Engineering for Heritage Masonry

By Michael Schuller, P.E. and Glenn Boornazian

Nearly all of the world's remaining ancient monuments contain some type of masonry. Working with historic construction involves carefully balancing engineering objectives with preservation principles and increased analytical efforts to make the best use of existing construction. The authors have had opportunities to apply these concepts to preservation of several heritage masonry structures, including work for the World Monuments Fund (WMF), **www.wmf.org**, at the temple of Angkor Wat (*Figure 1*).

Figure 1: Conservation of the stone roof structure being conducted by the World Monuments Fund at the "Churning of the Sea of Milk" gallery, Angkor Wat, Cambodia. Courtesy of the World Monuments Fund.

Preservation Philosophy

Structural engineers design for life safety and serviceability performance on a daily basis. When working with historic structures, engineers also have a responsibility to protect the construction itself and respect the original intent of the architect and craftsmen who were involved in the building's design and construction. Preservationists follow a series of simple principles that can be used to guide engineering efforts:

- **Minimal intervention**: Often the most challenging concept for engineers is the principle of *minimal intervention*. Stabilization or strengthening schemes should satisfy life safety and serviceability objectives using simple approaches that minimize changes to the structure's materials and appearance, while retaining as much original material as possible.
- **Compatibility**: Interventions must be physically and aesthetically *compatible* with original building materials. New materials must be similar to existing in terms of mechanical properties, porosity, and vapor transmission so as to not significantly alter the way the building reacts to applied loads and moisture transport. Many historic buildings have been irreparably damaged by good-intentioned efforts using modern materials that have a strength, density and stiffness very different from historic materials.
- **Reversibility**: The most appropriate structural interventions are designed to be *reversible*, or able to be removed in the future, and do not interfere with or prevent the possibility of future interventions.

The very nature of historic construction implies longevity of the structure and its materials, and structural interventions also need to consider service life expectations. Structural work is planned with an eye towards permanence, often considering a useful life cycle of 100 to 300 years. Engineering solutions should incorporate durable materials that are resistant to alteration by thermal cycles, moisture, and humidity with minimal maintenance. Masonry materials have proven their ability to withstand centuries of exposure, and substitute materials must be used with caution.

Codes and Guidelines

One of the great challenges to working with historic structures is the lack of Building Code guidance. Requirements of the *International Building Code* (IBC) and the Masonry Standards Joint Committee *Building Code Requirements and Specification for Masonry Construction* (MSJC) are intended for use with modern construction and it can be dangerous to apply many of their requirements to heritage masonry. Some published codes and guidelines contain concepts that can be applied to historic masonry construction.

- The MSJC Chapter 5, *Empirical Design of Masonry*, includes a series of "rules of thumb" and simple design requirements that are often used as a screening tool when evaluating historic masonry. Limitations on wall height to thickness ratio and the spacing of shear walls, for example, can be used to qualify structural elements and identify conditions requiring in-depth analysis.
- The *International Existing Building Code* (IEBC) contains requirements to be used on projects involving existing buildings. Appendix Chapter A1 includes masonry seismic strengthening provisions such as wall anchorage requirements and methods for determining the allowable capacity of masonry shear walls.
- ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings*, contains guidelines for masonry structures in Chapter 7. Particularly useful are discussions of evaluation and strengthening methods and default values for typical historic masonry material properties.

Both the IEBC and ASCE/SEI 41-06 are intended for seismic evaluation and may not always apply, particularly to buildings in regions of low seismicity. Nevertheless, the concepts contained in these documents can be useful.

Figure 2: Khmer technician using microwave radar to scan the stone bas-relief panel to evaluate subsurface conditions and identify the extent of stone deterioration. Scanning the full 150-foot length of the carved panel took about 2 days on site. Courtesy of the World Monuments Fund.

Figure 3: Measuring masonry compression response in place using the flatjack method of ASTM C 1197. Courtesy of Atkinson-Noland & Associates, Inc.

Diagnostics

Engineering analysis and design requires knowledge of as-built construction and material properties. Diagnostic methods play an important role in preservation projects for the simple reason that as-built drawings and material specifications typically don't exist. The best information is attained with a well-planned combination of visual evaluation, on site diagnostics, and laboratory testing.

Non-destructive techniques provide valuable information about hidden conditions without disturbing construction materials and are particularly attractive for evaluating heritage masonry. Methods such as microwave radar (*Figure 2*), pulse velocity measurements, and infrared thermography are commonly used to identify the nature of subsurface features, the presence of moisture, and damage in the form of cracks or voids. Nondestructive fiber-optic borescope examination of wall interiors is an important companion technique that permits verification of internal anomalies.

In-place testing provides valuable material property information without resorting to destructive sample removal. ASTM Test Methods C 1196 and C 1197 describe techniques to evaluate masonry compression response using flatjacks inserted into mortar joints (*Figure 3*). ASTM C 1531 contains three methods for evaluating the shear strength of mortar bed joints, and is used in conjunction with IEBC requirements to evaluate in-plane resistance of masonry shear walls. In-place methods require removal of a portion of a mortar joint or a masonry unit for insertion of loading devices, and, although not completely nondestructive, are often specified for use with historic masonry.

Engineering Considerations

Engineers unfamiliar with historic masonry all too often discredit its structural contribution because they can't find textbook solutions or specific code references. One big step towards minimizing the level of structural intervention necessary with historic masonry is recognizing the inherent capacity of original materials and the function of the original design.

Most historic masonry was constructed with thick, frequently spaced walls to take advantage of masonry's excellent compression capacity. This construction reflects the builder's knowledge of material properties and load paths, and engineering analysis often begins with simple thrust line analysis. Stability analysis is accomplished by resolving vertical and lateral loads to determine the force resultant at multiple sections and ensure the "thrust line" falls comfortably within the wall section. Self-weight of massive wall sections help resist overturning; consideration of axial forces and their contribution towards offsetting flexural tensile stress is essential.

Simplified analysis is adequate for some situations but it is often necessary to account for "secondary mechanisms" to fully understand structural behavior. So-called secondary mechanisms require additional engineering effort, but their consideration can result in significantly increased capacities, thereby reducing the level of structural intervention required.

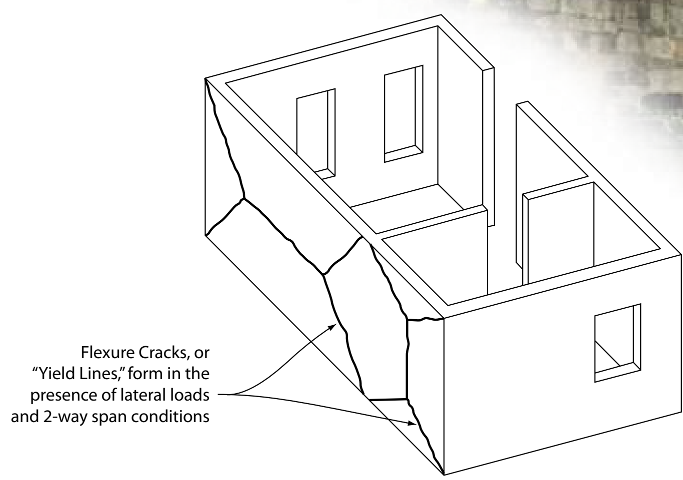

Figure 4: Yield line analysis considers 2-way wall spans.

- **Two-way Flexure**: Two-way action is commonly considered for designing floor diaphragms, yet walls are almost always analyzed assuming conservative assumptions of simple spans and one-way action. Most historic walls are supported laterally at each floor and the roof line, and also by frequently spaced shear walls (*Figure 4*). Yield line analysis and consideration of two-way spanning provides a better approximation of a masonry wall's flexural capacity.
- **Arching Action**: Structural behavior of a masonry arch is ultimately controlled by the masonry's compressive strength following the formation of flexural hinges (*Figure 5a*). A similar concept can be used to better understand a masonry wall's resistance to lateral loads (*Figure 5b*). "Arching action" is usually neglected with modern masonry construction and tall, slender walls, but can be significant to explain performance of thick walls used with historic masonry. If supports are sufficiently rigid to develop arching action, wall flexural capacity is limited by masonry compressive strength rather than mortar tensile bond at bed joints.
- **Veneer Contribution**: Veneers and facades are normally considered as nonstructural elements but the nature of historic construction often has a veneer or facing wythe making significant structural contributions. This is particularly true where the face wythe was built with regularly coursed, dressed stone or face brick, laid in high quality mortar. Multi-wythe walls are best analyzed as composite sections, distributing stresses based on the relative stiffness of the backup and face wythes.
- **Analytical Models**: Complex analytical models can be developed to provide a better understanding of expected performance. Masonry behavior is highly nonlinear and simple elastic analysis is unable to capture response beyond service loads, particularly when considering seismic loading. Properly calibrated, nonlinear finite element and distinct element models provide a reasonable approximation of masonry behavior.

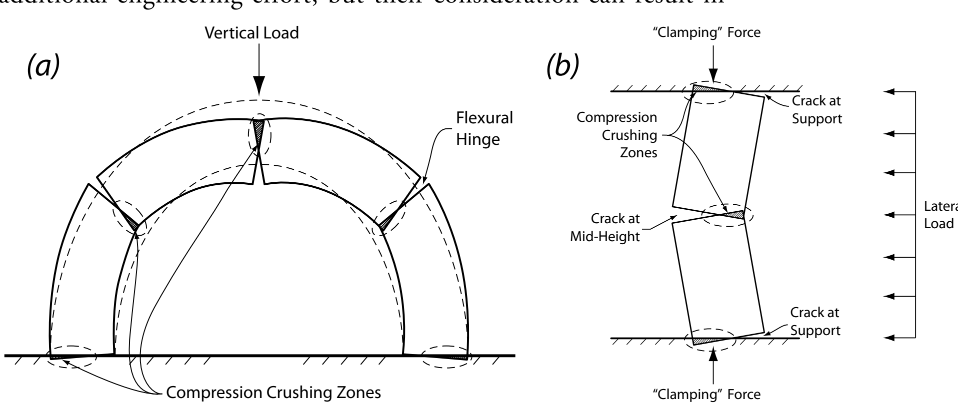

Figure 5: Thick masonry walls with rigid support conditions develop a failure mechanism limited by compressive strength, similar to that a masonry arch.

Architectural Conservation

Architectural conservation is an essential component of all heritage projects. The professionals working in this field apply a coordinated approach to such topics as: preservation theory and philosophy, architectural documentation, conservation science, condition surveys, archival

Figure 6: Stones removed from the Angkor Wat roof structure being conserved in the on-site workshop. Courtesy of the World Monuments Fund.

Figure 7: Stone conservation, Angkor Wat. Courtesy of World Monuments Fund.

research, in-situ and laboratory testing and mock-ups. When results of all this work are brought together and synthesized properly, the goal is to design a conservation program that is physically compatible with the substrate and aesthetically balanced to match the interpretation goal set for the specific site. For a heritage conservation program to be successful, structural engineers who specialize in this field must work closely alongside architectural conservators, each being open minded and creative to find the best solution to the challenges of the materials, threats and priorities found at a specific site. There are too many sites where the balance was not properly struck and the results are confusing, if not also damaging to historic materials. At heritage sites where we are the caretakers for future generations such mistakes are unacceptable.

Many international organizations regulate this field. In addition, numerous charters have been established to define the approach, goals and processes most widely accepted. Today at the Ancient City of Angkor, the Cambodian Government's APSARA National Authority is in charge of the safekeeping and coordination of the site. Together they work closely with UNESCO and over 10 countries from around the world who participate in the project on a daily basis.

Angkor Wat

Glenn Boornazian has been working with the WMF at the Angkor World Heritage Site in Cambodia since 2002 and Michael Schuller since 2004. WMF is a non-profit organization based in New York City with heritage preservation efforts in more than 90 countries around the world. WMF has been working at Angkor since the early 1990s and recently received a large grant from the US State Department for the conservation of Phnom Bakheng, the first site the Khmers built when they moved to the location we know as Angkor today. WMF President Bonnie Burnham said, "The conservation of this magnificent complex of monuments is a critical part of our mission, because of its prominence and because we are able to play a very meaningful role here by providing technical expertise and training for a new generation of Cambodians to conserve and manage the site and its numerous cultural treasures". At the Churning of the Sea of Milk Gallery at Angkor Wat, WMF has assembled a team of Khmer engineers, architects, archeologists, stone masons and conservators to stabilize the architecture of the third enclosure southeast intermediate gallery and provide long term protection for the Churning of the Sea of Milk (CSM) bas relief. The CSM bas relief panel measures over 150 feet in length and is considered to be one of the most important bas reliefs at Angkor, if not all of Southeast Asia.

Originally constructed in the 12th century, the gallery's corbelled stone roof structure was built with a series of massive sandstone blocks, dry-laid without mortar in an interlocking fashion (*Figure 6*). Work on site focuses on restoration of the roof structure's original passive drainage system and conservation measures to address stone deterioration. Initial diagnostics included the use of ultrasonic pulse velocity and microwave radar testing to evaluate the condition of prior patching repairs and identify the extent of deterioration within the carved panel (*Figure 2, page 26*). Additional work focused on the development of detailed drawings of the site, implementation of a unit-by-unit survey, sampling and testing of original materials and alterations over time which focused on defining and prioritizing the active decay. Laboratory and in-situ testing assisted in the development of conservation methods and materials which are in use at the site today. Coordinated and documented with the use of a database designed for this purpose, work is currently underway to remove inappropriate cement-based patching materials and transfer individual stones to the on-site laboratory for conservation (*Figure 7*). Stones are placed back in their position following desalination, consolidation, and treatment of fractures and breaks. An important component of the rebuilding effort is limited and selective installation of a series of 2mm lead sheets to augment the roof's passive drainage system. Observations during the 2009 monsoon season demonstrated that the repaired roof structure is working flawlessly. The WMF team expects a preliminary review of the work by the Cambodian APSARA Authority and UNESCO in June 2010, leaving time to make small scale modifications so that final completion can be achieved in December 2010.

Preservation Engineering and Conservation

Being involved with heritage masonry structures provides a certain sense of fulfillment, knowing that your efforts will be appreciated by future generations. Engineering analysis and stabilization of heritage masonry structures requires a willingness to dig deep to understand historic materials and construction methodologies. If you are interested in more exposure to preservation engineering and historic masonry, get involved with the Association for Preservation Technology International's Preservation Engineering Committee (**www.apti.org**) and The Masonry Society's Existing Masonry Committee (**www.masonrysociety.org**).▪

Michael Schuller, P.E., is president of Atkinson-Noland & Associates. Mr. Schuller is vice president of the Association for Preservation Technology International and is on The Masonry Society's Board of Directors. He may be reached at ***mschuller@ana-usa.com****.*

Glenn Boornazian is president of Integrated Conservation Resources and Technical Director of the World Monument Fund's conservation efforts at the Angkor World Heritage Site, Cambodia. He may be reached at ***gboornazian@icr-icc.com****.*

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