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Full-scale experimental evaluation of a panelized brick veneer wall system under simulated wind loading

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Abstract. Brick veneer over steel stud backup wall is lighter and easier to construct compared to brick veneer over concrete masonry backup wall. However, due to the relatively low stiffness of the steel stud backup, the brick veneer tends to crack under wind load. This paper briefly introduces a new panelized brick veneer with steel frame backup wall system that is developed to potentially address this problem. The experimental study of the performance of this system under simulated wind loading is discussed in detail. The test setup details and the test specimens are introduced, results of major interests are presented, and performance of the new system is evaluated based on the test results.

Keywords: brick veneer, steel stud; panelized wall; laboratory wind loading; wind-driven rain; full-scale experiment.

1. Introduction

Compared with other alternatives such as brick veneer over concrete masonry unit backup (BV/CM), brick veneer over steel stud backup wall system (BV/SS) (Trestain 2008) has many advantages such as light weight, low cost, and easy construction. However, unlike CMU backup walls, light gauge steel studs (SS) as backup systems are very flexible. The flexural stiffness of the SS backup is much less than that of the brick veneer (BV), while the flexural strength of SS backup is larger than that of the BV. As a result, the excessive deflection of the SS backup under out-of-plane loads such as wind loads may cause cracking of the BV. Wind driven rain can then more easily leak into the walls through the cracks, which can cause serviceability problem such as mold development and safety problem such as falling off of the walls due to corrosion of the SS and metal ties.

Besides problems related to wind induced cracking of the BV, conventional BV/CM or BV/SS also have other problems such as the following: 1) cracking or even failure of the BV under seismic load if the BV is not properly isolated (Borchelt 2004, Memari *et al.* 2003, Reneckis and LaFave 2009); 2) building science related problems such as condensation; and 3) safety of construction

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workers laying bricks at high elevations. In order to potentially address these problems of conventional BV/SS, the concept of a prefabricated and panelized BV with steel framework backup wall system (for brevity, the system will be referred to as a panelized brick veneer over steel stud backup wall system, or PBVSS, in this paper) was developed at the Pennsylvania State University. The pilot research program (Liang 2006) consisted of several focused studies including 1) design and development of the system with consideration of building science related issues; 2) 3-D finite element modeling and analysis; 3) full-scale wind loading test; and 4) full-scale seismic racking test to evaluate performance of the proposed PBVSS design.

It is desirable for the proposed new wall system to have less deflection under wind loads, minimize the possibility of cracking under service wind load, and not fail under ultimate wind load. On the other hand, a BV/SS wall is not isotropic and its performance is affected by many factors such as boundary conditions on the sides, attachment of the walls to the main structure at the top and bottom ends, and property of ties used. In such cases, full-scale tests can best help to evaluate performance of the proposed wall, potential improvement as compared to conventional wall, and factors that can affect performance of the walls. Full-scale tests can also help expose areas of potential improvements of the conceptual design of the proposed system. Finally, data from full-scale tests can greatly contribute to the development and refinement of finite element models that can properly model the proposed wall system for further evaluation and parametric analysis of the system. This paper concentrates on the evaluation of the performance of the proposed wall system under simulated wind loading test of full-scale mockups.

2. Literature review

2.1 Literature review on performance of BV/SS under out-of-plane loading

In general, although there have been some failures of BV wall systems, their structural performance has been acceptable compared with other cladding materials under strong wind loads (Lindegard 1990, Henderson and Fricke 1999, Holmes 2001). Nonetheless, under normal wind load conditions, BV walls, especially BV/SS, may have some performance deficiencies (McGinley and Ernest 2004). McGinley *et al*. (1986) performed wind load experiments on BV/SS to evaluate both individual wall components and the system as a whole. Wilson and Drysdale (1990) performed wind load tests on full-scale BV/SS as part of CMHC research on this system. Kelly *et al*. (1990) used finite element modeling to investigate the behavior of BV/SS system under wind and seismic loads analytically. Finite element analysis was also used by Grimm and Klingner (1990) to evaluate the performance of BV/SS system under wind loads. Their study concentrated on the cracking probability of BV under load. Furthermore, Reneckis and LaFave (2005) developed finite element models of BV walls used in residential construction based on experimental study results.

In Wilson and Drysdale's tests (1990), the BV cracked at an applied pressure of 1.20 kN/m^2, with the deflection of 1.02 to 1.52 mm, or 1/2500 to 1/1800 of the veneer height. Based on Grimm and Klingner's analysis (1990) on crack probability of conventional BV/SS walls, with the design load of 1.16 kN/m^2, flexural stress in all wall specimens exceeded the maximum allowable stress according to ASCE-ACI 530 code (The Masonry Standards Joint Committee 2002). Crack probability was as high as 57% for the wall analyzed if the wall was built using type N masonry cement mortar without inspection, which has generally been the case in the past. However, according to the recent IBC 2006 (ICC 2006), special inspections are generally required for BV, and thus may somewhat reduce the probability of wind related cracking.

Of course, cracking of the BV does not necessarily mean functional deficiency. In fact, all BV walls have some cracks at mortar joints due to shrinkage of the mortar. Normally, the main issues are related to water leakage through the cracks rather than structural issues associated with cracks themselves. Therefore, to control crack induced water migration problems, one has to ensure that: 1) SS are stiff enough to limit flexural cracks; 2) acceptable level of pressure moderation (Straube 2001) exists in the system to minimize the driving force for water penetration; or 3) functional drainage system be available in the system to drain out any water that penetrates the BV (Kelly *et al.* 1990, Suter *et al.* 1990). Theoretically, only one of these three measures is sufficient to prevent the problem, but it is common to adopt all of them simultaneously.

Because of their critical role and safety related issues, the performance of masonry ties in brick veneer wall systems has been of great interest to designers and researchers over the years (Reneckis *et al.* 2004, Choi and LaFave 2004, Yi *et al.* 2003, Memari *et al.* 2002). In conventional design of BV/SS (Chen and Trestain 2004, Gurevich 2004), it is assumed that all ties will have the same force (KPFF Consulting Engineer 1995). However, tests by McGinley *et al.* (1986) and others (e.g., Postma 1993) distribution of tie force is not uniform. Tests by McGinley *et al.* showed that before cracking, ties at the top portion had larger force than lower ties due to large deflection of top of the veneer under load. After the first crack developed in the BV, ties at the top and those closest to the crack had the largest force. The crack is normally located near mid-height of the BV if the sides of SS are not restrained (Wilson and Drysdale 1990, Yi *et al.* 2003). Cracking of BV also caused an increase in the tie force (Wilson and Drysdale 1990). Furthermore, the pressure moderation/equalization had an effect on tie force distribution and could change the tie force from compression to tension. Apart from other results, Wilson and Drysdale's research showed that the support of end studs had a significant influence on behavior of walls. The restraint of end studs could bring two-way bending mechanism to the system.

McGinley *et al.* (1986) demonstrated that walls with stiffer SS backup system showed smaller deflection at the top ends of SS and larger deflection at the top end of BV. Using more ties at the top portion of the wall could slightly decrease the deflection. More importantly, walls with stiffer ties and more ties on the top portion of the wall failed by cracking of the BV, and could develop enhanced post-cracking strength with less severe failure.

2.2 Literature review on wind loading studies and test methods

The study of problems associated with wind loads on building envelope has been an active research topic in the fields of both structural engineering and wind engineering due to reported failures of building envelope during wind storms, hurricanes and cyclones (Marshall 2002, van de Lindt *et al.* 2007, Yazdani *et al.* 2006, Prevatt 2003). Extensive research efforts have been devoted to measurements of wind speed around buildings and wind-induced pressures on buildings, with both full-scale field measurements and reduced-scale wind tunnel model measurements. Some of the important full-scale test facilities include the research building of Texas Tech University (TTU) Wind Engineering Research Field Laboratory (WERFL) built in late 80's, the test facility of Building Research Establishment (B.R.E.) built in Aylesbury, England in the 70's, and the test building at Silsoe, England built in late 80's. Recently, a full-scale test building called the Insurance Research Lab for Better Homes was also built in Ontario, Canada for test of low-rise buildings under strong wind (Kemp 2008).

Extensive amount of data has been collected by researchers using these facilities with respect to the distribution of wind pressure on building enclosures and different parameters affecting the distribution (Cochran and Cermak 1992, Ginger and Letchford 1999, Hanson and Sorensen 1986, Levitan and Mehta 1992a, b, Mehta *et al.* 1992, Mousset 1986, Richardson and Surry 1994, Uematsu and Isyumov 1999, Vickery *et al.* 1986, Xu 1995, Yeatts and Mehta 1993). Wall claddings and roofs are often tested under monotonically increasing pressure/suction as specified by the ASTM E 330 test method (ASTM 2002). Besides mean wind pressure, cyclic wind fluctuation can also affect performance of many kinds of building envelope, e.g., roofs with fatigue-prone fixations. Cyclic load test is suggested by ASTM for BV/SS due to the possibility of crack development under cyclic loads (ASTM 2000, LaTona *et al.* 1988). ASTM E 1233 (2000) provides a standard test method for cyclic test of exterior windows, curtain walls, and doors by cyclic air pressure differential.

Wind load spectra are developed by simplifying wind velocity/pressure time histories collected from field measurements or wind tunnel tests. Based on wind tunnel model of a tall building in a mid-western American city, a wind protocol was developed by Pantelides *et al*. for wind effects on building claddings in non-hurricane area (ASTM 2000, Pantelides *et al.* 1993). The test spectrum simulates wind event of four hours duration consisting of eight repeats of a loading sequence each having 131 pressure and suction cycles. Test spectra have also been developed for tests of wall claddings under strong winds of hurricanes or cyclones, with or without windborne debris, by Letchford and Norville (Letchford and Norville 1994, Minor 1994). These two wind load spectra are the wind load protocols recommended by the ASTM E 1233 standard test method for cyclic wall tests in non-hurricane-prone regions and hurricane-prone regions respectively. According to Minor (1994), the major differences between hurricane and normal wind are that the hurricanes can change direction slowly as they march, may carry lots of debris, can have longer durations, and are more turbulent. While the first two attributes may not be related to this research, the last two are relevant. Given that most parts of the United States are not hurricane-prone, the protocol developed by Pantelides *et al.* seems to be more appropriate. This protocol has also been adopted by ASTM E 1233 as the recommended load protocol for normal gust tests. As it is stated in the clause X 1.2.2.2 in the appendix, “Unless otherwise specified, apply the positive and negative pressure cycles as defined in Table X1.2”.

Since most cyclic loading protocols are developed for studying fatigue of the building claddings, the stress level and number of cycles are of more concern than frequency of loadings. Neither protocol in ASTM E1233 specifies the frequency of the cycles. However, a loading protocol with too low of a frequency will overestimate the level of pressure equalization, which highly relies on frequency of the incoming wind, and thus will underestimate the load carried by the BV.

3. Brief introduction of the PBVSS system design

Given the background on potential deficiencies of conventional BV/SS wall systems, it is desirable to minimize BV cracking possibility and crack width under high wind loads. It is also desirable to have in-plane seismic isolation of the wall system from the primary structural system. One can add to this the desire to avoid the use of scaffolding and the related potential hazards. Lindow and Jasinski (2003) provide some guidelines on panelized wall systems. The PBVSS developed in this study is based on prefabricating the entire BV and SS backup wall as a panel. The flexural cracking and rain penetration problem of the BV is addressed by controlling both the number and width of cracks. To control the number of cracks, the maximum stress and out-of-plane deflection of the BV have to be limited. To control the crack width, the SS maximum deflection has to be limited. To show that these design objectives are satisfied, the wall system in the proposed design should likely have decreased stresses and deflections. With this objective in mind, in addition to the BV wythe and SS backup, the PBVSS is enhanced by means of a structural (rolled) steel support framework. The frame is designed to also support the weight of the BV and backup wall during transportation and erection. The structural steel support frame consists of a lower support beam, an upper top beam, and two vertical load carrying members. The bottom member consists of a channel and an angle bolted together at three points (the two ends of the member and mid-span). The bottom member of the frame performs the function of the shelf angle. However, while shelf angles in conventional designs support only the BV, this member supports both the BV and the SS backup wall. The angle performs the function of the shelf angle to support the BV, while the channel sitting on the floor slab supports the SS. The top member consists of a channel and a steel plate bolted together. The top channel is under the bottom of the slab or spandrel beam of the floor above separated by movement joints. The top steel plate attached to the top channel extends all the way to the top to provide out-of-plane support for the BV. The two vertical members are made of steel channels framing into the top and the bottom channels and are designed for tension force to support the gravity loads when lifted by a crane.

Typically 18 gauge studs at 400 mm to 600 mm center-to-center spacing are used for the SS backup in conventional walls (Brick Industry Association 1999, Suter *et al.* 1990). In order to increase the flexural out-of-plane stiffness, heavier gauge SS (e.g., 12 gauge) framing or structural steel channels can also be used (McGinley 2000). For the proposed PBVSS system, since larger out-of-plane stiffness is desired, 12 gauge SS are used in the steel backup frame. To prevent lateral buckling of studs and to further increase the out-of-plane stiffness of the studs, in the example design shown here, two 12 gauge SS back-to-back are used at the center. Typical spacing between studs is 400 mm. The studs are connected to the BV with light gauge shear connectors that can be attached to the webs of the studs to more effectively engage them in out-of-plane lateral load resistance. Typical vertical spacing between ties is 400 mm. However, research (McGinley *et al.* 1986) has shown that ties at the top will experience larger forces than the others if they are uniformly spaced in the vertical direction. Therefore, smaller tie spacing (200 mm) is used at the top in the proposed PBVSS design. The actual spacing to be used would vary with the actual height of the panel and construction details.

The steel frame, together with heavy gauge SS backup and light gauge steel connectors, provides a stiff backup for the BV and thus can increase both strength and stiffness against wind loads. Of course, if the same gage studs and the same number of studs were to be used for construction of the conventional BV/SS system, one would expect some increase in stiffness and strength of that system as well. However, because of the boundary conditions, i.e., attachment mechanism of studs to the track and track to the floor, such increase in stiffness and strength will not be as effective as in the proposed system. For performance under in-plane seismic loads, a seismic isolation system consisting of bearing and tie-back connections is introduced to allow in-plane movement of the panel with respect to the main structure system. Therefore, the wall panels are intended to be isolated from in-plane movements of the main structure.

It should be noted that the intention of the proposed PBVSS system is to decrease number and width of cracks rather than totally eliminate the possibility of cracking in the BV of the wall panels. Eventually all BV will crack due to shrinkage of mortar, thermal expansion of wall components, differential movement between wall components, etc., and these cracks could lead to water leakage. Once water penetrates the BV, problems may arise if the water cannot be driven out. Therefore, a drainage system is also included in the proposed design. Vapor retarder and water barrier are also included in the design to prevent water from going further inside. Besides these components, other features such as thermal insulation and sheathings are designed to improve performance of the system regarding building-science related issues such as heat exchange, condensation, water leakage, and air leakage (Carll 2000, Hens *et al.* 2007, Tenwolde and Rose 1996). The design can also potentially help achieve pressure equalization/moderation (Baskaran and Brown 1992).

4. Testing program

4.1 Test scope and objectives

For the simulated wind loading tests, the performance of the PBVSS system under applied air pressures was evaluated and compared with that of the conventional BV/SS systems. The major objectives of the tests were to: 1) study the possibility and extent of cracking in the BV under simulated cyclic wind loading; 2) provide information for potential improvement of the design; and 3) compare the experimental results with the analytical results to evaluate the efficiency of the finite element model used in the numerical analysis of the system under wind loading.

Full-scale specimens consisted of a PBVSS wall and a conventional BV/SS wall. General performance of the walls under cyclic service and ultimate wind loads based on ASTM E 1233-00 (ASTM 2000) was studied. The extent of cracking and damage under load for both systems were investigated. Deflections of BV and SS at various locations as well as the magnitude and distribution of tie forces were recorded. Preparation of specimens and the test procedure followed the ASTM E 1233-00 test standard. The test cycles at lower pressure levels and duration of each cycle generally follows the requirements of the test standard. To measure the extent of cracking after cyclic loading, water penetration through the BV was tested per ASTM E514-03C (ASTM 2003).

4.2 Test specimens

The specimens were tested on the Wind Load Test Facility (WLTF) in the Building Envelope Research Laboratory (BERL) at the Pennsylvania State University. Cyclic air under positive pressure (wind blowing against the exterior surface of the BV) or negative pressure (wind suction on the exterior surface of the BV) were supplied to the air chamber through a manifold. Figs. 1 and 2 show the details of the conventional and PBVSS specimens attached to the test facility. Further details on the specimens as well as the chamber function are discussed subsequently. The dimensions of the BV specimens in this study were 2438 mm wide by 2438 mm tall and 100 mm thick. BV for both the conventional and the panelized specimens were supported by a bottom angle (shelf angle in the conventional specimen). The bottom angle of the conventional specimen was a L100 mm × 100 mm × 12.7 mm angle, connected to a reinforced concrete slab using *J*-hook anchor bolts. The bottom angle of the panelized specimen was connected to the bottom channel, which sat

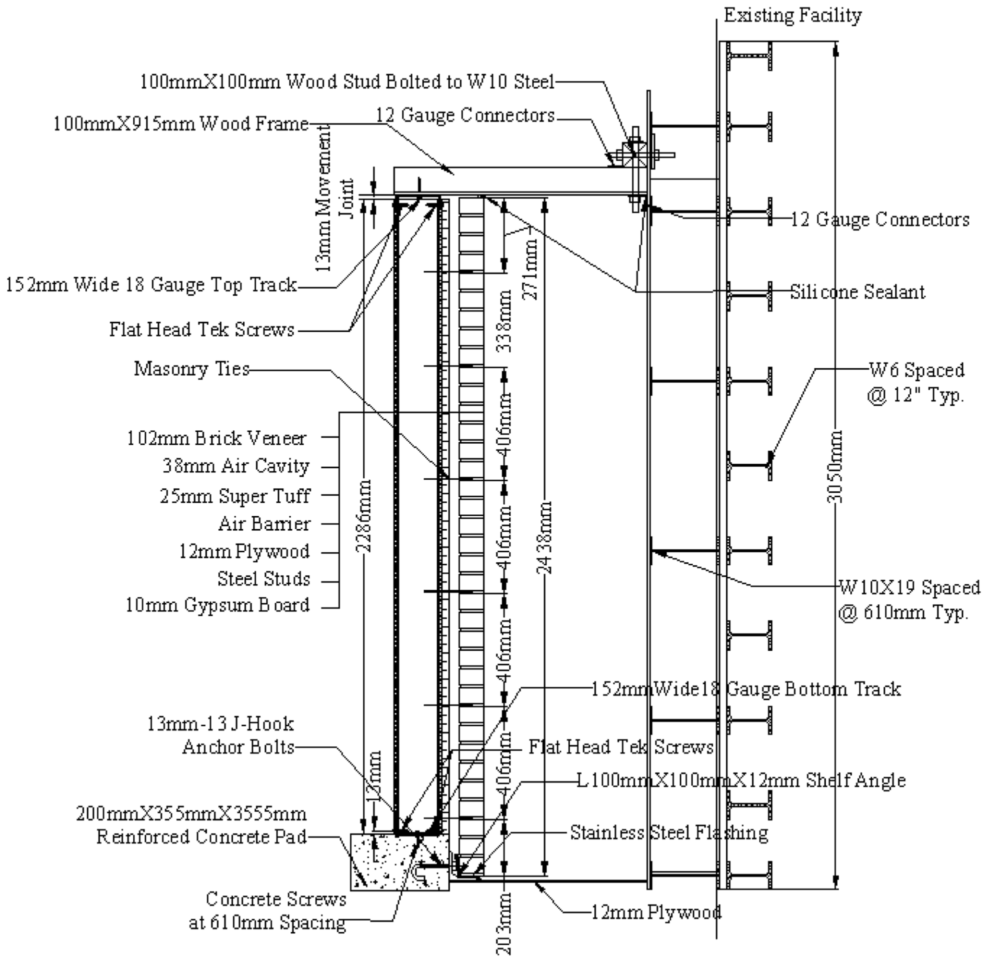

Fig. 1 Conventional wall attached to wind load test facility

on the slab. In the panelized specimen, short steel plates and segments of light gauge SS functioning as shear keys were used as out-of-plane restraints. At the bottom, the restraints were welded on the bottom angle and embedded in the holes of the hollow bricks. At the top, the restraints were embedded in the top bed joints.

For ventilation of the wall panels, weep holes and vents spaced at 609 mm were constructed by leaving some of the BV head joints open. Weep holes (normally at the bottom course) were located at the third lowest course to accommodate the water collection system. Similarly, to accommodate the water supply system, the vents were located four courses from the top. It should be noted that weep holes were included in the specimens for ventilation only rather than water drainage. However, in actual PBVSS design, weep holes should be located at the bottom course as usually specified in conventional design.

The backup system for the conventional wall specimen was made of seven 18 gauge steel studs spaced at 406 mm on center. The studs were supported on the web of the bottom track and connected to flanges of the top track with a 12.7 mm movement joint. The backup frame for the

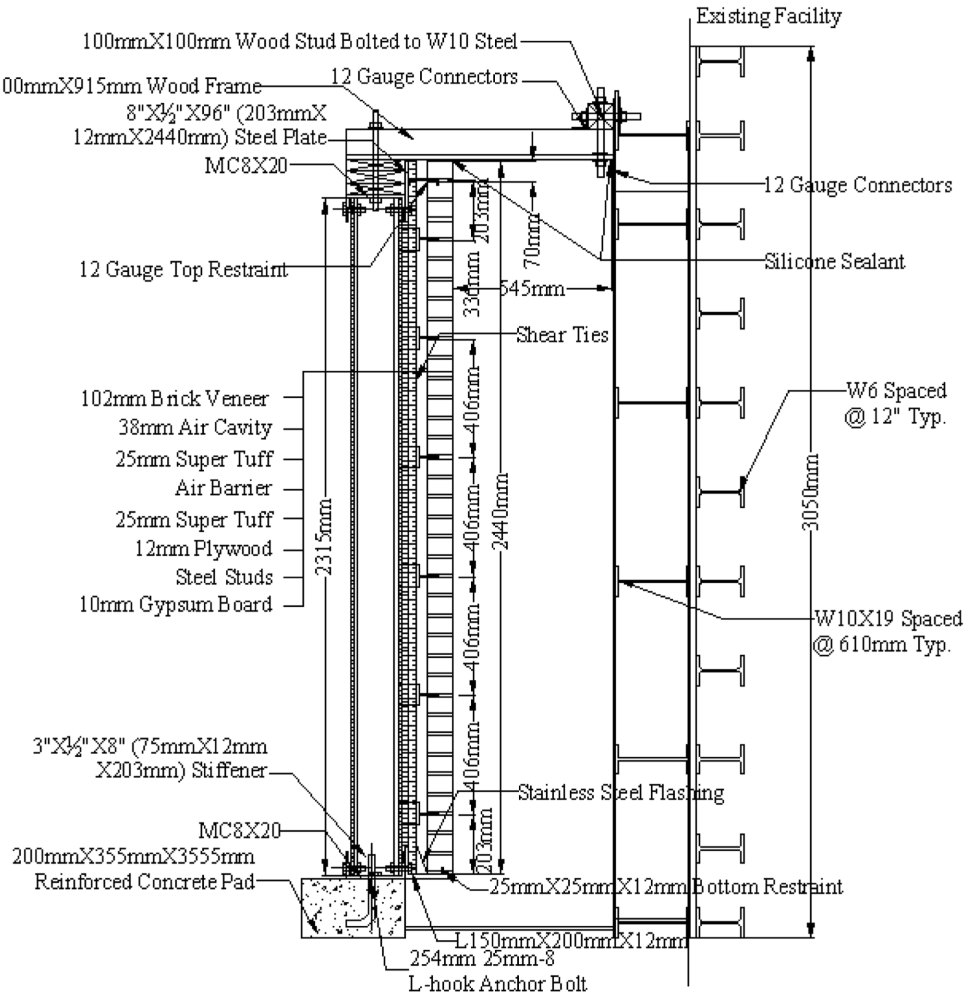

Fig. 2 Panelized wall attached to wind load test facility

Fig. 3 Backup system, connection details of vertical channels, and stiffeners at bottom channel

PBVSS specimens consisted of seven vertical members spaced at 406 mm on center. Structural steel channels (MC6X18) were used for the two end members, back-to-back 12 gauge double SS were used as the center member, and the remaining four members were single 12 gauge SS. The vertical end channels were bolted to the top and bottom channels (MC8X20). For both the conventional and the panelized specimens, lateral supports were provided to the vertical members at mid height by continuous bridging attached to both surfaces of the members. Fig. 3 shows the backup system, stiffeners, and the connection of the vertical steel channels to the horizontal steel channel for the PBVSS specimen.

Research (Drysdale and Suter 1991) has shown that under large out-of-plane loading, SS in BV/SS walls could fail by local buckling of the flanges at tie locations when ties are attached to exterior surface of the stud flange, which is very flexible. For better performance, in design of the PBVSS system, shear connectors (Stud Shear^{TM} Connectors (FERO 2009)), as opposed to conventional adjustable ties flexible in out-of-plane directions, that would be connected to the web of the SS were chosen as the connectors. Fig. 4 shows the shear connectors as attached to the wall during

Fig. 4 Attachment of shear connectors to the studs and wall assembly

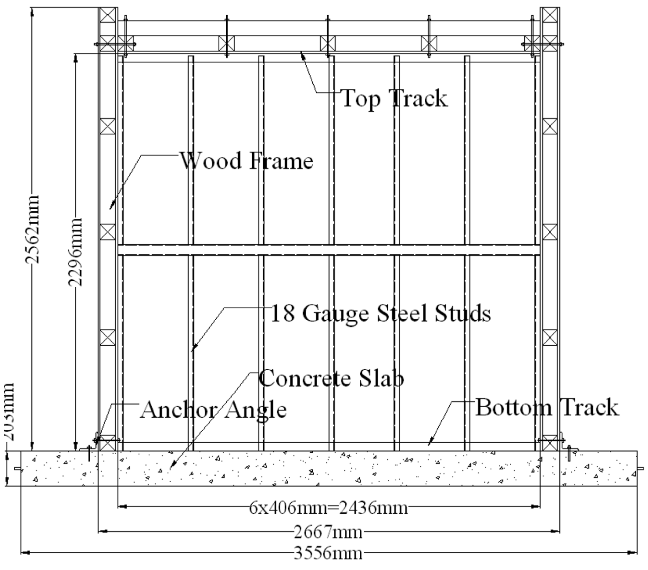

Fig. 5 Back view of conventional wall specimen attached to the wind load test facility

specimen construction. Besides enhanced shear strength in the vertical direction, the shear connectors chosen also have higher strength and stiffness under axial forces compared to most conventional masonry ties, so they can transfer loads from the BV to the SS more efficiently. In particular, the higher axial strength of the connectors and the attachment to the stud web were the reasons for choosing such a tie type. The manufacturer has conducted extensive tests to evaluate the induced internal loads in the wall assembly due to the vertical shear stiffness of the shear connectors (FERO 2009).

For the conventional specimen, DW-10 ties (Hohmann and Barnard 2010) as normally used in construction were used. For both specimens, ties were used on every vertical member, which made the horizontal spacing of the ties to be 406 mm. Typical vertical spacing was 406 mm, with smaller spacing at top as such ties would be subjected to higher forces under out-of-plane loads if uniform vertical spacing was to be used. With this configuration, the largest tributary area for a tie was 0.165 m^2, which met the code required maximum tie tributary area of 0.248 m^2 for adjustable two-piece ties according to the Building Code Requirements for Masonry Structures (The Masonry Standards Joint Committee 2002). The maximum spacing of the ties (406 mm in both directions) also meet the maximum spacing required by the same code (813 mm horizontally and 457 mm vertically). Also, the spacing used fits the brick pattern of the veneer nicely with one tie on every eight courses. In practical application, the tie patterns can be adjusted as necessary. Besides the BV and the steel backup, all other functional components used in typical BV/SS wall constructions such as air cavity, air barrier, thermal insulation, and sheathings were also included in the test specimens.

4.3 Wood chamber

A wood chamber was built to create an airtight space between the test frame and the BV as

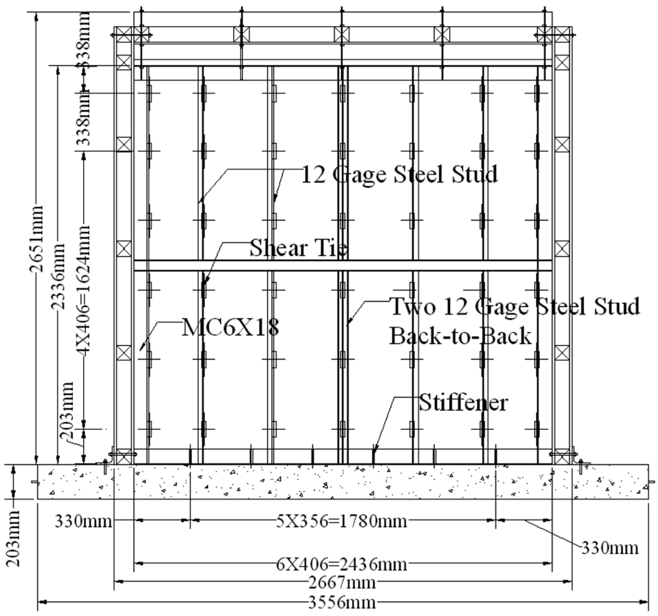

Fig. 6 Back view of panelized wall specimen

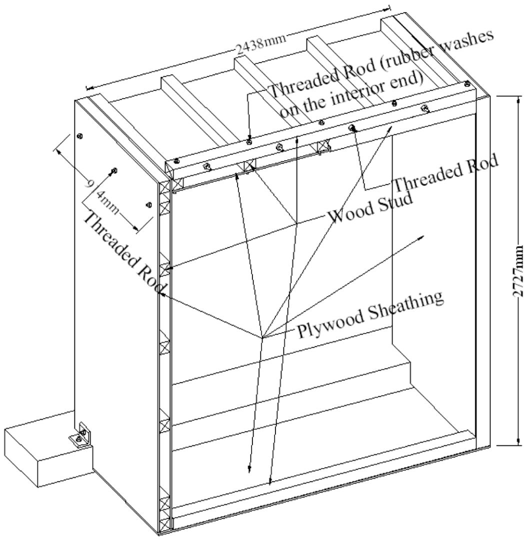

Fig. 7 Isometric view of wood frame for panelized specimen

shown in Figs. 1 and 2. To facilitate observation of the BV during the tests and to provide access to the front surface of the BV and the chamber during the tests, a window covered with acrylic panel was built on one side of the wood chamber. Besides serving as an air chamber, the roof of the wood chamber was also used to model the floor slab above the wall panels. The top track of conventional specimen and the top channel of the panelized specimen were attached to the roof of the wood chamber. The details of tie-back connections at the top of the PBVSS wall systems were not modeled here since the in-plane movement of the specimen was not a concern for the wind test. Figs. 5-7 show additional detailed drawings for the attachment of the conventional and panelized specimens to the chamber illustrating all the components already discussed. As shown in Figs. 1 and 2, a large cavity exists between the surface of the brick veneer (left side of the cavity) and the facility reaction wall (right side of the cavity). Air flows through a window on the reaction wall to apply positive pressure (push) or negative pressure (suction) against the brick veneer face.

4.4 Water supply and collection

A centrifugal pump was used to pump water to the top of the test frame. The supply water rate was measured with a water flowmeter. Under the roof of the wood chamber was a horizontal 19.1 mm PVC pipe along the width of the chamber. The pipe was suspended from the roof panel with 1.02 mm diameter holes at 25.4 mm spacing per ASTM E514 standard (ASTM 2005) to apply a relatively even water load. A light gauge stainless steel trough was installed in the air cavity of both specimens to collect any water that penetrated the BV during the water test. Then the water collected was drained out of the chamber to the flowmeter. Fig. 8 shows the PVC hose at top of the chamber and water collection system for the PBVSS.

To accommodate the water collection system, flashings in the specimens had shorter vertical leg than normally used and were not attached to the insulation board. The flashings in the specimens were included only to model the boundary conditions of the BV in the walls and were not used to

Fig. 8 Water supply at top of the chamber and water collection system behind the BV

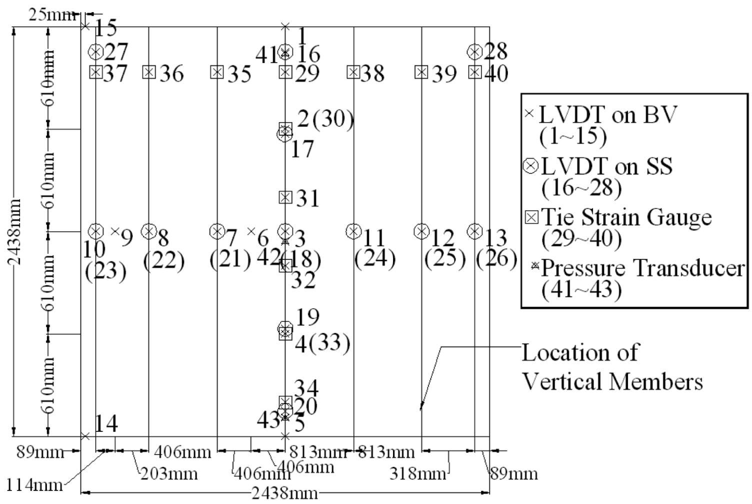

Fig. 9 Locations of data measurement points

collect and direct water in the air cavity. Water running in front of the BV was drained out of the chamber by four drainage ports at the bottom of the wood chamber to the same electronic water meter mentioned above. Therefore, depending on the amount of water penetration in the water tests, the water circuit could be routed so that the electronic water meter could be used to measure water either in front of or behind the BV.

4.5 Instrumentation and data acquisition

Measurements taken during the tests included pressure on the exterior and interior (within the air cavity) sides of the BV, out-of-plane deflection of the BV and the steel backup, and axial forces in ties as shown in Fig. 9.

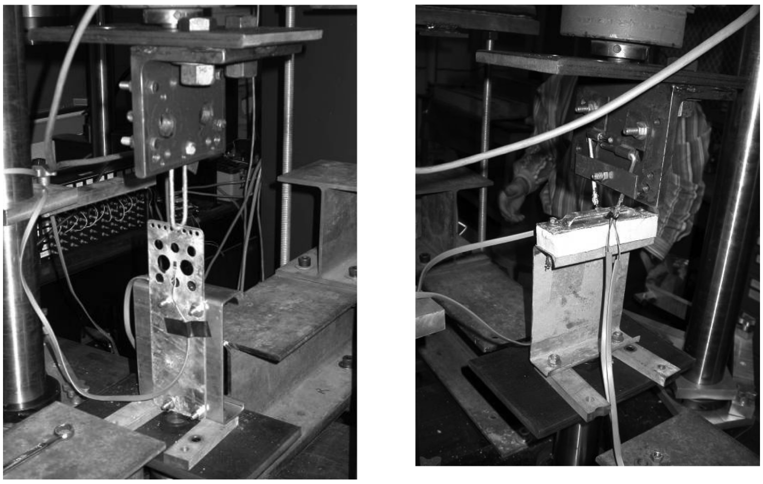

Fig. 10 Calibration tests of the ties

Deflection of the BV was measured to compare the out-of-plane deflection of conventional and panelized walls, to investigate the force distribution within the BV (one-way versus two-way bending), and to investigate the extent of composite effect between the BV and the steel backup. Measurements of out-of-plane deflection of the SS were taken to investigate the extent of deflection in the SS and the extent of composite effect between the BV and the SS. All pressure gauges and LVDTs were mounted on a separate supporting frame to isolate them from movement of the test specimens. The objectives of the measurement of tie forces were to investigate the tie force distribution and evaluate the performance of ties under load. Measurements were taken indirectly by measuring the strain in ties under the load and the distribution of tie forces in both horizontal and vertical directions was measured. For the panelized specimen, the strain gauges were applied on the tie plates; for the *X*-Seal ties used in conventional specimen, strain gauges were attached to the legs of the *V* ties. Because the two legs of *V* ties may not have the same force, strain gauges were attached to both legs. Similarly, because of the possible out of alignment of the shear connectors in PBVSS specimen, strain gauges were applied on both sides of the steel plates to cancel out stress due to bending. Due to factors such as holes on ties, unevenness of surface, and misalignment, the strain-force relationship would likely deviate from idealized Hooke's Law. Therefore, before attaching the ties to the vertical members (studs), the strain gauges were calibrated individually to establish the relationship between strain readings and tie forces. Fig. 10 shows photos of the test setups. The ties were attached to the same stud backup as the ones used in the full-scale specimens. This way, the isolated tie will have the same boundary condition as those attached to the studs on the wall. Tests on shear connectors also showed that although the location of holes used for connections did have some effect on the calibration results, the effect was minor provided the location of holes was close to the mid-height of the steel plates (within two holes distance).

4.6 Test procedure and loading profile

The conventional specimen was initially tested for water penetration before any wind load was applied. Then a lime wash coating was applied on the surface of the BV. The lime wash coating had

Table 1 Other extreme wind test spectrum (Table X1.2 of ASTM E 1233-00)

Loading Sequence	Loading Direction	Air Pressure Cycles	Number of Cycles
1	Positive	0.0-0.6P_{pos}	12
2	Positive	0.0-0.8P_{pos}	1
Repeat positive loading sequence 1 and 2 an additional four times prior to loading sequence 3			
3	Positive	0.0-1.0P_{pos}	1
4	Negative	0.0-0.6P_{neg}	12
5	Negative	0.0-0.8P_{neg}	1
Repeat negative loading sequence 4 and 5 an additional four times prior to loading sequence 6			
6	Negative	0.0-1.0P_{neg}	1
Repeat the loading sequence 1 through 6, in the order designated, an additional seven times			

two functions: a) to make it easier to observe the cracks if the wall cracked, and b) to minimize any water leakage through fine cracks at mortar joints due to mortar shrinkage since the main objective of the water penetration tests was to investigate the amount of water that leaks through the flexural cracks under wind loads. After application of the coating, another water penetration test was carried out to evaluate waterproofing performance of the BV with lime wash and before wind load test. After these initial tests, the cyclic wind tests were carried out. The wind load simulation was controlled manually during the tests, while the specimens were tested under both positive and negative pressure. Service wind pressure was calculated to be 1 kN/m^2 based on the method in ASCE 7-02 (ASCE 2003) assuming an exposure category C and a basic wind speed of 145 km/h. Cyclic wind tests were repeated with 1 kN/m^2 maximum pressure increments between steps until the specimen failed or the capacity of the test facility was reached. After the first wind cycle, the last wind cycle and some other intermediate cycles deemed important, water penetration tests were also carried out to study the influence of cyclic wind load on the amount of water leakage through the BV. After testing the conventional specimen, the PBVSS specimen was tested following a similar procedure.

Cyclic tests followed the standard test method ASTM E 1233-00 (ASTM 2000) where applicable. The load spectrum used in the tests was based on the “Other Extreme Wind Test Spectrum” specified in Table X1.2 of the standard test method (Table 1). However, in order to cut down the total number of cycles in the tests, instead of repeating the whole positive and negative cycle (Loading sequences 1 to 6 in Table 1) seven times as specified in the spectrum, only one repetition was done. Moreover, due to the difficulty in achieving high negative pressure, the negative steps 3 to 5 in Table 1 was just repeated once instead of four times as specified by ASTM standard. The cut down was also based on consideration that repeating the cycles more than once would not have substantial effect on the performance of the specimens. The duration of each air pressure cycle was 5 seconds. If cracking was observed during the tests or stiffness degradation due to cracking was noticed from the load-displacement plot, the cyclic tests were considered completed. Otherwise, another round of cyclic test with higher load level would be applied to the specimens (1 kN/m^2 increment) until the capacity of the facility was reached or the specimen failed.

The water penetration tests followed the standard test method ASTM E514-03C (ASTM 2005) where applicable. The test duration was four hours. The water supply system discussed before was used to apply a water load of 139 liter/m^2/hr, which resulted in an overall water load of 927 liter/hr on surface of the brick veneer wall. At the same time, the air supply system applied constant positive wind pressure of 0.479 kN/m^2 (per the ASTM test standard) on the exterior surface of the BV. It should be noted that this constant pressure is a relatively low level service type pressure and is not intended to cause significant bending in the wall to close any cracks. Furthermore, in BV walls, the water leakage also takes place through shrinkage cracks in the mortar. Water that ran down the front of the BV and water that penetrated the BV was collected for the duration of the tests and the total amount of water collected behind the BV of the two specimens was compared as an index of water penetration performance of the two systems.

5. Test results

The pressure cycles achieved were quite uniform, with pressure being distributed evenly in the chamber and in the cavity, and the magnitude of the pressure actually applied was quite close to the desired value, especially at lower levels. When the magnitude of the maximum pressure increased, it became more difficult to reach the desired pressure due to some air leakage in the setup. Therefore, the total number of wind load cycles was cut down to reduce the time taken for the tests starting from 4.02 kN/m^2 pressure level for both specimens.

5.1 Rigid body movement

Due to flexibility of the connections between the specimen and the chamber, when the load changed from positive pressure to negative pressure or vice versa, the whole specimen had a rigid body movement (rotation). Fig. 11 shows an example displacement-time history of the BV at the center of the PBVSS specimen under 5.03 kN/m^2 positive and negative pressure. Due to the rigid body movement, the total deflection of the measurement points shown on the plots is much higher than the actual deflection of the specimen, and when the pressure was released, the deflection did not return to zero. The rigid body movement was about 1.78 mm for the conventional specimen and about 7.62 mm for the panelized specimen. Since this rigid body movement is not of interest for this research, it was subtracted from the total displacement for the discussion that follows. Similarly,

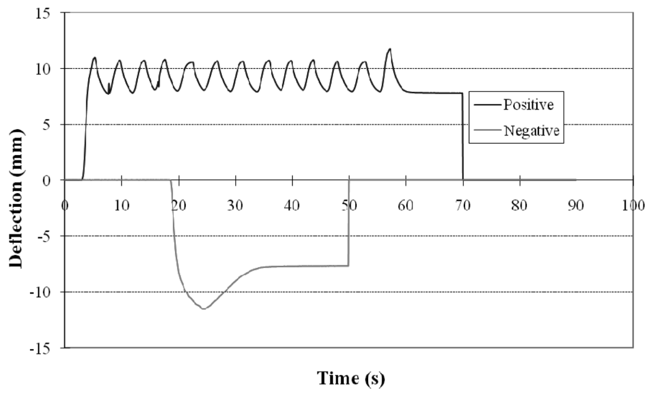

Fig. 11 Deflection of the BV vs. Time at the center: panelized, 5.03 kN/m^2

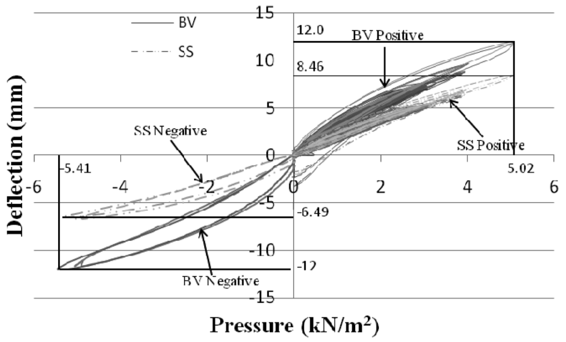

Fig. 12 Hysteresis of deflection at the center of the wall: conventional, 5.02 kN/m^2

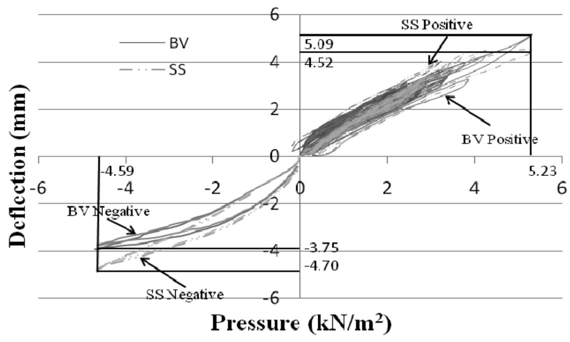

Fig. 13 Hysteresis of deflection at the center of the wall: panelized, 5.23 kN/m^2

the sides of the specimen also experienced some level of rigid body movement, especially at the high pressure levels, and this was also subtracted from the total displacement for the discussion that follows.

5.2 Hysteresis behavior

For both specimens, at each pressure level, 14 iterations were applied. Each pressure level started from five positive iterations, then two negative iterations, followed by five positive iterations, and finally two negative iterations. Figs. 12 and 13 show the hysteresis plots for displacement of the brick veneer and the steel backup for both specimens at 5.03 kN/m^2 pressure level. The response of both steel studs and BV are plotted on the same figure with labels distinguishing the respective curves. The plots show that the stiffness did not change much from iteration to iteration, even from positive to negative. Therefore, considering the large volume of data related, only one iteration will be shown in later sections as a typical example of any pressure level. Figs. 12 and 13 show that under the same pressure level, deflection of BV and SS of the conventional specimen are about two times those of the panelized specimen, which means the panelized specimen is considerably stiffer. This is also shown by the fact that the average equivalent stiffnesses of the BV and SS of the panelized specimen, which are calculated by taking reciprocal of the slope (change in deflection over change in pressure in Fig. 14), are 0.940 (kN/m^2)/mm and 0.930 (kN/m^2)/mm, respectively, while those of the conventional specimen are 0.412 (kN/m^2)/mm and 0.582 (kN/m^2)/mm respectively, which are about half of those for the panelized specimen. The figures also show that the curves of the BV and SS of the panelized specimen (Fig. 13) are largely overlapping, which means more obvious composite behavior compared to the conventional specimen (Fig. 12). Attempts were not made during the instrumentation design to collect data that would help determine the share of various factors leading to increased composite behavior. However, based on the design intent of PBVSS, the parameters that contributed to increased composite behavior include the use of rolled steel frame, use of higher strength studs, strong and stiff connection of the studs to the rolled steel top and bottom channels, use of masonry stud shear connectors, continuous boundary condition at top, and use of shear keys at the bottom.

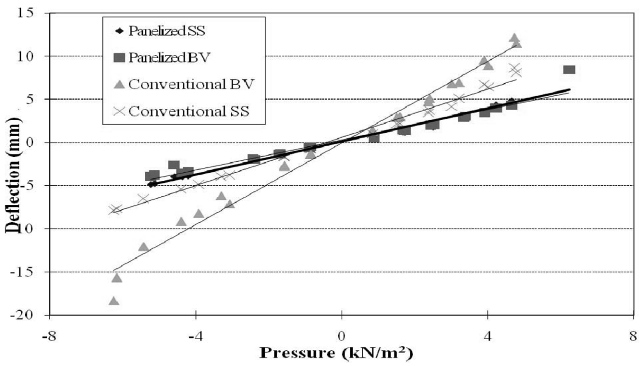

Fig. 14 Deflection of center point of walls vs. pressure

5.3 Deflection vs. pressure

Fig. 14 shows the change of deflection at the center point in the BV and the steel backup with the change of the maximum pressure. Both positive pressure cycles and negative pressure cycles for the panelized specimen and the conventional specimen are included. From the plots, it can be seen that both the deflection of the BV and the deflection of the SS increase with the increase in pressure level. Although considering all the points including the deflection at the highest pressure, one may fit a nonlinear or bi-linear curve through the data, however, as shown on the figure, most of the points can be considered falling within an approximate linear relationship between deflection and pressure. The gradients of the curves (ratio of increase in deflection to increase in pressure) of the deflection of conventional BV and SS are 2.36 and 1.40, respectively, while the gradients of the curves of deflection of panelized BV and SS are 0.877 and 0.963, respectively. Therefore, the deflection of the conventional specimen increases (2.69 times for BV and 1.45 times for SS) faster with increase in pressure than that of the panelized specimen, which will be discussed in more details in following sections. The difference between BV deflection and SS deflection is also much smaller in the panelized specimen than in the conventional specimen, which means the panelized specimen shows a higher degree of composite action. As mentioned earlier, several factors including the type of ties used has influenced the composite behavior.

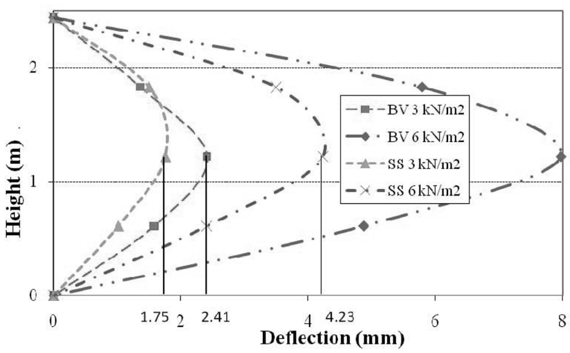

Fig. 15 Deflection vs. height: conventional specimen

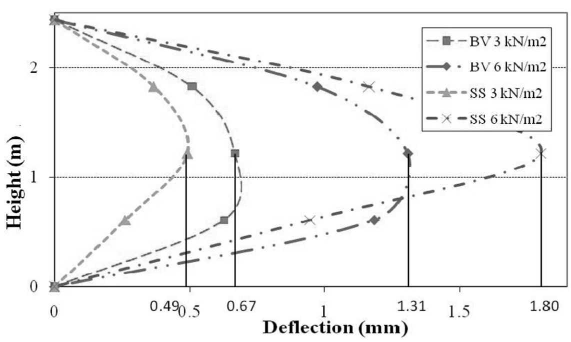

Fig. 16 Deflection vs. height: panelized specimen

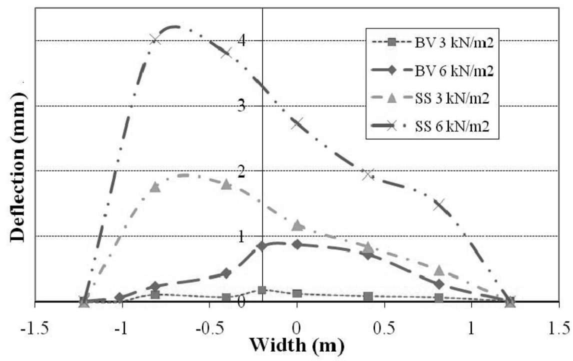

Fig. 17 Deflection vs. width: conventional specimen

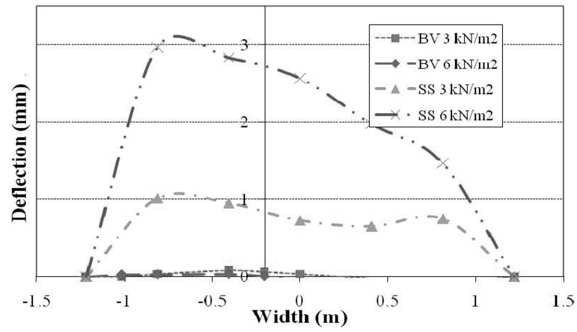

Fig. 18 Deflection vs. width: panelized specimen

5.4 Deflection vs. height

Figs. 15 and 16 show the variation of deflection in BV and steel frame with the height for both specimens. As example results, the deflection along the vertical centerline under the two pressure levels of 3.00 kN/m^2 and 6.00 kN/m^2 are shown in these figures. Curves shown in dashed line were fitting among the measurement points. At these two pressure levels, both specimens were uncracked. The deflection curves show that the peak deflection of the panelized specimen is much smaller than that of the conventional one.

5.5 Deflection vs. width

In the tests, the only restraints for the out-of-plane movement on the sides of the specimens were the silicone joints between the BV and the wood frame, which were very weak. As a result, although the panelized specimen was expected to have increased two-way behavior due to the stiffer backup on the sides, neither specimen demonstrated any substantial two-way bending under the load. Further tests with rigidly restrained sides of the chamber and specimen attachment to the chamber are necessary to explore a possible advantage of the panelized specimen in this aspect. The variation in the level of restraint on the sides also makes the plots unsymmetrical. This phenomenon is more obvious at higher pressure levels when the silicon joints started to break. Figs. 17 and 18 show the variation of deflection along the horizontal centerline in the BV and the steel backup for both specimens. Two example pressure levels of 3.00 kN/m^2 and 6.00 kN/m^2 are plotted.

5.6 Composite behavior

In conventional BV/SS walls, due to the flexibility of the steel studs and conventional adjustable ties, load cannot be transferred efficiently from the BV to the SS. Therefore, as expected, the BV in the conventional specimen resisted a larger portion of the load and had slightly higher deflection than that of the steel backup. On the contrary, due to the stiffer structural steel frame and shear connectors used in the PBVSS specimen, load can be transferred much more efficiently. Therefore, the BV and steel frame could work as an integrated system with composite behavior. The composite behavior of the panelized specimen can be noticed in Figs. 14 and 15. Under the pressure level of

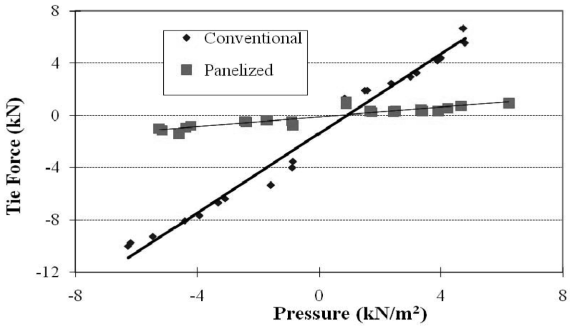

Fig. 19 Tie force vs. pressure

6.00 kN/m^2, the steel backup of the panelized specimen had larger deflection at the center than the BV.

5.7 Tie forces

The tests showed some random variations in tie force results likely due to several reasons. First, the variation of tie geometry and the surface condition of ties due to the galvanization process may introduce some variation in the stress reading. Second, during the construction of the BV, the mortar joints elevation would not be perfectly aligned with that of the ties, this may introduce some bending moments initially and may cause the two-component ties to slide when loaded. Third, due to the small size of the tie components and the circular shape of the *V* tie in conventional specimen, slight variation in the attachment of the strain gauges may also affect the readings. Finally, the strain amplifiers and connection boxes had some built-in white noise which could not be separated from the actual readings during the tests. This can also affect the accuracy of the readings especially at the low pressure levels. At high pressure levels, some of the readings did not seem reasonable, which may also indicate that some of the ties started to behave nonlinearly.

Fig. 19 shows the plot of tie forces versus pressure levels. The tie was located on the centerline of the brick veneer and was the second one from the top. For the conventional specimen, the relationship between tie forces and the pressure applied is seen to be generally linear, with some nonlinear portion at higher pressure levels. The R^2 values for the first, second, and third order regression turned out to be 0.975, 0.977, and 0.984 respectively. The maximum force in this tie under 6.00 kN/m^2 negative pressure was 10.0 kN, which is much higher than the capacity of the ties and the ties likely behaved nonlinear under high negative pressure. Therefore, the relationship between strain and tie force was no longer linear and the calibration factor established under relatively low forces (up to 2.2 kN) was no longer valid. The conventional specimen was dissembled after the wind tests and it was observed that some ties and/or screws used to attach the ties to the SS were pulled out. This also proves that the actual forces in some ties exceeded the expected value and tie force distribution can be far from uniform.

For the panelized specimen, although the maximum tie force increased with the increase of pressure, the tests showed that the relationship between pressure and tie force does not have the same level of linearity as that of conventional specimen. The R^2 values for the first, second, and third order regression turned out to be 0.798, 0.818, and 0.819 respectively. Measurement of strain

Fig. 20 Cracking of the conventional BV at the bed joint

in ties was extremely difficult in the test of panelized specimen due to the high stiffness of the shear connectors and the extremely low level of strain as a result.

Plots of tie forces along the height and width of the brick veneer show that there is no definite relationship between tie forces and location of ties, which may indicate that strain gauges on some of the ties were damaged during the test. Another possible reason is that during the load cycles, some eccentricity was induced in the connections of the two-component ties as mentioned before. The tie strain gauge calibration and behavior of the ties during the wind tests are discussed in more detail in Liang (2006).

5.8 Description of damage to the specimens

The conventional specimen cracked under 6.00 kN/m^2 negative pressure. A horizontal crack developed at a bed joint located close to mid-height of the BV and eventually developed through the whole length of the wall (Fig. 20). The crack was closed during the positive pressure iteration that followed and reopened with a larger width during the repetition of the negative pressure iteration. At the same time, some screws used to attach the conventional ties to the SS were also pulled out during the initial 6.00 kN/m^2 negative pressure iteration. Because of this, fewer ties were involved in load resistance during the second iteration, which resulted in pulling out of even more screws. Therefore, in a sense, under the 6.00 kN/m^2 negative pressure, the conventional BV not only cracked, but also failed due to loss of reliable attachment of the BV to the SS and the potential safety concerns. The panelized specimen was loaded up to 8.62 kN/m^2 positive pressure and 6.00 kN/m^2 negative pressure when the capacity of the test facility was reached. No cracking or other form of failure was noticed.

Although the conventional specimen cracked at a negative pressure level up to 6.00 kN/m^2, this does not necessarily mean that in reality the conventional system can be used for pressure up to 6.00 kN/m^2. It should be noted that the brick units used for the test specimens were hollow bricks. Hollow bricks generally have higher strengths because of more uniform drying and burning. And the mortar squeezed in the holes during construction of the BV worked as shear keys and increased flexural cracking strength of the BV (Taly 2000). The conventional walls may also start to have serviceability problem due to the large movement at the joints.

5.9 Water penetration test

After the wind load test and cracking of the conventional specimen at 6.00 kN/m^2, the specimen was tested for water penetration. The BV started to leak right away and altogether 0.454 kg of water was collected by the end of the test. The relatively small amount of water collected was due to the test condition used. Based on the ASTM E 514 test method (ASTM 2005), during the water penetration test, a positive pressure of 0.479 kN/m^2 was applied simultaneously with the water supply. However, as mentioned before, the crack in the conventional specimen was formed under negative pressure. Therefore, the superimposed positive pressure during this water test closed the crack and decreased the amount of water penetration. It is believed that if negative pressure (instead of positive pressure) has been applied on the BV with its exterior surface is previous wetted by rainwater, much more water leakage would be collected. Also, other than wind-driven rain, gravity, surface tension, kinetic energy, air currents, and capillary action may also cause water leakage once the wall is cracked (KPFF 1995). No water leakage was recorded for the panelized specimen in the water penetration test after the 8.62 kN/m^2 cycle.

6. Comparison of conventional and panelized system

Figs. 14 to 16 show that the deflection of the panelized specimen is much smaller than that of the conventional one. The deflection of conventional BV can be up to approximately 6 times that of panelized BV and the deflection of conventional SS can be up to approximately 4 times that of panelized SS. Also, the deflection curve of the BV for the panelized specimen is also flatter than that of the conventional one, which suggests smaller curvature. Table 2 compares the main performance features for the two specimens under positive pressures of 3.00 kN/m^2 and 6.00 kN/m^2. The results show that the panelized specimen is much stiffer than the conventional specimen. Moreover, the panelized specimen also showed more obvious composite behavior than the conventional one. The difference in deflection of the brick veneer and steel backup for the conventional specimen can be more than 7 times that of the panelized specimen. Under the same level of positive/negative pressure, tie forces of the panelized specimen were generally much

Table 2 Comparison of performance of conventional and panelized specimens

	3.00 kN/m^2			6.00 kN/m^2		
	Conventional	Panelized	Ratio	Conventional	Panelized	Ratio
BV Deflection (mm)	2.41	0.660	3.65	7.98	1.35	5.91
SS Deflection (mm)	1.75	0.483	3.62	4.24	1.85	2.29
Difference in Deflection	0.66	0.178	3.71	3.73	-0.508	7.34
Ratio of Difference over BV Deflection	0.274	0.270	1.02	0.467	0.377	1.25
Cracking of the Specimen	Conventional specimen cracked/failed at 6.00 kN/m^2. No cracking or damage of the panelized specimen was observed.					
Water Leakage	Water leakage collected in the conventional specimen after cracking. No measurable water leakage for the panelized specimen.					

smaller than that of the conventional specimen although the ratio vary, which also indicates that the panelized specimen showed more composite behavior. Because the differential deflection between the BV and steel backup frame in the panelized specimen was smaller, deformation was also smaller.

It should be noted that the improvement of performance of the PBVSS over the conventional specimen as respect to the capacity, deflection, and composite action is due to the combined action of stiffer vertical steel members used, the improved boundary condition due to the steel frame backup, and the stiffer masonry connectors used among other factors. As mentioned earlier, at this stage no attempt was made experimentally to isolate the effects of these three valuables. However, extensive parametric study was performed using the finite element analysis (Liang 2006). Based on the analysis results (not presented here), both steel backup stiffness and boundary condition can have significant effects on the performance, while connector stiffness has relative less effect. The relative contributions of the valuables are interdependent and vary in different cases. For example, the stiffer backup and the boundary condition each contributes 24% to 48% of the decrease in deflection, while stiffer connectors contributes 6% to 22%.

7. Conclusions

The conventional and panelized BV with SS backup wall specimens were tested for both cyclic wind loading and water leakage (before and after wind tests). Based on the test results, the panelized specimen has shown to have a much higher stiffness than the conventional one. The deflection of the center point of the BV in the conventional specimen was about six times that of the panelized one, while the deflection of the center point of the steel backup in the conventional specimen was about four times that of the panelized specimen. The smaller deflection of the panelized wall indicates that the possibility of cracking of the BV under wind loading can be reduced, and damage to the joints between panels due to differential movement can be avoided.

Due to several parameters discussed the composite behavior of the panelized specimen was improved over the conventional system. The deflection difference between the BV and steel backup in the conventional specimen was more than seven times that of the panelized one. The improved composite behavior can make the system work as a whole and help prevent flexural cracking of the brick veneer. The conventional specimen cracked under a negative pressure of 6.00 kN/m^2. Some fasteners attaching the ties to the steel stud backup system were also pulled out. Water leakage was also measured during the water test afterwards. Therefore, this wall specimen demonstrated both serviceability damage and safety related damage at that stage of loading. The panelized specimen was loaded up to the positive pressure of 8.62 kN/m^2 and the negative pressure of 6.00 kN/m^2 when the capacity of the facility was reached. The specimen did not crack.

Due to lack of full restraint on the sides of the specimens, the tests were not able to fully realize the two-way bending of the wall panel. Therefore, more tests with better side restraints may be necessary to test this potential important advantage. Also, in order to establish the guideline of panel design to achieve different performance levels, more tests with various configurations of steel frame backup and tie patterns may be necessary to verify the results of parametric study using finite element analysis. Finally, testing panels with joints will also help to understand the performance of the proposed PBVSS system for practical applications.

In conclusion, the panelized specimen showed much higher stiffness, better composite behavior and sustained higher pressure without cracking. Therefore, compared to the conventional BV/SS system, the proposed design of the PBVSS system improved both the serviceability performance of BV with steel backup wall system under moderate wind and the capacity of the wall system under strong wind. This study has shown that the proposed wall system has merits detailed study for cost optimization and commercialization for practical applications.

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