10th Canadian Masonry Symposium, Banff, Alberta, June 8 – 12, 2005

ANALYTICAL MODELING OF IN PLANE SHEAR OF BRICK VENEER AND WOOD STUD WALLS

Eric N. Johnson[1] and W. Mark McGinley[2]
[1]Director of Engineering, Brick SouthEast, Inc., Charlotte, NC, USA, BrickEric@aol.com
[2]Professor of Architectural Engineering, North Carolina A & T State University, Greensboro, NC, USA, mcginley@ncat.edu

ABSTRACT

Conventional brick veneer in residential construction is typically supported by wood stud walls attached using 22 gauge corrugated wall ties and 8d nails. Previous research has demonstrated that the brick veneer offers significant resistance to in plane shear loads. As part of this phase of the research, analytical modeling of typical residential structures with and without brick veneer was performed using analytical and experimental results from previous investigations. The analytical modeling determined typical ranges for the lateral load resistance of the brick veneer.

KEYWORDS: brick, veneer, residential, modeling, lateral loads

INTRODUCTION

In the United States, conventional light-framed wood construction is currently the predominant framing system for residential housing and has been over the twentieth century. Construction configurations and requirements for light-framed wood construction have evolved over this time period and continue to evolve. Configurations and requirements that have evolved include, but are not limited to, changes in member sizes (nominal sizes replacing actual sizes), plywood sheathing panels and oriented strand board replacing board sheathing, nailing techniques, and codified prescriptive resistance requirements.

Brick veneer is one of several basic cladding options used with a conventional light-framed wood framing system. Historically, the brick veneer itself is assumed to behave as a cladding and any inherent resistance is not accounted for in the design of the wood framing system. In other words, a wood framed residential structure was framed identically regardless of whether the exterior cladding was brick veneer or vinyl siding. Intuitively, it is postulated that brick veneer construction should have more resistance to lateral loads than many other residential cladding systems. This can have a significant effect on residential housing construction in the United States since brick cladding has a wall market share of approximately 20%. The overwhelming majority of this wall market share is constructed with light-frame wood construction.

The introduction of light-framed wood construction, often referred to as conventional construction, occurred in the mid 1800s [1]. Historically, conventional light-framed wood construction has been based on an empirical rationale rather than engineering analysis [2]. In 1971, the Council of American Building Officials (CABO) first published the One- and Two-Family Dwelling Code [3]. The intent of this code was to provide prescriptive requirements for construction of residential structures, such as construction without the direct services of a design professional. Recently, the International Code Council (ICC) published new prescriptive code provisions for residential construction, the *International Residential Code For One- and Two-Family Dwellings (IRC)*. This code was published for the first time in 2000. The current version of this code was published in 2003 [4].

The Residential Structural Design Guide: 2000 Edition [1] reports on whole building tests in its chapter on Lateral Resistance to Wind and Earthquake. Research reported in this reference includes testing conducted in Japan, United States, Australia and England. In general, this research indicates that light-frame construction exhibits significantly more stiffness and capacity than anticipated at pressures produced by typical design wind speeds. Furthermore, in England, to account for this behavior, system factors have been incorporated into shear wall design to address material effects, wall configuration effects and interaction effects. These system factors recognize shear loads on wood framed structures are reduced in a full brick-veneered building.

In comparison to the amount of research on out-of-plane behavior of masonry veneers, little published research is available on in-plane behavior of veneer systems. Allen and Lapish [5] report the results of in-plane tests on wood framed walls clad with brick veneer. The walls were tested by applying a displacement up to ±40 mm. In all tests, the brickwork remained intact, and the veneer had to be removed after the test, course by course. Differential in-plane movements were observed between the veneer and wood frame.

The lateral design of light-frame buildings is not a simple procedure that provides exact solutions. However, earlier phases of this research have shown that the brick veneer can significantly affect the performance of the building system and increase the lateral load resistance of the structure. The focus of this phase of the investigation is to develop an analytical model to predict the behavior of the in-plane load interaction of the brick veneer and wood backing wall.

BACKGROUND/PREVIOUS RESEARCH/PROTYPE MODELING

The first phase of this multi-phased research involved identifying and comparing lateral loads on typical residential structures [6]. These lateral loads included those induced from wind and seismic events. The second phase of this research involved a laboratory testing program in order to provide information on the in-plane shear transfer between brick veneer and wood stud walls [7].

The one-story and two-story prototype analytical models used are presented in Figures 1 and 2, respectively. For the seismic loading analysis, two cladding types were assumed. These cladding types were identified as “Brick”, having an exterior wall weight of 2.155 kN/m^2 (45 lbs/ft^2), and “Other”, having an exterior wall weight of 0.478 kN/m^2 (10 lbs/ft^2).

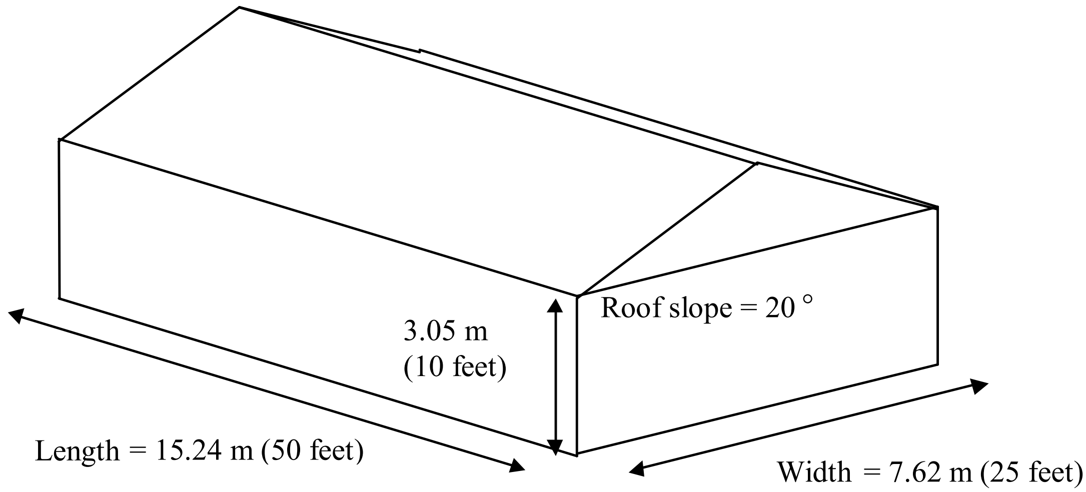

Figure 1 - One-Story Residential Structure Configuration

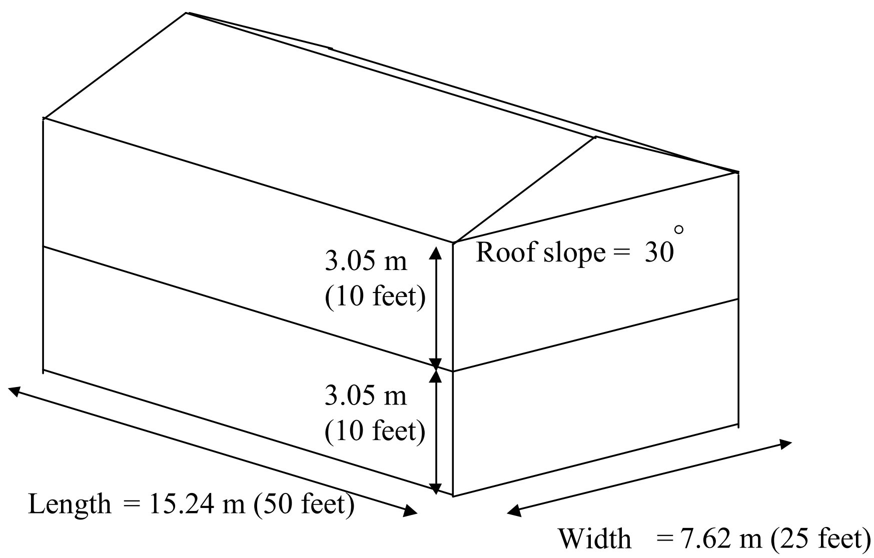

Figure 2 - Two-Story Residential Structure Configuration

Figures 3 and 4 represent typical brick veneer over wood stud wall section details. As shown by these details, the brick veneer is vertically supported at the base by the foundation and is attached to the wood frame by ties. The purpose of these ties is to transfer out-of-plane lateral loads from the exterior brick wythe to the wood backup. Spacing of the ties is dictated by building codes. Although there are numerous types of ties, the 22 gauge corrugated tie is the predominant tie used in residential construction. These ties are typically fastened to the wood studs using 8d nails.

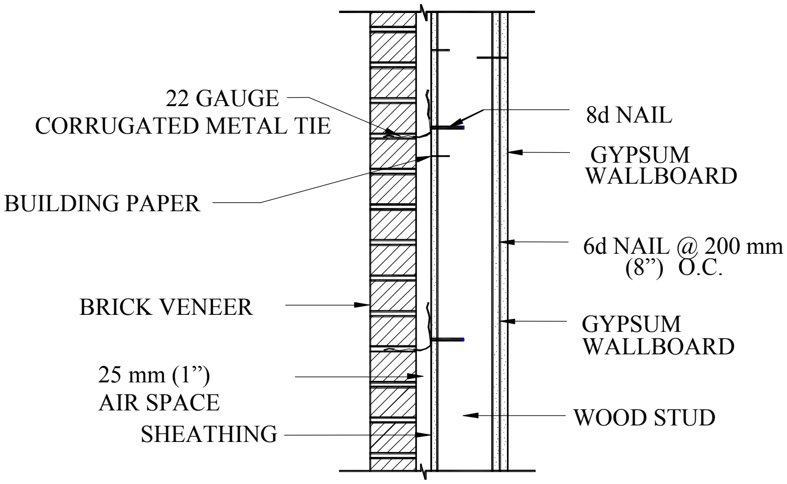

Figure 3 - Typical Brick Veneer Residential Construction – Wall Section

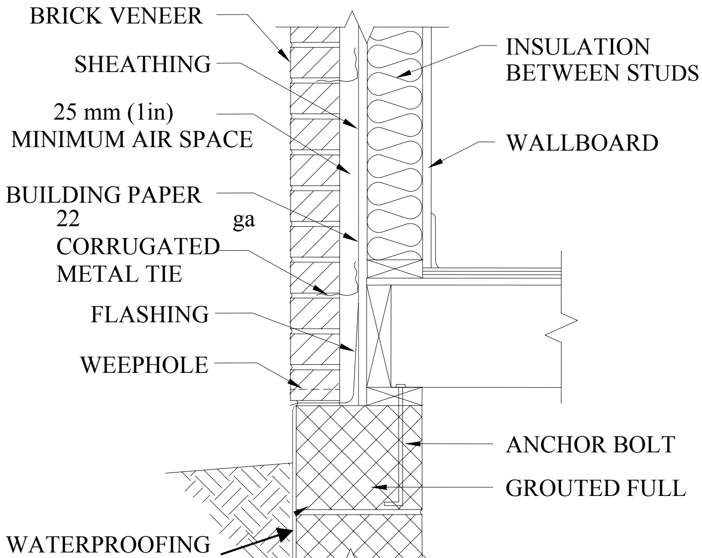

Figure 4 - Typical Brick Veneer Residential Construction – Foundation Section

The second phase of this research [7] demonstrated through laboratory testing that there are significant in-plane loads transferred between conventionally constructed residential wood frame systems and the attached brick veneer. Therefore, the brick veneer can contribute to the lateral load resistance of the structure. As part of this research [7], load-deflection curves were generated for in-plane load transfer between a wood frame and brick veneer in typical construction. These tests determined that a single 22 gauge corrugated tie used in typical construction can transfer approximately 934 N (210 lbs), of in-plane shear load from the wood frame to the brick veneer.

MODELING ANALYSIS

During the experimental evaluation of the in-plane load transfer between stud backing walls and brick veneer, load - deflection curves were produced and these curves had two distinct slopes [7]. For the load range from 4,448 N (0 – 1,000 lbs), the slope of the line (i.e., stiffness, $k_1 = P_1/\Delta_1$)

can be approximated as 1,751 N/mm (10,000 lbs./inch). Adjusted to a per tie basis, this is 1,751 N/mm /12 ties = 145.9 N/mm (833 lbs/in). For the load range from 4,448 N to 11,120 N (1,000 – 2,500 lbs), the slope of the line (i.e., stiffness, $k_2 = P_2/\Delta_2$) can be approximated as 6,672 N/22.86 mm or 292 N/mm (1,670 lbs./inch). Adjusted to a per tie basis, this is 292 N/12 ties = 24.3N/mm (140 lbs/in). Although this testing program did not specifically determine the elastic range for the in-plane response of the ties, the load-deflection curves suggest that from 0 – 4,448 N (0 – 1,000 lbs) the ties may be in the linear-elastic range. Furthermore, at some point in the 6672 N – 11120 N (1500 – 2500 lb) range, the ties may possibly exhibit inelastic behavior. Figure 5 graphically shows the two distinct stiffness values (including the per tie stiffness). The test results showed a relatively high level of ductility in the in-plane tie failures.

The stiffness of the ties needs to be integrated into the whole house behavior. Whole-house building tests on two-story models [1] exhibited relatively low maximum deflections, on the order of 1.0 mm (0.04 inches) at a wind pressure of 1,216 N/m^2 (25 psf) and 2.54 mm (0.1 inches) at a design wind load corresponding to 185 km/hr (115 mph). Furthermore, as stated earlier, the behavior of light-frame buildings is highly dependent on the interaction of structural and nonstructural components. It has also been reported that nonstructural components in conventional housing can account for more than 50 percent of the lateral resistance of a building [1].

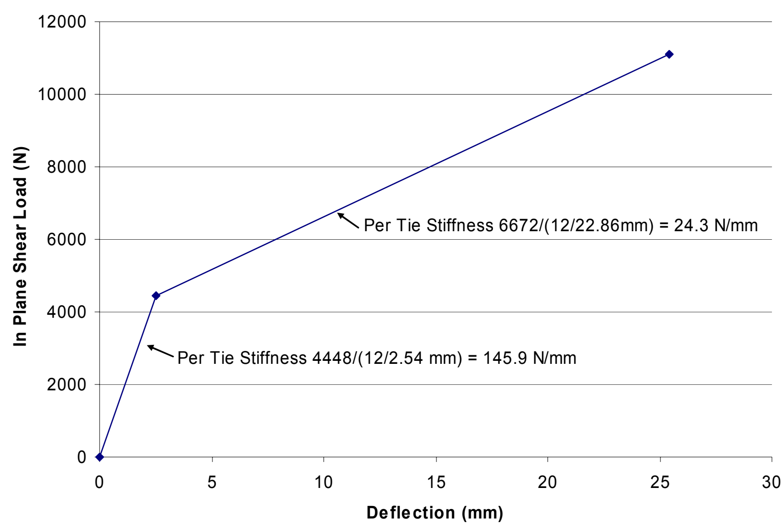

Figure 5 – Corrugated Tie Stiffness Model

In the International Residential Code [4], Exposure B is the default design wind exposure and the overwhelming geographic majority of the continental United States (on the order of 90%) uses a design wind speed of 145 km/hr (90 mph) or less. In addition, one- and two-family detached structures are exempt from special seismic provisions in Seismic Design Categories A, B and C. Geographically, these regions represent approximately 80% of the area in the continental United States. Since the International Residential Code can be prescriptively used for design wind speeds up to 177 km/hr (110 mph), this wind speed and Exposure B, which includes the vast majority of the United States, was used to determine the lateral loads for the prototype models presented in Figures 1 and 2 [6]. This analysis produced base shear values of 55.6 kN (12.5 kips) and 123.7 kN (27.8 kips), respectively. Neglecting any interior shear walls, each of the

7.62 m (25 feet) long end walls would be subjected to 27.8 kN (6,250 lbs) for the one-story prototype model and 61.83 kN (13,900 lbs) for the two-story prototype model. For the 145 km/hr (90 mph) wind speed the base shear values are 18.68 kN (4,200 lbs) and 41.37 kN (9,300 lbs) for each end wall of the one- and two-story prototype models, respectively.

For a vinyl sided, two-story model presented in Figure 2, the gable end walls will be subjected to a total lateral load of 82.74 kN (18.6 kips) or 41.37 kN (9.30 kips) per end wall at a design wind load of 145 km/hr (90 mph) (Exposure B). At 177 km/hr (110 mph), the gable end walls will be subjected to the same loads as the brick veneer.

A simple analysis was performed on the two-story, vinyl sided, prototype model using two load cases, 41.37 kN (9,300 lbs) and 61.83 kN (13,900 lbs). Each of these gable end loads was assumed to produce one of five deflections at the roof diaphragm level: a deflection, Δ, of 0.25 mm (0.01) inch, 1.0 mm (0.04 inch), 1.78 mm (0.07 inch), 2.54 mm (0.10 inch) and 13 mm (0.50 inch), as shown in Figure 6. For the two-story model clad with vinyl siding, it was assumed that each of the two load cases (41.37 and 61.38 kN) produces a lateral load on an end wall causing a drift deflection of Δ. Assuming a linear response, stiffnesses for each of these four deflections were calculated for each deflection as the ratios k_i = 41.37 kN/Δ and 61.38 kN/ Δ as presented in Tables 1 and 2, respectively.

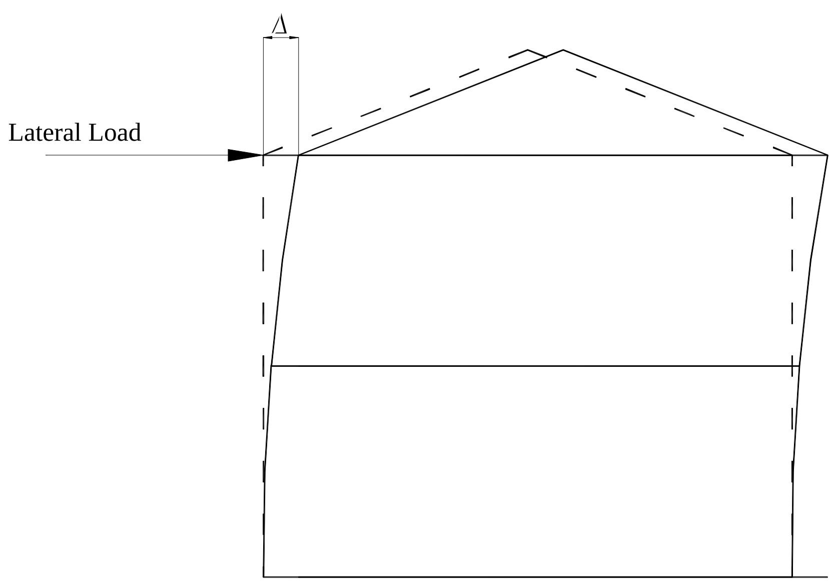

Figure 6 - Deflection, D, at Roof Diaphragm Level

It can be assumed that if these same two loading cases (41.37 and 61.38 kN total shear loads) were applied to the same two-story model clad with brick veneer and not vinyl, the wood wall would deflect under load and the stiffer brick veneer would resist this motion through the ties.

The 2003 International Residential Code requires a minimum of one tie for every 0.248 m^2 (2.67 ft^2) for design wind speeds less than or equal to 185 km/hr (110 mph). For the two-story prototype model, there is 54.81 m^2 (590 ft^2), assuming no openings. For 54.81 m^2 of area, 221 ties are required (54.81/0.248).

Table 1 - End Wall Stiffness of Two-Story Vinyl Sided House at Various Deflections

	145 km/hr (90 mph) (Exposure B)				
	Deflection (D) (mm)				
	0.25 mm (0.01 in)	**1.0 mm (0.04 in)**	**1.78 mm (0.07 in)**	**2.54 mm (0.10 in)**	**13 mm (0.5 in)**
Lateral Load (kN)	41.37	41.37	41.37	41.37	41.37
Lateral Load (lb)	9,300	9,300	9,300	9,300	9,300
Stiffness (kN/mm)	165.5	41.37	23.24	16.28	3.18
Stiffness (lbs/inch x 100)	9,300	2,320	1,330	930	186
	177 km/hr (110 mph) (Exposure B)				
Lateral Load (kN)	61.38	61.38	61.38	61.38	61.38
Lateral Load (lb)	13,900	13,900	13,900	13,900	13,900
Stiffness (kN/mm)	245.5	61.38	34.48	24.16	4.72
Stiffness (lbs/inch x 100)	13,900	3,470	1,990	1,390	278

If it is assumed that 221 ties are displaced due to a relative movement between the backing wall and the brick, then significant shear load will be transferred to the brick veneer. The total stiffness of 221 ties is equal to 221 x 145.9 N/mm per tie or 32.24 kN/mm (184 kips/in). This stiffness must be modified by dividing the 32.24 kN/mm in half (16.12 kN/mm or 92.0 kips/in), since wall ties located along the roof diaphragm height will deflect the full Δ, the mid-height will deflect $\Delta/2$, and the base will not deflect laterally. To account for the restraint provided by the tie, the tie stiffness can be combined with that of the wood wall system. The results of the effect of the two-story house clad with brick versus vinyl for the two loading cases and the same stiffness ranges previously discussed are presented in Tables 2 and 3.

It should be noted that the values for the reduction in load in the wood shear wall presented in Tables 2 and 3 are in the same order of magnitude as the system factors of 45% used in England [1]. The amount of stiffness increase and, thus, the amount of gable end load that is transferred to the brick veneer will vary with the deflection of the end wall. It should be emphasized that the analysis presented previously makes several assumptions (e.g., no openings, nor any effects of flashing). However, the concept is not only intuitive, but also supported by engineering rationale.

Whether or not the brick veneer has sufficient capacity in shear and overturning to resist the level of loads induced on it must evaluated. Assuming an allowable shear strength of 0.255 MPa (37 psi) [8] and a modular sized brick unit, the shear capacity for the 7.62 m gable end walls would be 1.5 x 92.0 mm x 7.62 x 0.255 = 268.2 kN (60,300 lbs). The highest load presented in Table 3 is 47.46 kN (10,670 lb). A shear load of 47.46 kN would result in a shear stress of 0.103 MPa (1.5 x 47.46 kN/(92/1000 mm x 7.62 m) (15.0 psi). There appears to be more than sufficient capacity in the brick veneer to resist shear loads transferred from the wood frame and ultimately to transfer these forces directly into the foundation. The effects of flashing at the base of the wall and any reduction in the allowable shear stress were not considered in this investigation. At this relatively low level of stress, it is possible that friction alone could be sufficient. The overturning moment resulting from a shear of 47.46 kN (10,670 lb) can be calculated as (2/3)(6.1 m)(47.46 kN) = 193.0 kN.m (142,300 ft.-lb). The gravity restoring moment can be calculated as ((54.81 m^2)(1.915 kPa))(7.62./2) = 399.9 kN.m (295,000 ft.-lbs). It should be noted that the restoring moment is over two times greater than the overturning moment (399.9/193). Therefore, it is evident that overturning moment will not be an issue.

Table 2 - Effect of Two-Story House Presented in Table 1 Clad with Brick Veneer instead of Vinyl, 145 km/hr (90 mph) (Exposure B)

Vinyl Sided – Total Deflection	**0.25 mm (0.01 in)**	**1.0 mm (0.04 in)**	**1.78 mm (0.07 in)**	**2.54 mm (0.10 in)**	**13 mm (0.50 in)**
Total Lateral Load kN	41.37	41.37	41.37	41.37	41.37
Total Lateral Load (lbs)	9,300	9,300	9,300	9,300	9,300
Wood Wall Stiffness (k_w) (kN/mm)	163	41	23	16	3
Wood Wall Stiffness (k_w) (lbs/inch x 100)	9,300	2,330	1,330	930	186
Tie Stiffness (k_{bt}) (kN/mm)	16	16	16	16	16
Tie Stiffness (k_{bt})(lbs./inch x 100)	920	920	920	920	920
Brick Sided Combined Stiffness[1] (k_t) (kN/mm)	179	57	39	32	19
Brick Sided Combined Stiffness[1] (k_t)	10,220	3,250	2,250	1,850	1,106
Brick Sided - Total Deflection[2] (mm)	0.23	0.74	1.04	1.27	2.13
Brick Sided - Total Deflection[2] (inches)	0.0091	0.029	0.041	0.050	0.084
Brick Sided - Load in Wood Wall[3] (kN)	37.63	29.80	24.47	20.77	6.94
Brick Sided - Load in Wood Wall[3] (lbs)	8,460	6,700	5,500	4,670	1,560
Brick Sided - Load in Brick Veneer[4] (kN)	3.74	11.57	16.90	20.60	34.43
Brick Sided -Load in Brick Veneer[4] (lbs)	840	2,600	3,800	4,630	7,740
Wood End Wall load –Brick Reduction Veneer versus Vinyl (%)	9.0	28	41	50	83
Reduction in Total Deflection for Brick Veneer versus Vinyl (%)	9.0	28	41	50	83

[1] Brick Sided Combined Stiffness, $k_t = k_w + k_{bt}$

[2] Brick Sided - Total Deflection = $(41.37)/k_t$

[3] Brick Sided - Load in Wood Wall = $(k_w)/(k_t)(41.37)$

[4] Brick Sided - Load in Brick Veneer = $(k_{bt})/(k_t)(41.37)$

Table 3 - Effect of Two-Story House Presented in Table 2
Clad with Brick Veneer instead of Vinyl, 177 km/hr (110 mph) (Exposure B)

Vinyl Sided – Total Deflection	**0.25 mm (0.01 in)**	**1.0 mm (0.04 in)**	**1.78 mm (0.07 in)**	**2.54 mm (0.10 in)**	**13 mm (0.50 in)**
Total Lateral Load kN	61.83	61.83	61.83	61.83	61.83
Total Lateral Load (lbs)	13,900	13,900	13,900	13,900	13,900
Wood Wall Stiffness (k_w)(kN/mm)	243	61	35	24	5
Wood Wall Stiffness (k_w)(lbs/inch x 100)	13,900	3,470	1,990	1,390	278
Tie Stiffness (k_{bt})(kN/mm)	16	16	16	16	16
Tie Stiffness (k_{bt})(lbs/inch x 100)	920	920	920	920	920
Brick Sided Combined Stiffness[1] (k_t) (kN/mm)	260	77	51	40	21
Brick Sided Combined Stiffness[1] (k_t)	14,820	4,390	2,910	2,310	1198
Brick Sided - Total Deflection[2] (mm)	0.24	0.81	1.22	1.52	2.95
Brick Sided - Total Deflection[2] (inches)	0.0094	0.032	0.048	0.060	0.116
Brick Sided - Load in Wood Wall[3] (kN)	57.83	48.93	42.26	37.37	14.37
Brick Sided - Load in Wood Wall[3] (lbs)	13,000	11,000	9,500	8,400	3230
Brick Sided - Load in Brick Veneer[4] (kN)	4.00	12.90	19.57	24.47	47.46
Brick Sided - Load in Brick Veneer[4] (lbs)	900	2,900	4,400	5,500	10,670
Reduction in Load in Wood End Wall for Brick Veneer versus Vinyl (%)	6.5	21	32	40	77
Reduction in Total Deflection for Brick Veneer versus Vinyl (%)	6.0	20	31	40	77

[1] Brick Sided Combined Stiffness, $k_t = k_w + k_{bt}$
[2] Brick Sided - Total Deflection = (61.83 kN)/k_t
[3] Brick Sided - Load in Wood Wall = (k_w)/(k_t)(61.83)
[4] Brick Sided - Load in Brick Veneer = (k_{bt})/(k_t)(61.83)

CONCLUSIONS AND RECOMMENDATIONS

The work reported in this study focused on the in-plane shear performance of brick veneer and wood stud walls. The conclusions from this study are as follows:

1. Significant in-plane loads are transferred between conventionally constructed residential wood frame systems and brick veneer.
2. The in-plane load transfer allows lateral loads from the wood frame back-up to transfer into the brick veneer and subsequently directly into the foundation. This has the ultimate effect of reducing the amount of shear load resisted by the wood frame and results in a stiffer, stronger wall system. The results of this investigation demonstrate that a brick veneered wood-framed residence can realize significant reductions in deflections, loads and distress potential as compared to some other siding systems.

This study did not consider the effect of openings, the effects of flashing, the effects of joint cracking, and the extent to which ties can deform and return to their original shape. However, the study is an important step toward understanding and accounting for the contributory effect of brick veneer with respect to the shear resistance of the exterior shear wall in wood framed residential construction. It is recommended that the inherent shear resistance provided by brick veneer in residential construction and subsequent reduction in deflection and lateral loads within the wood frame should be either accounted for or at least recognized. This could be: 1) the application of an empirical systems factor; 2) recognition by building codes; and/or 3) a reduction in insurance premiums.

REFERENCES

1. Residential Structural Design Guide: 2000 Edition, National Association of Home Builders (NAHB) Research Center, Inc., February, 2000.
2. Light Frame House Construction, Vocational Division Bulletin No. 145, U.S. Department of Health, Education and Welfare (HEW)(GPO), Washington, DC, 1931 (reprinted 1956).
3. CABO: Council of American Building Officials, One- and Two-Family Dwelling Code, Fall Church, Virginia.
4. International Residential Code for One- and Two-Family Dwellings (2000 & 2003 editions).
5. Allen, D. and Lapish, E.B., “The Interaction of Timber Framed Walls with a Tied Masonry Veneer under Cyclic Racking Loads.” Proceedings of the Fourth Canadian Masonry Symposium, 702-715, 1986.
6. McGinley, W. Mark, and Johnson, Eric N., “Lateral Loads on Brick Veneer Residential Structures.” Ninth Canadian Masonry Symposium, 2001.
7. Johnson, Eric N. and McGinley, W. Mark, “The In Plane Shear Performance of Brick Veneer and Wood Stud Walls.” Ninth North American Masonry Conference, 2003.
8. MSJC, 2002: The Masonry Standards Joint Committee. “Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02)”