A MORTARLESS PRESTRESSED MASONRY HOUSE: CASE STUDY

DAVID T. BIGGS, P.E.

Principal
Ryan-Biggs Associates, P.C.
Troy, New York USA

THOMAS E. FORSBERG, P.E.

Baker, Ingram & Associates.
Lancaster, Pennsylvania USA

INTRODUCTION

Researchers in several countries have been experimenting with various forms of mortarless masonry construction as a means to provide low-cost residential construction. It also has been viewed world-wide as a construction method that reduces the number of skilled masons required to complete a project. Meanwhile, prestressed masonry has been developed to the point where it is now codified in England, New Zealand, Switzerland, Australia, the United States, and other countries.

Since the late 1990s, a system for mortarless masonry construction using post-tensioning has been under development and marketed in the United States. It utilizes special concrete masonry units, post-tensioning tendons, post-installed tendon anchors, and surface bonding.

This paper describes this mortarless masonry system and a residential application in Texas where a one-story, three-bedroom house was constructed on a slab on grade. The system uses post-tensioned masonry to provide both flexural strength to the walls and an integral tie-down for the roof trusses to resist high-wind forces. Surface bonding in combination with post-tensioning provides shear resistance, resists water penetration, and acts as a finish for the masonry. Using unrestrained tendons, post-tensioning minimizes the amount of grouting required, leaving the cores of the concrete masonry units available for insulation.

BACKGROUND

The use of masonry began with mortarless (dry-stack) construction. For centuries, stone has been laid dry. The Pyramids of Giza are an exquisite example of limestone ground smooth and fit tight without mortar (Figure 1). Throughout the world, there are numerous examples of residences, walls, fortresses, and towers constructed with masonry without mortar. These structures rely on gravity and friction to maintain their stability.

The fascination with dry-stack masonry continues today. While stone retaining walls are still popular in some regions, the emphasis now is primarily on the use of unit masonry. A relatively recent adaptation of mortarless masonry has been applied to segmental retaining walls using either gravity or mechanically stabilized earth techniques (NCMA, 2004).

The concept of mortarless construction applied to buildings has been addressed internationally (Anderson 2001; Glitza 1991; Kowalsky 2004; Ngowi 2005; Ramamurthy 2004). Applications have primarily been for residential construction, but commercial construction is also possible. A particular appeal of mortarless masonry is that it requires fewer skilled masons to complete a project since much of the work can be performed by laborers directed by masons. There are several features common to most systems. These include:

1. Special masonry units that interlock and have cores that align to accommodate grout.
2. Reinforcement either mortared or grouted in place for strength. (However, there are some systems that continue to use unreinforced masonry.)
3. No building codes controlling the design of such systems. The justification for their use is often based on performance-based design.

Figure 1 – Great Pyramid at Giza, c. 2500 B.C.

Some examples of mortarless systems and standards include:

South Africa

To encourage innovation, South Africa has developed a methodology for evaluating dry-stack systems not meeting the conventional standards for reinforced masonry. The masonry walls are tested to meet loading criteria from the code using "Structural Assessment of Dry-Stack Masonry Building Systems" (Figure 2). One- and two-story construction may be tested.

Figure 2 – Wall tested for out-of-plane loading (South Africa).

Australia

There are several examples of dry-stack systems in Australia. The Smart Masonry™ system is composed of stretchers (Figure 3) and corner units. It is used with grouted construction to provide structural capacity. Developed in Australia, it has also been used in Sri Lanka and South Africa.

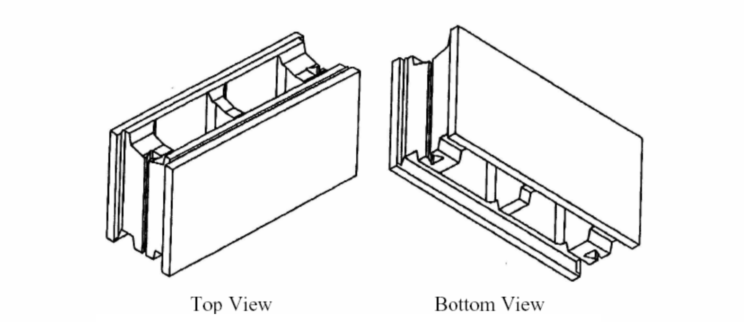

Figure 3 – Smart Masonry system (Australia).

Another Australian system is the Boral Connex™ mortarless system. This also relies on conventional reinforcement (Figure 4). Corner and half units are available.


Figure 4 – Boral Connex ™ system (Australia).

Canada

The Azar Dry-Stack Block™ is another variation on an interlocking system with conventional reinforcement (Figure 5). Canada has an evaluation service, the Canadian Construction Materials Centre, which reviews products and systems for acceptance. The system is approved for buildings of three stories or less.

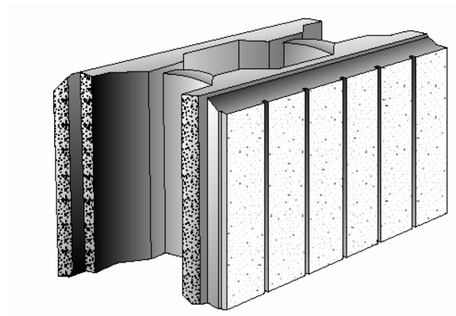
Figure 5 – Azar Dry-Stack Block ™ (Canada).

United States

Currently, there is no design standard for reinforced masonry using dry-stack construction. Efforts are underway by The Masonry Society and the American Concrete Institute to develop guidelines and recommendations for reinforced walls.

The National Concrete Masonry Association has published its own recommendations but they do not have code approval (NCMA 2003). However, the publication does address three types of dry-stack construction:

1. Unreinforced, fully-grouted walls.
2. Reinforced, fully- or partially-grouted walls.

3. Surface bonded walls.

Because of seismic and high-wind considerations, unreinforced masonry has limited applications in the U.S. Most masonry has converted to reinforced construction.

Surface bonding is one dry-stack method that has been codified for over 30 years (IBC 2003). It includes using a coating to provide shear and flexural strength (Figure 6). While this method has been allowed for unreinforced masonry, it has not been widely used.

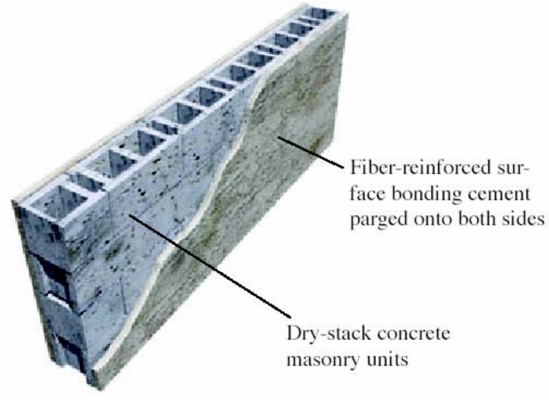

Figure 6 – Surface Bonding (United States).

There is significant interest in dry-stack construction in the United States as evidenced by the large number of patents issued. Most patents are for novel masonry units and rely on conventional grouted construction. Figures 7 through 11 show several of the current or proposed systems. Figure 10 utilizes a metal starter strip for alignment.

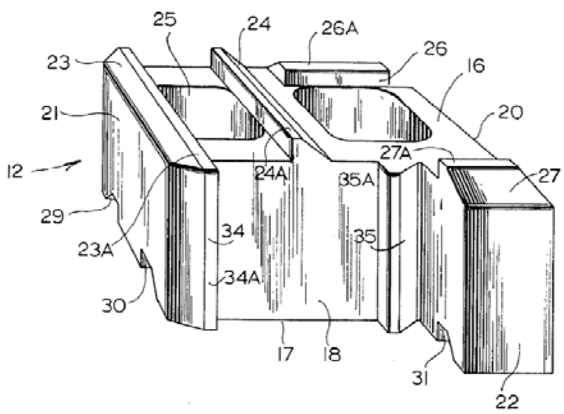

Figure 7 – Patent 3,962,842, Mortarless Interlocking Blocks (1976).

Each system has its own alignment feature to make installation easier than conventional masonry units.

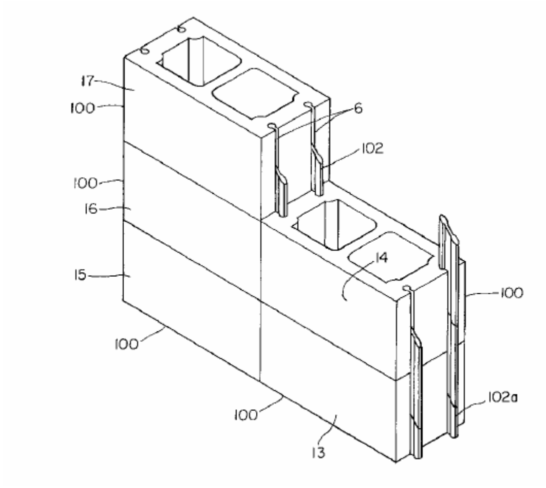

Figure 8 – Patent 6,189,282 B1, Mortarless Concrete Block (2001).

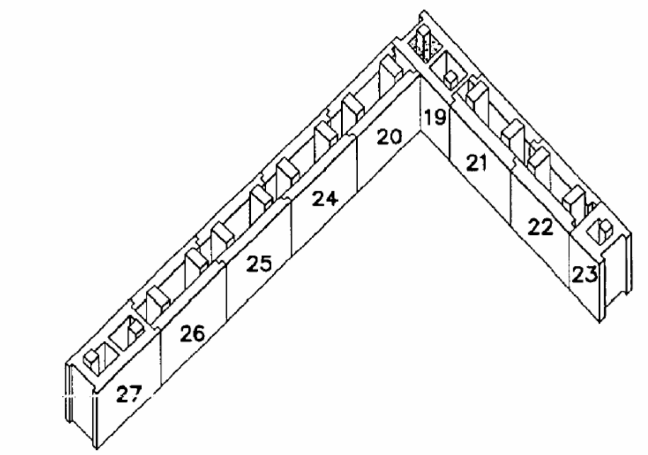

Figure 9 – Patent 6,907,704 B2, Interlocking Mortarless Load Bearing Building Block System, 2005.

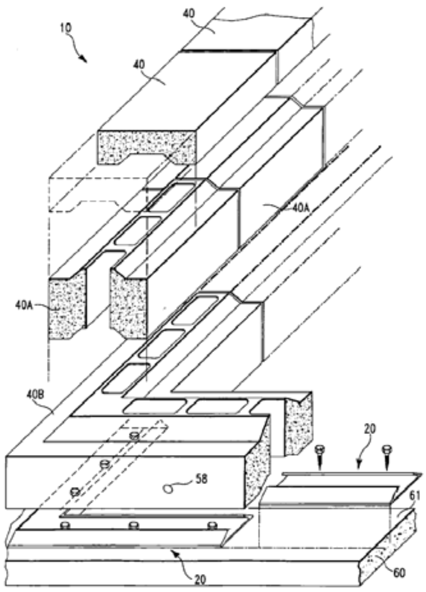

Figure 10 – Patent Application US 2007/0011979 A1, 2007.

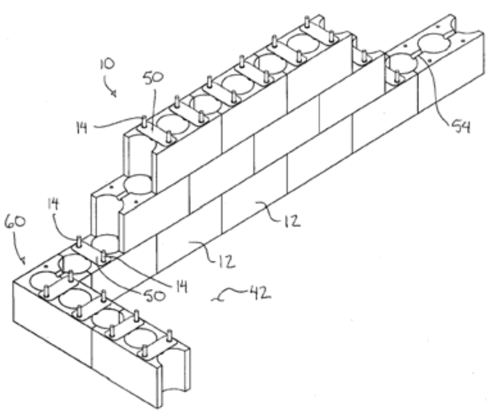

Figure 11 – Patent Application US 2007/0017176 A1, Masonry Wall System, 2007.

SYSTEM DESCRIPTION

There has been research performed on dry-stack, post-tensioning systems in the United States (Biggs 2002) and Germany (Marzahn 2002). In New Zealand, the first mortarless, post-tensioned house was constructed in 2006 based on research on post-tensioning performed at the University of Auckland (Wight 2006). It used grouted, post-tensioning tendons.

The FlexLock Wall System is patented in the United States and utilizes vertical post-tensioning to reinforce the walls. The system has both residential and commercial applications. Additional testing is under development along with code approval. Until code evaluation approval is completed, the system is used under the terms of a special structure in accordance with the *International Building Code* (IBC 2003).

The primary components are special masonry units, post-tensioning tendons, and conventional masonry reinforcement as needed to satisfy prescriptive code requirements.

The units are unusual in that they are calibrated to exacting tolerances so that they mate without rocking. Calibration is accomplished during the manufacturing process by grinding both the top and bottom surfaces of the units, making them flat, smooth, and parallel to one another. After the units are calibrated, lasers measure the unit sizes and ensure the units are within tolerance. This is essential for a tight fit so the units stack evenly and the post-tensioning forces do not cause them to crack during tensioning.

Unit dimensions and shapes are other unique features. Conventional unit masonry is specified by modular dimensions (e.g. 20 cm x 20 cm x 40 cm), while the actual size is 10 mm (3/8 inch) smaller in each direction. With the FlexLock units, the modular size is the actual size in all three directions. The units are open on one end with a vertically slotted web for ease of placement around vertical tendons (Figure 12). The units are installed by alternating the open ends. None of the units have to be lifted over the tendons.

Figure 12 – FlexLock masonry unit.

The post-tensioning tendons are steel bars that are typical for U.S. masonry, post-tensioning applications. The first course is set in mortar to ensure leveling of the wall (Figure 13). Conventional reinforcing and grout are used for horizontal lintels over openings and may be used vertically at jambs as conditions warrant. The top course is constructed as a horizontally reinforced and grouted bond beam to provide a bearing surface for the post-tensioning cap plate and to distribute the post-tensioning forces throughout the wall below.

Besides satisfying prescriptive code requirements, conventional reinforcing and grout may be used at jamb openings as various conditions dictate. Where units are cut to form openings, vertical reinforcing and grout are used to locally stabilize the wall and provide additional strength.

Figure 13 – First course set in mortar around vertical tendons.

CASE STUDY – HOUSE IN MAGNOLIA, TEXAS

A residential structure was completed in Magnolia, Texas, 2006, the first of its kind using the FlexLock Wall System. The house is a one-story structure with an approximate footprint of 14.6 m x 18.3 m (Figure 14). Using about 213.7 square meters of FlexLock units, all perimeter walls, one interior bearing wall, and the demising wall separating the garage from the interior living space were fully erected in approximately four days.

Like most building projects, the process begins with the design and production of detailed drawings showing the location of building elements. The foundation plan includes a layout plan for the first course of units along with dimensioned locations for the post-tensioning tendons. Particular attention is required to coordinate locations and dimensions for wall openings because of the actual dimensions of the units.

Design Criteria

The structure was designed in accordance with the *International Building Code* (IBC 2003) for load development, IBC Section 2109, Empirical Design of Masonry, for in-plane shear strength, and Chapter 4, Prestressed Masonry of the *Building Code Requirements for Masonry Structures* (ACI 530-02) for both in-plane and out-of-plane loads. ACI 530-02 does not specifically apply to mortarless systems. The design decision was to use it because the walls were being kept in compression.

Figure 14 – FlexLock house structure near completion.

In-Plane Shear Strength

For lateral stability, the walls of the Magnolia house were designed as shear walls. Static in-plane shear tests have been performed on various FlexLock wall panel configurations by NCMA. To date, there is no consensus on the allowable shear strength of the FlexLock system, and additional testing is pending.

For determining allowable shear stress, mortared masonry uses a 0.45 factor to account for the frictional interaction between the mortar and the masonry units. Tests on the FlexLock panels resulted in a coefficient of friction of approximately 0.20. For design purposes, a coefficient of friction of 0.10 was used. Tests performed by NCMA resulted in an actual stress of approximately 138 kPa (20 psi) before the shear test panel deflected to H/400.

Because of the limited test data, a cementitious surface-bond coating was applied to the FlexLock shear walls to enhance the shear strength, resulting in a conservative design. The IBC allows a maximum shear stress of 69 kPa (10 psi) for surface-bonded, dry-stacked masonry walls. Shear walls for the Magnolia house were proportioned based on this maximum allowable shear stress.

Out-of-Plane Flexural Strength

Without mortar, dry-stack units cannot resist tension. The post-tensioning tendons were designed to induce compression in the walls to overcome the tension created by out-of-plane flexural loads.

Under the provisions of ACI 530, Chapter 4, the tendons were designed as laterally restrained and unbonded. The moment strength was determined based on the axial compression from the prestress load, the partial weight of the wall units, and the additional dead load from the roof structure where applicable.

Once placed, the tendons were prestressed to 35.6 kN (8,000 pounds). Accounting for losses, the net result is approximately 24.9 kN (5,600 pounds) for a tendon under service conditions. This corresponds to a uniform compressive stress of 297 kPa (43 psi) on the net wall section with tendons spaced at 1.22m (4 ft). Design tension values without consideration of the prestressing were in the range of 172 kPa (25 psi) to 207 kPa (30 psi) were based on flexural loading conditions. The prestressing was added overcome these stresses. No consideration was given to the surface-bond coating for flexure.

Since the controlling design condition was to avoid tension in the joints under lateral loads, the maximum compressive stress in the units was only 517 kPa (75 psi). The strength of the units generally exceeded 13.1 MPa (1900 psi) and the design compressive strength of the system exceeded 10.3 Mpa (1500 psi). Thus, the compression on the wall only utilizes 5 percent of the compressive capacity of the system.

Support for the walls was achieved by placing a reinforced concrete slab on grade. The 13-cm-thick slab is conventionally reinforced with a haunched perimeter and thickened areas under the interior bearing wall.

After slab placement and curing, the post-tensioning tendon locations were laid out on the slab. Holes were drilled into the slab to a specified embedment depth, and the tendons were placed and secured with a high-strength cementitious grout. Once the grout cured, the tendon anchorages are proof loaded to verify the required strength. To facilitate placement of the units, the tendons may be installed with mechanical splices as the wall installation progresses upward (Figure 13).

Once the tendons are installed in the slab, the first course of FlexLock units is laid in mortar. The mortar under the first course is critical to ensure that the units are level. The placement method, referred to as “one forward, one back,” requires the mason to set one unit in mortar and then set another unit on top, one-half course behind. This method aides in leveling the units and ensuring that there is no height differential between adjacent units.

After the first course was laid, installing the remaining dry-stack walls progressed rapidly. The perimeter bond beam was installed at the top of the wall, and the post-tensioning tendons were tensioned with a jack and locked off to a bearing plate sitting on the bond beam. As with conventional post-tensioning design, the tendons and corresponding post-tension loads used in the wall system account for both short-term and long-term load losses.

An added benefit is that the vertical tendons were also used to anchor the dimensional lumber top plate on which the wood roof trusses bear, eliminating the need to provide a separate anchor bolt embedded into the bond beam at the top of the wall. Connecting the top plate to the tendons provides a direct load path for structural forces.

Once the walls were erected, the exterior surface was coated with a cementitious, surface-bond coating. The purpose of this coating is twofold: to provide resistance to water penetration and to enhance the in-plane shear strength of the wall system. In this case, a stone band was added to the lower portion of the wall (Figure 14).

With the walls complete, the remaining framed construction was performed by conventional means. Metal-plate connected, wood roof trusses were installed and sheathed. The interior surfaces of the masonry walls were furred out to provide space for electrical wiring and fixtures and a surface to which the interior finish materials were fastened.

Post-construction, a cost study was performed by Cercorp Initiatives, the developer of the FlexLock system, to compare the cost of using the FlexLock system with conventional masonry construction. Working with a mason contractor, the study estimated that the cost of using FlexLock was approximately 25 percent less than conventional means, along with an increase in productivity of nearly 120 percent. The savings were generated through reductions in mortar and grout materials, time and labor to prepare and place those materials, and time required for installation. The need for fewer skilled masons was also a contributing factor.

The result was a high-performance house constructed in a short timeframe that is a model for innovative design, cost savings, and productivity.

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