The Future of Masonry Design

By Richard E. Klingner, Ph.D., P.E.

Any article that attempts to predict the future must be written and read with the understanding that it represents the author's sincere attempt at the impossible, as a way of focusing the readers' attention. This article is no exception. Masonry differs from many modern construction systems in that it often serves simultaneously as envelope, as architecture, and as structure. The future of masonry structures will depend on the extent to which they can continue to perform those functions in a cost-effective and energy-efficient manner. In this article, some of the challenges facing masonry in that regard are noted, along with ways that the technical community involved in the manufacture, design, construction and testing of masonry can respond to those challenges. The structural design of masonry is emphasized.

Performance of Masonry as Building Envelope

Masonry must usually function as part of a building's exterior, or envelope. In that function, it might be required to perform in the following ways:

- resist liquid water;
- control water vapor;
- control the environment inside the envelope (temperature, humidity and noise);
- resist fire;
- resist hail and wind-borne debris;
- resist or transfer externally applied loads; and
- accommodate differential movement.

Based on forensic experience, most problems with masonry buildings involve the performance of masonry as building envelope, rather than the performance of masonry as structure. This suggests that if masonry is to be added incrementally to university engineering and architecture curricula, then the proper specification and detailing of masonry should be a higher priority than structural design. Our challenges in this regard are as follows:

- find effective ways to introduce masonry specification and detailing into undergraduate engineering and architecture curricula;
- encourage more university professors to become involved in the ASTM process, where they can learn about specification and detailing issues in addition to structural design; and
- encourage the continuing education of practicing architects, engineers, contractors and building officials regarding the proper specification and detailing of masonry.

Loadbearing walls constructed of autoclaved aerated concrete (AAC) masonry units for a church addition.

Performance of Masonry as Architecture

For more than 10,000 years, masonry has been used in a wide variety of architectural forms, including domes, pyramids, arches, walls, facades, and shells. It is architecturally flexible because it is composed of relatively small, hand-placed units. It is architecturally appealing because of its range of colors, textures, patterns and shapes. This inherent appeal is enhanced by increases in its architectural flexibility and visual attractiveness.

For this article, "masonry as architecture" refers to all appearance aspects of masonry – its global appearance in a building, and its local appearance as a composite of units, mortar, grout and accessory materials.

Challenges in enhancing the global appearance of masonry with respect to architectural details include the following:

- find ways to increase the variety of architectural details (such as corbels, racks, quoins, and different bond patterns) that can be laid without cutting units or unduly increasing cost; and
- develop construction techniques or tools that will make it easier to construct masonry architectural details more quickly and reliably.

Challenges in enhancing the local appearance of masonry include the following:

For this university building, the walls are brick veneer with reinforced CMU. The CMU acts as shear walls for the steel frame.

- find ways to improve the consistency of color of units and mortar;
- find ways to decrease cracking and chipping of masonry units;
- find better ways to control the alignment of units and mortar joints, the variation in thickness of mortar joints, and the variation of masonry walls from level and plumb;
- develop industry-wide standards of acceptance for the installation of masonry (tolerances, joint widths);
- find better ways to control staining and improve cleaning techniques; and
- find better ways to decrease or eliminate efflorescence.

Performance of Masonry as Structure

Masonry as structure must resist gravity and wind loads, and occasionally extreme loadings such as earthquake. Teaching masonry design, we often spend more time on structural calculation than on specification and detailing. The ultimate goal of masonry design, however, is design rather than calculation. Most masonry can be designed with only a few calculations, augmented by prior experience with similar elements.

In general, our challenges include the following:

- develop simplified design provisions, consistent with the more complex ones, for the design of structural elements that we use often;
- develop user-friendly design aids to take the drudgery out of complex calculations; and
- develop "deemed-to-comply" designs for simple masonry structures.

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A biotechnology building whose exterior walls are brick veneer over light gauge framing.

In specific areas of structural design, some issues should be examined in more detail:

- strength versus allowable-stress versus empirical design;
- inconsistencies and unnecessary complexities in the current MSJC Code; and
- structural behavior of masonry under extreme loads.

Strength Design versus Allowable-Stress Design versus Empirical Design

Masonry design provisions are intended to produce designs with acceptable probabilities of failure. In general, different design approaches – strength, allowable-stress, and empirical – should produce designs with similar probabilities of failure. To compute a probability of failure requires knowledge of the statistical variability of the load. To compare probabilities of failure is simpler, however, because it requires only a comparison of the strengths of the final designs. In general, elements designed by different approaches should have similar strengths, while allowing for the possibility of some differences. A simpler design method, for example, might be required to produce more conservative results, while a more rigorous and hopefully more accurate design method might be permitted to produce less conservative results.

For masonry elements designed by the different approaches of the 2005 MSJC Code, in the context of ASCE 7-05 (Supplement) and the 2006 *International Building Code (IBC 2006)*, the following tendencies are evident:

- Unreinforced masonry bearing walls designed by the strength approach are in general not required to be as thick as those designed by the allowable-stress approach, because although the flexural tensile capacities of the two approaches are equivalent, the critical loading combination for strength design involves *0.9D*, while the critical basic loading combination for allowable-stress design involves *0.6D*. The lower axial load in the latter case increases net design tensile stress, and requires more conservative design.
- Reinforced masonry elements designed by the strength approach in general require significantly less reinforcement than those designed by the allowable-stress approach, because the effective safety factor associated with strength design is significantly lower than the effective safety factor associated with allowable-stress design.

In harmonizing allowable-stress and strength design, the following should be noted:

- If the formulas used for predicting capacity for strength design are more accurate than the corresponding formulas for allowable-stress design, then their increased reliability can be reflected in lower effective factors of safety. This is true for flexure of tension-controlled elements. Shear capacities, however, are predicted with considerable scatter by strength equations as well as allowable-stress ones, and significant decreases in effective factors of safety for shear are difficult to justify.
- Strength design equations are usually more obviously related to the actual strength of structural elements, than are their allowable-stress counterparts. Because of this, they are often easier to learn and use correctly by designers who have prior experience with strength

design of reinforced concrete. This is an advantage.

- Strength design generally gives more consistent probabilities of failure (collapse) than allowable-stress design. Because allowable-stress design is less consistent, it may sometimes require less material than strength design. Attempts to adjust strength design so that it is always more economical than allowable-stress design should be approached with caution.

Comparisons between rational design (strength design or allowable-stress design) and empirical design are not as clear. Empirical design is generally based on maximum permissible *h/t* ratios, maximum permissible plan aspect ratios of floor diaphragms, and maximum permissible stresses on the gross areas of walls. It presumes that axial forces act only within the kern of the cross-section of empirically designed elements, so that these elements do not experience net flexural tension. In the presence of axial load, empirical design may produce elements that are comparable with their rationally designed counterparts. Empirically designed elements with little or no axial load, however, may not meet the requirement for no net flexural tension, and may have factors of safety significantly lower than their rationally designed counterparts. Examples of such elements are parapets and non-bearing walls spanning horizontally between pilasters. At the same time, indications of satisfactory performance by masonry elements not meeting rational requirements should stimulate code developers to explore possible explanations for such satisfactory behavior, and, if justified, to incorporate those explanations into rational design provisions.

The walls of this school have architectural CMU veneer over loadbearing CMU.

Empirical design is restricted to a relatively narrow range of building configurations, and to walls with few or no openings. It is also becoming increasingly restricted by MSJC provisions and also model code provisions. The Masonry Society's Design Practices Committee is working on "direct design," a user-friendly subset of MSJC strength design procedures that could offer designers the speed of empirical design without its limitations and potentially unconservative results.

Inconsistencies or Unnecessary Complexity in Current Design Provisions

Some design challenges for masonry are related to inconsistencies and unnecessary complexity in our current design provisions. For example, the 2005 *MSJC Code* (MSJC 2005a) has inconsistencies or unnecessary complexity in the following areas:

- Minimum and maximum flexural reinforcement requirements for allowable-stress design should be made comparable to those in strength design.
- Moment magnifiers for masonry elements should be introduced into allowable-stress design, and should be consistently used for in- and out-of-plane loads in strength design.
- Development and splice length provisions, including those intended to protect against splitting, should be made consistent with strength provisions.
- The ⅓ stress increase should be eliminated, and replaced by harmonization

A school constructed with CMU and brick veneer walls within a steel frame.

of allowable-stress and strength provisions for flexural and shear design for flexure and shear.

- Requirements should be clarified regarding designs in which masonry elements are designed for flexure as reinforced in one direction and unreinforced in the other.
- Inconsistencies for tie requirements for multi-wythe, non-composite masonry vis-à-vis masonry veneer should be eliminated, perhaps through research results now being obtained in NSF NEES research on masonry and masonry veneer.
- Unnecessarily complex seismic design provisions should be rewritten.

Many of these issues have been addressed in the draft 2008 MSJC provisions.

Research Needs Related to the Seismic Design of New Masonry

Masonry structural systems can be designed to respond inelastically by using low quantities of distributed flexural reinforcement, and by carrying out capacity design for shear. These design constraints favor a structural system composed of cantilever walls, lightly coupled by horizontal diaphragms. Such systems typically have a limiting story drift of about 0.8%, governed by gradual deterioration of the compressive stress blocks of the shear walls under repeated, reversed cycles. For most such systems, this is equivalent to a displacement ductility ratio of at least 3. In the near term, we should continue with that approach for the seismic design of new masonry, while working with other code-development groups to develop designer-friendly alternatives to the bewildering array of classifications for lateral force-resisting systems ("ordinary," "intermediate," "special").

In the longer term, however, we must also recognize that many masonry structural systems must be designed in more complex configurations of walls with irregular openings. Inelastic response of such systems often requires complex combinations of flexure-governed and shear-governed wall segments, which are not well addressed by the MSJC's current seismic design provisions. The Building Seismic Safety Council's Technical Subcommittee 5 (Masonry) is currently developing displacement-based design procedures intended to better address such configurations.

Research Needs Related to the Evolution of Masonry Design

As masonry design provisions continue to evolve, some will say, "These changes are needed because our current factors of safety are too low or too inconsistent." Others will respond, "If our current provisions are inadequate, why haven't we seen more failures?"

Rational discussion of this issue requires the following:

- A primer on engineering probabilities for non-mathematicians. Developers of design provisions need to know the significance of a combination of statistically distributed design loads and statistically distributed resistances. For a particular design load (and associated scatter), and a particular mean resistance (and associated scatter), what is the probability of failure in a given year? In 10 years? What is the probability of failure of at least some masonry buildings in a city in 10 years?
- A clear understanding of all available resistance mechanisms in masonry structural systems, so that they can be quantified and incorporated into design.
- Specific quantitative data on the response of masonry structures to extreme loads, perhaps obtained from standard instrumentation packages placed on standard designs of large retail chains.▪

Parts of this article were originally prepared by the author, under the auspices of The Masonry Society's technical committee on Research, as a report for a research workshop. The contents have been updated and augmented since then. They reflect the views of the author alone, and not necessarily those of the MSJC or its sponsoring societies.

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