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Title:	Characterization and Computer Modeling for Brunelleschi's Dome of Santa Maria del Fiore in Florence.
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Characterization and Computer Modeling for Brunelleschi's Dome of Santa Maria del Fiore in Florence.

(How Los Alamos can help save ancient world heritage)

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In 1420 Brunelleschi began construction on the enormous dome of Santa Maria del Fiore church in Florence Italy[1]. Of special interest was the fact that his design did not require temporary supports from below (the distance from the ground level to the dome was too high to build such scaffolding/centering). Instead he made use of the stabilizing effect of compressive hoop stresses. As the dome went up, it was always in balance since no part extended beyond the other. Thus, the compressive forces were distributed both radially from the apex of the dome and circumferentially about the center of the dome, providing a stable configuration. The other special design feature was that the dome was actually two domes, the structural weight-bearing one inside and below the outer one, which protected against weather.

Recent earthquakes such as the 2009 L' Aquila M. 5.8 have demonstrated that near field moderate magnitude events can produce extremely large vertical accelerations. Because the dome is unreinforced and largely a compression structure it may be vulnerable to large (a > 1g) vertical accelerations.

The domes were constructed without major problems. After the domes were completed, a rather heavy tower-like structure was placed on the top. The weight of the tower added to the compressive stress in the domes. Almost from the beginning small cracks began growing vertically in four of the eight curving faces of the domes. Subsequently, other minor cracking was noticed at corners and around circular windows. The cracks have been monitored for years and in the past fifty years a major monitoring program has been in place(2). The rate of growth of these cracks is slow enough that the dome is in no immanent danger of collapsing. However, there is some concern that the cracking in the structure has weakened its seismic capacity. For this reason, the Italian Government and university system have been studying possible behavior of the dome under various loading conditions. Finite element models have been used to study the problem (3,4) but have been of limited use due to approximations and low resolution used.

Having read reports of these studies, we think Los Alamos might be able to provide some assistance, particularly in the modeling area, dynamic analysis, including soil-structure interaction analysis, and also in material property characterization, remote sensing of structure, etc..

The Problem

The basic problem with the dome's stability is common to most such domes. Starting from the apex and continuing downwards, the curve of these domes is close to a catenary (i.e. the lines of force point along the curve of the dome resulting in stability (no outward nor inward thrusts). However, the curve of all such domes terminates at a lower cylindrical base, effectively departing from the catenary with the result that forces vector outwards beyond the structure, similar to those in a circular dome. If the strength and stiffness of the cylinder is strong enough to resist the thrust due to the dome, the structure will perform well, however, cracks in the dome may begin or grow if the ring supporting the dome is insufficiently stiff or strong. Most domed structures currently designed, such as sports arenas, are designed with a large compression ring at the top of the circular cylinder that reacts the thrust caused by the dome. Additionally, differential settlement about the base of the dome could lead to cracking in the structure.

The Florence Duomo dome is octagonal resting on four arches and four pillars. Four of the faces extend above the pillars and four above the arches. Since the arches can flex downwards slightly, the four faces above these are in compression, while those above the pillars come into tension. Thus the largest cracks in the dome are in the middle of the faces above the pillars. Also an asymmetry exists in the extent of these cracks, the largest being away from the nave which apparently adds stability. In addition to these four major cracks, easily visible from within the inner dome, there are several other sets of cracks, some at the intersections of the 8 faces, and some extending down to the so-called circular drum, associated with the enclosed four large circular windows.

Finite Element analysis of the dome have been able to reproduce some of the major cracks lending credence to current understanding of the forces within the domes(1). However, because these analyses have been preliminary and of relatively low resolution, and because it has proved impossible to verify the accuracy of these simulations, it has been deemed advisable to rely more on monitoring(5,6) rather than modeling to determine what modifications might be effective. Unfortunately, these approaches give only a limited understanding of the structure problems leading to the fear that any modifications might either prove ineffective or worse, render the structure more vulnerable to collapse.

Proposal

Los Alamos National Laboratory has built up a capability in large-scale computer simulations of structures and is tasked with modeling large reinforced concrete and masonry structures subject to earthquakes. The purpose of these seismic vulnerability assessments is to address the safety of the structures, and to make recommendations on strengthening when needed. To this end, LANL has expertise in a variety of disciplines related to such problems including dynamic analysis, seismic hazard assessments, local site response analysis, and soil structure interaction analysis. We perform soil structure interaction analysis both in the time and frequency domains.

As such LANL is looking into whether it might be able to assist in studies that would lead to greater confidence in methods to stabilize the Florence dome (and perhaps other similar ones). The following is a very preliminary list of efforts LANL might be able to supply it they seem worthwhile.

The proposed model-based investigation would combine site-specific ground motion, soil structure interaction, a generally nonlinear structural dynamic finite-element model with an embedded sub-scale discrete element crack evolution model in order to assess the influence of site specific ground motion on:

(1) the mechanics leading to the current crack pattern,
(2) the potential for catastrophic collapse of the dome, and
(3) possible mitigation strategies.

LANL, and this research team in particular, has expertise in each of these areas. The application of such cutting edge modeling technologies motivates a detailed model verification and validation process, for which LANL is also renown. Model verification comprises code verification to assess the faithfulness of implemented algorithms to the underlying physics and calculation verification which addresses the error associated with particular mesh and time discretization of the problem. It is within this activity that the research team hopes to quantify the mesh resolution needed to accurately address the posed technical questions. Finally, model validation will be based on material and then integrated component level experiments to assess whether the models contain the appropriate physics to predict damage and crack evolution.

We anticipate a large increase in zoning of the finite element calculations--much higher resolution including as well as possible other parts of the Church (perhaps including only the nearest part of the nave). Clearly, an important aspect of this simulation is the combination of the Discrete Element technique with the Finite Element formulation(7,8,9) (combined FEM/DEM method) to allow cracks to grow prognostically instead of diagnostically.

Two primary simulations are needed: a quasi-static thermo-mechanical simulation to address the thermal cycling, water absorption and desorption due to annual humidity cycles and, lastly, and a dynamic soil-structure interaction analysis.

Another set of studies would look at efficacy of different stabilization techniques.

Los Alamos expertise is in the following areas:

(1) advanced computer simulations(7,9),
(2) earthquake engineering (10,11,12),
(3) structural dynamics,
(4) soil-structure interaction analysis,
(5) material properties (13),
(6) monitoring analysis to understand implications of existing measurements and suggest additional ones.

Finally we propose a study of material properties, in particular the strength of the mortar used, since the cracks seem to proceed through the mortar without fracturing the intervening bricks. The mortar resistance to cracking is explicitly dependent on the current state of stresses and it might be affected by high strain rate (earthquake scenario), temperature and moisture content.

Other contributions might include, three-dimensional visualization of modeling results, some of which might be interactive.

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