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Seismic Strengthening of Unreinforced Masonry Walls using Sprayable Eco-Friendly Ductile Cementitious Composite (EDCC)

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Abstract

In another paper at this workshop, the development of Eco-Friendly Ductile Cementitious Composite (EDCC) and its response to uniaxial tensile is described. Here, its performance when used as a strengthening coat on unreinforced masonry is described. This paper elaborates on the results of shake table tests on full-scale masonry wall specimens, each about 2m wide by 3m high, retrofitted using sprayed EDCCs. Six full-scale unreinforced non-grouted masonry wall specimens were assembled and then retrofitted using Sprayable EDCC. The walls are tested at the Earthquake Engineering Research Facility (EERF) at UBC on the Linear Shake Table (LST) under different ground motions with varying intensities. The wall specimens were fully instrumented and data were collected using 34 different channels including 10 accelerometers, 8 channels of displacement sensors, 8 strain gauges and time synchronized video recording using eight HD cameras. Test indicated that even a single-sided retrofit with appropriate EDCC can significantly enhance the overall ductility of the system and change the fundamental behaviour of the wall from a typical “Rocking Mechanism” to a “Beam” type behaviour, with significant rotations at the hinge supports of the base. The added flexibility to the system resulted in a substantial increase in energy dissipation, and thereby increasing the overall drift limits before collapsing, causing the wall to withstand extensive levels of shaking under different types and intensities of earthquake generated ground motions.

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Keywords: EDCC; ECC; FRC; Eco-Friendly Ductile Cementitious Composite; Engineered Cementitious Composite; Fiber Reinforced Concrete; High Strain Rate; Tensile Strength; Dynamic Effect; Dynamic Loading; High Rates of Loading; Strain Rate Effect; Loading Rate Effect

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1. Introduction

Unreinforced masonry (URM) is considered one of the most common types of partition wall systems in many of the mid-age, low-rise to mid-rise, school and hospital buildings in Canada, Unites States, and many other countries across the globe. URM partition walls are known to have very low drift limits in seismic events and the failure mechanisms are known to be mostly brittle and catastrophic during an earthquake shaking. Compared to any other partitioning systems, URM walls generally perform poorly during earthquake events.

The UBC developed EDCC retrofit technology is a cost effective novel methodology for seismic retrofit of existing infrastructures using Sprayable Ecofriendly Ductile Cementitious Composites (EDCCs), which is a form of fiber reinforced engineered cementitious-based composite material. In particular, this retrofit strategy primarily targets strengthening of unreinforced, non-grouted, and unconfined non-loadbearing masonry walls, typically referred to as URM walls, in order to provide restrain for the wall to prevent the OP failure under an earthquake ground shaking.

Due to their good sound and thermal insulation properties, URM walls are widely used in partitioning many of the commercial and residential buildings worldwide, either as in-fill or stand-alone. According to the British Columbia (BC) Ministry of Education in Canada, with reference to the Seismic Upgrade Program for BC schools, currently there are about 384 school buildings, only in the province of British Columbia, classified as high risk, which are in urgent need of Seismic Upgrade. This assessment has been done using the methods introduced by the 3rd edition of the Seismic Retrofit Guideline, referred to as “SRG III”. From the aforementioned school buildings, there are a large number of them with URM partition walls, which need to be retrofitted as part of the BC seismic upgrade program.

It is essential to emphasize that, from July 2017, EDCC is an officially recognized retrofit option by SRG III, for out-of-plane retrofit of URM walls. Referred to as “URM # 11” in Volume 7 of SRG III, use of sprayed or troweled EDCC as a retrofit option for URM walls is included as part of the code and detailed designs are provided to allow the design engineers to spontaneously prescribe this retrofit option with a peace of mind for different projects. It is worth mentioning that SRG III, along with its web-based platform, is currently the only available tool, which is recently developed through a joint effort by APEGBC and UBC. The guideline was requested and paid for by the BC Ministry of Education, to be explicitly used by design engineers working on the projects related to the aforementioned seismic upgrade program for BC schools [1].

This paper presents the details of the experimental setup, specifics of the data acquisition system, and a summary of the results of the shake table testing which is done at the Earthquake Engineering Research Facility (EERF) at UBC on the methodology proposed for retrofitting URM wall using sprayable EDCC.

1.1. EDCC: A composite material explicitly developed for seismic applications

EDCC (Eco-Friendly Ductile Cementitious Composite) is considered one specific class of engineered fiber reinforced cementitious composites with strain-hardening type behavior under tension. EDCC uses about 30% cement content of a typical fiber reinforced mortar mix, contains only natural sand, and adapts a hybridized fiber system, about 2% in volume fraction, for exhibiting strain-hardening type behavior and achieving about 5% ultimate strain capacity under pure tension.

This unique tensile strain hardening modus results from an elaborate design using a micro-mechanical approach which takes into account the interactions amongst fibers and the matrix as well as the fiber-matrix interface. Therefore, not only the achieved ductility makes EDCC a perfect choice for seismic applications, but also these attributions make EDCC a much more cost-effective, practical, and a considerably more sustainable material, compared to other conventional cement based repair systems. Additionally, the unique UBC developed spray system for this material, as shown in Fig. 1, is a low velocity shooting mechanism, using a rotary type bump, which is fairly similar to the spray systems typically used for spraying cementitious-based plasters and fire proofing polymer coatings. Hence, the typical particle and fiber rebound issues of a shotcrete process is avoided, and rebound is less of a concern when it comes to spraying EDCC, making it a far more sustainable repair material, compared to any typical shotcrete repair system.

There are two different EDCC mixes used for retrofitting the six walls tested on the shake table. The two mixes are referred to as the “Regular EDCC Mix” and the “Premium EDCC Mix”. The specifics of the composition and mix proportioning for these two EDCC mixes are presented in another paper at this meeting [2].

1.2. The specifications of the tested specimens

There are six walls are built to be retrofitted and tested on the Linear Shake Table (LST) at the Earthquake Engineering Research Facility (EERF) at UBC. All of the walls are of Unreinforced Masonry (URM), built with nominally 4 inches thick Concrete Masonry Units (CMU). As illustrated in Fig. 2, all the walls are 0.1m thick, 1.6 m wide, and 2.8 m tall. Some of the walls have ladder like joint reinforcements, formally called "wall-locks", which is normally laid flat on top of the full row of the CMUs, placed inside the mortar joint, between the two courses (rows) of the CMUs. This is adopted and tested in four of the walls, as it is a known to be a practice for many of the masonry walls built in 1970s and 1980s time across BC. The wall-locks are present at every second mortar joint throughout the height of the wall, starting from the top of the first course (row) of the CMUs. The specimens were retrofitted with either regular or premium EDCC mixes, having the retrofit material hand applied on either or both sides of the wall.

Table 1. Summary of the specimens tested on shake table

Specimen ID #	Wall-Lock	Retrofit Material	Single or Double Sided
Wall-1	Yes	Premium Mix EDCC	Double-Sided
Wall-2	Yes	Premium Mix EDCC	Single-Sided
Wall-3	Yes	Regular Mix EDCC	Double-Sided
Wall-4	Yes	Regular Mix EDCC	Single-Sided
Wall-5	No	Regular Mix EDCC	Double-Sided
Wall-6	No	Regular Mix EDCC	Single-Sided

1.3. The application methods for EDCC

This retrofit material can be applied in three different methods: hand troweled, hopper sprayed, or pump sprayed. The thickness of the EDCC layer, plastered over the height on the surface of a typical URM partition wall, can vary between 10mm to 20mm, applied on either or both sides of the wall, depending on the design variables.

Fig. 1. Different Application Methods for EDCC

1.4. Dynamic testing of full-scale retrofitted wall specimens (OP behaviour)

Six full-scale retrofitted masonry walls are tested on the uniaxial shake table for the out of plane behaviour; the specimen dimensions (left) and the test setup (right) are shown in Fig. 1. As the wall dimensions and the building block sizes are consistent with the previous full scale wall tests at UBC, for the Schools Retrofit Project, there was no need to test any control, none-retrofitted, specimens. Thus, all six walls could be tested as retrofitted walls and the previous test results could be used to compile a complete set of data. Some variables were decided based on the results of the previously tested miso scale specimens during the retrofit material development and optimization phase.

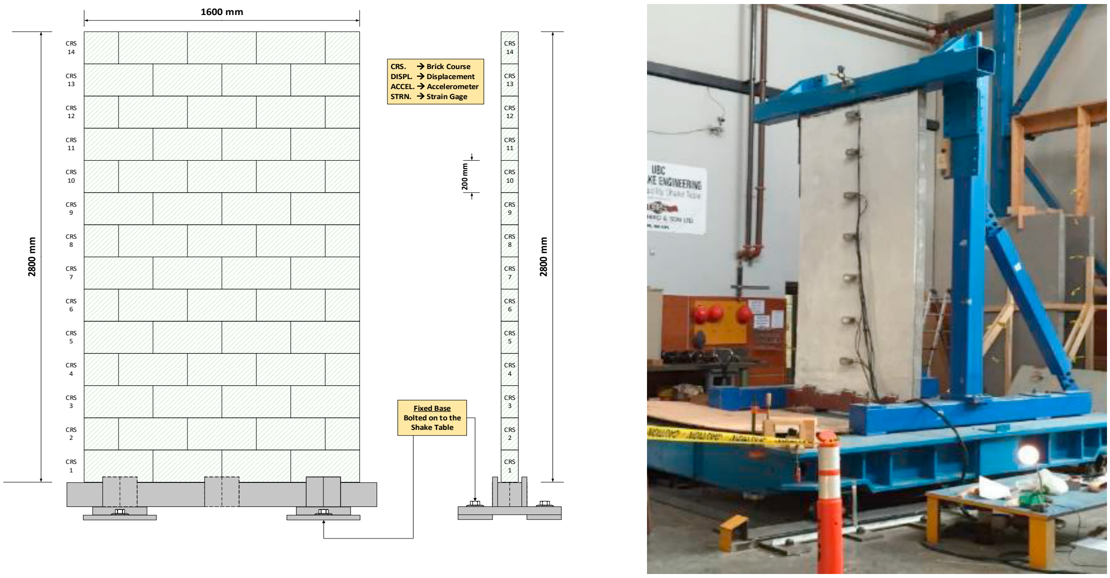

Fig. 2. Wall Specimens – six specimens, 1.6m wide by 2.8m tall

1.5. Summary of the ground motions used

There is a complete suite of ground motions used for this experimental work, in terms of type, nature, location, magnitude, and duration. This is kept aligned with the set of ground motions selected and sued for the analytical work done for SRG III, previously developed at UBC for the BC Ministry of Education, as part of the seismic mitigation action and seismic upgrade program for schools in British Columbia, Canada. The selected ground motion records are then scaled to the mean hazard spectrum of different targeted cities across the province of British Columbia. The scale factors are chosen in accordance with SRG III, targeting different locations. Table 1 lists the ground motions used.

Table 2. Summary of the ground motions used and their corresponding designation number

Record ID #	Type	Magnitude	Year	Country	Region	Recording Station
GM-1	Subduction	9.1 M_w	2011	Japan	Tohoku	Miyagi-Oki
GM-2	subduction	8.3 M_w	2003	Japan	Tokachi-Oki	Hombetsu HKD 090
GM-3	Crustal	7.7 M_w	1999	Taiwan	Chi-Chi	Jiji
GM-4	Crustal	6.9 M_w	1995	Japan	Kobe	Nishi-Akashi
GM-5	Crustal	6.7 M_w	1994	United States	California	Northridge-USGS 5108-Santa Susana Ground
GM-6	Sub-Crustal	7.3 M_w	1992	United States	California	Landers – Joshua
GM-7	Synthetic	-	-	-	-	Verteqii Waveform – Synthetic motion

2. Experimental procedure

Dynamic testing of full-scale specimens is one of the most effective experiments, which can be performed to fully understand the out of plane behaviour of such walls. In fact, in this type of test, the location of the plastic hinge formation fully depends on the overall behaviour of the wall, opposed to a quasi-static test where the location has to be predetermined and set prior to testing.

2.1. Instrumentation and data acquisition

The test was setup using the "blue frame" on the Linear Shake Table (LST), previously fabricated at the Earthquake Engineering Research Facility (EERF) for testing wall specimens in out-of-plane (OP) action for the school project at UBC during the testing program for SRG III.

In this experimental work, the six full-scale walls are tested with uniaxial shaking out-of-plane under different ground motions with varying intensities, as described in the preceding section. For this experimental phase, six full-scale URM wall specimens were casted in mid-January of 2016 and got field cured for a few weeks. The specimens then were retrofitted using Sprayable Eco-Friendly Ductile Cementitious Composites (EDCC) in February 2016, followed by another 56 days of field curing for EDCC, and subsequently tested over the months of June and July of the year 2016, one wall at a time. The 56 days of curing is highly recommended as the repair material consists of high volumes of fly ash, which can delay the long-term hardening and maturity of the repair system. As seen in Fig. 3, the walls are fully instrumented and data are collected in 34 different channels, as follow:

- Accelerometers @ 10 channels
- Displacement sensors (string pods) @ 8 channels
- Strain sensing (strain gages) @ 8 channels
- Time-synchronized video recording by 8 cameras

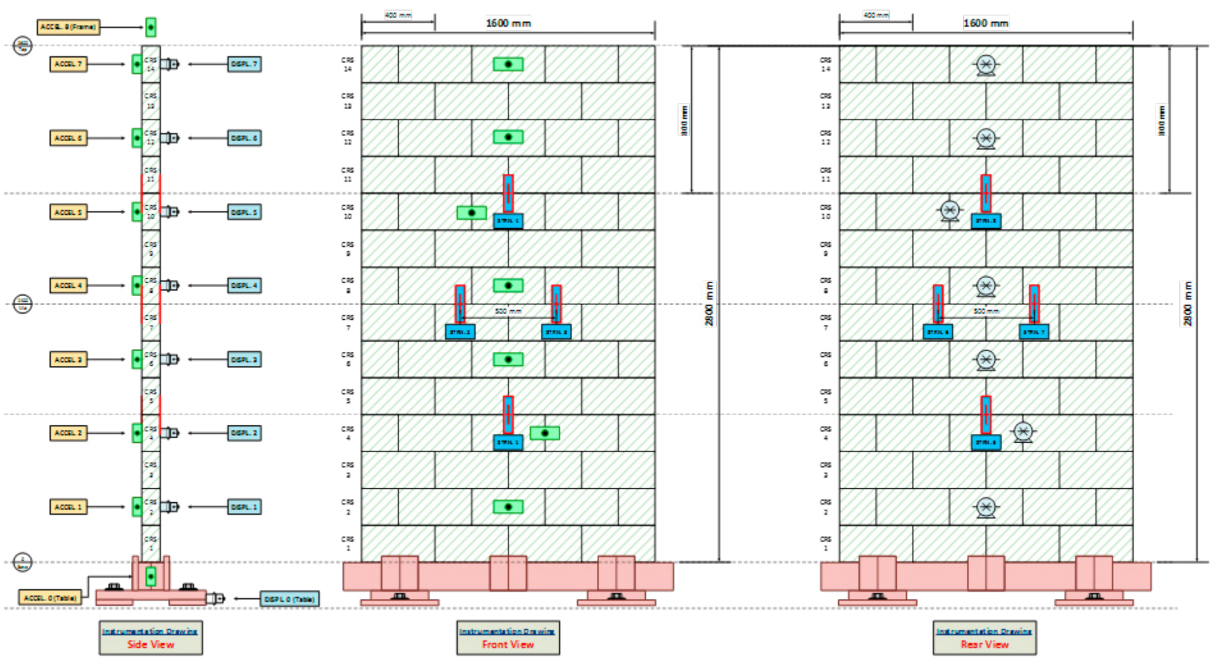

Fig. 3. Schematics of the instrumentation of the wall tests

2.2. Testing program and setup

Out of the six walls, three of them were retrofitted only on one side and three of them were double sided retrofit. There are two different mixes of the EDCC materials, the “Premium Mix” and the “Regular Mix”, studied in this testing program. The walls were tested with different ground motions of all three types of crustal, sub-crustal, and subduction, with different intensities, as previously discussed. Generally, each wall is first tested with 100% of the actual intensity of the targeted ground motions, from the same records used throughout the analytical phases of the SRG III. Thereafter, the intensity was subsequently increased until the failure and eventually collapse of each wall. Fig. 4 shows a single-sided wall flexing under 200% of the actual intensity of the Japan’s 2011 Tohuku earthquake.

Fig. 4. Single Sided Retrofit using the Premium EDCC Mix tested at 200% Actual Intensity of the 2011 Tohuku Motion (GM-1)

The preliminary analysis of the test results confirms that a single sided retrofit with premium mix can extremely increase the overall ductility of the system and changing the fundamental behaviour of the wall from a typical “Rocking Mechanism” to a “Beam” type behaviour, with significant rotations at the hinge supports. In this system, a plastic hinge is formed at one and every single wall joint and the observed deformations are significant. This flexibility of the system results in a substantial amount of energy dissipation, and therefore, pushing the wall to the deformation limits beyond what is normally observed for non-retrofitted URM walls.

The wall developed a major plastic hinge at about 40% height from the base, and a localized crack was formed at the EDCC layer, where the wall started to rock at this joint and failed after four full rocking cycles. Fig. 5 shows the failure sequence of this wall at the final test, undergoing the second run of 200% actual intensity of the GM-1 record.

Peak accelerations of up to 5.6 g were recorded at the mid-height of this wall during the test, and significant damping were noticed at each of the loading and unloading cycles. The wall shown in Fig. 4 and Fig. 5 collapsed during the second run of the 200% scale of the actual intensity of the 2011 Tohuku ground motion of Japan, recorded at the Miyagi-Oki Station (Record ID # GM-1); this is considered a long duration subduction event. Particularly, the GM-1 is a shortened version of the actual recorded ground motion, which is originally 6 minutes long worth of ground shaking, from which a 3 minutes long truncated section, containing its strong motion part, is used as the GM-1 record.

Fig. 5. Different views of the single sided wall at extreme deformations at 200% intensity of the 2011 Tohuku Earthquake of Japan

The results conclude that the double-sided retrofit is performing beyond most of the requirements, but it can be a very good solution for areas with extreme seismicity. The double-sided retrofitted wall using Premium EDCC Mix was tested up to 300% actual intensities of most of the natural ground motions in hand, but finally it had to be tested with a 250% scale factor of a very aggressive UBC generated synthetized waveform, called the "Verteqii Motion", formally listed as the Record ID # GM-7 in Table 2.

3. Summary of the shake table testing results

As previously mentioned, all of the six EDCC retrofitted specimens listed in Table 1 are made of unreinforced 4" thick CMUs and are tested under a number of different ground motions, as listed in Table 2. A summary of the test results is presented in Table 3, which also shows the performances of these walls under different ground motions. Please note that, for each wall, the results are presented in the table at the same order in which the wall is tested.

Table 3. Summary of the Shake Table Testing Results

Specimen ID	Ground Motion	Scale factor (% of actual intensity)	Collapse (Yes / No)	Comments on the damage state
Wall-1	GM-1	10 %	No	No damage
Wall-1	GM-1	20 %	No	No damage
Wall-1	GM-1	30 %	No	No damage
Wall-1	GM-1	40 %	No	No damage
Wall-1	GM-1	50 %	No	No damage
Wall-1	GM-1	80 %	No	No damage
Wall-1	GM-1	100 %	No	No damage
Wall-1	GM-1	120 %	No	No damage
Wall-1	GM-1	150 %	No	No damage
Wall-1	GM-1	180 %	No	No damage
Wall-1	GM-1	200 %	No	No damage
Wall-1	GM-4	100 %	No	No damage
Wall-1	GM-4	120 %	No	No damage
Wall-1	GM-4	150 %	No	No damage
Wall-1	GM-4	200 %	No	No damage
Wall-1	GM-3	100 %	No	No damage
Wall-1	GM-3	150 %	No	No damage
Wall-1	GM-3	200 %	No	No damage
Wall-1	GM-3	250 %	No	No damage
Wall-1	GM-3	300 %	No	Minor cracks
Wall-1	GM-7	100 %	No	Minor cracks
Wall-1	GM-7	150 %	No	One major crack
Wall-1	GM-7	200 %	Yes	1 localized crack @ lower 1/2 of height
Wall-2	GM-1	100 %	No	No damage or visible cracks present anywhere
Wall-2	GM-4	100 %	No	No damage or visible cracks present anywhere
Wall-2	GM-1	120 %	No	Minor cracks at some joints
Wall-2	GM-1	150 %	No	Minor cracks at most joints
Wall-2	GM-1	180 %	No	Cracks at all the joints
Wall-2	GM-1	200 %	Yes	One localized crack at the mid-height of the wall
Wall-3	GM-2	100 %	No	No damage or visible cracks present anywhere
Wall-3	GM-4	100 %	No	No damage or visible cracks present anywhere
Wall-3	GM-1	100 %	No	No damage or visible cracks present anywhere

Wall-3	GM-1	150 %	No	No damage or visible cracks present anywhere
Wall-3	GM-4	150 %	No	No damage or visible cracks present anywhere
Wall-3	GM-4	180 %	No	No damage or visible cracks present anywhere
Wall-3	GM-2	150 %	No	No damage or visible cracks present anywhere
Wall-3	GM-3	100 %	No	No damage or visible cracks present anywhere
Wall-3	GM-3	150 %	No	Minor cracks at some joints
Wall-3	GM-6	150 %	No	Minor cracks at some joints at the mid-height of the wall
Wall-3	GM-3	200 %	No	Due to a system error, an emergency shutdown happened causing a major crack at about the mid-height of the wall
Wall-3	GM-1	50 % (1st aftershock)	No	One major crack at about the mid-height of the wall
Wall-3	GM-1	100 % (1st aftershock)	No	One major crack and some minor cracks at about the mid-height of the wall
Wall-3	GM-2	100 % (1st aftershock)	No	One major crack and some minor cracks at about the mid-height of the wall
Wall-3	GM-4	100 % (1st aftershock)	No	One major crack and many cracks at about the mid-height of the wall
Wall-3	GM-6	100 % (2nd aftershock)	No	One major crack and many cracks at about the mid-height of the wall
Wall-3	GM-3	50 % (2nd aftershock)	No	One major crack and many minor cracks at about the mid-height of the wall
Wall-3	GM-3	100 % (2nd aftershock)	No	One major crack and many major cracks at about the mid-height of the wall
Wall-3	GM-4	100 % (2nd aftershock)	Yes	One major localized crack (same crack) became unstable and fails
Wall-4	GM-5	100 %	No	No damage or visible cracks present anywhere
Wall-4	GM-4	100 %	No	Minor cracks at some joints
Wall-4	GM-4	120 %	Yes	One localized crack at the upper half height of the wall
Wall-5	GM-6	100 %	No	No damage or visible cracks present anywhere
Wall-5	GM-1	100 %	No	No damage or visible cracks present anywhere
Wall-5	GM-2	100 %	No	No damage or visible cracks present anywhere
Wall-5	GM-4	100 %	No	No damage or visible cracks present anywhere
Wall-5	GM-6	150 %	No	No damage or visible cracks present anywhere
Wall-6	GM-6	100 %	No	No damage or visible cracks present anywhere
Wall-6	GM-3	100 %	No	Minor cracks at some joints
Wall-6	GM-6	150 %	No	Minor cracks at some joints
Wall-6	GM-3	150 %	Yes	One localized crack at about the mid-height of the wall

4. Discussion of the results and Conclusions

Dynamic testing of full-scale specimens is one of the most effective experiments, which can be performed in order to fully understand the out of plane behaviour of such walls. The experimental results from the shake table testing revealed that EDCC is the perfect material for seismic retrofitting of such walls. The unreinforced non-grouted non-load bearing masonry walls are very prone to failure when it comes to sever ground shakings; and, currently securing this type of wall during seismic upgrade is almost impossible. Therefore, in most cases of retrofit design and planning, the removal of such walls is the most common solution now, which can be very costly and affects the construction time by a great factor.

When it comes to ground shaking, the predominant mode of failure for such walls is known to be collapse after a number of “rocking” cycles. In fact, considering the week mortar joints, which hold the masonry units together, the wall becomes non-linear at the very first moments of the ground motion. The non-linearity of such walls is very easy to predict by mathematical models. Indeed, due to the very weak nature of the masonry mortar joints in tension, the wall usually develops a major crack at the mortar joint located at about 40% of the wall height from the top of the wall, and then start rocking about the same joint. Although the mentioned localized crack is sometimes referred to as a “plastic hinge”, the formed hinge shoes almost zero plastic type deformation, so having zero stress carrying capacity, it mostly acts as pivot point which lets the masonry blocks above and below the joint to rotate about it, creating a rocking mechanism for the wall. Considering that the wall is now divided into two rigid bodies, the rocking motion is ongoing with a higher momentum each piece of the rigid body. Depending on the degree of fixity at the walls upper and lower boundary conditions, the wall may or may not develop a few more plastic hinges, at different mortar joints throughout the height of the wall, usually between 30% and 70% points of the wall height from the top or bottom. The more plastic hinges formed usually results in a more energy dissipative rocking behaviour during the motion, leading the wall to stay upright, and not collapse, for a longer duration of time during the seismic event. This type of rocking manner is known to be the fundamental behaviour of URM walls undergoing an earthquake ground motion. This experimental work illustrated that this fundamental rocking behaviour is changed to a bending-type behaviour for these walls, when a 20mm thick layer of EDCC is applied only on one side of the URM wall. This change in fundamental behaviour results in cracks to form at one and every mortar joint, generating a very high drift capacity for the wall due to the uniform, highly energy dissipative deformations during the entire stretch of the ground motion.

In addition, as a result of the EDCC retrofit, especially for the single-sided retrofitted walls, the base rotation is much more evident during the ground motion. Not only does this decrease the out of plane base shear demand on the wall, which sometime causes sliding and collapse for such walls, it also keeps the deformations more uniform and the geometrical instability happens at much higher drift limits for the wall. When an URM wall undergoes rocking, the center of the weight goes back and forth with respect to the center of the geometry of the wall out of its own plane during the ground motion. Anytime that the center of weight is pushed away from the center of geometry, beyond the half-thickness of the wall, by the momentum of the wall rocking, there is a significant p-delta effect which puts an extra overall bending demand on the wall. A typical URM wall has a very low bending capacity, due to its rocking type behaviour, whereas, now the wall will be able to withstand the bending forces, through some base rotations, and restore its position back to upright by the spring action of its overall bending stiffness.

Furthermore, the testing program confirms that a single-sided EDCC retrofit of 20mm thickness would be sufficient for most of the low-rise school buildings across the province of British Columbia. The numerical estimations, based on the experimental results, also indicate that even a 10mm thickness of the Premium Mix EDCC would be enough to keep the wall intact for a major earthquake in areas far away from the coast of BC, where the major fault lines are located. However, a double-sided EDCC retrofit is also an option for cases where ultimate drift needs to be limited for special cases, like hospitals where walls generally contain several mounted accessories or libraries where heavy bookshelves need to be attached to the wall; thus, the wall movements need to be limited for safety or even serviceability concerns. A double-sided retrofit can be applied in either 10mm or 20mm thickness and the Regular Mix EDCC would be more than enough, since there will not be any extensive strain demand on the EDCC layer during the course of the earthquake, as the overall wall deformations are now much limited in such case. Whereas, the Premium EDCC Mix, having a higher toughness, is ideal for single-sided applications, in which the wall is undergoing a number of large deformation cycles during the ground motion and, hence, the EDCC layer is required to take much larger tensile strains in order to dissipate the feed energy coming from the many repetitive large deformation phases.

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