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SEISMIC PERFORMANCE OF PARTIALLY GROUTED REINFORCED CONCRETE MASONRY BUILDINGS

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ABSTRACT
Partially grouted reinforced concrete masonry is a common building system in the eastern US. Past and current research on masonry components has indicated a significant difference in behaviour of partially and fully grouted reinforced concrete masonry. Current codes' design provisions for reinforced masonry shear walls are based on fully grouted construction. Thereby, these provisions may not be applicable to partially grouted masonry. This paper presents a review of past research and challenges in performance-based design of partially reinforced concrete masonry. Past and current research on partially grouted masonry assemblages and wall component at Drexel University are briefly presented. Recent test results of assemblages and walls indicates that the behaviour of partially grouted reinforced masonry walls are different from that for fully grouted walls and that the shear strength of partially grouted walls are significantly less than that of similar fully grouted walls. Future research at Drexel will include testing of 1/3 scale two story partially grouted reinforced masonry wall-bearing masonry building. This building test will allow investigating the effect of flanges, wall openings and interaction between perpendicular walls. It is hoped that the proposed system-level research will provide a realistic prediction of the seismic performance and will lead to a more accurate seismic codes' design provisions for reinforced masonry shear wall buildings.

KEYWORDS: concrete masonry, partially grouted masonry, shear walls, seismic performance, system-level research, reduced scale modelling of masonry

MOTIVES AND OBJECTIVE
Historically, the challenges to masonry construction posed by seismic provisions have been limited to western states. However, with the recent adoption of the International Building Code (IBC 2003) throughout the nation, seismic provisions are now negatively impacting the economy of masonry structures in the eastern US. While it is widely postulated among the masonry

industry that the IBC provisions are particularly harmful to masonry construction (thus passively promoting the use of competing systems) there is little, if any, basis for such claims in the literature, as masonry bearing wall buildings remain one of the least studied structural systems. Consequently, the masonry industry finds itself at a crossroads: it can continue to support targeted material or component-level research in a fragmented manner, and continue to expect incremental gains; or it can form partnerships among the many industry organizations and pool funds towards more meaningful, system-level research capable of clearly identifying areas of excessive conservatism and affecting appropriate code changes.

The overarching goal of current and future masonry research at Drexel is to argue for the latter, and to illustrate the opportunity at hand to begin to emphasize the many positive attributes of masonry bearing wall systems. A new vision for masonry research will be articulated founded on the identified gaps and the authors' experiences, and aimed at uncovering current conservatism to develop more appropriate seismic provisions for partially grouted reinforced concrete masonry, particularly for the eastern US.

IBC SEISMIC PROVISIONS-THE CHALLENGE

In 1997 the International Code Council (ICC) initiated an effort to draft a comprehensive building code consistent with and inclusive of the existing model codes. This effort resulted in the development of the International Building Code (IBC) in 2000, which is now maintained and updated every three years. A consequence of this unification is that provisions developed for one region now influence the entire country.

For masonry buildings, current seismic provisions define five lateral force resisting systems and their corresponding detailing requirements, and provide limitations on their use based on the SDC, see Table 1. (Note in Table 1, NL refers to not limited, NP refers to not permitted, and numerical values represent height limitations). Schematics of the various types of reinforced masonry shear walls are shown in Figure 1(a). In addition to the reinforcement and grout shown, several provisions prescribe the required connection details between orthogonal walls and diaphragms. To provide a perspective on this discussion, Figure 1(b) shows a map of approximate SDCs to illustrate the influence of the IBC seismic design provisions throughout the eastern US.

In general, there are two critical aspects of these provisions that represent the core challenge to masonry bearing-wall construction. First, the limitation placed on the lateral force resisting systems for masonry is quite severe and results in significant cost increases. Although objective, quantitative cost data is difficult to come by, it is clear that the required increase in reinforcement and grout, and the corresponding labor for SDC C through F significantly impacts cost (especially when one considers that construction of plain masonry in the eastern US has been the norm for centuries).

The second primary challenge posed by the IBC seismic provisions relates to the response modification coefficients (R-factors) shown in Table 1. These R-factors represent a measure of a system's inherent robustness and ductility and serve to decrease the seismic demand that must be considered in design (i.e. the higher the R-factor, the lower the demand that must be designed for). As can be seen from Table 1, the masonry system R-factors are lower than some competing systems. For example, if we compare an ordinary reinforced masonry shear wall (R = 2½) with ordinary steel braced frames in light-frame construction (R = 4), it is apparent that the masonry system must be designed to resist 60% more lateral force. Whether these R-factors are justified by system-level response attributes is still open to much debate.

While many believe that the IBC seismic provisions do not meet these goals in the case of masonry, it must be recognized that without demonstrated proof of system behaviour, such as in the case of many masonry systems, conservatism must be leveraged to ensure the most fundamental responsibility of the code - to protect life safety - is achieved.

Throughout the second half of the 20th Century RM structures were constructed in high seismic regions and, for the most part, performed reasonably well in earthquakes. Unfortunately, the initial approach to RM design -- a mixture of empirical rules based on heuristics and a working stress (elastic) design methodology -- ultimately proved incapable of reliably satisfying the ductility and strength requirements of seismic design. By the late 1970s it was clear that RM was falling behind competing structural materials such as concrete and steel, and was becoming increasingly rare in high seismic regions.

To combat this, in the mid-1980s the US National Science Foundation (NSF) and the corresponding agency in Japan funded the "US-Japan Coordinated Program for Masonry Research" [1]. To organize the US portion of the program the NSF formed the Technical Coordinating Committee for Masonry Research (TCCMAR). The broad goal of this initiative was to jump start the transition of masonry codes and standards to a more rational limit state design methodology in the hopes of improving the economy of RM construction to stimulate competition and foster lower building costs. However, due to limited resources, TCCMAR recognized early on that this effort could not be comprehensive, but rather should be aimed to provide a body of knowledge and framework for future development. Given this limitation, it was decided to focus on RM for high seismic regions (i.e. consistent with a fully-grouted special reinforced masonry shear wall system). Therefore, the MSJC design provisions [2] are based on testing fully grouted (FG) heavily reinforced masonry shear walls [3, 4] and sub-system [5]. The applicability of these provisions to partially grouted (PG) masonry is questionable.

Given the description above, it is clear that masonry research conducted to date has focused on the extremes of masonry construction: either heavily reinforced, fully grouted masonry or URM. As a result, there is little information about the response of lightly reinforced, partially-grouted masonry construction that is likely appropriate for the higher seismic regions in the eastern US.

Aside from technical considerations, this vision provides the only means to develop a persuasive rebuttal to the current seismic provisions that are challenging masonry construction in the eastern US. To that end, a research program aimed at bridging the knowledge-gap associated with the system-level performance of lightly reinforced partially grouted masonry shear wall systems has been initiated in 2007 at Drexel University. The overarching goal of this research is to investigate the response of lightly reinforced, low-rise masonry buildings and to identify system-level mechanisms that contribute to displacement and force capacity. It is envisioned that such an effort will clearly uncover any sources of excessive conservatism within current seismic provisions and inform future seismic provisions regarding the limitation of masonry structural systems and masonry system R-factors.

Table 1: Basic seismic force resisting system limitation and response modification coefficients based on SDC (IBC 2003)

BASIC SEISMIC-FORCE-RESISTING SYSTEM	RESPONSE MODIFICATION COEFFICIENT, R^a	SYSTEM LIMITATIONS AND BUILDING HEIGHT LIMITATIONS (FEET) BY SEISMIC DESIGN CATEGORY AS DETERMINED IN SECTION 1616.3[c]				
		A or B	C	D[d]	E[e]	F[e]
1. Bearing Wall Systems						
A. Ordinary steel braced frames in light-frame construction	4	NL	NL	65	65	65
B. Special reinforced concrete shear walls	$5^1/_2$	NL	NL	160	160	100
C. Ordinary reinforced concrete shear walls	$4^1/_2$	NL	NL	NP	NP	NP
D. Detailed plain concrete shear walls	$2^1/_2$	NL	NP	NP	NP	NP
E. Ordinary plain concrete shear walls	$1^1/_2$	NL	NP	NP	NP	NP
F. Special reinforced masonry shear walls	5	NL	NL	160	160	100
G. Intermediate reinforced masonry shear walls	$3^1/_2$	NL	NL	NP	NP	NP
H. Ordinary reinforced masonry shear walls	$2^1/_2$	NL	160	NP	NP	NP
I. Detailed plain masonry shear walls	2	NL	NP	NP	NP	NP
J. Ordinary plain masonry shear walls	$1^1/_2$	NL	NP	NP	NP	NP
K. Light frame walls with shear panels—wood structural panels/sheet steel panels	$6^1/_2$	NL	NL	65	65	65

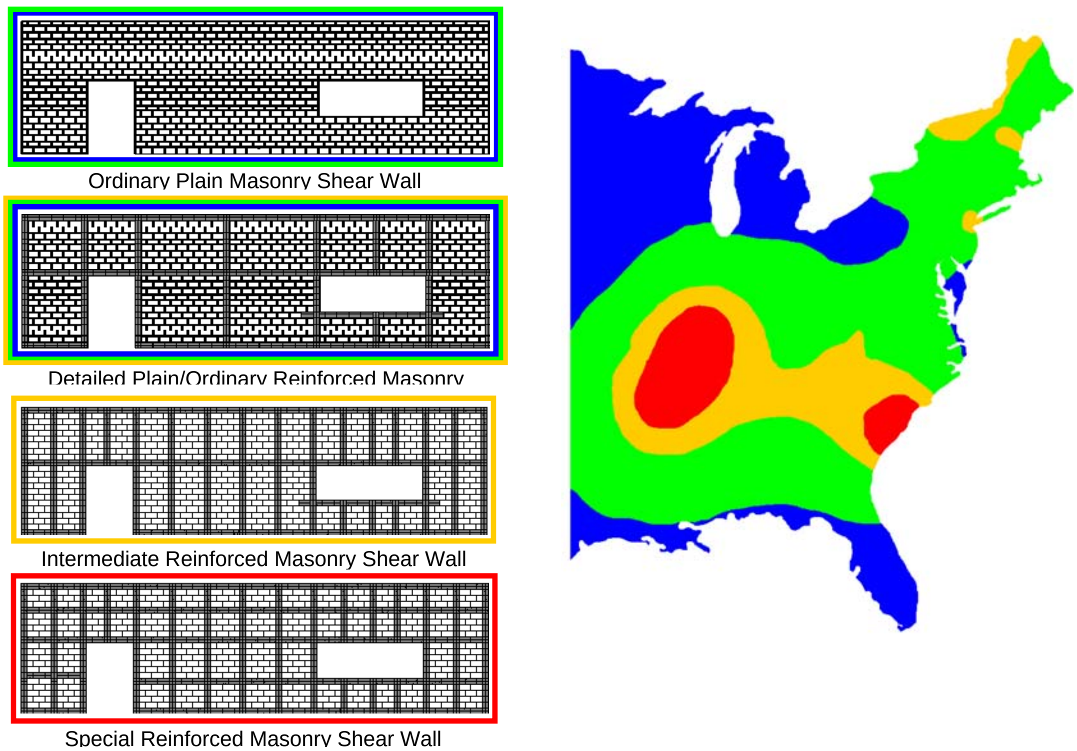
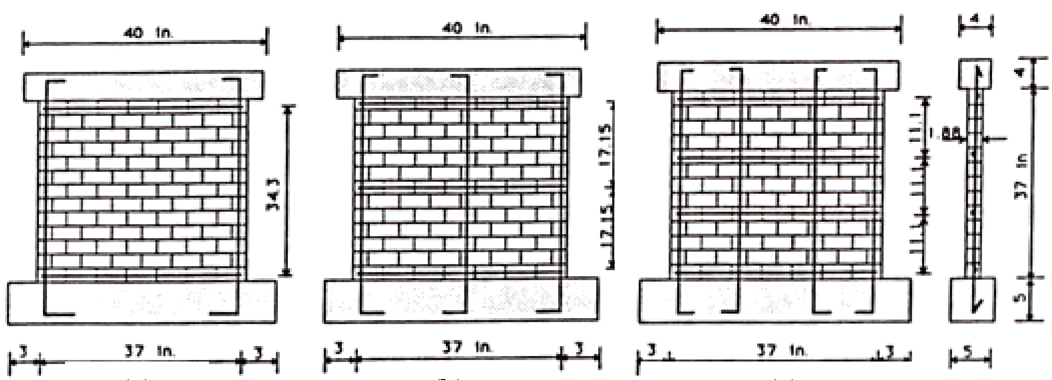


Figure 1: (a) Schematic of the IBC reinforced masonry shear walls and (b) SDC of the Eastern US for soil condition C (IBC 2003 [6])

PAST AND CURRENT RESEARCH ON PARTIALLY GROUTED REINFORCED MASONRY SHEAR WALLS AT DREXEL

In 1992, Ghanem et al. [7] conducted 1/3 scale tests of partially grouted concrete masonry cantilever shear walls under monotonic lateral load. Three different reinforcement arrangements were used, see Figure 2. Vertical and horizontal steel reinforcement percentages were kept constant for the three walls. The spacing of reinforcement and extend of grouting (only at the cells containing steel reinforcement) were the main variables. Figure 3 presents the load-displacement curves for the three walls. As shown, stiffness, strength and post-peak response are different for the three walls. It was concluded that the behaviour of partially reinforced masonry is strongly dependent on the distribution of reinforcement. As the reinforcement is more uniformly distributed, both the strength and deformation capacity of the walls increased. In addition, the distribution of reinforcement had a marked effect of wall failure mode. As the reinforcement went from being concentrated in local areas (SWA) to being more uniformly distributed (SWC), the failure modes switched from shear to shear/flexure to flexure. Finally, it was concluded that in order to avoid brittle shear failure the horizontal reinforcement should be distributed; however, to enhance flexural strength the vertical steel should be concentrated at the ends of the wall.



(a) (b) (c)

Figure 2: Reinforcement configuration for (a) Wall SWA, (b) Wall SWB, and (c) Wall SWC (taken from [7])

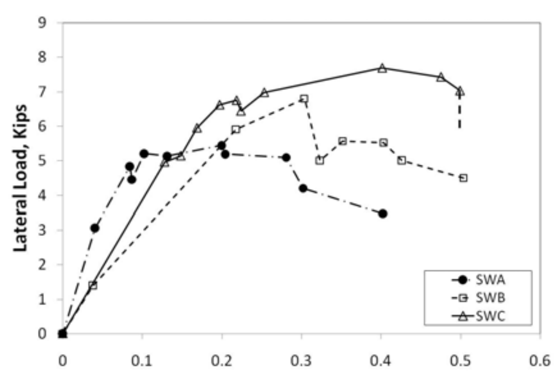


Figure 3: Monotonic force-displacement response of Wall SWA, Wall SWB, and Wall SWC (Redrawn from [7]).

In 2007, a comprehensive research study was initiated to investigate the seismic response of partially grouted concrete masonry at the assemblages [8] and wall components [9] levels. The main goal is to determine the effect of partial grouting on shear wall cyclic response. Figure 4 shows a schematic of the shear wall test setup. With the two displacement-controlled vertical actuators it was possible to control the rotation at the top of the specimen to create fixed-fixed boundary conditions.

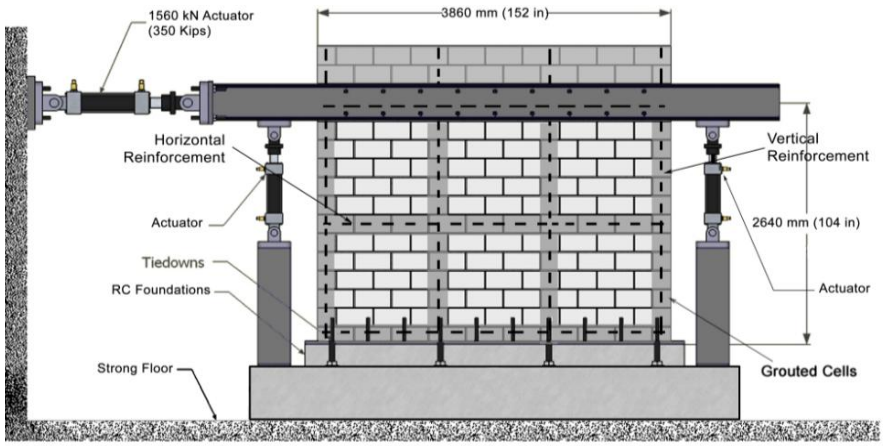


Figure 4: Shear Wall Test Setup [9]

Figure 5: Cracking and Failure mode of partially grouted walls [9]

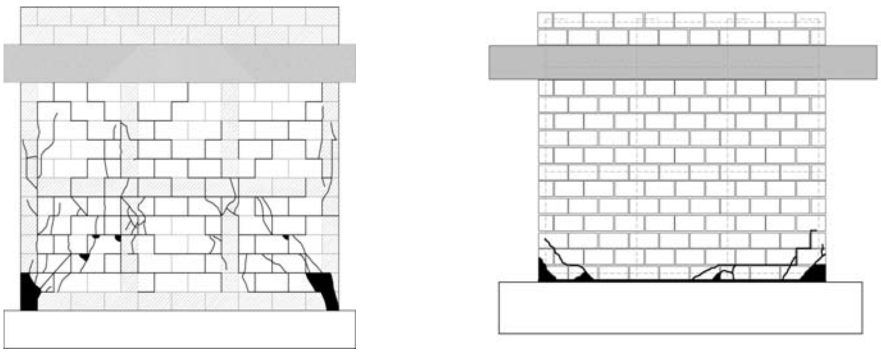


Figure 6: Wall cracking and failure modes of partially and fully grouted walls

Tests indicated a distinct difference in behavior of partially and fully grouted walls with similar reinforcement. The behavior of partially grouted shear walls is similar to that of masonry in-filled frames. As shown in Figure 7 the shear strength of partially grouted wall is significantly less than that of fully grouted wall with the same reinforcement. Based on the experimental data from this research program and past researches, the MSJC code is non-conservative in predicting the strength of partially grouted shear walls.

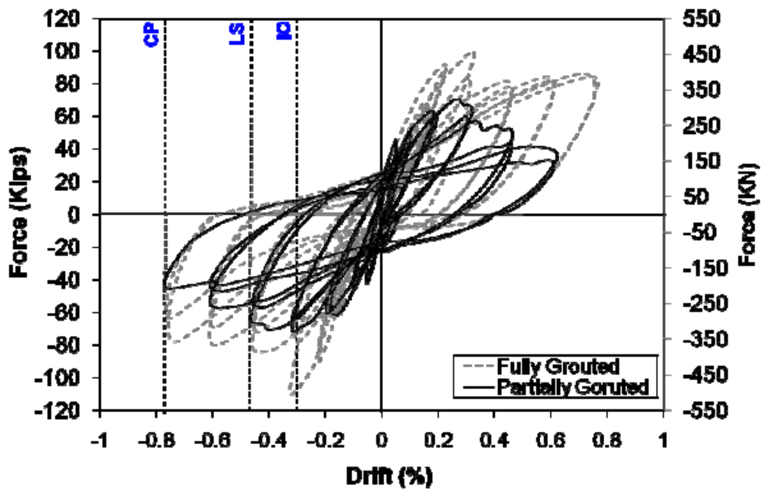


Figure 7: Cyclic load-displacement curves for partially and fully grouted walls

FUTURE SYSTEM-LEVEL MASONRY RESEARCH AT DREXEL

To fill this knowledge-gap and to identify and reduce any excessive conservatism it may be sustaining, investigations into system-level performance must become the norm for masonry research. While the behaviour of structural systems such as frames may be reasonably approximated by investigating the response of primary components (e.g. columns and beams), this is not the case for bearing-wall systems. Such systems are highly indeterminate and interconnected, which precludes the accurate a priori identification of continuity conditions and force-resisting mechanisms that affect individual component response. As a result, component-level investigations of such systems are hampered by considerable levels of epistemic uncertainty. Faced with this challenge, past researchers have been forced to employ conservatism by isolating individual components and neglecting poorly understood system-level mechanisms. Such studies implicitly ignore the many desirable attributes of bearing-wall systems and are prone to providing overly conservative results.

In order to perform such an investigation with the limited resources likely available, this effort will leverage the established field of reduced-scale structural modelling [10]. The salient tasks for the proposed investigation are listed in the following and shown schematically in Figure 8.

With funding from the masonry industry (NCMA, PCA and IMI) a 1/3 scale two story partially grouted reinforced masonry wall-bearing masonry building with configuration similar to what is shown in Figure 8 will be constructed with 1/3 scale blocks produced in-house using the shown block-making machine (Figure 9) and rigid concrete diaphragms. This test will allow investigating the effect of flanges, wall openings and interaction between perpendicular walls. Two displacement-controlled actuators at each floor level will impose equal cyclic displacements to the in-plane walls and the restoring force will be measured. Load-displaced hysteretic curves will be drawn to determine wall stiffness, strength and ductility.

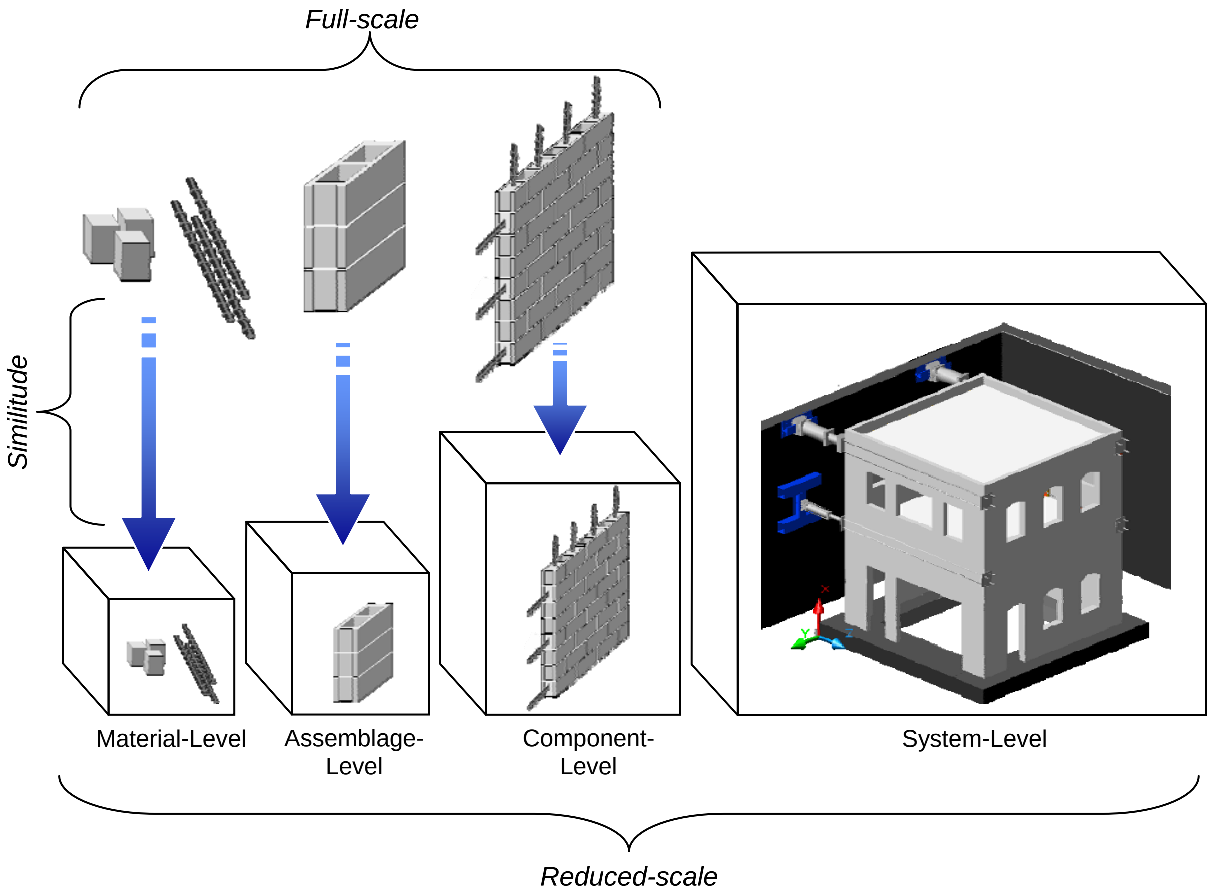


Figure 8: Overview of small-scale validation at the material-, assemblage-, and component-levels building to reduced scale experiments of complete masonry bearing-wall systems.

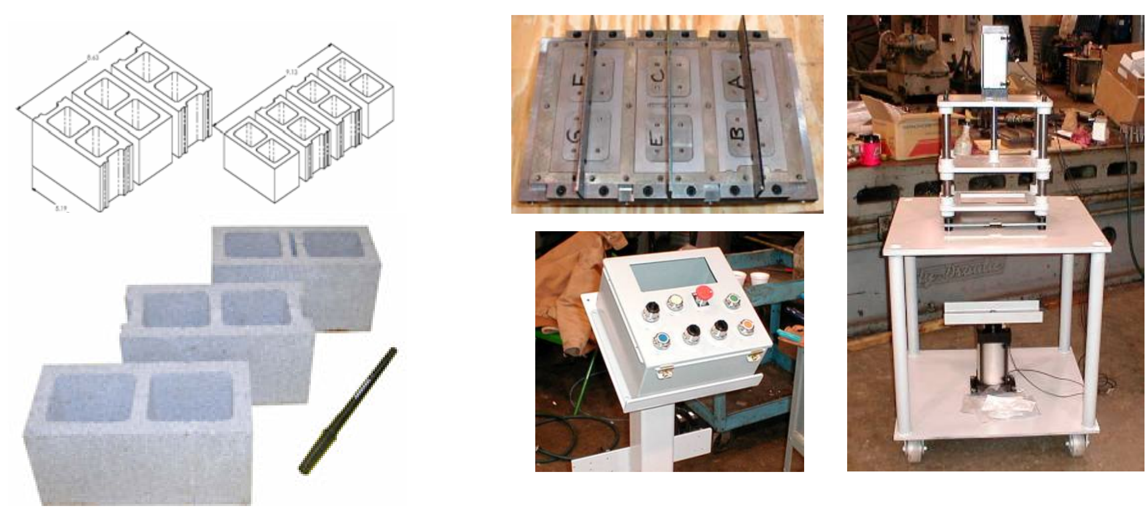


Figure 9: Small-scale blocks produced in-house at the Masonry Research Lab of Drexel University

CONCLUSIONS

Past and current research on masonry components has indicated a significant difference in behaviour of partially and fully grouted reinforced concrete masonry. Current codes' design provisions for reinforced masonry shear walls are based on fully grouted construction. Thereby, these provisions may not be applicable to partially grouted masonry. It is planned to test a 2-story 1/3 scale partially grouted reinforced concrete masonry building at Drexel University. It is hoped that this system-level research will provide a realistic prediction of seismic performance and will lead to a more accurate design provisions for partially grouted reinforced masonry buildings.

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