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Performance Evaluation of Different Masonry Infill Walls with Structural Fuse Elements

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ABSTRACT-Masonry infill walls in multi-story buildings are intended to function as envelope and partition walls, and without sufficient gaps between the infill and the frame, the infill tends to contribute to lateral seismic load resistance, which can lead to damage. Presented herein is a seismic design approach developed for a proposed infill wall "structural fuse" system for use in building frames. The purpose of this system is to prevent damage to frame or infill walls due to infill wall-frame interaction during potentially damaging earthquakes by isolating them through a "sacrificial" component or a structural fuse.This paper discusses the performance of a structural fuse concept developed for use as a seismic isolation system in the design and retrofit of masonry infill walls. An experimental program was developed and executed to study the behavior of the structural fuse system under cyclic loads, and to evaluate the performance of the system with various masonry materials. Cyclic tests were performed by applying displacement controlled loads at the first, second, and third stories of a two-bay, three-story steel test frame with brick infill walls; using a quasi-static loading protocol to create a first mode response in the structural system. In this chapter, initially, a review of the literature on seismic performance of masonry infill walls is presented. This is then followed by explanation of the concept of the masonry infill structural fuse.

KEYWORDS-Masonry Infill Wall, Structural Fuse, Muiti-storey Building

I. INTRODUCTION

Masonry bearing wall systems were the predominant structural systems prior to the use of framed structures. Once steel and concrete framing systems replaced bearing wall systems, especially for multistory buildings, masonry walls were then used as infill walls to provide the envelope and partition wall functions. Besides such functions, the role of masonry infill walls in seismic resistance of buildings has long been well recognized. In fact, because of participation of masonry infill walls in resisting lateral seismic loads, infill walls and/or their framing systems can sustain damage with life-safety hazard potential.

Traditionally, masonry infill walls are specified by architects as exterior envelope walls, backup walls for veneer systems, or interior partition walls. Such construction does not carry gravity load from floors and only carries its own weight. Depending on the details of joints between the edges of infill walls and infilled frames, the interaction between the infill wall and frame can adversely affect the seismic behavior of the structure. In most cases, the small gaps between the infill wall and the structural frame are infilled with caulking and in some cases with mortar . This tight-fit construction engages the infill wall in in-plane lateral load resistance . Depending on whether the wall is solid (complete infill) or the existence of large openings that make the infill wall partial infill, the wall's interaction with confining frames could possibly lead to premature column failure as a result of short column effect or to increased levels of ductility demand in columns. Furthermore, because these tight-fit infill walls essentially behave as shear walls, their distribution in plan could increase torsional moments and create structural irregularities, if not placed symmetrically. The manner infill walls resist lateral loads is much like a compression brace, and the cyclic interaction of this effective brace with structural frame connection may lead to either the failure in the masonry and/or damage to the beam-column connection. Tight-fit construction of infill walls, whether of partial height or full height can lead to extensive damage to walls, columns, or beam-column joints. Besides the life-safety hazard that such damage will pose,

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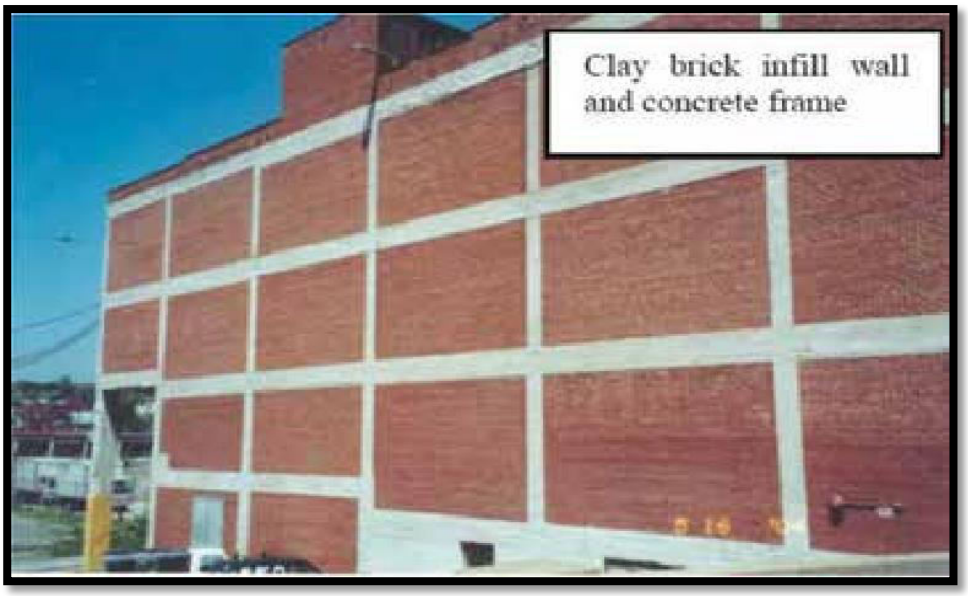
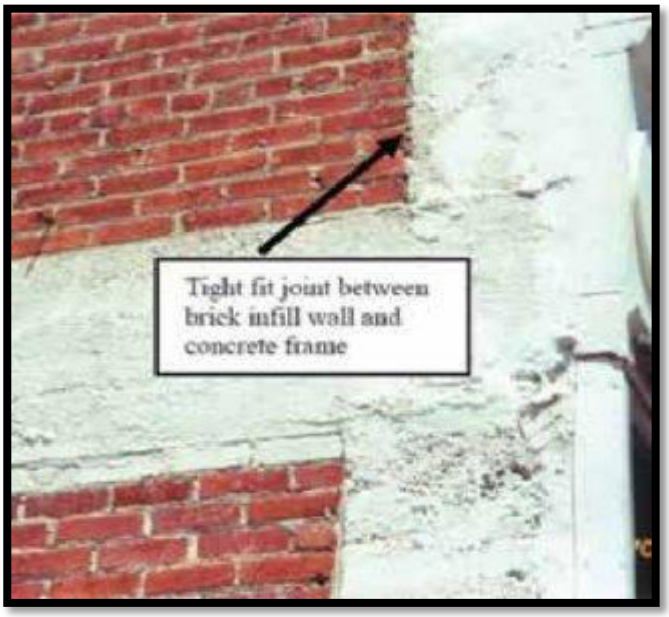
in terms of financial loss, infill wall damage and subsequent repair/replacement work can seriously challenge building owners and tenants.

By isolating the infill wall from the frame and avoiding their interaction in buildings with moment-resisting frames as their primary lateral force-resisting system, damages to infilled frames, failure of infill walls, and potential life-safety hazards can be avoided. However, in that case, the building is deprived of the potential benefit from the strength and stiffness that masonry infill walls can offer even if they are not designed as shear walls. It should be noted that even unreinforced masonry walls inherently possess considerable stiffness that can be properly and advantageously employed in lateral force resistance.



(Fig.1 :Examples of masonry infill wall in a reinforced concrete frame building)



(Fig.2 : Example of a tight-fit masonry infill wall construction)

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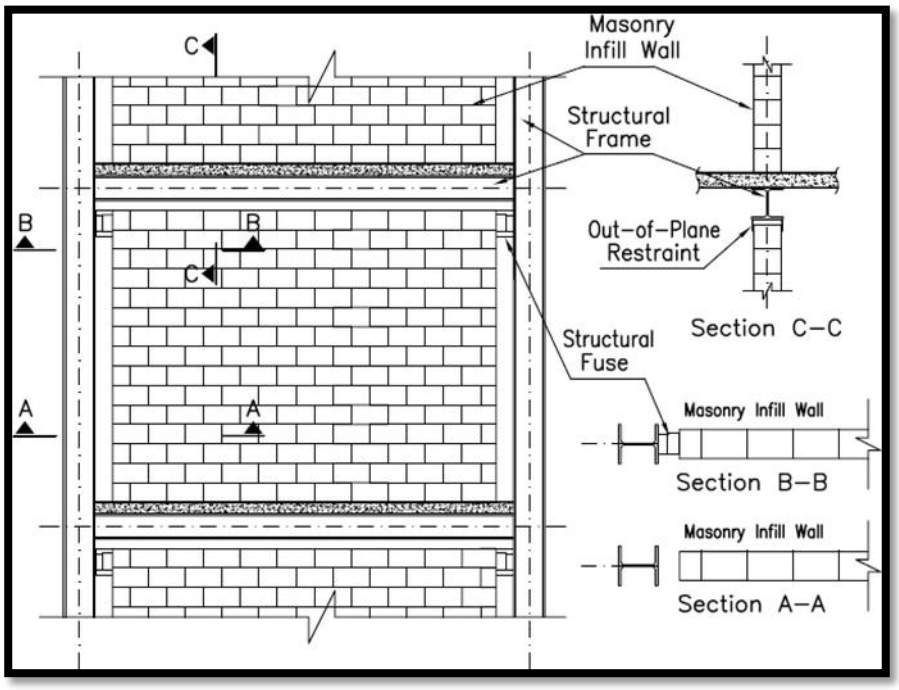

(Fig.3 : Schematic representation of fuse elements in a masonry infill wall)

(Fig.4 : RC Frame building shell with infill masonry wall)

The structural properties of masonry infill walls are often overlooked by designers who do not consider the increase in stiffness and potential decrease in ductility introduced into structural frames by the addition of unreinforced masonry infill materials. Typically, concrete and steel building frames are designed to resist all of the gravity and lateral loads,

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including wind and seismic forces. Infill walls are often treated as nonstructural elements even though they have a significant influence on the in-plane behavior and seismic performance of the structure.

Ignoring the contribution of masonry infill walls to the strength and stiffness of building frames can lead to damage in the masonry walls as well as resulting in an inefficient use of materials and uneconomical design [21]. According to Colombo et al. [22], neglecting the effects of the infill panels, as suggested by various building codes, does not lead to a safe seismic design. The assumption that masonry infill walls in concrete and steel frames will only increase the lateral load capacity of these structures is a common misconception [23]. This oversight can result in severe structural damage and collapse in buildings where the ability of the frame to safely dissipate seismic input energy has been significantly overestimated. Overstressing of the masonry walls and the formation of a collapse mechanism in the structural frame can occur if the composite interaction between masonry infill walls and bounding frames is not accounted for during design.

Two common design philosophies have been developed which consider the influence of infill walls on the response of structural frames to lateral loads [24]. One approach is to isolate the masonry infill walls from the bounding frame with a physical gap [25]. This allows the frame to act independently of the masonry walls and to be designed without consideration of the interaction between the frame elements and the infill panels. Isolating the infill panels from the frame can prevent severe cracking and damage to the masonry materials. This is an important consideration since falling debris from damaged and collapsed infill walls is a major life safety issue for buildings in seismic areas. By isolating the infill walls from the concrete or steel frame, the structure can dissipate the seismic input energy in a predictable and safe manner.

II. SEISMIC STRUCTURAL FUSE CONCEPT

The fuse element is the key component of the structural fuse system. The purpose of the fuse is to serve as a link between the structural frame and the masonry infill walls and prevent damage to the infill material. An extensive analytical and experimental study has been carried out on fuse materials and systems . Under typical loading conditions, the fuse mechanism transfers the story shear forces from the structural frame to the masonry infill panels, which help to resist the in-plane lateral loads and limit frame deflections. If the story shear forces are sufficiently high to cause inelastic behavior in the masonry panels, the fuse element is designed to “break” and disengage the infill wall from the frame before damage occurs to the masonry material.

The fuse concept proposed consists of mounting structural fuse elements between infill walls and columns. Conceptually, the fuse elements can be placed in the vertical components of a subframe system consisting of sandwiched light-gage steel studs. Within the subframe member at top of the wall, which will not have fuse elements, and in open spaces of the subframe vertical elements, there can be an appropriate flexible filler material for sound insulation and fire-resistance. The infill wall then is to be constructed within the subframe just like a usual masonry wall. The lateral stability of the infill wall will be ensured by out-of-plane restrainers such as brackets and guides usually at top. The location of fuse elements shown near the top of the masonry wall panel is chosen because the frame will first contact the infill wall at that point and will tend to close the gap if there were no fuse elements. To provide flexural stability and eliminate flexural failure of masonry wall in fuse-equipped system, vertical components of the subframe (in the initial concept of using subframe) attached at each end of the wall panel act as a tie-down element. Other equivalent tie-down concepts can be used if such subframe is not to be employed. In case a subframe is not to be used, the fuse element can be fitted within a small space on the wall edge by using a partial masonry unit or leaving one unit out. It is envisioned that the fuse element used in this fashion will be enclosed and protected against environmental effects, e.g., moisture and thus the deterioration will be minimized. Nonetheless, in case of any kind of damage due to material breakdown after long time or due to breakage under interaction loads, i.e., performing its fuse function, the detail to be developed should allow replacement of the fuse element.

The fuse-equipped system is designed such that under small to moderate levels of structural frame in-plane interface force (low to moderate seismic event or wind), the fuse will act as a rigid link and transfers the force to the infill wall for the benefit of its stiffness in reducing drift. Such reduction in drift can prevent damage to nonstructural components such as glazing, plaster, drywall, veneers, and ornamental components attached to the building façade. At larger levels of in-plane force (moderate to high seismic event), the fuse elements will likely crush (break) after its capacity is overcome by the frame-wall interaction force and allow the structural frame to displace without

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transferring force to the infill wall. Depending on the stiffness and strength of the masonry wall and the level of confidence in the wall material, its strength, and the desired safety factor, the capacity of fuse element can be customized and different grades can be de signed and specified. The upper bound capacity of the fuse element needs to be lower than the lower bound strength of the masonry wall. Consideration needs to be given weather the designer is willing to accept some masonry wall damage or desires little or no damage. The fuse system can be used with different configurations of masonry infill walls including walls with or without openings, partial-height or fullheight infills, and infills with different types of masonry units ranging from higher strength concrete masonry blocks and clay brick units to lower strength masonry such as thin wall hollow clay tile units and autoclaved aerated concrete (AAC) blocks.

The early concept of the fuse element intended to make a rigid-like connection between the infill wall and the frame to engage the infill wall in in-plane load resistance up to a certain load level. Accordingly, once this load limit is exceeded, the fuse element will crush and result in full or partial disengagement of the infill wall from interaction with the frame. The capacity of the fuse element is designed to be a percentage of the cracking load of the infill wall, with the percentage reflecting the desirable safety margin. The fuse element discussed in this study is that of the initial concept and has no tension resistance capacity. There could be various design alternatives for fuse element. For example, the fuse element can include a spring component of desirable stiffness to control in-plane movements after the crushing of the fuse element. Furthermore, a dashpot mechanism can be added to the element to enhance seismic performance of a structure by increasing its energy dissipation capacity.

Depending on the type and material of fuse element, its material deterioration and possible impact on long term performance and capacity of the fuse system need to be considered and evaluated. If common structural materials such as concrete, steel, wood and some types of epoxies are used, it is expected that the fuse element maintains its capacity and performance during the life of fuse system, considering the fact that the element will be located inside subframe or upper corner block and further more protection against weather and water can be provided by wall covers, if any, such as gypsum boards or other architectural elements. However, if for any reason (e.g., the nature of the material used) the capacity of fuse elements deteriorates by time, this will not create life safety problems or concerns. The whole concept of fuse system is to disengage the infill wall from structural frame under certain threshold load level, after which the structural frame will provide serviceability and strength requirements as per structural codes and standards. The fuse elements can be investigated after any major event and if needed they can be replaced through accesses in subframe. Depending on the material, it might be appropriate to specify a life limit for fuse elements as well, after which they all need to be replaced. In case the fuse loses strength for reasons such as rot, material useful life, or any other factor not considered in detail, the fuse simply breaks at a smaller load and leads to elongation of the natural vibration period of the entire system, but it should not affect the structural strength after fuse breakage.

III. PROPOSED METHODOLOGY

This paper discusses the details of the follow-up testing program [29]. In the test program discussed here, two series of tests were performed in the Building Components and Envelopes Research Laboratory (BCERL) at the Pennsylvania State University, on the same test frame used by Aliaari [19]. For the first test series, quasi-static, cyclic in-plane loads were applied to the test frame with brick infill wall panels in place. In the second series of tests, a parametric study was completed by replacing the brick infill panels with infill walls constructed of concrete masonry units (CMU) and autoclaved aerated concrete blocks (AAC). For these tests, displacement-controlled monotonic loads were applied in only one direction to match the loading protocol used by Aliaari [19]. Both series of tests were performed on the 1/4 scale, two-bay, three-story steel test frame shown in Figures 1 and 2, respectively. The test frame shown in Figure 1 consists of HSS 127 mm × 127 mm × 9.5 mm (5 × 5 × 3/8 in.) hollow structural steel members pin connected using 38.1 mm diameter steel bars to allow for adequate floor movements during racking and to enable the study of the system in a braced (stiff) and partially braced (flexible) configuration. The masonry infill wall specimens were supported by the bottom beam of each bay of the test frame with a 152.5 mm gap between the sides of the walls and the HSS columns, and a gap of between 38.1 mm and 60.3 mm between the top of the walls and the upper beam. Steel angles were welded to the top of the support beams on either side of the infill panels to prevent the base of the walls from sliding in the in-plane direction. Out-of-plane movement at the bottom of the infill panels was prevented by steel angles welded to the sides of the HSS beams. In order to prevent overturning

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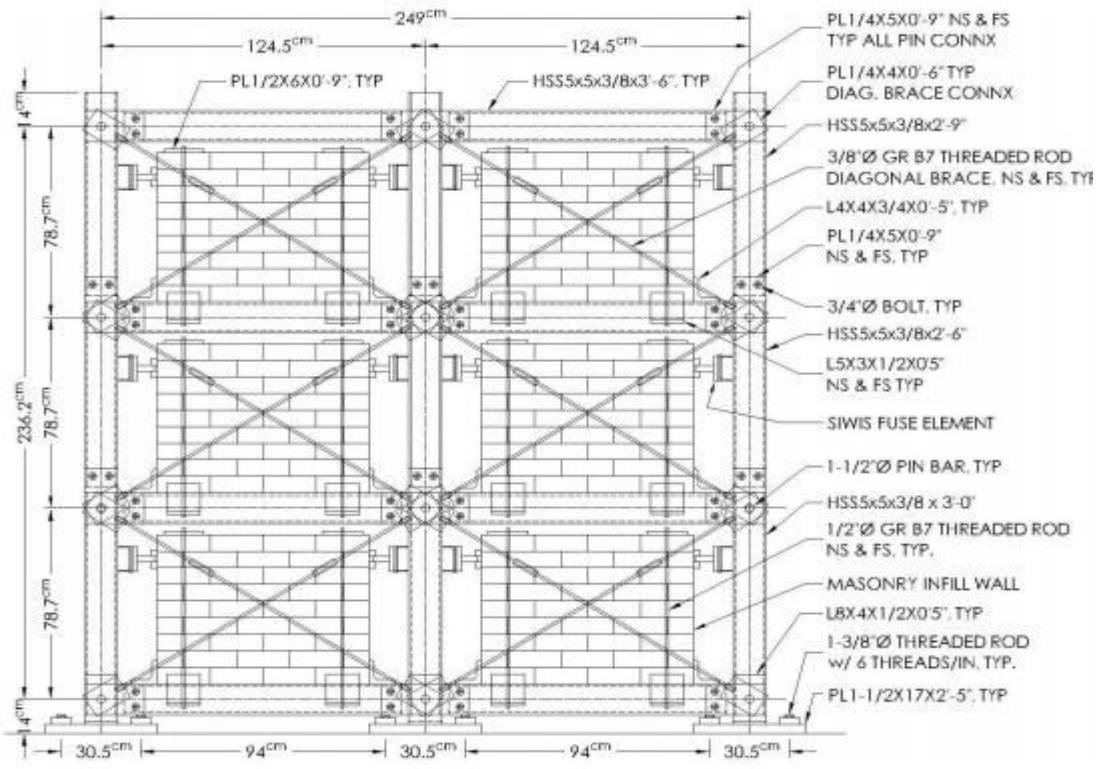
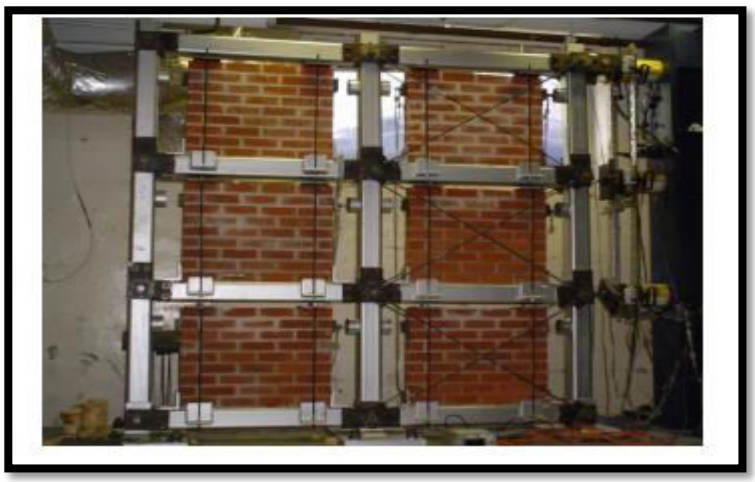
of the infill panels, steel plates were secured to the top of the walls using 12.7 mm diameter threaded rods bolted to the outstanding legs of these angles.



(Figure 1. 1/4 scale, two-bay, three-story steel test frame.)



(Figure 2. Concrete test platform and steel reaction frame.)

In-plane, lateral stability of the test frame was provided by diagonal steel bracing rods. In the fully braced configuration, a total of four diagonal braces were used in each bay, with two bracing rods on each side of the infill panels. For the half-brace configuration, bracing rods were used in only one bay of each story. The diagonal bracing system was designed so that in the fully braced configuration, the pin-jointed steel frame had the same in-plane stiffness as an equivalent steel frame with moment resisting connections. Each diagonal brace member consisted of two 9.5 mm diameter, Grade B7, threaded rods with opposite hand threads joined together using a special coupling nut with right-hand threads in one side and left-hand threads in

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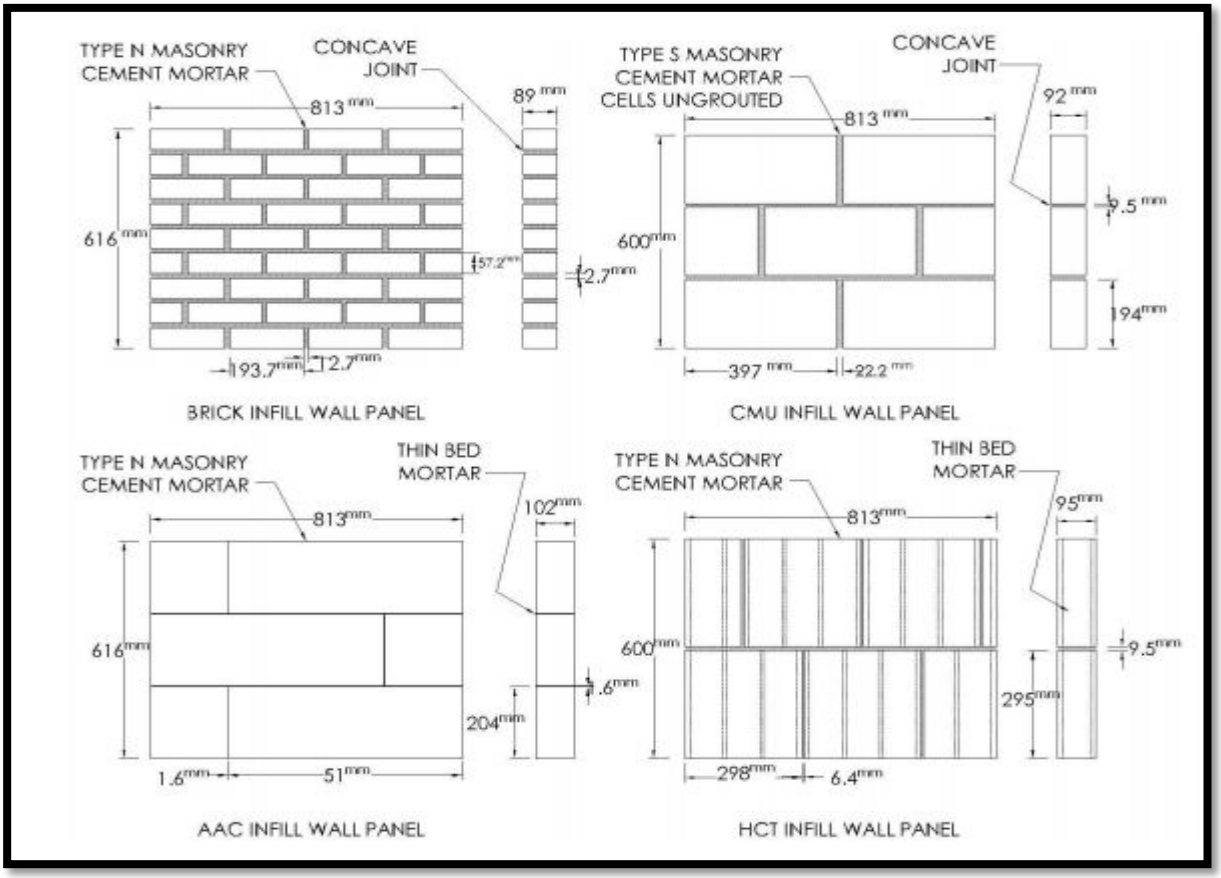
the other. The bracing rods were attached to the test frame using steel connection plates that fit over the 38.1 mm diameter steel pin bars. The rods were attached to the connection plates using welded coupling nuts.

The masonry infill walls used in the cyclic and parametric tests were constructed in the BCERL test facility by professional masons. Destructive shear tests were performed to determine the in-plane shear strength of each type of masonry wall panel. The brick, CMU, AAC, and hollow clay tile (HCT) infill wall specimens used for this testing program are shown in Figure 3. The brick wall panels were used for the cyclic tests, while the CMU and AAC specimens were used for the parametric study. The HCT infill wall specimens were included in the destructive shear tests, but not used in the structural fuse system tests due to their low in-plane shear capacity. The set-up for the destructive shear tests is shown in Figure 4. The results of these tests are given in Table 1.

During the structural fuse system tests, lateral loads were applied to the test frame at each story level using hydraulic cylinders attached to the steel reaction frame shown in Figure 2. The in-plane lateral loads were transferred from the steel test frame to the masonry infill walls through the fuse mechanism shown in Figure 5. As shown in this figure, the 100 mm diameter, lumber disk fuse elements were held in place by a steel seat disk and pipe assembly welded to the HSS columns near the top of the infill panels. The fuse punching mechanism consisted of a 22.4 mm diameter, half-threaded steel rod attached to a steel bearing plate which was epoxied to the infill panels. The lumber disk fuse elements used in the cyclic and parametric testing programs were cut from hard maple boards. Lumber disk puncture tests were performed to evaluate the strength of the fuse elements and determine the appropriate disk thickness to use with each type of masonry infill material [29]. The results of the initial series of lumber disk puncture tests performed as part of this testing program are provided in Table 2. The structural fuse test presented here builds on the results obtained from tests presented in an earlier study [28] where different materials including concrete and wood disks were tested. The study also provided loaddisplacement diagrams for typical fuse elements and indicated that wood disks have better deformation capacity and provide desirable ductility for the infill wall system with fuse elements. Calibration issues related to the fuse elements as needed for the test programs may be found in the documents developed by Aliaari [19] and Kauffman [29].



(Figure 3.Masonry infill wall specimens.)

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(Figure 4. In-plane, destructive shear test set-up.)

Table 1. Masonry wall panel shear tests results.

Wall Specimen	Masonry Material	Peak Capacity	Average	Standard Deviation	Coefficient of Variation	Stiffness	Average	Standard Deviation	Coefficient of Variation
		kN	kN	kN	CV%	kN/mm	kN/mm	kN/mm	CV%
W1	AAC	61.47	56.8	6.2	11.3	5.62	7.0	1.5	21.3
W2	AAC	52.09				6.37			
W3	AAC	61.16				8.27			
W4	AAC	52.44				7.76			
W5	CMU	114.50	97.7	20.0	20.5	13.38	15.5	2.3	14.7
W6	CMU	108.49				16.41			
W7	CMU	87.36				17.64			
W8	CMU	80.51				14.73			
W9	HCT	9.70	18.6	6.2	78.4	1.66	3.7	1.5	80.5
W10	HCT	27.49				5.66			

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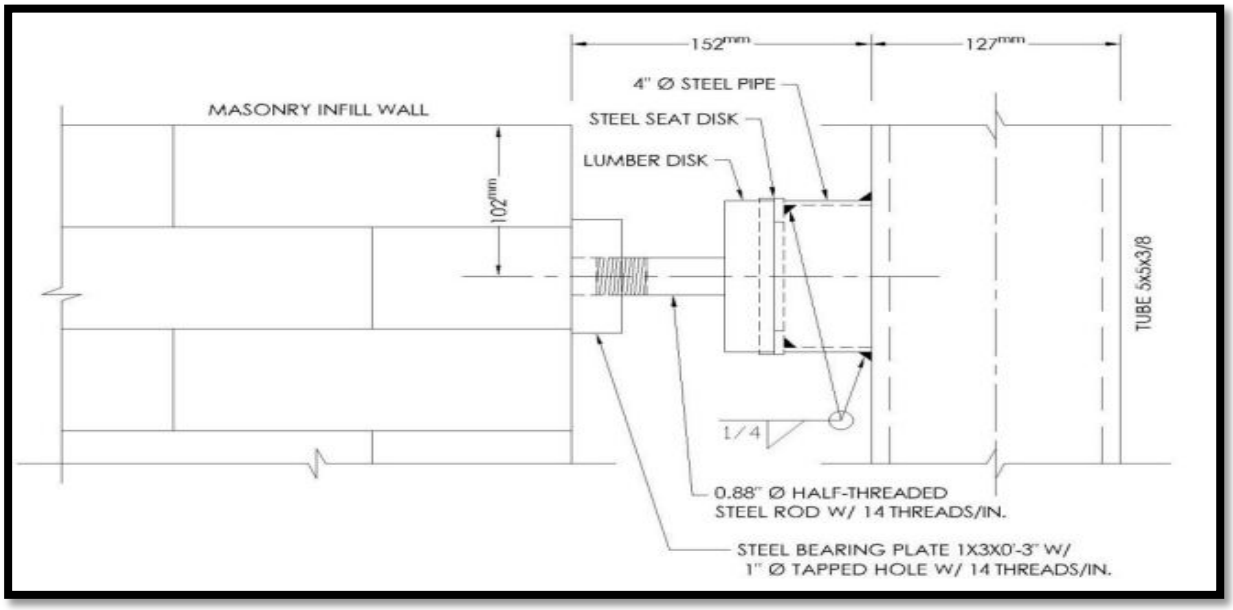

(Figure 5. Fuse mechanism detail.)

For the cyclic testing program, quasi-static, displacement-controlled loads were applied simultaneously at the first, second and third story levels using three hydraulic jacks. Two different bracing configurations were tested, including full-brace and half-brace, in order to observe the performance of the structural fuse system for frames with different in-plane stiffness properties. The fuse element thicknesses were also varied. For some of the tests, the same fuse element thickness was used at each story level. For other tests, a different fuse element thickness was used at each story level. A test matrix of the cyclic testing program is given in Table 3. As the table indicates, the test specimen included bare frame, full brace, and half brace configurations. Diagrams of each test configuration are shown in Figure 6. Figure 7 shows the location of the fuse elements on the steel test frame during the cyclic tests. The data collected during the cyclic tests included the load applied to the test frame by the hydraulic cylinders, the in-plane deflection of the test frame at each story level, and the shear forces transferred from the test frame to the brick infill walls through the structural fuse elements.

Table 2. Lumber disk puncture test results.

Disk Specification	Thickness	Weight	Volume	Density	Average	Standard Deviation	Coefficient of Variation	Capacity	Average	Standard Deviation	Coefficient of Variation
	mm	gr	cm^3	gr/cm^3	gr/cm^3	gr/cm^3	CV%	kN	kN	kN	CV%
D1	12.9	74.9	100.9	0.74				8.47			
D2	12.9	74.0	100.9	0.73	0.72	0.0249	3.3	11.21	10.66	1.97	18.5
D3	12.9	70.4	100.9	0.70				12.29			
D4	19.1	106.7	149.1	0.72				18.72			
D5	19.3	108.5	151.1	0.72	0.71	0.0111	1.7	19.16	19.11	0.37	1.9
D6	19.3	105.1	151.1	0.70				19.46			
D7	25.4	139.4	197.9	0.70				22.46			
D8	25.6	142.3	199.8	0.71	0.70	0.00830	1.2	19.94	21.99	1.87	8.5
D9	25.4	137.6	197.8	0.70				23.59			
D10	38.3	243.1	301.7	0.81				38.31			
D11	38.1	236.1	298.2	0.79	0.77	0.0498	6.4	35.53	37.05	1.41	3.8
D12	38.1	215.2	301.2	0.71				37.32			

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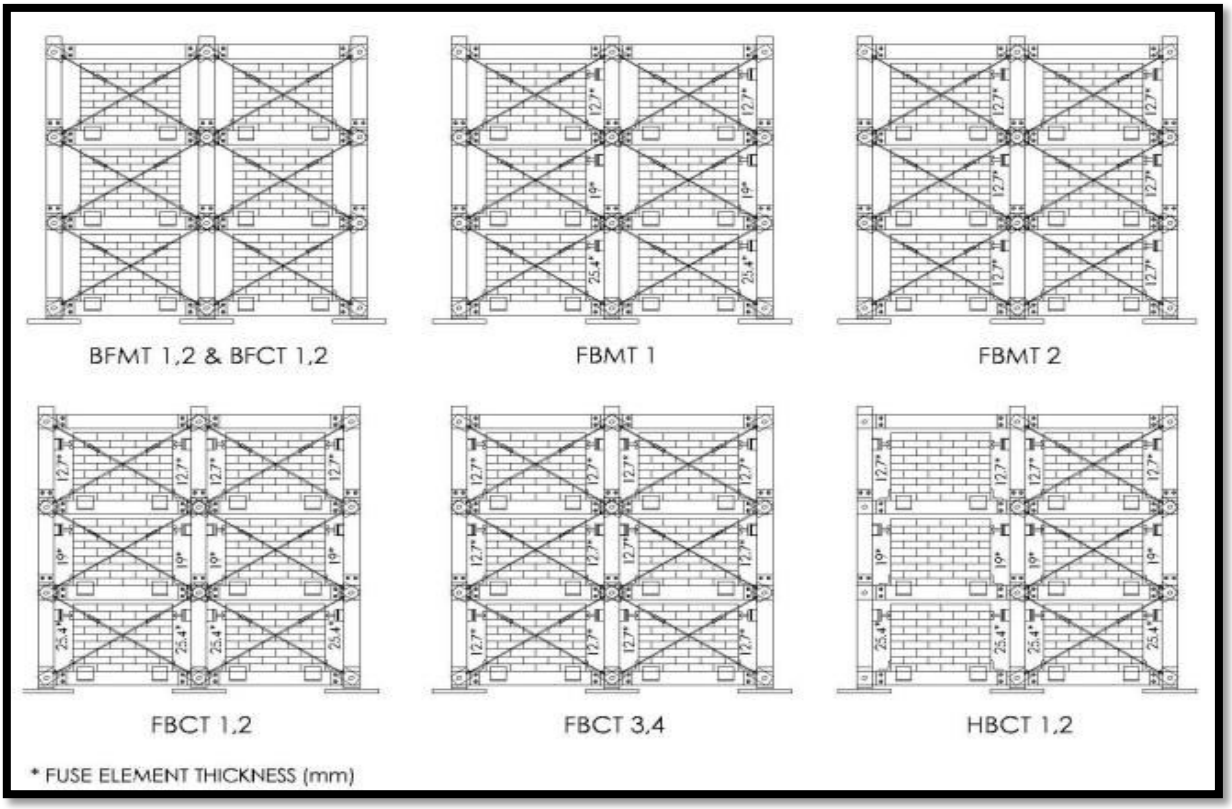
Table 3.Cyclic testing program test matrix.

Test	Type	Description	Fuse Element Thickness (mm)		
			1st Story	2nd Story	3rd Story
BFMT1	Bare Frame Monotonic Test	Fully braced, no fuse elements	NA	NA	NA
BFMT2	Bare Frame Monotonic Test	Fully braced, no fuse elements	NA	NA	NA
FBMT1	Full Brace Monotonic Test	Fully braced, with fuse elements	25.4	19.1	12.7
FBMT2	Full Brace Monotonic Test	Fully braced, with fuse elements	0.5	12.7	12.7
BFCT1	Bare Frame Cyclic Test	Fully braced, no fuse elements	NA	NA	NA
BFCT2	Bare Frame Cyclic Test	Fully braced, no fuse elements	NA	NA	NA
FBCT1	Full Brace Cyclic Test	Fully braced, with fuse elements	25.4	19.1	12.7
FBCT2	Full Brace Cyclic Test	Fully braced, with fuse elements	25.4	19.0	12.7
FBCT3	Full Brace Cyclic Test	Fully braced, with fuse elements	12.7	12.7	12.7
FBCT4	Full Brace Cyclic Test	Fully braced, with fuse elements	12.7	12.7	12.7
HBCT1	Half Brace Cyclic Test	Half braced, with fuse elements	25.4	19.1	12.7
HBCT2	Half Brace Cyclic Test	Half braced, with fuse elements	25.4	19.1	12.7



(Figure 6.Test frame configurations for cyclic test program.)

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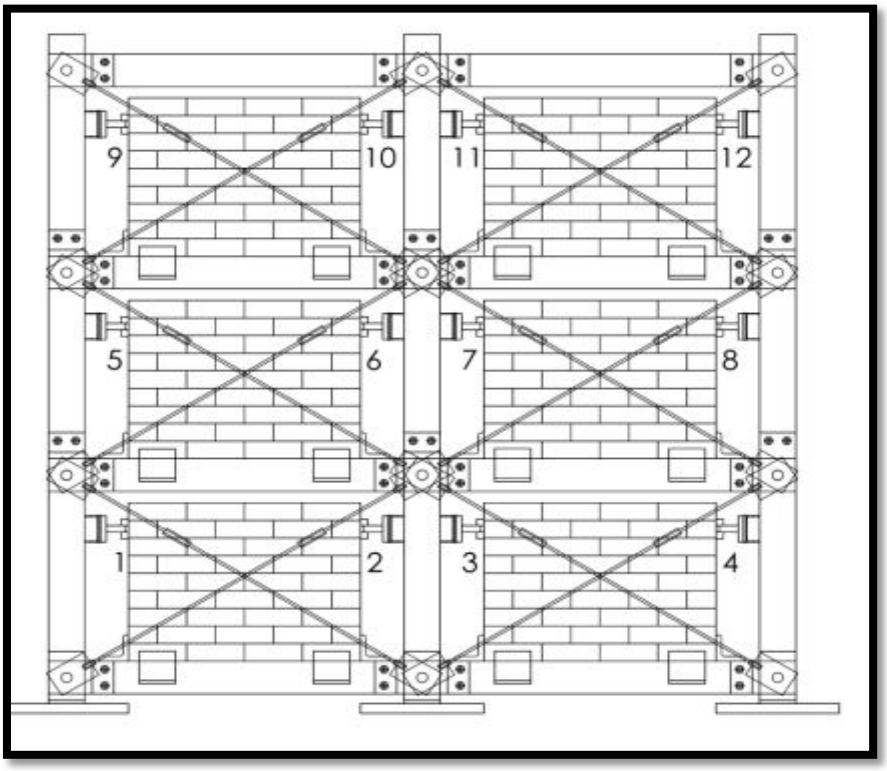

(Figure 7. Fuse element locations on test frame)

For the parametric tests, monotonic loads were applied at the third story of the test frame using one hydraulic cylinder. As with the cyclic tests, varying fuse element thicknesses and bracing configurations were tested. A test matrix for the parametric test series is given in Table 4. Figure 8 shows typical elevations of the fully braced and half braced specimens. The data collected during these tests included the load applied at the third story level of the test frame by the hydraulic cylinder, and the in-plane deflection of the test frame at each story level.

Table 4.Parametric testing program test matrix.

Test	Masonry Material	Description	Fuse Element Thickness (mm)		
			First Story	Second Story	Third Story
CMUT1	CMU	Fully braced, with fuse elements	22.2	19.1	12.7
CMUT2	CMU	Fully braced, with fuse elements	22.2	19.1	12.7
CMUT3	CMU	Fully braced, with fuse elements	12.7	12.7	12.7
CMUT4	CMU	Fully braced, with fuse elements	12.7	12.7	12.7
CMUT5	CMU	Half braced, with fuse elements	22.2	19.1	12.7
CMUT6	CMU	Half braced, with fuse elements	22.2	19.1	12.7
AACT1	AAC	Fully braced, with fuse elements	19.1	12.7	6.4
AACT2	AAC	Fully braced, with fuse elements	19.1	12.7	6.4
AACT3	AAC	Fully braced, with fuse elements	6.4	6.4	6.4
AACT4	AAC	Fully braced, with fuse elements	6.4	6.4	6.4
AACT5	AAC	Half braced, with fuse elements	19.1	12.7	6.4
AACT6	AAC	Half braced, with fuse elements	19.1	12.7	6.4

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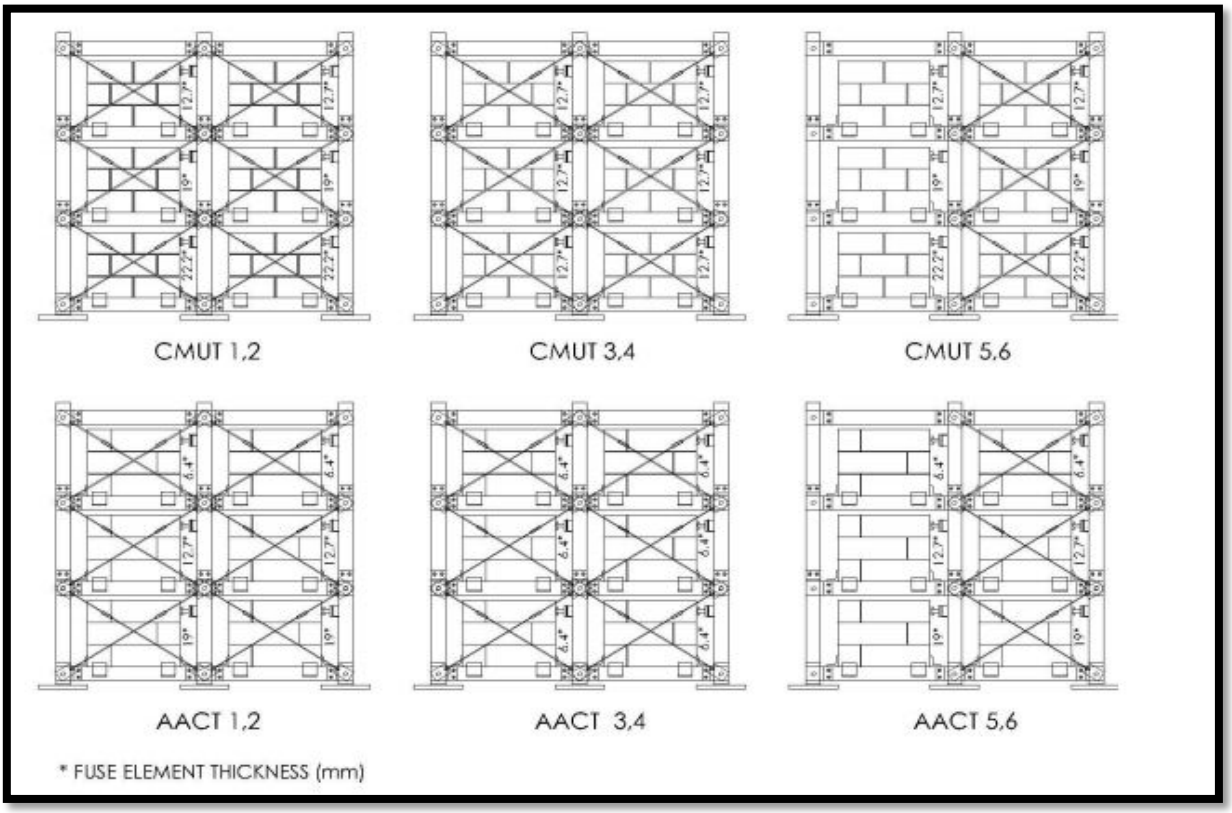

(Figure 8.Test frame configurations for parametric testing program.)

IV. CONCLUSION

A new concept in the performance and design of masonry infill walls is the idea of a structural fuse system. This seismic isolation system allows for composite interaction between infill walls and the structural frame under normal lateral loads. Brittle failure of the infill walls or frame elements is prevented by the introduction of a fuse mechanism which isolates the infill material from the frame under higher loads. Simultaneous, displacement controlled loads were applied at the first, second, and third stories of the test frame to create a first mode response in the structural system; seismic loading conditions were simulated using quasi-static, cyclic loading; a parametric study of the fuse system under static monotonic loads was performed with concrete masonry units (CMU) and autoclaved aerated concrete (AAC blocks); the performance of the lumber disk fuse elements as a viable option for use in a fuse mechanism seismic isolation system was evaluated; and the shear and compressive strength of the masonry materials used in the parametric study were evaluated.

The quasi-static load protocol used is a good approach for use in cyclic load testing of masonry infill wall systems.

- The inverted triangle, first mode deflection shape used to distribute in-plane loads to the test frame is a reasonable approach for applying displacement controlled loads to multi-story frames to simulate seismic loading.
- The quasi-static load protocol used in this testing program resulted in more realistic seismic load behavior than the previously used monotonic protocol.
- The structural fuse system allows the masonry infill walls to contribute to the in-plane stiffness of the test frame at lower levels of lateral load, but prevents damage to the masonry walls by isolating the infill panels from the test frame as the lateral loads increased.

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