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OUT-OF-PLANE SHAKE TABLE TESTING OF RETROFITTED URM PARTITION WALLS

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ABSTRACT: A significant effort has been made towards seismic retrofitting of public school buildings in BC. In many of these schools, there is a significant quantity of unreinforced masonry partition walls. A shake-table testing program has been undertaken to determine economical and effective retrofit methods, to restrain the walls at their top, and to strengthen the walls along their height. The test specimens are 1.6m wide and 2.8m high using 90mm blocks. The concept for top of restraint utilizes steel angles attached to the structure above. Several retrofits were tested included vertically grouted deformed bars, use of U-channel attached vertically with masonry screws, and attachment of the walls to a horizontal beam. The walls were tested using an earthquake selected from the suite of design records used in the retrofit program, and scaled according to the Vancouver Uniform Hazard Spectrum. The test program featured application of the test records in sequence, with each run increasing the amplitude until failure. Additionally three bare walls were tested as a baseline. Most of the retrofits performed well, surviving up to the design level earthquake. The U-channel retrofitted specimen performed the best, surviving up to 150% of the design level.

1. Introduction

A shake-table testing program has been undertaken to evaluate a series of retrofit methods for URM partition walls in the out-of-plane direction. The retrofits explored methods to restrain the walls at their top, and for strengthening the walls along their height. The tested specimens were 1.6m wide and 2.8m high, using 90mm concrete blocks. The concept for top of wall restraint utilizes steel angles attached to the structure above. Several retrofits were tested included vertically grouted deformed bars, use of U-channel attached vertically with masonry screws, and attachment of the walls to a horizontal beam. The walls were tested using an earthquake selected from the suite of design records used in the retrofit program, and scaled according to the Vancouver Uniform Hazard Spectrum. The test program featured application of the test records in sequence, with each run increasing the amplitude until failure. Additionally three bare walls were tested as a baseline. Most of the retrofits performed well, surviving up to the design level earthquake. The U-channel retrofitted specimen performed the best, surviving up to 150% of the design level. This paper provides a summary of the test program, including the design of the retrofit specimens, test setup and results for selected tests.

2. Background

In order to create a standardized basis of retrofit for all public schools, the Ministry of Education of British Columbia has partnered with UBC and APEGBC to create the Seismic Retrofit Guidelines (SRG, 2014) which are used by design engineers. They are performance-based guidelines that utilizes a system of Lateral Deformation Resisting System (LDRS) prototypes that allow the designer to achieve the desired performance in terms of drift exceedence for that particular LDRS. The technical development for the prototypes was done by UBC, with a significant effort made in a laboratory testing program (SRG Manual 6, 2014). The primary tests done for the first two versions of the SRG were monotonic and cyclic tests. These allowed for creation of backbone curves that defines the performance of each prototype that are used for design. The next set of tests, which will lead to the third version of SRG, includes dynamic tests performed on the shake tables at UBC. The static tests done have been on wood, masonry and concrete walls, both in and out of plane.

The first set of dynamic tests were performed on unreinforced masonry walls. A large amount of these walls are found in many schools, made of 4" (90mm) concrete block; they are generally built flat on the ground up to the underside of the floor above without being connected. For the engineers, there is a desire to find straightforward, economical and effective retrofit methods, in order to deal with the large amount of these walls in the schools. A preliminary set of retrofit concepts was suggested by the SRG Technical Review Board (TRB), which included concepts with a consideration of their practical implementation. The various retrofit concepts were proposed to be implemented on partial width wall specimens tested out-of-plane on the shake-table, subjected to earthquakes chosen from the suite available in SRG2.

The proposed test specimens included walls made from 90mm concrete masonry blocks, 2.4 and 2.8m high, by 3.0m wide. The retrofits included using a horizontal beam attached to the wall with masonry screws, using U-channel attached to the wall and to the floor above and below; and with a vertically cored retrofit that proposed to insert wire in two cut holes near the top and bottom of the wall. Mud would then be poured into the top hole for bonding with the wire. Modifications of this test program were made in consideration of practically mounting to the shake table and also depending on the installation of the retrofits.

The test program development considered previous testing on out-of-plane masonry walls. Previous tests had been done at UBC, examining the effect of diaphragm stability on the out-of-plane behaviour of URM (Penner and Elwood, 2012). The test setup featured a flexible base and top attachment for the wall, which allowed for adjustment of the simulated diaphragm stiffness. This setup uses the inertial of the walls for the seismic loads. Another test by Al Shawa et al. (2001) tested a set of walls, one out-of-plane with two in-plane flanking walls for support. Again this used the inertial mass of the walls for load, but did not require an external support frame. A challenge with the proposed test program is to properly restrain the wall out-of-plane without impacting the behaviour of its inertial response.

3. Test Program

The test program was designed by members of the SRG Technical Review Board (TRB), to evaluate the performance of various retrofits on the URM walls out-of-plane. The intent of the retrofit concepts is to explore cost-effective alternatives that can be applied in a practical way. The tests were intended to be comparative between retrofit methods and not necessarily provide detailed structural information on each method.

Retrofit Concepts

Two types of retrofit are defined for these tests based on their function. The retrofit is a means to restrain the wall at its top; the second is to reinforce the wall along its height. For the top restraint, two methods were proposed. The first was to create a pin-type connection, which involves installation of steel angles into the floor above. These angles would then press against the top of the wall preventing out-of-plane movement. This concept is shown in Figure 5. A second option is to install grout between the top of the wall and underside of the floor above, to create a pseudo fixed connection. This was not used for the first test program that is described in this paper.

For the reinforcement along the height of the wall, three separate retrofit techniques were proposed: cutting and reinforcing the block cores in a vertical direction; horizontally restraining the wall using a Hollow Steel Section attached using masonry screws, and by the use of vertical U-channel attached along the height of the wall using masonry screws. The initial drawings are show in Figures 6 and 7, for the U-channel and horizontal beam retrofit methods.

The implementation of the cutting and grouting method was the most challenging and ultimately resulted in poor performance. The original idea was to minimize the amount of cutting of the face that was required. This involved cutting a hole at the top and bottom of the wall, inserting a flexible wire into the cores and filling with muddy grout. This method was proven to not work very well and in the end the cores were cut from top to bottom and a 10mm deformable bar was used as the reinforcement. Further testing on this method will be performed.

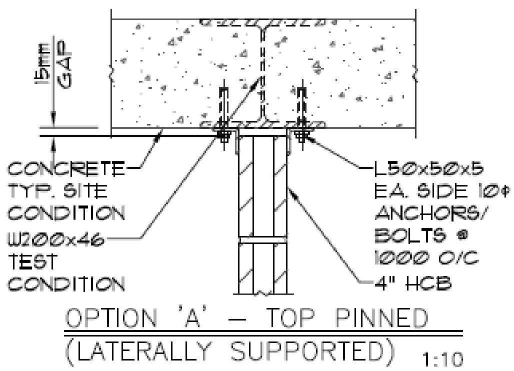

Figure 5: Top Pin Connection Detail

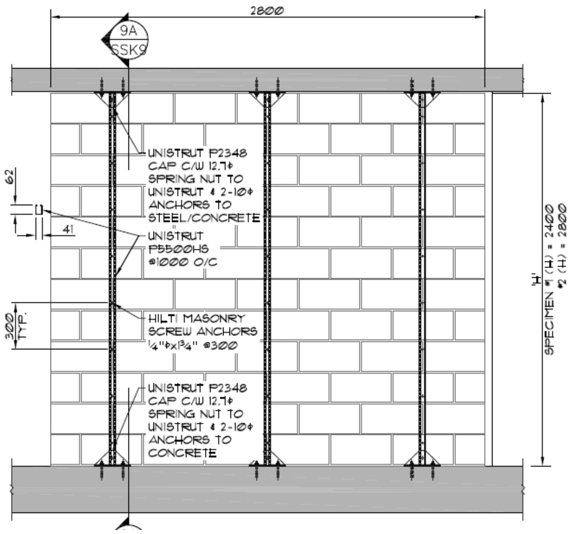

Figure 6: Vertical U-Channels

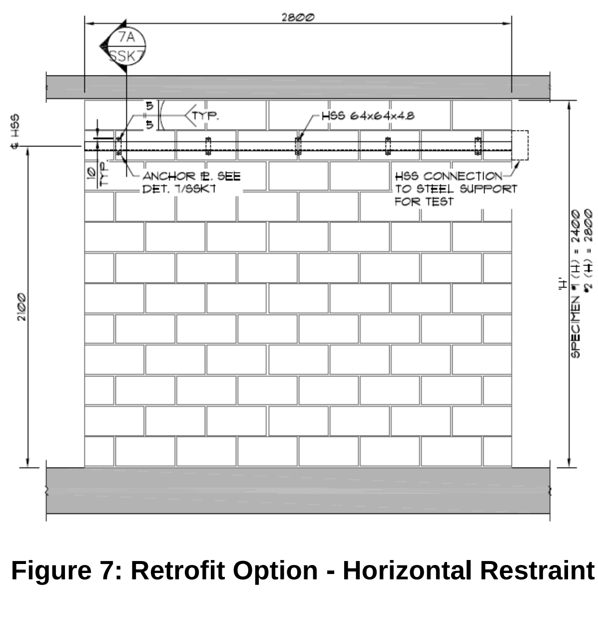

Figure 7: Retrofit Option - Horizontal Restraint

For the horizontal beam retrofit, the intent of the specimen design was to use the smallest beam possible since the span was very short compared to what would be done in practice. Ultimately a 64x64x4.8 HSS was placed at the 2/3 height horizontally across the wall, shown in Figure 8. The beam was attached to the wall using eight masonry screws with a diameter of ¼" and total length of 1-¾". One design consideration is the placement of the screws, either in the web or the flange of the block. While the flange is more convenient due to the availability of a larger area, it was found that when using a hammer drill a wedge of concrete is broken off inside the core, reducing the total depth of penetration for the masonry screw. It is useful to note that despite this, it did not seem to affect the performance and in fact after significant shaking it was found that the screws were still held tight; this is an issue that merits further investigation.

Fig. 8 – Horizontal Restraint Retrofit

For the U-channel retrofit, a pair of Unistrut™ P1000T sections were used. They were installed with a 1000 mm spacing and attached using masonry fasteners spaced vertically at 300 mm. The U-channels were cut shorter than the full length of the wall, both at the top and bottom to eliminate any restraint effect at the ends of the channel in contact with the top or bottom. The initial design proposed the proprietary end connectors which attach to the floors above and below. Instead it was chosen to cut them short to create a pin effect and have the channel only restrain the wall on its face.

The walls were built using standard 90mm concrete blocks and Type S mortar. Each specimen was 2.8m high and 1.6m wide. The walls were built in sets of 5, with 15 in total. They were built on steel base beams, and only were mortared to the basebeam only, with no dowels or physical restraint.

An out-of-plane test rig was used to support the walls at the top; a separate, detachable top beam was fabricated to serve as the top restraint and act as the upper floor. This was a 203 x 203 HSS beam, which allowed for the width of the wall and two 50mm angles to be attached (one on either side). The frame and top angles can be seen in Figure 9.

The walls were instrumented in a manner consistent with the expected response of the walls. This included: an accelerometer on the shake table to measure the input shaking, accelerometers along the height of the wall and displacement sensors (string pots) along the height of the wall. The accelerometers and string pots were attached in the middle of the face of each wall. Two video cameras were used for each test, typically one was placed on a front angle and one on a rear angle. In some of the tests a high speed camera was used at the side of the wall.

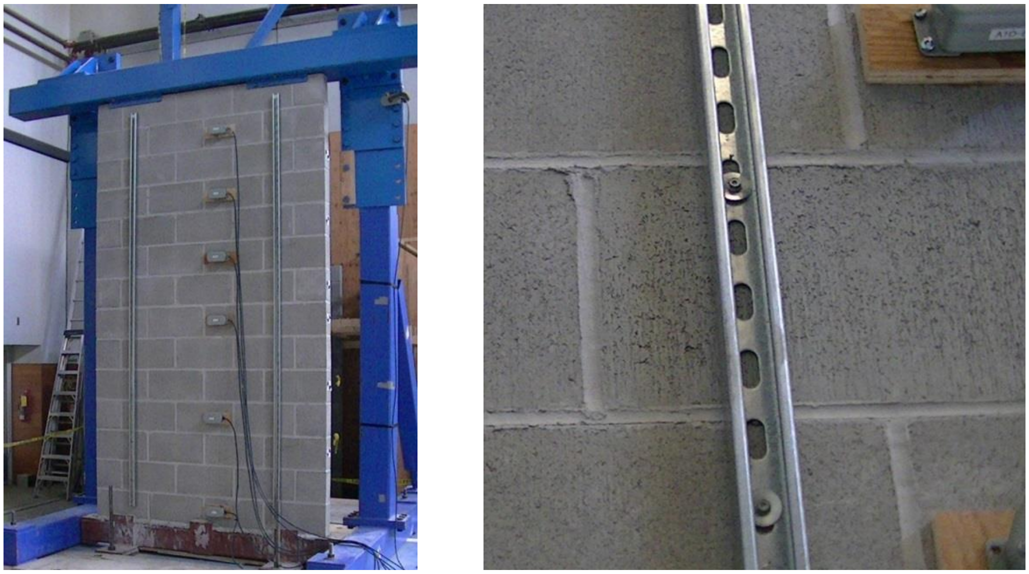

Fig. 9 – U-Channel Retrofit

Test Ground Motion

The test ground motion used for the testing was the Nishi-Akashi record from the 1995 Kobe, Japan earthquake. It was chosen as part of the suite of suite of 20 records that are available in the Seismic Retrofit Guidelines (Pina et al 2010) The general criteria for the selection of the record was to have strong shaking and a significant number of displacement cycles. Also the intent was to choose a record that was intense at frequencies greater than 1 Hz (less than 1 sec period) and have a peak velocity greater than 30 cm/s.

As part of the selection process results from non-linear analysis of URM prototypes were used to compare peak drift and probability of failure values from 3.0 m and 2.4 m high 90mm URM prototypes. The analysis was done on these walls using each of the 20 SRG records at 10% intervals of intensity, from 10% up to greater than 150%. From those results it was seen that there would be i) large drifts and ii) a high probability of failure at lower intensity levels for the chosen record. This is important for comparison of the retrofits at design levels of the earthquake. The main parameters of the records are given in Table 1 and the acceleration time history is shown in Figure 10. It is acknowledged that this record has a relatively short duration, and future tests will examine the effects of long duration records on these walls.

Table 1 – Test Input Record Parameters

Record Name	Max. Accel (g)	Max. Velocity (cm/s)	Max. Displacement (cm)
CUE 99999 Nishi-Akashi	0.51	37.29	9.53

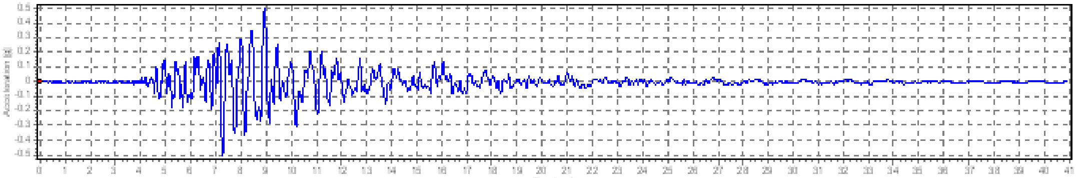

Fig. 10 – CUE 99999 Nishi-Akashi Acceleration Time History

4. Testing Results

A total of 15 tests were performed in this test program. In addition to the retrofit tests described in section 3, a series of bare wall benchmarks were tested. For this paper, the results of three tests will be compared: a bare wall, the HSS and the U-channel.

For each of the tests, the ground motion was initially applied at 40% of the design level, and then increased in intensity by 10% until failure was observed. This method was applied the same way to each specimen to allow for direct comparison.

Bare Walls

Three tests were done on bare specimens, which were supported at the top using the two angles on either side of the wall and had no additional reinforcement. The behaviour of these walls was all very similar; at the lower intensity tests, the wall cracked near the top third of wall. After this initial cracking the wall begins to move in a pin-pin rocking mode that was restrained at the top by the steel angles. The rocking continues until it reaches a critical displacement after which the wall collapses. It was seen that the bare wall could survive up to 100% of the design level in this rocking mode; collapse occurred at 135% of the design level in the extreme case but this number was not consistent and could not be relied upon. Figure 10 shows the behaviour during the tests, with the crack appearing above mid-height and the pin-pin mechanism. The right side photo is shown just before collapse. In that case a second crack had opened in the top course due to the angle restraint.

Fig. 1 – Failure Location for Bare Wall

Horizontal Restraint

Two tests were done on horizontal restraint specimens. For both tests, the behaviour was the same. The course attached to the beam and those above were undamaged after all runs; the courses below the beam crack about halfway between the basebeam and the HSS beam and fails. It was found that the lower wall failed at 120% of the design level. The performance of the lower section was seen to be worse than the fully unreinforced wall. This is likely due to the fact that the wall is shorter, and is more susceptible to the higher frequencies of the chosen record. The smaller height may also have an impact on the critical displacement of failure. Figure 11 shows the failure mode.

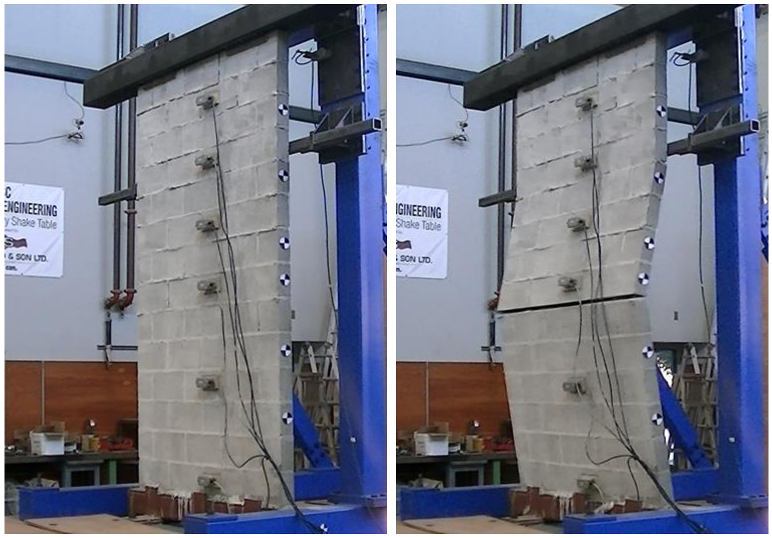

Fig. 2 - Failure Locations of Horizontal Restraint Wall

U-Channel

Three tests were performed on the U-Channel retrofit, although in three different ways. The main test was the first one, which used two U-Channels spaced 1000mm apart. The wall survived up to 150% of the design level, with significant displacements at mid-height (up to110mm). After the final test, each of the masonry screws were checked and all of them were found to be tight.

Two other tests were performed, one on a previously damaged wall and another with only a single U-Channel in the middle of the face of the wall. In the first case, several of the masonry screws were loosened early in the application of the test program, and the wall failed at a lower level (120%). For the second case, the wall failed very early (60%) due to masonry screws failing at the top, and then quickly came apart. Figure 12 shows the behaviour of the system during the tests.

Fig. 3 – Deformed Shape of U-Channel Retrofitted Wall

Table 2: Summary of Test Results

Test	Max. Test Level	Pk. Displacement (Midheight)	Pk. Acceleration (Midheight)
Bare Wall	135%	100mm	0.57g
Horizontal Beam	120%	35mm	1.20g
U-channel	150%	110mm	3.50g

Table 2 presents a comparison of the performance of three of the test specimens. The bare wall is shown to have a significant rocking displacement failure before failure, and therefore a higher test level. The performance is however dependent on the location of the initial crack, which makes it an unreliable mechanism. It is also worth noting that the highest acceleration was relatively low compared to the other two retrofits. Peak displacements were taken from the last cycle before failure, at the midheight of the wall. The acceleration time histories were filtered between 0.1 and 25Hz.

5. Summary and Conclusions

There are a significant amount of unreinforced 90 mm block partition walls located throughout schools in BC. The cost of remediating the walls can become prohibitively high; cost effective methods with simple, fast installation procedures are required. A seismic test program using a shake-table with 1.6m wide and 2.8m high walls was performed at UBC. Overall, 15 walls were tested for the project. Tests were performed on bare walls (for use as a benchmark), a vertical core reinforced wall, HSS beam horizontally restrained walls, and U-channel reinforced walls.

The horizontal restraint and U-channel walls demonstrated good performance and proved to be relatively simple to install. The U-channel wall performed the best with two C-channels installed; it did not collapse when subjected to 150% of the design earthquake, and it was very flexible, exhibiting high displacements. The horizontal restraint wall did not collapse when subjected to 120% of the design earthquake.

The mid

Overall, the retrofit options tested provide good insight into a possible direction to take with future retrofit schemes when considering vulnerable school buildings. Consideration must be made with designing the number and spacing of the masonry screws which govern in the performance of the U-channel retrofit.

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