HYBRID MASONRY STRUCTURES

David T. Biggs[1]

Abstract

Load-bearing masonry as a structural system is often in competition with frames of structural steel or concrete as the primary structural system for a building. However, masonry is also used as an infill for exterior walls of framed systems. The interaction of masonry with a frame often leads to construction interferences, particularly with diagonal bracing in building frames. Masonry can be used in combination with steel- or concrete-framed construction to create an efficient hybrid structure that uses the specific qualities of each structural material.

In the late 1890s when framed construction began for commercial construction in the United States, structural frames were encased with masonry for wall infill and fireproofing. Partitions were masonry as well. Those building frames were generally designed for only gravity loads; the masonry provided redundancy for lateral load support. In the 1940s as the design of framed construction advanced, the walls became decoupled from the structure and lighter and less durable wall systems were introduced as a masonry substitute; masonry elements started to take on a non-structural role. Overall, the redundant stiffness of framed structures has decreased.

With the growing concerns for preventing progressive collapse and building safety, reinforced masonry offers a renewed opportunity to provide structural redundancy when used in combination with structural frames.

This paper will introduce the concept of hybrid masonry structures, framed construction used in combination with reinforced masonry. It will relate these structures to the historical development of framed buildings and will compare them with confined masonry systems (reinforced concrete frames with unreinforced masonry infill) used throughout the world and in the high-wind areas of Florida. An example will be provided showing how masonry can be used as a primary structural element in framed buildings, thereby creating a system which

---

[1] Principal, Ryan-Biggs Associates P.C., Troy, New York, 12180, USA, dbiggs@ryanbiggs.com

eliminates conflicts with frame bracing, makes the frame more economical, and provides structural redundancy to resist progressive collapse.

Introduction

Masonry has been used as structure since man began building buildings. Over time, new uses have been developed for masonry that include performing as façade, backup, infill, or fireproofing. It has been used as infill for other structural systems for decades.

Masonry Walls and Structural Systems

There are several distinct phases in the progression of masonry walls. That development is closely aligned with advancements in framed structural systems. These include:

a. Bearing walls, b. Infill walls (nogging), c. Caged construction,
d. Transitional walls, e. Confined masonry, f. Cavity walls

This paper recommends that the next phase of masonry development should be hybrid masonry.

Bearing Walls

Bearing walls were the first use of masonry providing form and function in one system. They were the primary structural system until beams and column systems developed. Prior to the 1890s, most major buildings used load-bearing masonry walls for multi-story construction. The walls of multi-story buildings were thick at ground level and became thinner as additional floors were added.

Infill Walls (Nogging)

As other structural systems developed, masonry was also used as infill walls. Brick nogging was the first infill type to combine with timber framing. England began using brick nogging in the 1500s after quality bricks were available (Biggs 2005). This system of masonry infill was commonly used for both interior and exterior walls. On the interior, nogging was placed between the wood studs and served as excellent fireproofing. On the exterior, nogging sometimes functioned as veneer, fire protection, and backing for an interior finish. Brick nogging was commonly used for wood-framed buildings in the United States into the early 1900s.

.

Caged Construction

Structural frames began with the wrought-iron framed Glass Palace in France in 1851. This was an iconic structure. The technology spread, and in the 1880s structural frames came to the United States. With the development of structural steel, buildings grew taller.

In 1882, architect George Post introduced the first framed building using a new system called caged construction. A structural framework was mixed with masonry exterior walls. The term caged walls resulted from the exterior walls being built around a structural cage. The frame supported the floor and roof loads; the masonry was independent of the frame and self-supporting. As a result, the wall thicknesses were only slightly less than those in bearing wall buildings. Caged-wall buildings were only used from about 1890 to 1910 in New York and a few other cities.

Other cities continued to use exterior bearing walls and interior structural frames, including the famous Monadnock Building in Chicago. Constructed in 1892, this 15-story building has exterior walls up to 6 feet (1.83m) thick at the base and was the world's largest office building when completed. Ironically, it was the last high-rise built with exterior masonry bearing walls and an interior frame.

Transitional Walls

With the advent of structural frames, designers were looking for ways to build taller buildings. They also tried to reduce the thickness of the exterior walls. These frames of structural steel or reinforced concrete were used to support building loads and exterior wall loads. Curtain walls developed during this time.

The designation as the first skyscraper is attributed to the ten-story 1883 Home Insurance Building in Chicago (Columbia 2005). These transitional buildings took traditional masonry walls and constructed them integral with the exterior structural frame (Searls 2000). Brick or hollow clay tile was used as an inner wythe, usually 8 inches (200 mm) thick. An exterior wythe of brick, cast stone, terra cotta or stone was anchored or headered to the backup to function as a composite wall system, but there was no accommodation for the masonry walls to take differential movement.

It was common to design these buildings for gravity loads only. While the wall system was not intended to be structural, it provided lateral stiffness. The masonry also provided exterior finish, fire protection for the frame, and backup for the interior finish.

Confined Masonry

There are masonry structures throughout the world using unreinforced masonry within a concrete frame; the walls are therefore confined. This practice, dating to the 1800s, has developed globally but apparently has no specific origin.

Confined masonry is used primarily for residential construction. The type of masonry infill varies by region or country and includes either clay brick, clay tile, stone, or concrete masonry.

Modern day confined masonry is semi-engineered in many areas. The concrete frame includes columns and tie beams that are engineered along with unreinforced or reinforced masonry dependent upon the local building code. In the United States, Florida's building code has a section for high wind velocity zones (Florida 2004) which includes confined masonry that is reinforced.

Cavity Walls

There were some ancient Greek and Roman constructions with cavity walls, but the majority of walls used solid masonry. The British reinvented the cavity wall in the early-19th century but it did not appear in the US until the late-19th century (Masonry Advisory Council 2002). Up until this time, masonry walls were primarily barrier walls that relied upon thickness and mass to prevent water penetration.

Modern veneer construction began in the late 1940s. A major change occurred in the structural concept in that the wall systems were isolated from the frames. The masonry walls became thinner and lighter.

These lighter frames resulted in a structure that was not as stiff as previous frames in the transitional buildings. The walls included cavity walls with a backup, veneer, and drainage cavity.

The exterior masonry walls acted as a veneer; the backup supported the interior finish and provided fire protection for the frame. The masonry backup was generally unreinforced. Reinforced masonry came into use as seismic effects were included into the design.

During this time, relieving angles were added to the construction vernacular. While the backup was supported directly by the floor structure, the veneer was supported by the frame using relieving angles that allowed the veneer to accommodate frame movement.

Hybrid Masonry Systems

In recent decades, architects and engineers have primarily used only cavity walls. Codes usually require that these are constructed within a framed structure so that the masonry infill backup is isolated from the building's lateral movement. Thus no lateral loads are imparted to the masonry; they only support out-of-plane (flexural) loads. In this paper, the term infill walls will be used for these backup walls.

Hybrid masonry represents a return to using masonry infill for lateral stiffness and strength within frames in addition to supporting out-of-plane (flexural) loads. A chief difference is that hybrid masonry walls are constructed of reinforced masonry, not unreinforced masonry as was common in transitional buildings. While hybrid masonry systems can be applied to either concrete or steel-framed structures, the emphasis in this paper will be directed to steel frames.

There are several primary reasons for the development of hybrid masonry systems. The first is to simplify the construction of framed buildings with masonry infill. While many architects prefer masonry infill walls as the backup for veneers in framed buildings, there is often a conflict created by structural engineers who insist on positioning steel bracing in exterior walls. This leads to detailing interferences trying to fit masonry around braces. A solution is to use the masonry infill as the bracing.

The second reason for hybrid masonry is to provide structural redundancy which can be utilized to limit progressive collapse. The Unified Facilities Criteria (UFC 2005) of the Department of Defense has criteria for both steel-framed buildings and load-bearing masonry for limiting progressive collapse. Using hybrid masonry, there is an alternative load path for the gravity loads that provides redundancy. The resulting system is more efficient than either a frame or a bearing wall system alone when subjected to progressive collapse design conditions. If a column is damaged in a hybrid masonry frame, the gravity loads are transferred to the masonry. If the masonry is damaged, the gravity load transfers to the frame.

Recent Revelations

During the 1985 Mexico City earthquake, unreinforced masonry infill prevented the progressive collapse of several concrete framed buildings (Beall 2003). The infill was backup for the veneer and often was not anchored by modern standards. Even though these walls were not designed as structural elements, they absorbed seismic loads and increased the lateral stiffness of the buildings.

Recent events in the United States have highlighted the concern for preventing progressive collapse. Starting with the collapse from the bombing of the Murrah Office Building in Oklahoma in 1995 and later with the collapse of the World Trade Center towers in New York on September 11, 2001, the concept of structural redundancy and preventing progressive collapse has become more important.

During the investigation of the World Trade Center disaster, it became evident that some of the transitional buildings performed well because of the redundancy provided by the masonry portions of the buildings (Biggs, 2005). Hybrid masonry offers an opportunity to provide the strength redundancy for modern buildings by combining reinforced masonry with frame construction.

Types of Walls

There are three wall types dependent upon how the masonry is constructed. These walls have the ability to potentially transfer axial loads from the beam/girder of the frame as well as transfer shear from the beam/girder or the columns. The wall systems are defined in Table 1. All wall systems listed address the backup for cavity wall construction. If a veneer is used, it is constructed with relieving angles and is isolated for differential movement as with conventional cavity wall construction.

Masonry System	**Axial Load**	**Shear at Beam/Girder**	**Shear at Column**
Infill Wall	No	No	No
Ordinary Hybrid Shear Walls	No	Yes	No
Intermediate Hybrid Shear Wall	Yes	Yes	No
Special Hybrid Shear Wall	Yes	Yes	Yes

Table 1 – Masonry Wall Systems Based Upon Performance

Infill Walls

Description: Infill walls carry only out-of-plane (flexural) loads. The tops and sides of the walls are anchored to support the flexural loads dependent upon whether the wall spans horizontally, vertically, or both. The anchors do not impart any shear loads or axial loads into the masonry. The isolation joint sizes should accommodate frame drift without touching the masonry wall.

Design Methodology: The masonry design is based upon the MSJC code (MSJC 2005) for reinforced masonry. The steel structural system can be a braced frame, moment-resisting frame, or other. The design is based upon IBC (IBC 2003) factors R (response modification coefficient), Ω_0 (system over-strength factor), and C_d (deflection amplification factor) for the system selected. The infill masonry has no influence on the lateral load-resisting system.

Hybrid Shear Walls – General Discussion

Description: Hybrid walls carry out-of-plane loads in addition to in-plane loads. Dependent upon the type of hybrid wall selected, the masonry can also carry axial load. Hybrid masonry walls are identified as ordinary reinforced, intermediate reinforced, and special reinforced. These walls are described in greater detail later.

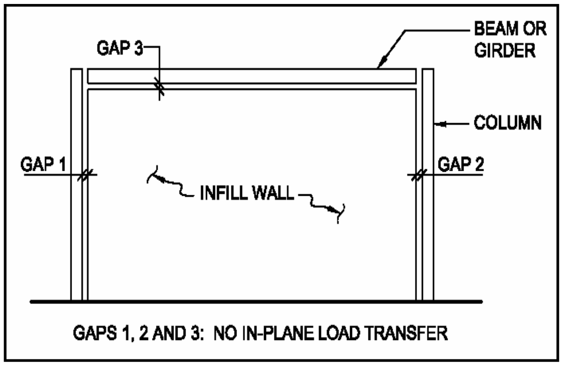

Figure 1. Infill wall

Design Methodology: The masonry design is based upon the MSJC code (MSJC 2005) for reinforced masonry using allowable stress design. The analysis results in a linear elastic design. As strength design procedures gain acceptance, load factor design with non-linear elastic evaluation of the masonry will be possible.

The structural steel system design and the in-plane loads to the masonry are based upon IBC (IBC 2003) factors for R (response modification coefficient), Ω_0 (system over-strength factor), and C_d (deflection amplification factor) applicable to the type of shear walls used with building frames. These factors are given in Table 2:

Shear Wall Type	**R**	**Ω_0**	**C_d**
Ordinary Reinforced	3	2.5	2.25
Intermediate Reinforced	4	2.5	2.5
Special Reinforced	5.5	2.5	4

Table 2 – Factors Based Upon Shear Wall Type

Ordinary reinforced shear walls are permitted in Seismic Design Categories (SDC) A, B, and C. The building height is unlimited for SDC A and B and limited to 160 feet for SDC C. Intermediate reinforced shear walls are permitted in SDC A, B, and C. The building height is unlimited.

Special reinforced shear walls are permitted in all seismic design categories. The building height is unlimited for SDC A, B, and C, limited to 160 feet (48.8 m) for SDC D and E, and limited to 100 feet (30.5 m) for SDC F.

Ordinary Hybrid Shear Walls

Description: This wall differs from the infill wall in that anchors are provided at the top of the wall such that they transmit out-of-plane loads and shear loads. The top anchors should not transmit axial loads. The column anchors should not transmit shear loads.

Design Methodology: The masonry design is based upon the MSJC code as a non-loadbearing shear wall that also supports out-of-plane loads.

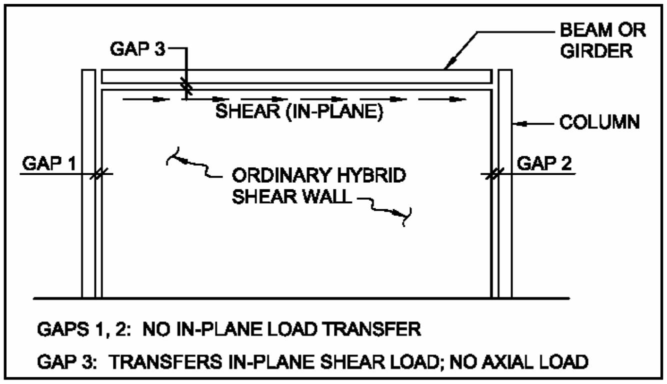

Figure 2. Ordinary Hybrid Shear Wall

Intermediate Hybrid Shear Walls

Description: This wall is a modification of the ordinary hybrid shear wall such that the masonry is constructed tight to the framing and axial loads are transmitted to the wall. The top anchors transmit out-of-plane loads and shear loads. The column anchors do not transmit shear loads.

Design Methodology: The masonry design is based upon the MSJC code as a load-bearing shear wall that also supports out-of-plane loads.

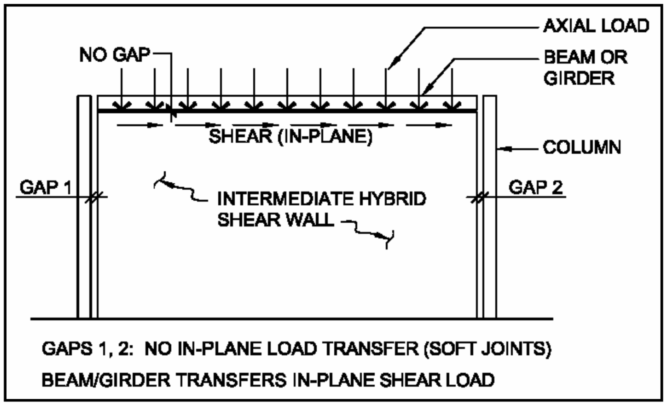

Figure 3. Intermediate Hybrid Shear Wall

The designer has the option to reduce the size of the beam/girder framing members by load sharing with the masonry wall. For example, if the masonry is constructed after the dead loads of the framing and floor/roof system are installed, the masonry wall can take the gravity loads that are added to the structure after the walls are built. The framing (columns and beams/girders) sizes can be limited to support only the dead loads. If there is a likelihood the masonry wall will be modified in the future to accommodate an addition or modification, the framing should be designed for the full gravity loads.

Special Hybrid Shear Walls

Description: In this system, the masonry is constructed tight to the framing, both columns and beams/girders. It is most similar to the transitional buildings from the early 1900s. However in this modernized version, the masonry is engineered and reinforced to support axial and shear loads in addition to the out-of-plane loads. As with the intermediate hybrid shear wall, the designer has the option to design the columns and beams/girders for the portion of the gravity loads installed before the masonry.

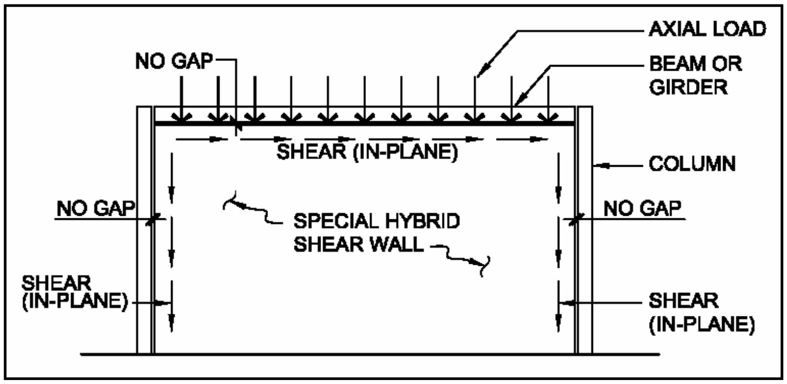

Figure 4. Special Hybrid Shear Wall

Design Methodology: Currently, there are no standards in the United States that govern the design of this type of wall. The MSJC Infill Subcommittee is developing criteria. If designers want to work with this type of wall, they need to look to concrete methodology using a strut and tie system.

Shear Wall Concept

The confinement of the steel frame can modify the behavior of a traditional shear wall. There are three methods of shear wall design that can be considered when used with frames.

Figure 5 shows the load application, deflected shape, and support forces to resist overturning with a gap between the columns and beam/girder and the shear wall (ordinary hybrid). The tie-down forces are a key component to the support of the wall against preventing overturning.

The performance is similar to a traditional shear wall without applied vertical load. The horizontal deflection, Δ, is the minimum gap required at the columns.

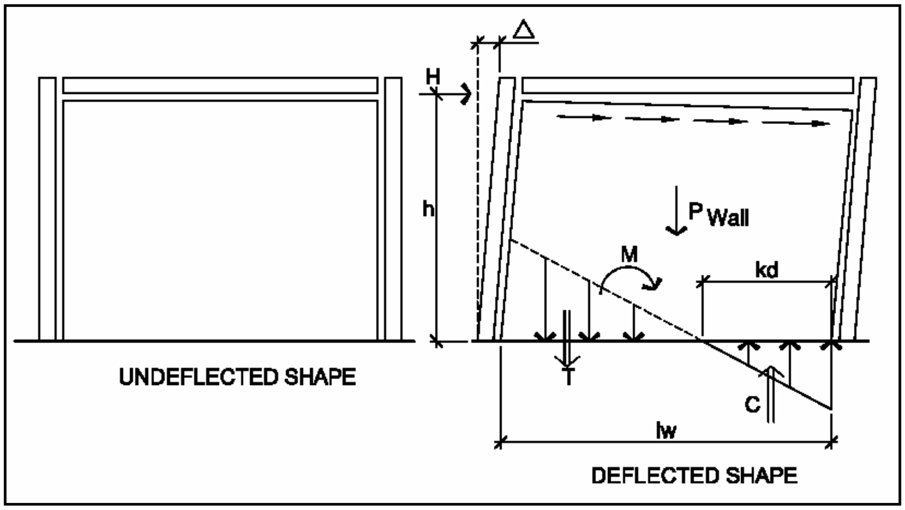

Figure 5. Ordinary Hybrid Shear Wall

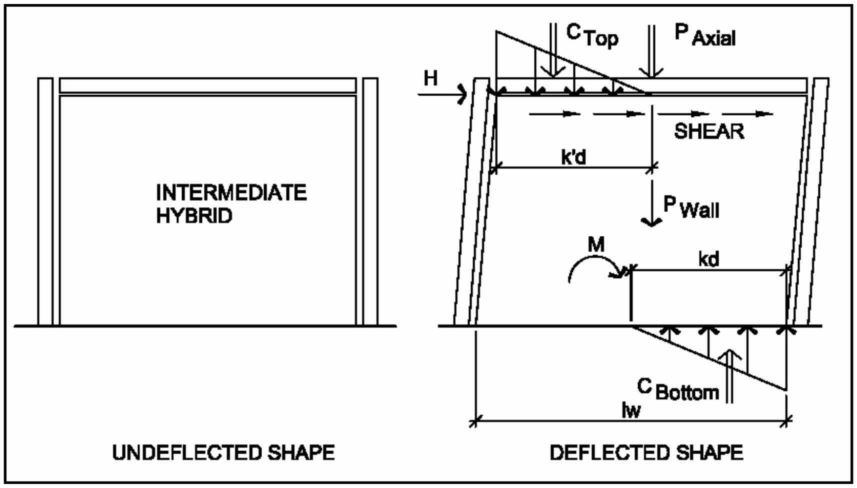

Figure 6. Intermediate Hybrid Shear wall

Figure 6 shows the load application, deflected shape, and support forces to resist overturning where there is no gap between the beam/girder and the shear wall (intermediate hybrid). The frame confinement limits the overturning and the wall imparts restraint forces. A beneficial effect is that the walls do not require tie-down forces. The tension force noted in Figure 5 can become a compressive force on the steel frame at the top. This is a significant benefit to multi-story buildings such that the tie-down to the frame is <u>not</u> required.

At the base of the wall, $C_{Bottom} = P_{Axial} + P_{Wall} + C_{Top}$ **[1]**.

Tension (tie-down) reinforcement can be added if desired.

$$M = C_{Bottom}\left(\frac{l_W}{2} - \frac{kd}{3}\right) + C_{Top}\left(\frac{l_W}{2} - \frac{k'd}{3}\right)$$ **[2]**.

Figure 7 shows the load application, deflection shape, and support forces where there is no gap between the beam/girder and the shear wall (special hybrid). No loads are shown for the column connection. If the connection is adequate, the wall can transfer vertical shear as well. The frame confinement limits the overturning and the wall imparts restraint forces. Similar to the intermediate hybrid, a beneficial effect is that the walls do not require tie-down forces.

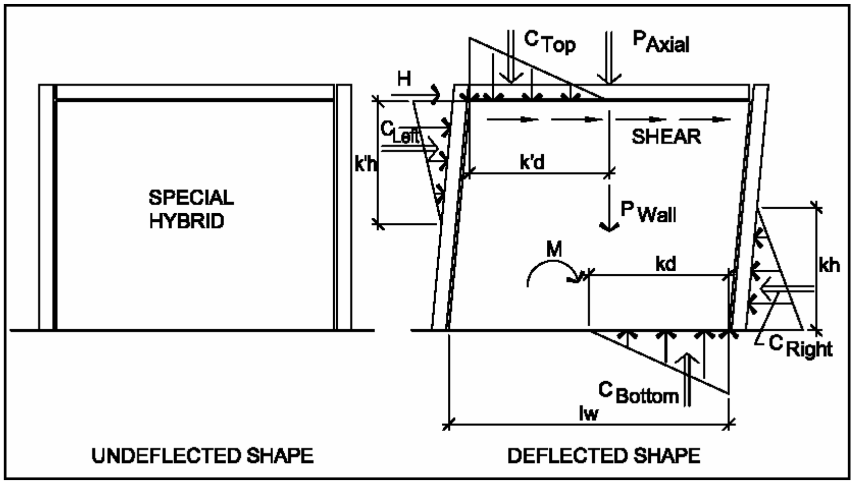

Figure 7. Special Hybrid Shear Wall

The analysis would result in a strut and tie for the wall. However, the MSJC does not address this as yet. Statics can be used to generate formulas comparable to [1] and [2].

Example

Figure 8a shows a rigid frame with a horizontal load of 10 kips (44.5kN). The infill wall is not shown. The frame translation is 4.08 inches (104 mm). The 8-inch (203-mm) CMU infill wall with a strength of 1,500 psi (10.3 MPa) spanning vertically requires No. 7 @16 in. (M22 @ 400 mm) on center, designed using the 2002 MSJC Allowable Stress without a 1/3 increase in stress based upon ASCE 7.

The analysis was evaluated using masonry software (NCMA 2005 and RAM 2006). The resultant stiffness of the frame is 10 kips/4.08 inches (44.5 kN/104 mm) = 2.45 kips/in. (0.43 kN/mm). The steel frame weighs 2,500 pounds (11.1kg). Based upon the calculated deflection, there has to be a soft joint of over 4 inches (102 mm) at the columns and 0.14 inches (4 mm) at the girder to isolate the infill masonry wall.

Figure 8b shows the frame modified to use a tension brace. Again, the infill wall is not shown. The framing sizes are reduced, the connections are pinned, and the translation is 0.04 inches (1 mm). The stiffness is 250 kips/in. (44.5 kN/mm), which is 102 times stiffer than the rigid frame. The steel framing weighs 1,425 pounds (6.3 kg), which is a 43 percent weight reduction in comparison to the rigid frame.

To isolate the infill masonry wall, there has to be a soft joint of 0.10 inches at the columns and 0.07 inches at the girder. A nominal 3/8 in. (10mm) joint would satisfy this requirement. However, the infill wall cannot be constructed in-plane with the frame because the diagonal brace interferes. If the infill wall is placed outside the frame, there needs to be approximately

2.5 inches clear between the frame and the wall because of lateral load deflection (out-of-plane) based upon a 30 psf (1.44kN/m^2) load.

Figure 8c shows an ordinary hybrid shear wall and a steel frame. The framing sizes are the same as in Figure 8b and the translation is further reduced to 0.02 inches (0.5 mm). The stiffness is increased to 500 kips/in. (89 kN/mm).

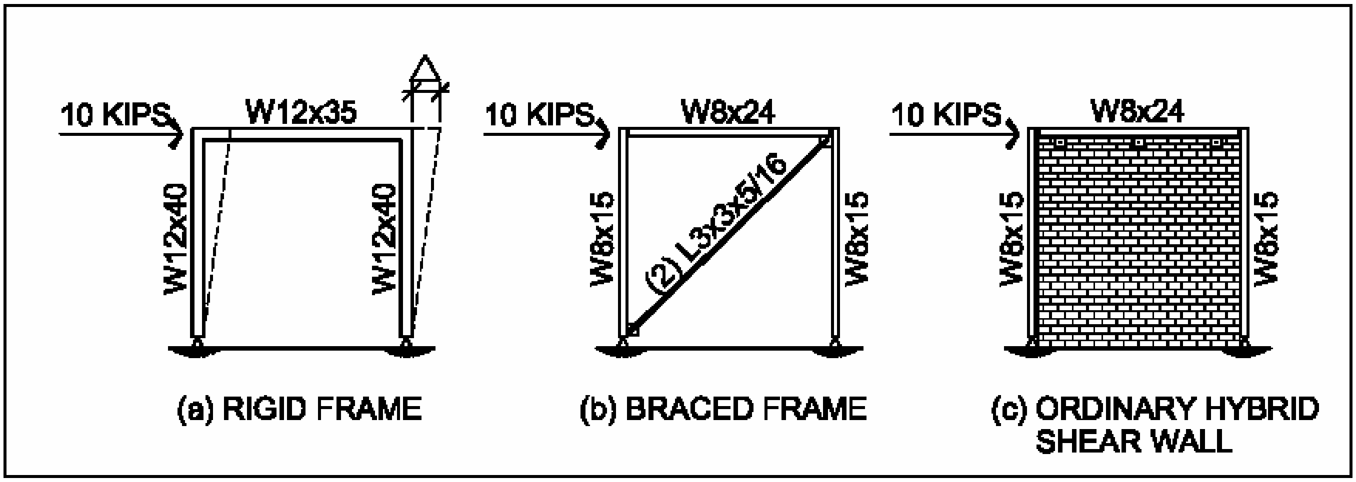

Figure 8. Comparison - Rigid Frame, Braced Frame, and Ordinary Hybrid Shear Wall

For this example, out-of-plane conditions control the wall design using 30 psf (1.44 kN/m^2). Thus, the same infill wall design from 8b applies except that the vertical reinforcing must be anchored to the foundation to tie-down the shear wall. The shear wall design is satisfied without any horizontal reinforcement; minimum prescriptive horizontal reinforcement would be required for a seismic design. Therefore, the ordinary hybrid shear wall does not add any extra reinforcement, provides twice the stiffness of the diagonal brace, creates no interferences, and a typical 3/8-inch (10-mm) isolation joint can be used at the columns.

A second example was constructed using a three-story single bay and comparing the stiffness of a rigid frame, braced frame and a hybrid shear wall again. The floor heights were 14 feet (4.27m) and the bay was 20 feet (6.1m). The applied lateral loads were 10 k (44.5 kN) at the floors and 5 k (22.3kN) at the roof.

The rigid frame was optimized for lateral loads and deflected 8.3 in. (211 mm) at the roof. The braced frame deflected 0.85 in. (22 mm) and reduced the frame weight by 40 percent. Both frames would not easily accommodate infill walls due to excessive deflection or the interference of the brace.

An intermediate hybrid shear wall was used with a door opening at the first floor and window openings at the other two floors. Using the same material properties of the first example, the reinforcement was again the same as an infill wall. Detailed as an intermediate hybrid shear wall, the frame deflected 0.08 in (2 mm). In addition, the steel framing sizes were the same as the braced frame. In this example, constructability is improved by removing the diagonal bracing. In addition, the masonry is capable of accommodating openings for architectural effect without an increase in masonry cost over an infill wall.

Conclusions

Hybrid masonry offers many benefits to framed construction. By using the masonry as a structural element for in-plane loads, the constructability of the masonry with the frames is improved, the lateral stiffness increases, the redundancy is improved, and opportunities for improved construction cost are created.

While both examples presented are very simple, they indicate the stiffness that can be achieved with hybrid masonry systems. Many more examples would indicate the beneficial effect on the framing through the load-sharing abilities of the system. Those qualities, stiffness and redundancy, can be useful in preventing progressive collapse.

For now, ordinary and intermediate hybrid systems can be designed in the United States using existing codes and standards.

Special hybrid shear walls require additional code development by the MSJC. A strut and tie analysis should be developed in masonry to allow the further development of hybrid masonry shear walls. This shear wall system will provide an added benefit in that the traditional shear wall tie-down can be deleted and the masonry can be used to its full potential as a compression element.

References

Beall 2003: Beall, C., “Masonry Design and Detailing, Fifth Edition,” McGraw-Hill, 2004

Biggs 2004: Biggs, D.T., “Masonry Aspects of the World Trade Center Disaster”, The Masonry Society, Boulder, CO.

Biggs 2005: Biggs, D.T., “Brick Nogging: Investigation and Repair,” Proceedings of the 10th Canadian Masonry Symposium, Banff, Alberta, 2005

Florida 2004: “2004 Florida Building Code, Building, Section 2121 High-Velocity Hurricane Zones- Construction Details”, International Code Council, Falls Church, VA 22041-3401

IBC 2003: “2003 International Building Code”, International Code Council, Falls Church, VA 22041-3401

Masonry Advisory Council 2002: “Design Guide for Taller Cavity Walls,” Masonry Advisory Council, Park Ridge, IL, 2002

MSJC 2005: “Building Code Requirements for Masonry Structures (ACI 530-05/ASCE 5-05/TMS 402-05)”, The Masonry Society, Boulder, CO

NCMA 2005: “NCMA Masonry Design System 3.1.1.2”, National Concrete Masonry Association, Herndon, VA

RAM 2006: “RAM Advanse Version 8.0”, Masonry Wall, RAM International, Carlsbad, CA

Searls 2000: Searls C. L, Bronski, M.B., “Early Twentieth Century Transitional Facades in the United States: Common Maladies,” Proceedings of UNESCO-ICOMOS Millennium Congress, Paris, France, 2000

UFC 2005: “Unified Facilities Criteria (UFC) Design of Buildings to Resist Progressive Collapse”, UFC 4-023-03, United States Department of Defense, 2005