies with actual measurements. Accelerometers were used to measure 30 minutes of ambient vibrations on 41 points on the casemate. The vibration response of the casemate, recorded in the time-domain, was post-processed to extract the first two natural frequencies at 27.48 Hertz and 45.2 Hertz.

Natural frequencies are linear properties of the global behavior of the system and, thus, were used to calibrate material parameters that define linear behavior and boundary conditions. For the FE model of the casemate, three input parameters were selected for calibration: the elastic modulus of both the barrel vault and the walls and piers, and the stiffness of the foundation springs. The calibrated input parameters were obtained such that the FE model reproduced the measured natural frequencies with 10% accuracy.

Support Settlement Analysis

Four settlement scenarios were considered with smoothly varying profiles including sagging settlements, pier settlements and tilting of the ground. Each settlement scenario is simulated with a maximum magnitude of 100 mm in increments of 2.5 mm.

Scenario 1 (*Figure 5*) simulated an unsymmetrical sagging in the north-south direction, including both the scarp wall and piers. With this scenario, a significant through crack originating at the base of the scarp wall on the south side ran diagonally across the scarp wall. Also, severe cracking at the springing

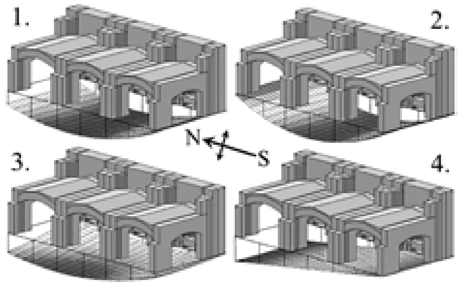

Figure 5: The four settlement scenarios considered in the analysis.

of the arch on the south-side was observed. Scenario 2 simulated symmetrical sagging under the casemate in the north-south direction. This scenario resulted in a crack that began at the base of the scarp wall at both ends and converged in the center, forming a load bearing arch.

Scenario 3 simulated the settlement of the north piers. Differential settlement of a pier caused an unsymmetrical cracking of the vault close to the pier that has settled, while the pier that has settled less experienced more damage.

Scenario 4 constituted the tilting of the casemate in the north-south direction. This scenario resulted in heavy cracking of the south pier, diagonal cracks in the scarp wall and a rapidly developing through crack in the vault. Cracking in the vault must be treated as an instability condition as the progression of cracks once initiated in these members was rather rapid (*Figure 6*).

Summary

The computer simulation indicated that unsymmetrical sagging types of settlements were characterized by diagonal cracking of the scarp wall, originating from the bottom on the less-settled side. Symmetric sagging under the casemate, however, formed cracks that originate from the bottom of the scarp wall from both sides and converge at the center forming an arch that spans the length of the casemate and bears the loads of the wall above. Cracks due to stress concentrations were seen for most settlement configurations at the intersection of structural members, such as the springing of the arches and vaults. Cracking of the vault was observed in configurations that involve differential settlements of the piers. Cracks, once formed in the vaults, progressed rapidly without warning as settlement increased. Thus, cracking of the actual vault should be taken as a structural stability concern. The formation and progression of cracks were observed to be unique to each settlement configuration.

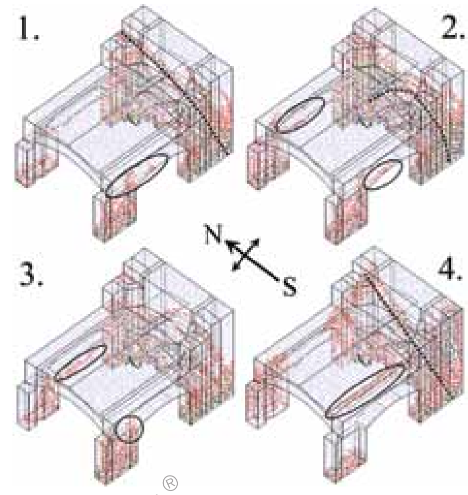

Figure 6: Crack development under the settlement scenarios shown in Figure 5.

By utilizing visual investigations of these peculiar early warning signs in the form of cracks, the stewards of this historic monument can use these computer simulations to help draw conclusions whether settlement may be causing damage to the structure. This of course assumes that the cracks are not due to external loads, which too can be incorporated into the numerical model, making simulations a useful tool for historic structural assessment.▪