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IN-PLANE SHAKE TABLE TESTING OF FRP STRENGTHENED URM WALLS

Martin TUREK[1], Carlos E. VENTURA[2] and Steven KUAN[3]

SUMMARY

Due to the number of unreinforced masonry buildings in seismically active regions, it is desirable to find effective and economical retrofit techniques to mitigate the potential hazards. One such technique is the external application of fibre reinforced plastics (FRP) to add strength and ductility to the unreinforced-masonry (URM) walls both in- and out-of-plane. This paper describes a research project involving a series of in-plane shake-table tests performed on a set of unreinforced and FRP strip strengthened concrete-block walls 2400mm high by 3000mm long. The unreinforced walls were tested as a benchmark for comparison against the behaviour of the FRP strengthened walls. Five configurations of FRP strips were tested in total, primarily examining the behaviour of the strips applied vertically. The walls were subjected first to design-level earthquake records to determine their behaviour. The walls were then subjected to extreme-level earthquake records, to determine the failure modes and behaviour of the various FRP configurations. It was observed from the testing that all of the strengthened specimens, regardless of configuration, performed well during the application of the design-level records. Four of the five FRP configurations also performed well to application of the extreme-level record. It was concluded from these tests that the use of vertical FRP strips is an adequate configuration to improve the in-plane performance of URM walls. The behaviour of vertical strips was comparable to that of horizontal strips, which were also tested and found to be very effective. The vertical strips were found to be effective in restoring strength of cracked walls. They were also found to help control the failure modes of the specimens, and prevent collapse even after severe damage had occurred, which can be a strong contributor to improving life-safety during a severe event.

BACKGROUND

Fibre-Reinforced-Plastics (FRP's) have been in use for retrofits of concrete members for many years with great success. This can be seen in many bridges, particularly on columns. The primary advantages for this type of application are the ease of installation and the gain in ductility. This technology has since been applied to unreinforced concrete masonry, mainly for walls and out-of-plane loading. There are other types

[1] *Graduate Research Assistant, Earthquake Engineering Research Facility, Department of Civil Engineering, The University of British Columbia, Vancouver Canada, meturek@civil.ubc.ca*
[2] *Professor, Department of Civil Engineering, The University of British Columbia, Vancouver Canada, ventura@civil.ubc.ca*
[3] *Senior Seismic Engineer, Public Works and Government Services Canada, Pacific Region, Vancouver Canada, steven.kuan@pwgsc.gc.ca*

of repair for unreinforced masonry (URM) walls available, but external application of FRP is less intrusive, quicker, and easier. The use for adaptation of these technologies in the retrofit of URM structures has been addressed by governments and other agencies [Cheung et al., 1999], [Saadatmanesh, 1997].

Most of the previous research performed on FRP strengthened masonry components has dealt with clay-brick masonry and testing in the out-of-plane direction using cyclic loading. However, an in-plane shake-table test of concrete block walls was performed at the U.S. Army Construction Engineering Research Laboratories [Al-Chaar and Hasen, 1998]. The objective was to test the effectiveness of the fibre manufacturer's method of anchoring the fibre sheets. The test set-up involved two URM walls connected at the top by a concrete slab and tested simultaneously. Only one wall was wrapped in glass fibres. One conclusion was that the external FRP reinforcement led to excellent performance of the walls but the heavy slab might have affected the results. Another conclusion is that proper anchoring of the FRP must be imposed in order to achieve optimal results. Currently, another shake-table test is being planned at the University of Wyoming, headed by the Marketing Development Alliance of the composites industry [MDA, 2004]. Examples of the other types of testing include strength testing of the composite FRP/URM wall system [Hamilton and Dolan, 2001], which in that example dealt with cyclic testing of larger scale specimens; simulated seismic loading applied in the out-of-plane direction [Ehshani et al., 1999] to smaller-scale specimens; and pseudo-dynamic testing applied to a complete URM building [Paquette, 2002].

UBC TESTING PROJECT

A research project to test URM walls on a shake table was carried out at the University of British Columbia (UBC) in Vancouver, Canada. Compared to other shake table tests of masonry walls, this test involved full-scale specimens and real-time dynamic loading as opposed to small-scale samples and slow, cyclic loading.

The purpose of this research project was to examine the performance of FRP strips applied as reinforcement to URM walls when subjected to two different levels of in-plane seismic loading. The first loading level is a 'design-level' in accordance with the Canadian building code [NBCC, 1995]. Two ground motions were examined at this level. One represents a near-field event that would be expected for the southwest British Columbia mainland region, and the other was for the same region but caused by a subduction record at a far away distance, specifically the Juan-de Fuca fault zone off the west coast of British Columbia. The second loading level used was a higher level representing an 'extreme-level' event.

A total of eight walls were tested. Each of the walls tested had identical dimensions, with the only variable being the externally applied FRP reinforcement configuration. Three of the walls did not have FRP reinforcement and were used as the benchmark for the wall behaviour. One of the bare walls was subjected to an impulse load, one was subjected to the design-level record, and one was subjected to the extreme-level record. The remaining walls were reinforced using five different FRP configurations. The reinforced walls were subjected to a series of three earthquakes. First the design-level near-field record was applied, then the design-level subduction-type record, and finally the extreme-level record. The extreme-level record was applied repeatedly until failure was observed. A photo of a typical wall mounted on the shake-table is shown in Figure 1.

METHODOLOGY

The specimens used in the testing program were single wall units 2400mm high by 3000mm long by 200mm thick (details shown in Figure 2a). These dimensions were chosen to simulate a wall from a typical room using standard block sizes. The length of the wall was governed by the lifting capacity of the overhead crane in the laboratory. Each wall was constructed on a reinforced concrete basebeam, which provided a base for anchoring the specimens onto the shake-table. The walls were unreinforced except for three vertical steel dowels from the bottom course into the basebeam and three vertical threaded dowels located at the bondbeam at the top of the wall. The basebeam dowels were intended to prevent the sliding failure from occurring at the interface with the concrete. The top dowels allowed for the fastening of a surcharge mass to the wall and transfer the inertial shear force into the wall. The surcharge mass was 2700 kg and was designed to simulate the weight of a second storey wall plus the tributary loads from the upper floor

Figure 1: Specimen Mounted on Shake-Table

The retrofit material used for the tests was the Tyfo SHE-51A fibreglass strips embedded in Tyfo S Epoxy manufactured by Fyfe Company in California. The composite is a custom-weave, uni-directional fabric using glass fibres oriented in the sheet strong direction (long direction), with additional "yellow" glass fibres oriented in the weak direction. The strips are 300 mm wide. The ultimate tensile strength of the composite is 575 MPa in the strong direction and 20.7 MPa in the weak direction. It has a tensile modulus of 26100 MPa.

The first specimen (R1) was reinforced using two vertical strips, shown in Figure 2b. It was intended to examine the effects on in-plane shear resistance of the walls with strips applied vertically. The second specimen (R2) was reinforced using 8 strips laid horizontally on the face of the wall, shown in Figure 3a. This represents a common wrapping approach used by the manufacturer. The third specimen (R3) was reinforced with three vertical strips, shown in Figure 3b. This was intended to examine the effect of spacing of the strips. The fourth specimen (R4) was reinforced similar to R1, utilizing two vertical strips on either end, shown in Figure 4a, although it differed by having a pre-existing horizontal along the top of the 3rd course.

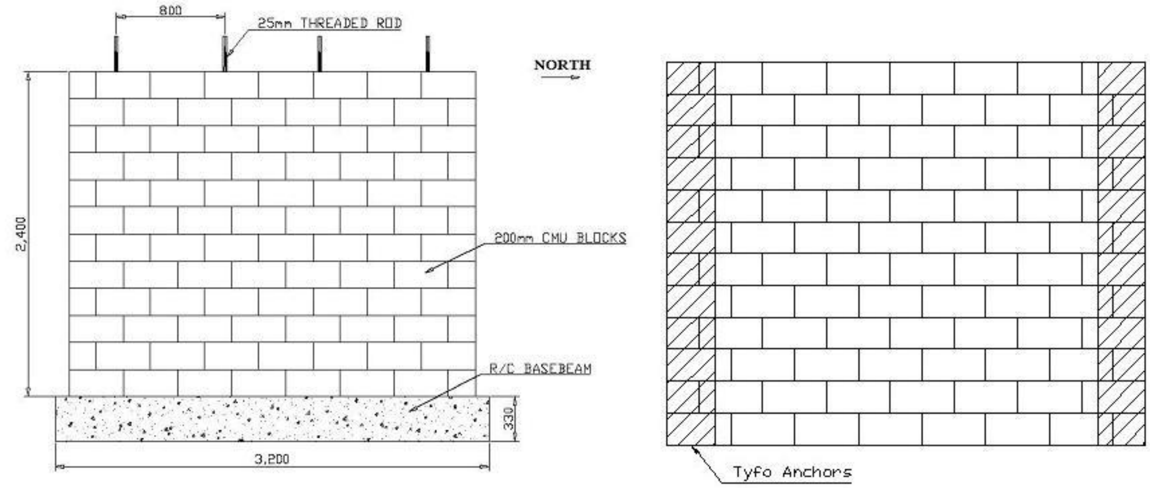

Figure 2: (a) General Specimen Design and (b) FRP Layout R1

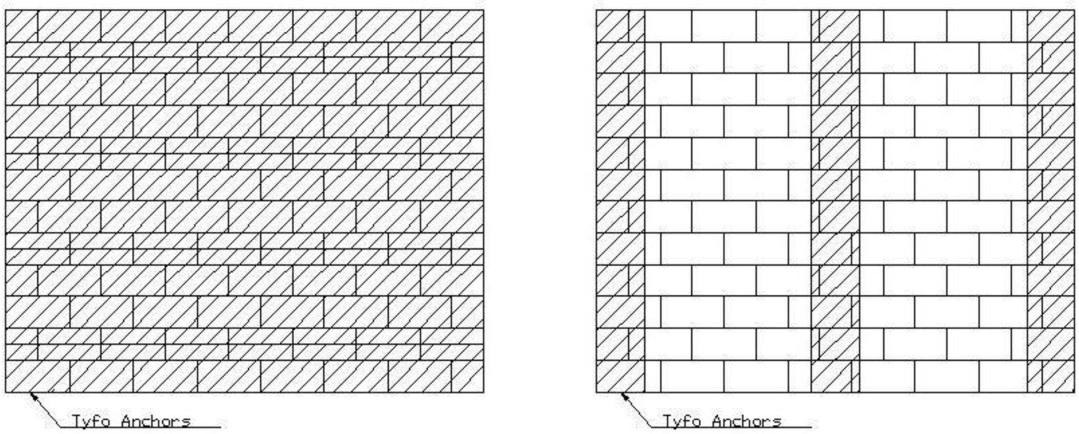

Figure 3: (a) FRP Layout R2 and (b) FRP Layout R3

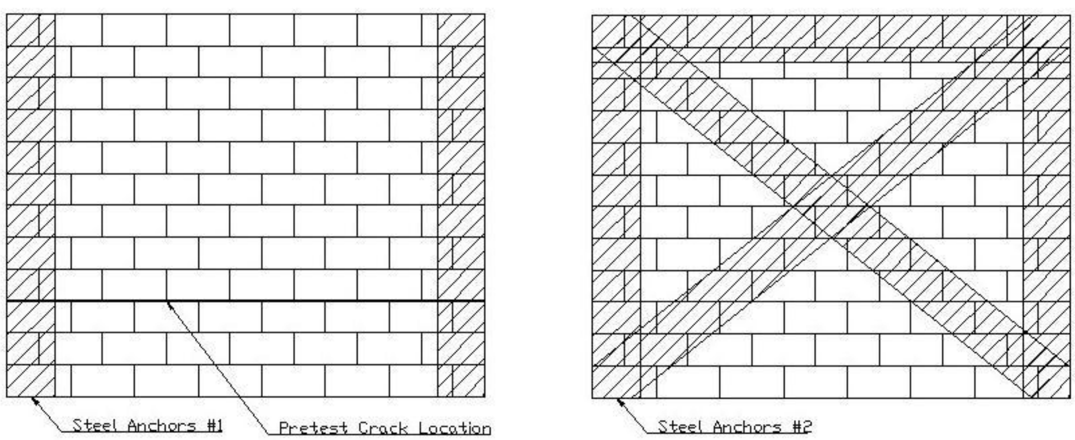

Figure 4: (a) FRP Layout R4 and (b) FRP Layout R5

This allowed for the examination of the effectiveness of the FRP's for restoring strength and behaviour of cracked walls. In actual in-situ situations, it is not uncommon to find existing cracks along mortar joints in concrete masonry walls. In Specimens R1 to R4, both sides of the wall were strengthened with an identical FRP layout. The fifth specimen (R5) was reinforced using a series of single strips, laid out in an X-pattern, plus vertical strips on either end and one horizontal strip across the top of the wall on one side only. The layout is shown in Figure 4b. The intention of this layout was to prevent diagonal tensile cracks from opening up from one corner to the opposite corner under shear action.

The first three specimens were anchored to the basebeam using Tyfo Fiber anchors. They are simply a fibre rope with one end drilled into the basebeam, and the other end splayed out and attached to the underside of the strip, shown in Figure 5a. The anchor on Specimen R4 was a steel plate laid horizontally and bolted through the fibre strip into the basebeam, shown in Figure 5b. The anchor on Specimen R5 was a steel angle, and bolted down into the basebeam, and through the fibre strip into the first course of the wall, shown in Figure 5c.

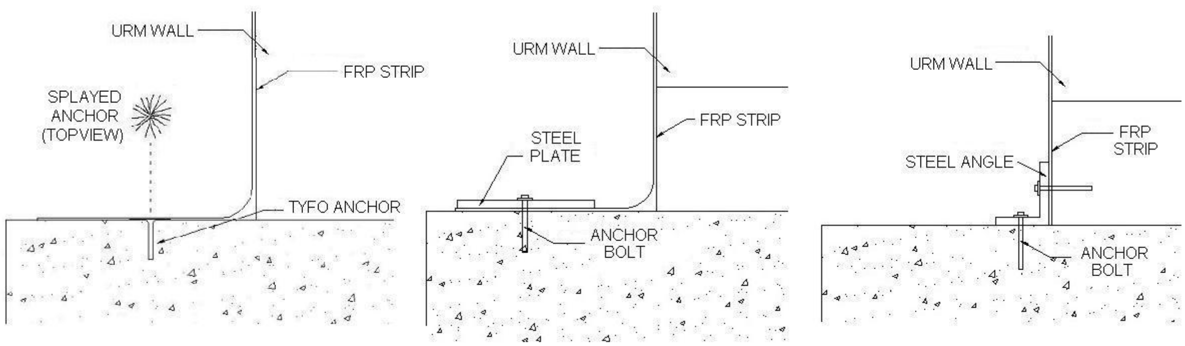

Figure 5: (a) Tyfo Fiber Anchors (b) Steel Anchor #1 (c) Steel Anchor #2

The walls were tested in-plane using simulated ground motions generated with the UBC Earthquake Engineering Research Facility (EERF) uni-directional shake-table. The top of the wall was restrained in the transverse direction by steel cables. The total weight of a complete specimen including concrete base beam and top weights was approximately 55 kN. The specimens were instrumented with two accelerometers, one at the top mass and one at the table level; two displacement transducers, one at the op and one at the table; and two dual-axis strain gauges, attached to the FRP strips.

For the ground motion records, a record from the 1995 earthquake in Kobe, Japan (obtained from http://peer.berkeley.edu/smcat/) was chosen as the near-field record and a recorded from the 1985 Valparisio earthquake in Llayllay, Chile (obtained from http://db.cosmos-eq.org/) was chosen as the subduction record. The extreme-level record (called VERTEQII) was chosen based on its higher frequency content, which was needed because of the stiff retrofitted wall specimens. The Telcordia VERTEQII time history is a synthetically generated record used for the testing of telecommunications equipment [Telcordia, 1995]. It is a part of the GR-63-CORE criteria, Generic Requirements documents (GR's) that provide the Telcordia Technologies view of proposed generic criteria for telecommunications equipment, systems, or services. The response spectra from the Kobe, LlayLlay, VERTEQII records and the spectrum from the National Building Code of Canada [NBCC, 1995] are plotted in Figure 6. The NBCC 1995 Spectrum is plotted using the accelerations for the Vancouver, Canada region.

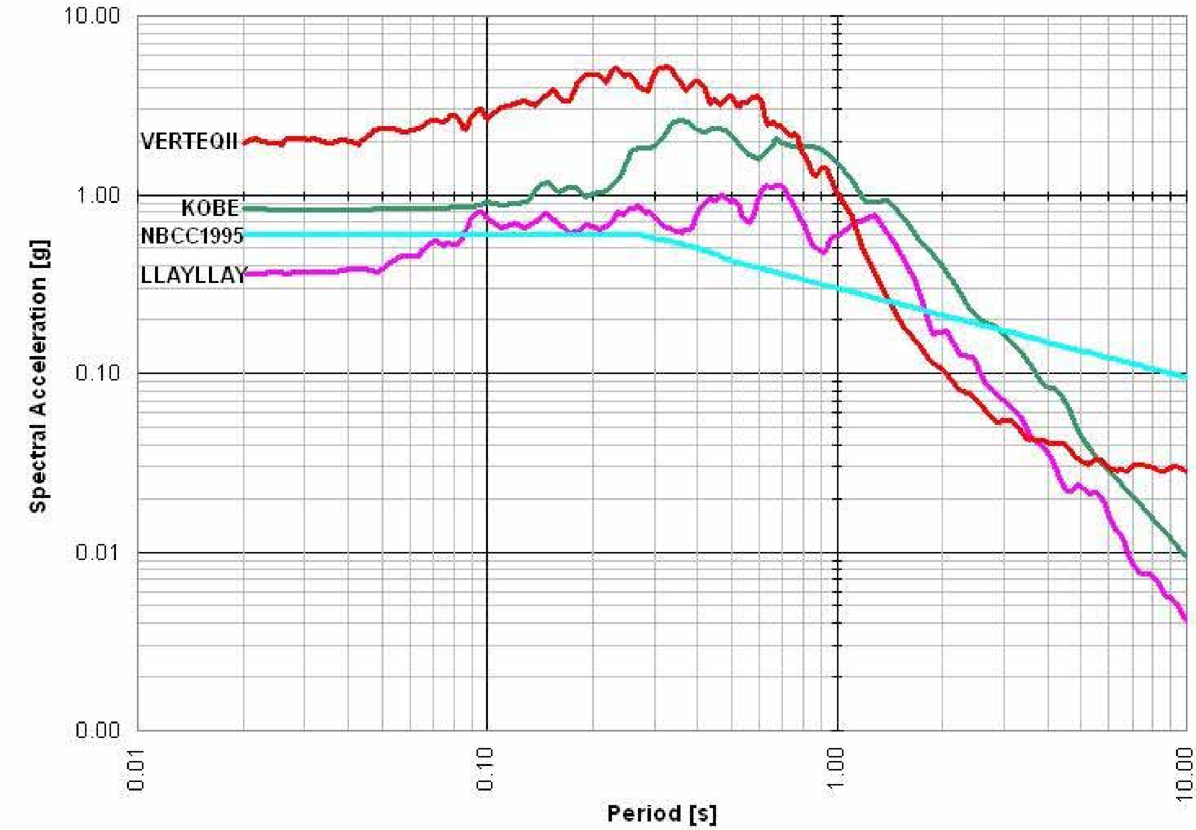

Figure 6: Response Spectra of Records Used for Testing Program (Shown with 5% Damping)

TEST PROGRAM AND OBSERVATIONS

Due to the difficulty of building many full-scale specimens, it was decided to apply more than one record to each specimen to examine different behaviours. In the case of all five FRP-reinforced specimens, this meant subjecting them first with the design-level records, and then the extreme-level record. Once the performance to the lower design-level records was deemed satisfactory, the extreme-level record was applied consecutively until failure was observed. A summary of the tests is given in Table 1. The table shows the specimen code, a brief description, the amount of strengthening added in terms of surface area and a summary of the significant records applied to the specimen. In the overall test program, other records were also applied but they are not mentioned here [see Turek, 2002]. The URM walls, however, could not be subjected to both record types since failure occurred even due to the design-level records.

Three separate tests were performed on URM walls for use as a benchmark for the study. In the first test (U1) an impulse-type load was applied to the wall. The resulting crack formation is shown in Figure 7a. For the second specimen (U2), the Kobe record was applied and the crack formation was similar to test U1, shown in Figure 7b. In both cases the walls remained standing after the initial cracking had occurred.

Table 1: Test Summary

Specimen	Description	Percent Strengthened [% of surface area]	Records Applied
U1	Bare URM	0	Impulse
U2	Bare URM	0	Kobe
U3	Bare URM	0	VERTEQII
R1	Strengthened 2 Vert Strips	20 (both sides)	Kobe, Llayllay, VERTEQII, VERTEQII
R2	Strengthened Horiz Strips	100 (both sides)	Kobe, Llayllay, VERTEQII, VERTEQII
R3	Strengthened 3 Vert Strips	30 (both sides)	Kobe, Llayllay, VERTEQII, VERTEQII
R4	Strengthened 2 Vert Strips (precracked)	20 (both sides)	Kobe, Llayllay, VERTEQII
R5	Strengthened X Pattern	45 (strengthened side) 0 (bare side)	Kobe, Llayllay, VERTEQII, VERTEQII

The URM wall subjected to the extreme-level record failed completely during the first seven seconds of the record. The cracking began at the top of the second course in the lower half of the wall. Several more cracks opened at the lower portion of the wall early in the record; these opened due to a combination shear/flexural behaviour of the wall. From these lower cracks, a 45˚ diagonal crack opened in the rest of the wall and finally a complete failure occurred. The initial crack patterns are shown in Figure 8a.

Each of the five FRP-reinforced specimens performed well to both runs of the design-level records. No cracking was observed in any of the specimens. After the first two design-level records, the extreme-level record was applied consecutively until a failure was observed.

The first specimen (R1) exhibited minor cracking after the first run of the extreme-level record. During the second run, the specimen failed completely. The wall performed well until the fibre anchors failed, allowing the wall to undergo large displacements at the top. The crack patterns are shown in Figure 8b. The second specimen (R2) was not damaged during the first run of the extreme-level record. During the second run, the wall exhibited a sudden failure along the top of the first course, due to the horizontal joint of the corresponding FRP-strip being laid too closely to the mortar joint. The third specimen (R3) was not damaged during the first run of the extreme-level record. During the second run the wall suffered damage. Similar to the Specimen R1, the anchors failed first. In this case however, the wall was stiffer, so less damage occurred in the wall (in the form of cracking) and more energy was dissipated through the deterioration of the anchors, which detached completely from the base. The crack patterns are shown in Figure 9a.

The fourth specimen (R4) failed during the first run of the extreme-level record. The cracking that the specimen exhibited was similar to that of the first specimen except that it exhibited multiple long diagonal cracks due to the pre-existing horizontal crack. The crack patterns are shown in Figure 9b. The fifth specimen (R5) failed at the anchors during the first run of the extreme-level record. Both of the anchors pulled out vertically from the base, and this was considered the failure mode for this specimen. Another run of the extreme-level record was then applied, resulting in an out-of-plane failure. This was initiated by grinding of the first course on the unstrengthened side. Once the block faces had disintegrated the wall fell outwards. It did not completely collapse however, because the bond between the FRP strips and the blocks did not fail.

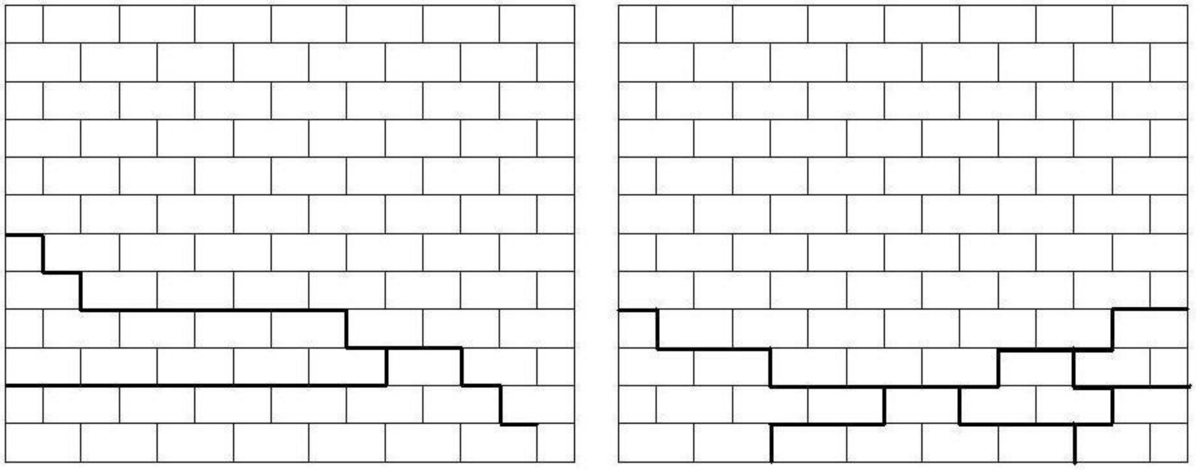

Figure 7: Crack Patterns in (a) Specimen U1 (b) Specimen U2

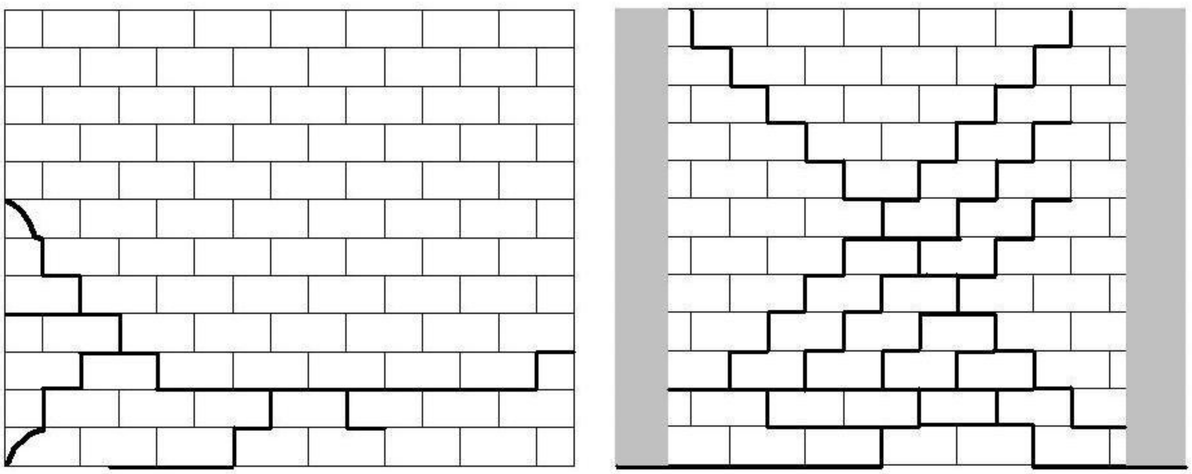

Figure 8: Crack Patterns in (a) Specimen U3 (b) Specimen R1

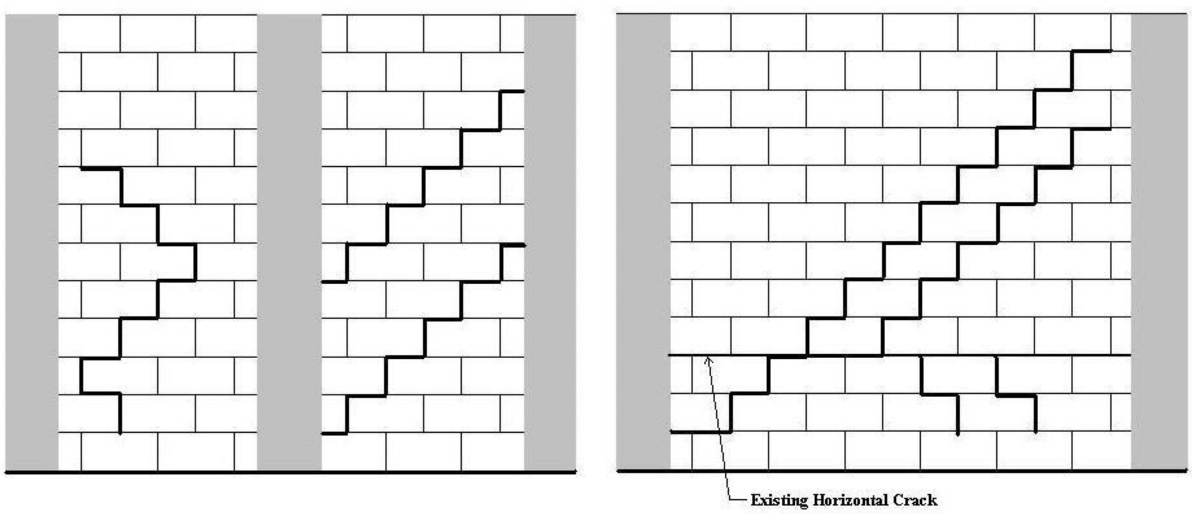

Figure 9: Crack Patterns in (a) Specimen R3 (b) Specimen R4

Table 2 summarizes some of the peak results from the testing program. This includes peak measured accelerations at the shake-table level (input), peak measured accelerations measured at the top of the wall (response) and the measured drift between the top of the wall and the shake-table. All of the values are presented with respect to the record that was applied. Although several records were applied to each specimen, the values in the table are those corresponding to the tests that exhibited a failure. The drift is computed as the measured top displacement minus the measured table displacement, divided by the height of the wall. The low drift levels indicate that this is an acceleration sensitive system. These are representative of the highest drift observed before failure occurred.

Table 2: Test Results Summary

Specimen	Input Record	Peak Accel. Input [g]	Peak Accel. Response [g]	Measured Drift [%]
U1	Impulse	0.99	0.58	0.76
U2	Kobe	0.28	0.36	0.06
U3	VERTEQII	1.39	0.92	1.43
R1	VERTEQII	1.26	1.64	0.17
R2	VERTEQII	1.40	1.64	0.23
R3	VERTEQII	1.30	1.85	1.20
R4	VERTEQII	1.28	1.63	1.55
R5	VERTEQII	1.31	1.80	1.60

FRP CONFIGURATION EFFECTS

The results of these tests can be described in terms of the various retrofit configurations. There were a total of five different FRP configurations and three different anchor configurations. The behaviour of these various retrofit configurations can be compared in three groups: vertical strip application (R1, R3 and R4), other strip configurations (R2 and R5) and anchor configuration (three types).

Vertical Strip Configurations

Vertical FRP strips were applied to specimens R1, R3, R4 and R5. The addition of the strips showed a significant improvement in performance over the unreinforced specimen. All specimens performed well to the design-level records. In three of the four tests, the specimens survived one run of the VERTEQII record, before experiencing failure during the second run. Specimens R1 and R3 were standing at the end of two runs as well. This is in contrast to the URM wall, which collapsed in 7 seconds. The addition of a third strip to Specimen R3 illustrates the improvement gained from applying vertical strips. The observation from Specimen R3 was that the wall was significantly stiffer than walls R1 and R4, and the bare wall sections were only slightly damaged during the test. Upon completion of the runs, the wall itself still had significant shear resistance, as well as its vertical load carrying capacity. This means that the reduction of spacing between strips improves the shear capacity of the wall. The concern with this configuration is that, by stiffening the system, more load would be directed to the anchors, which was shown to be detrimental. So the design of the anchors of the fibre strips is a critical detail. In the case of Specimen R4, the existing horizontal crack had reduced the initial shear capacity of the wall. This was apparent because the wall failed during the first run of VERTEQII as opposed to the second in Specimen R1, although both were retrofitted in the same way. The URM wall subjected to the VERTEQII record failed quickly, and it is likely that the pre-cracked wall without FRP would behave similarly. The addition of the FRP strips prevented the wall from collapse, and displayed its effectiveness in a damage-repair application.

Other FRP Configurations

There were two other FRP configurations that can be discussed. The first type was on Specimen R2, with horizontally placed strips. The horizontal strips increased the shear capacity of the wall significantly. In the test however, the wall failed prematurely due to a poor construction detail. The part of the wall above the failure joint however, did not show any signs of distress. It is also noted that although the joint between the strips was placed too close to the mortar joint, it did survive one run of the VERTEQII record. The other type was a wall retrofitted on one-side using an X-pattern (R5). The X-pattern seems to be a more economical use of this type of retrofit. Although Specimen R2 was much stiffer, R5 used less material and still showed an increased shear capacity. Specimen R5 did not show much stress during the first four runs. There was no visible cracking anywhere except at the bottom of the wall near the base, where there was no immediate FRP reinforcement. The blocks in the other 3 exposed triangles showed no cracking. The test with the X-pattern was applied to only one side of the wall, to simulate a practical case, in which there is limited access for application and materials. For the design level records, this did not have much impact. During the second run of the VERTEQII record, the one-sided reinforcing caused a failure of the first course on the unstrengthened side. By comparison of the first run in all cases, and taking into consideration the amount of material used, Specimen R5 was the most effective configuration.

Anchor Configurations

Three different anchor configurations were tested. The first type, Tyfo Fiber Anchors, were used in Specimens R1, R2 and R3. During all runs of the design level records (Kobe and Chile), the anchors performed satisfactorily. In the two-strip case (R1), the anchors failed partially, although they did not fail completely due to the energy dissipation that occurred due to the continuous wall cracking. In the three-strip case (R3), the anchors failed completely, since the wall was stiffer and did not crack as much.

The behaviour of the steel anchors was different from that of the fiber anchors. In the case of the steel plates (Steel Anchor #1) which were not mounted directly against the wall, the initial behaviour was similar to Specimen R1. Once the strips had separated from the base to their limit and pulled against the plates, more load was transferred into the strips. This was evident by the tearing of the FRP strips at the top corners of the wall. It was observed that the wall with the steel plate anchors (R4) performed better than the wall without (R5), even though R4 had a pre-existing crack. During the test there was a quick failure of the base anchor bolts. The very stiff wall transferred the load to the anchors and quickly reached the tensile capacity. This is different from the effect of the steel plates, where the FRP pulled from the base, but did not pull out the steel plates. In that case, the loads on the anchor bolts are in tension and shear, rather than purely in tension in the case of Specimen R5.

In the case of the steel angles (Steel Anchor #2), there was a quick failure of the base anchor bolts during the first run of the extreme-level record. The stiff wall transferred the load to the anchors and quickly reached the tensile capacity. This is different from the effect of the steel plates, where the FRP pulled from the base, but did not pull out the plates. The brittle failure of the anchors in Specimen R5 showed a lack of ductility, while the anchors in Specimen R4 allowed for a degree of ‘yielding’ without complete failure. This would provide some additional out-of-plane resistance if the wall was subject to additional loadings (i.e. aftershocks). The anchors in Specimen R5 had already failed and could not provide that out-of-plane resistance.

CONCLUSIONS

In general, a number of important observations were noted. One observation was that the URM responded to earthquake loadings as a series of impulse loads, with damage occurring due to large peaks of the record. This was evident by comparing the two URM tests that were subjected to the earthquake records (Specimens U2 and U3) to the impulse test. In both of the earthquake record tests, the first two cracks that the walls experienced were from a single pulse of the record, one in each direction. This implies that the response of URM is a force response, and not a frequency response. A second observation is that the URM walls in this test set-up fail in shear as the primary mode, but are influenced by a flexural component. This flexural component is evident from the behaviour of the initial cracking that was exhibited by all three specimens.

The application of the higher extreme-level loading allowed for a comparison of the effectiveness of the different reinforcement configurations. The URM wall subjected to the VERTEQII record did not perform well, collapsing completely after the first 7 seconds of the record. The catastrophic failure observed poses a potential life-safety hazard.

All 5 of the FRP configurations provided a significant improvement in the performance of the wall in comparison to the corresponding URM test. The improvements from using these various configurations can be summarized as follows:

- The addition of vertical FRP strips improves the in-plane performance
- Reduction of the spacing between vertical strips improves the shear capacity of the system
- The addition of vertical strips is effective in repairing damaged walls
- Complete coverage of the wall with horizontal strips is effective in improving shear capacity
- Use of strips in an X-Pattern is an effective and efficient way to improve in-plane capacity
- Anchor details are important for the stiff URM/FRP systems
- Ductility in the anchors is important to improve overall capacity of URM

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