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PRELIMINARY CONSIDERATIONS FOR THE APPLICATION OF FEMA P695 TO CONFINED MASONRY STRUCTURES

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ABSTRACT

Confined masonry structures are typically designed according to prescriptive guidelines, and as a result it is difficult to obtain a quantitative assessment of the appropriateness or conservatism of design assumptions in terms of collapse margin ratios for seismic risk. As confined masonry is a common building system in regions of high seismicity such as Indonesia, Haiti, and Central and South America where low-cost, earthquake-resistant housing construction is a critical need, the development of a more rigorous procedure for design will be a valuable tool to optimize designs and use resources most efficiently.

As part of a larger effort by the Confined Masonry Network to develop standardized design procedures for confined masonry systems following the requirements of accepted model codes, this paper considers the appropriateness and required steps for using the methodology of FEMA P695 [1] to determine appropriate seismic performance factors: response modification coefficient (R), system overstrength factor (Ω_0), and deflection amplification factor (C_d) for the eventual inclusion of confined masonry as a seismic force resisting system in model building codes.

Much pseudo-static and cyclic in-plane testing for confined masonry assemblies and systems has already been done. It is our aim to use these existing data to validate materials, assembly, component, and system assumptions that will be used in creating archetypes and nonlinear models.

It is envisioned that this strategy will lead as a step to a FEMA P695 analysis and Section 8 peer review process for adoption of confined masonry into model codes for low-rise structures. Continued testing and modeling will be required for the eventual application of the P695 process to multi-story applications.

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Introduction

Confined Masonry (CM) is a structural system consisting of gravity load-bearing masonry shear wall panels which has been used successfully around the world, primarily as an improvement over unreinforced masonry (URM) construction techniques. In CM, URM wall panels are surrounded on all sides by reinforced concrete confining elements, which are

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mechanically bonded to the masonry wall panel and hold the panel together during intense cyclic shaking seismic events. They add ductility and drift capacity to what is otherwise an extremely brittle system. CM has performed well in large seismic events over the past 75 years (Chillán, Chile, 1939, M7.8; Llolleo, Chile, 1985, M7.8; Mexico City, Mexico, 1985, M8.1; Maule, Chile, 2010, M8.8; West Sumatra, Indonesia, 2009. M7.9) [2,3,4,5]. The different areas of Asia, Europe, and Latin America where CM is widely used employ the system with varying materials and material/construction quality and cultural preferences which affect the configuration and performance of the wall panels and buildings. For example, hand-made fired clay bricks are typically 10-11cm wide and laid in a single wythe, resulting in thinner walls and larger wall height to thickness ratios. Hollow concrete block (or CMU) construction results in thicker walls, but lower material compressive and shear strengths, especially on the net section. In the selection of structural system archetypes for the FEMA P695 evaluation process, it is important to set minimum parameters for these factors and evaluate CM as a structural system in such a way that flexibility is maintained for its application but the importance of critical factors that contribute to the selection of seismic response coefficients (R, Ω_0, C_d) is considered explicitly. These include, among others, material strengths, wall aspect and thickness ratios, roof types, and treatment of wall openings.

Most guidelines and building codes for CM construction are prescriptive. Thus, the majority of CM buildings in use today are non-engineered. This approach has worked well for low-rise, 1- and 2-story construction, but CM buildings are also built up to 4 and 5 stories, where the demands on the lower floors become so great that the prescriptive methods no longer capture the response requirements. We propose to start the P695 process for low-rise applications, in keeping with the testing that has been done that can be used to verify the archetype selection required for the P695 Methodology ("the Methodology"). It is hoped that, given the current availability of larger scale cyclic testing facilities, research can be expanded to multi-story configurations, which will then allow an expansion of permissible story number and building heights to which CM can be applied as an engineered lateral force resisting system.

There is broad agreement on response characteristics and failure mechanisms for well-built CM panels. When subjected to lateral loading, the masonry panel first tries to transfer shear loads vertically, until there is a tensile failure, typically in the mortar between masonry courses. The next available load path is what can be viewed as a diagonal compression strut which transfers shear load diagonally through the wall panel. RC tie elements provide tensile and compressive strength surrounding the panel. Upon load reversal, when the principal tensile stresses in the masonry panel exceed the tensile capacity of the masonry assembly, diagonal cracks form, substantially reducing the stiffness and strength of the masonry panel. This increases the shear demand upon the tops and bottoms of the confining RC columns. When the shear capacity of the columns is exceeded the diagonal cracks propagate through the columns, at which point confinement of the panel is lost. This constitutes failure of the system as it will now easily fail out-of-plane. We will assume that other observed failure mechanisms, such as separation of the wall panel and confining column or out-of-plane bending failure of the ring beam will be addressed through design and construction requirements.

To this end the Confined Masonry Network's 2011 "Seismic Design Guide for Low-Rise Confined Masonry Buildings." [6, referred to hereafter as the "CMN Guidelines"], will be used in the development of the Methodology archetypes. This choice aligns well with other code guidance (Mexican Building Code [7], Eurocode 6, Chinese Building Code [8], Peruvian Building Code), and will be discussed further below. It also aligns well with configuration decisions that have been made in previous testing, making those test results applicable as a means of archetype and model verification.

Various attempts at establishing an R-value for CM have already been made, mostly by using test data to compare strength or drift response to that required by the Maximum Considered Earthquake (MCE). These data will be used in confirming the appropriateness of the nonlinear modeling used in the Methodology process. Subjecting CM to a rigorous P695 analysis, documentation, and peer review will allow the use of this system to move forward on a more rational basis, eventually incorporating opportunities for engineered multi-story CM approaches. In developing countries where CM is used there is an increasing need for urban densification. Being able to provide bearing wall solutions to multi-story needs is important in the absence of effective code enforcement and inspection, as the redundant load paths provided by these systems are more tolerant of construction error than frame systems with critical moment connections. However, the use of multi-story confined masonry structures is intended for situations where design and construction quality are properly monitored.

Literature Survey

Much research and analysis of the seismic response of CM components, systems, and buildings has already been done. While there is not space in this paper to provide a complete survey of the literature and testing results available, such a survey will be part of the Methodology approach, along with analysis of the applicability and limitations of each. Of particular interest are the research efforts that have been done, using both analytical and physical modeling and testing, in the effort to define an appropriate R-value for CM and other traditionally non-engineered structural systems. The existence of these studies provides an opportunity to proceed with a P695 analysis with fairly high confidence that required confirmation of approach and assumptions regarding materials and assemblies, although not necessarily with regards to seismic response coefficient selection, is available.

The guiding document for this study will be FEMA P695 itself. The Methodology is clearly defined and explained, laying out required steps and requirements for each step. The basic steps are: Ground motion parameter selection, Seismic force resisting system concept development, Provision of required system, component, and materials specifications, Archetype development, including trial R-value selection and division into design groups that will allow the incorporation of various configurations of building height, materials, and other irregularities that are permitted by the model codes currently in use, Nonlinear model development, Nonlinear analysis, Performance evaluation, Verification of trial R-value through collapse margin results, Documentation, and Peer review.

Challenges of Application of FEMA P695 to Confined Masonry

The application of the Methodology to CM structures presents a number of challenges due to the fact that CM is a traditionally non-engineered structural system. Unlike established engineered seismic systems such as steel moment frames and reinforced concrete shear walls, the design requirements for which are well-codified in US and international standards and for which structural analysis methodologies and software are well-established, there is no universal agreement on the best methodologies for the design and analysis of CM.

Lack of Established Design Methodology

According to FEMA P695, "the methodology is recommended for use with model building codes and resource documents to set minimum acceptable design criteria for standard code-approved seismic-force-resisting systems, and to provide guidance in the selection of appropriate design criteria for other systems when linear design methods are applied" [1, pp1-2]. Further, the document states "for new (proposed) systems the Methodology requires identification and use of applicable structural design and detailing requirements in ASCE/SEI 7-05, and development and use of new requirements as necessary to adequately describe system limitations and ensure predicable seismic behavior of components" [1, pp1-3]. Therefore, traditionally non-engineered structures which do not currently have codified design requirements are not excluded from the Methodology provided that calculation-based design requirements can be established.

Since ASCE/SEI 7-05 has no requirements for CM, other sources must be consulted. The primary resources for the design of CM include the Mexican Building Code [7], The Chinese Building Code [8], and most recently, the CMN Guidelines [6]. The majority of code criteria that exist for CM are prescriptive, and as such, cannot be readily converted to a procedure in which the use of an R-factor would be applicable.

Lack of Established Analysis Methodology

A second challenge in the application of the Methodology to CM is the fact that there is no consensus on the most accurate way to model and analyze CM structures. Various modeling methodologies have been proposed and validated in a limited fashion against experimental results.

In the "wide-column" model by Teran-Gilmore et al [9], CM panels are represented by frame elements with equivalent flexural and shear properties, and in a modified version, a nonlinear rotational spring at the base of each wide-column is used to simulate the nonlinear response of the CM panel. While pushover analyses using this modeling technique have been demonstrated to correspond well to experimental results, this method may not be appropriate for use with the Methodology because there is no straightforward way to adjust the global nonlinear behavior that is defined by the rotational springs to account for the variation of parameters that is necessary in the archetype analysis process.

A second modeling technique is the "strut-and-tie" model, a frame model in which the confining elements are represented by beam and column frame elements and the contribution of the masonry is represented by an equivalent diagonal compression strut. This modeling technique was developed for moment frames with masonry infill walls, but according to experimental testing, it may be applicable to CM structures which have experienced sufficient lateral loading for the wall to form significant diagonal cracks and for the tie columns to separate from the wall. However, this methodology is also likely not appropriate for use in the Methodology because it disregards the bond between the confining elements and the masonry wall and does not account for the effects of gravity loading on the masonry.

Finally, there are numerous other more detailed approaches to modeling CM in which 2D or 3D finite elements are used to represent the confining elements and masonry. While the most cumbersome to build, this type of modeling may hold the most promise for use in the Methodology because it has the ability to capture the greatest number variations in the design and account for many more complex nonlinear behaviors such as the interface between the confining elements and the walls.

Quality Control

A final challenge in applying the Methodology to CM systems is that because this system is traditionally non-engineered and is used in many different circumstances and environments around the world, there are no generally-accepted standards for quality control. Quality control applies to the masonry, steel and concrete material quality, and the construction techniques employed to build masonry walls, place steel reinforcing, and place and cure concrete. A survey of CM structures in China, Haiti, and Indonesia demonstrates that quality of materials and quality of construction can vary significantly, which has an impact on the performance of this structural system in a seismic event. Several of the existing design standards for CM, such as the Mexican Code and the CMN Guidelines, provide minimum strength requirements for construction materials. However, in the field, particularly in locations where the majority of CM structures are built, there are few techniques available for verifying material strength, particularly for locally-made materials such as brick, CMU, and concrete.

Because the purpose of the Methodology is to generate equivalent and predictable performance of all structural systems, it is essential for the quality of materials and construction to be monitored. The implementation of a quality control program for CM will be critical where engineered methods of design which make use of the R-factors resulting from the Methodology are employed. However, because the goal of this process is to move in the direction of codifying this traditionally non-engineered structure, it is likely that quality will be better controlled in situations where engineers are involved.

Proposals for Addressing Challenges

The primary purpose of this paper is to present a proposed strategy for applying the FEMA P695 Methodology to CM systems in order to gain feedback from the seismic engineering community, particularly those people who are most familiar with FEMA P695 implementation and those who are most familiar with CM behavior. Proposals for addressing the challenges that were presented above, therefore, are presented here for review and feedback by the seismic engineering community. The intent is to generate a consensus on best practices and approaches, particularly for the first two challenges listed which can be used in the implementation of the Methodology to produce the most accurate and widely accepted results.

Proposed Design Methodology

To address the challenge that ASCE/SEI 7-05 does not provide design guidance for CM and other international building codes provide mostly prescriptive guidelines, our proposal is to use the CMN Guidelines as the basis for the structural design of the archetypes used in the Methodology. The advantage of using this guide is that it provides an approach for computing equivalent elastic lateral seismic forces on CM structures that is very similar to ASCE/SEI 7-05's methodology, and it includes proposed R-factors for brick and CMU CM (4 and 3 respectively) which can be used as trial values. It also provides equations for computing the in-plane shear capacity of CM walls. Therefore, based on an assumed seismic hazard, these guidelines can be used to generate archetype designs in which the required layout and length of CM walls is calculated using a trial R-factor and the performance of these walls under their respective elastic force demands can be analytically tested. One drawback to use of this guideline is that all other design considerations such as the size and reinforcement detailing requirements for the confining elements are prescriptive, so it is not possible to correlate their design to a seismic demand through the R-factor. A second drawback of the CMN Guidelines is that it they are limited to 1-2-story structures so the results of the FEMA P695 implementation will not be applicable to all CM structures, many of which are as high as 3-4 stories. Furthermore, it is the taller structures which would likely benefit the most from the development of more rigorous engineering design procedures.

Proposed Modeling Methodology

While there is no universally-accepted analysis methodology for CM structures, our proposal is to use a family of detailed nonlinear finite element analysis models for the archetype analyses required as part of the Methodology. Detailed finite element models in which the masonry and confining elements are modeled explicitly have the best ability to capture the most important nonlinear behavioral effects, such as flexural and shear response in the masonry walls, degradation of the shear interface between the masonry wall and confining elements and axial flexural and shear response of the confining elements. The most simplistic version would be to represent the confining elements as frame elements with nonlinear hinges and the masonry wall as 2D shell finite elements with nonlinear properties. The interface between the frame elements and shell elements could be represented with frequently-spaced nonlinear shear links. As this may not be an established method for modeling CM, extensive validation would be necessary. The most detailed modeling option would be to model each member as a 3D solid element, including individual bricks. This type of modeling technique has been shown to produce accurate results although it would be the most time-intensive. However, based on the parameters proposed, it may be possible to limit how many models are needed since some of the variables relate to loading rather than geometry. Regardless of which modeling approach is selected, significant validation against experimental data will be needed, not only for the system as a whole but individual components and materials.

Because of the labor-intensive nature of the modeling, it is proposed that the analyses be conducted on individual two-dimensional CM panel models rather than three-dimensional building models. According to FEMA P695, two-dimensional models are typically sufficient because "building code provisions regarding plan configuration and three-dimensional effects (e.g. redundancy, accidental torsion) are usually not system specific" [1, pp5-13]. However, the guide also states "there may be cases where three-dimensional behavior or three-dimensional geometry (e.g. reinforced-concrete C-shaped core walls) are important to simulate" [1, pp5-13]. While it could be argued that the behavior of a CM panel which is bounded by two orthogonal walls will be different from one that is not (due to the bond between the tie columns and the adjacent walls which will engage the orthogonal walls and possibly reduce the tension demands on the columns), the influence of "flange effects" of orthogonal walls is not as significant as it is in reinforced concrete shear wall systems and would be likely to increase capacity rather than decrease it, so we propose to neglect three-dimensional effects in this study. The use of 2D analysis will also eliminate the need to consider bi-directional effects on tie-columns which are shared between walls. While ignoring this effect is not ideal, we do not feel that there is a straightforward way to incorporate this aspect of the system into the Methodology. Finally, the use of 2D analysis will also require assumptions to be made regarding the out-of-plane behavior of the masonry wall panels. We propose to ignore out-of-plane effects based on the assumption that other design requirements will be implemented to prevent out-of-plane failure from occurring, such as limitations on aspect ratio of the panels and spacing of confining elements, maximum height-to-wall-thickness ratios, and lateral bracing requirements for ring beams at floors and roofs.

Proposed Variables for Confined Masonry Archetypes

One of the first steps in the FEMA P695 process is to create a "well-defined concept for the seismic-force-resisting system, including type of construction materials, system configurations, inelastic dissipation mechanism and intended range of applications." [1, p2-2]. Because CM is used around the world in many different contexts and constructed with significant variability, this first step is an essential one to bounding the variables such that the process is manageable. Table 1 provides a summary of the variables that have been considered, whether or not they are proposed to be included in the development of archetype design and performance groups and an explanation for the decision made and whether there are other ramifications that should be considered. The purpose of this process was to develop a concept for the seismic force resisting system which is sufficiently restricted to be manageable yet broad enough to be practically applied in many circumstances.

Table 1. Variables considered for development of confined masonry archetypes.

Variable	Included?	Explanation and Other Considerations
Seismic Design Category (SDC)	No	Although FEMA P695 recommends considering the full range of Seismic Design Categories in which the system is permitted, it states that it is typically sufficient to consider only "the maximum and minimum spectral intensities of the highest Seismic Design Category (SDC) in which the system will be permitted" [1, pp4-13]. Several examples provided in FEMA P695 and NIST GCR 10-917-8 proceed in this fashion in order to limit the effort required. We propose to do the same and consider only SDC D_{max} and SDC D_{min}
Number of Stories (Fundamental Period)	No	Because the CMN Guidelines are applicable to 1- and 2-story buildings only, only 1- and 2-story buildings will be considered in the procedure. Since both 1- and 2-story CM buildings have similar, short periods, there is no need to consider them separately in this respect.
Number of Stories (Gravity	Yes	Because 1- and 2-story buildings can have significantly different gravity loads on the ground floor masonry bearing walls and because the magnitude of gravity loads is known to influence in-plane capacity of confined masonry panels, this

Load)		variable will be considered.
Masonry Material	Yes	In the CMN Guidelines, different R-factor values are proposed for hollow versus solid brick masonry (3 and 4 respectively) due to a difference in ductility factor (note: the source of these data is not clear). Therefore, the masonry material type is considered to be an important variable in resulting behavior.
Aspect Ratio of Panels	Yes	Although certain limitations will be placed on wall panel dimensions and aspect ratios as part of the design, variations within these limits will be studied. To limit the variables, we propose to standardize the height of the panels to 3m and to only vary the width.
Wall Openings	No	We propose to ignore the effects of wall openings because according to the CMN Guidelines, large openings are required to be bounded by confining columns, therefore they would essentially create two smaller confined panels. Based on the results of experimental testing, small openings are accounted for by reducing the length of wall considered in the shear capacity calculation. Therefore, it is not critical to model openings in the archetype designs.
Confining Column Size	Yes	According to experimental research [9, p12], the size of a column relative to the masonry wall thickness plays an important role in the in-plane behavior of confined masonry panels and the ultimate character of damage/failure. The larger the confining column, the closer the behavior will be to a moment frame with infill. Therefore, it is anticipated that this variable is an important one to consider in the archetype development. The CMN Guidelines provide minimum required dimensions for tie columns only so the way in which this variable is implemented will require further consideration.
Confining Element Detailing	No	As explained in the previous section, the CMN Guidelines do not provide a methodology for varying the confining element reinforcing based on level of seismic risk. However, the guideline does specify a different spacing of column ties for regions of moderate versus severe seismicity. To reduce the number of variables in this process, it is proposed that only the detailing corresponding to regions of severe seismicity will be used as the practice of spacing ties more closely at confining column ends is a generally recommended practice.
Wall Thickness	No	Wall thickness will not be considered explicitly in different performance groups although there will be variation in wall thickness as a function of the masonry wall type (CMU versus brick) and possibly as a result of the seismic demands for certain wall configurations (eg 2-story structures may require thicker ground floor walls such as double-wythe brick walls to satisfy seismic demands for certain layouts). Also, as discussed earlier, out-of-plane effects, which are significantly influenced by wall thickness, will not be considered.
Diaphragm Type	No	Whether the floor or roof is a rigid or flexible diaphragm will not be considered as a variable because the analyses conducted will be 2D as described earlier and the distribution of seismic loads to walls based on the diaphragm type will be determined prior to the archetype analysis process.
Wall Config/ 3D Effects	No	Because the analyses will be 2D, C and T-type wall configuration effects will be ignored.

Next Steps and Other Considerations

The discussion so far has focused on the initial, basic steps in the FEMA P695 process which primarily relate to the bounding of variables to limit the complexity of the problem. This section provides some preliminary thoughts on the next two important stages of the process: acquiring of test data for validation of analytical models, and determination of quality ratings for input data. Subsequent steps in the process, such as nonlinear model development and performance evaluation are not discussed herein and will be the subject of a future publication once these preliminary steps are agreed upon.

Obtain Test Data

Reliable test data from experimental testing programs for materials, components, connections, assemblies and systems are essential in the P695 process to "validate material properties and component behavior, calibrate nonlinear analysis models, and establish performance acceptance criteria" [1, p3-1]. For CM systems, these tests must include not only full-scale in-plane shear testing on CM panels but also testing of concrete, steel and masonry materials, testing of reinforced concrete confining columns, beams and connections, and test of interfaces including that between the columns and the masonry wall. A substantial amount of experimental testing has been conducted on CM structures over the past 20 years and we propose to collect the data that are currently available from material-level to system-level testing rather than initiate additional testing for this effort. This proposition is reflected in the proposed quality rating of test data described below.

Select Quality Ratings

The selection of quality ratings for input data is a key component of the Methodology because the seismic performance factors resulting from the process are directly tied to the quality of information used in the process through the collapse fragility curves. According to FEMA P695, "systems that have more robust design requirements, more comprehensive test data, and more detailed nonlinear analysis models, have less collapse uncertainty, and can achieve the same level of life safety with smaller collapse margin ratios" [1, p2-9].

Table 2 provides proposed quality ratings for the four categories of data required in the FEMA P695 procedure and explanations for the proposed rating selection for peer review. These sources of uncertainty include 1) record-to-record uncertainty, 2) design requirements-related uncertainty, 3) test data-related uncertainty, and 4) modeling uncertainty.

Table 2. Proposals for uncertainty ratings.

Uncertainty	Rating	Explanation
Record-to-Record	TBD	Value to be determined based on calculation of period-based ductility factor (m_T)
Quality of Design Requirements	(C – Fair, 0.35) or (D, Poor, 0.50)	Completeness and Robustness Characteristics are suggested as Medium or Low due to the fact that failure modes are not well-correlated to specific design features and requirements. Confidence in Basis of Design Requirements is suggested to be Medium because the system has been tested in numerous real earthquakes.
Quality of Test Data from Experimental Investigation Program	(C – Fair, 0.35) or (D, Poor, 0.50)	Completeness and Robustness Characteristics are suggested as Medium ("experimental evidence is sufficient so that all, or nearly all, important behavior aspects at all levels (from material to system) are generally understood" [1 p3-20]) or Low ("experimental evidence is sufficient so that the most important behavior aspects at all levels (from material to system) are fairly well understood, but the results are not adequate to quantify or deduce with high confidence many of the important parameters that significantly affect design requirements and analytical modeling" [1 p3-21]). Confidence in Test Results is suggested as Medium ("a measure of uncertainty in important parameters can be estimated from the test results. Test results are supported by basic principles of

		mechanics" [1 p-3-21])
Modeling Uncertainty	(C, Fair, 0.35)	Representation of Collapse Characteristics is suggested as Medium ("where the complete design space is not fully represented in the set of models, there is reasonable confidence that the range of response captured by the models is indicative of the primary structural behavior characteristics that affect collapse" [1, p5-24]). Accuracy and Robustness of Models is suggested as Medium because the level of detail in the models is expected to be fairly high but likely not high enough to warrant a rating of High.

Conclusion

This paper considers a 3-step approach for applying a rational methodology to the use of CM as a lateral force resisting system. The first step is the strategy presented here, allowing for informal peer review and comment on the appropriateness of the application of the FEMA P695 Methodology to CM, the applicability of the research that has already been done to the verification of archetypes and models, the limitations and difficulties in the application of the Methodology, and the areas in which low quality ratings may be a significant factor. The application of the Methodology to low-rise structures to determine seismic response coefficients will be step two. Upon successful documentation and peer review of the approach, the next step will be to pursue larger-scale testing to confirm the appropriateness of extension of the results to multi-story engineered CM structures.

As the P695 Methodology for CM becomes standardized and accepted, there will be opportunity in the future to use results of further testing and analysis to optimize individual components of the system, such as reinforcing ratios for confining elements, that until now have only been considered prescriptively. This is a major long-term advantage of subjecting CM to a rational analysis now. The gains in understanding behavior of the system will allow correlation of system performance with design requirements of individual components.

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