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SEISMIC STRENGTHENING OF HOLLOW CONCRETE MASONRY WALLS USING ECO-FRIENDLY DUCTILE CEMENTITIOUS COMPOSITES (EDCC)

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ABSTRACT
In seismic zones, strengthening of existing masonry structures that do not comply with new building regulations is a necessity, especially plain masonry structures. The results presented are part of a comprehensive experimental study, aimed at investigating the effects of bonding Eco-friendly Ductile Cementitious Composite (EDCC) repair material in improving structural behaviour of hollow concrete masonry walls in seismic-prone areas of British Columbia. In this study, four groups of hollow concrete block walls were constructed. Each group consisted of three 1.8 m square specimens built with 390 × 190 × 190 mm (actual size) hollow concrete blocks and Type S mortar. Of the four groups, one group was assigned as the control group, and the remaining three groups were strengthened by applying the EDCC to one of three different thicknesses (5, 10 and 20 mm) on both sides of the walls. The objective was to find the most cost-effective thickness of the EDCC. The structural behaviour of specimens was evaluated through two kinds of tests: in-plane free vibration tests and in-plane quasi-static cyclic loading. The shear capacity, ductility and energy dissipation were evaluated using in-plane quasi-static tests while the dynamic characteristics of the specimens were investigated through in-plane free vibration tests. The vibration tests were carried out on the specimens prior to and after the quasi-static shear loading, in the uncracked and cracked conditions. The results showed the specimens that had the EDCC with a thickness of 5 and 10 mm on both sides performed better than those strengthened with a thickness of 20 mm.

KEYWORDS: *eco-friendly ductile cementitious composites (EDCC), energy dissipation, free vibration, hollow masonry, in-plane cyclic test, seismic strengthening*

INTRODUCTION
In seismic zones, masonry buildings, especially ones constructed of plain masonry, are prone to extensive damage during a seismic event because of predominantly non-ductile behaviour. In

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masonry structures, walls are usually supposed to maintain structural integrity and to dissipate the earthquake input energy. Therefore, the strength, ductility and post-peak behaviour (stiffness and strength degradation) of masonry walls are the most important parameters that should be taken into account to improve the seismic performance of masonry structures. The mechanism of stiffness degradation depends on the loading history and the characteristics of the walls such as material properties, ductility and geometry. The effects of stiffness degradation are more significant for buildings constructed on soft soil, especially those with a period shorter than that of the ground motion [1]. Multiple techniques are being developed to improve the seismic performance of masonry walls, such as: Textile-Reinforced Mortar (TRM), Near Surface Mounting (NSM) or External Bonding (EB) of reinforcement, fibre reinforced cement stucco, Engineered Cementitious Composite (ECC) shotcrete [2-7]. The most effective and consistent technique should be determined based on the aim of the strengthening and the characteristics of existing walls.

In the work described here, the effectiveness of an Eco-friendly Ductile Cementitious Composite (EDCC) repair material was investigated for seismic strengthening of hollow concrete masonry walls. Specimens representing partition walls in schools in British Columbia (BC), Canada, were tested under free vibration tests and quasi static loading, further to the work of Kaheh et al. [8-9].

EXPERIMENTAL PROGRAM

Wall Fabrication

Four groups of walls were tested to evaluate the effectiveness of the EDCC repair material on the in-plane shear response of concrete blockwork. Each group consisted of three 1.8 m square specimens, constructed from hollow concrete masonry units of actual dimension, 390 × 190 × 190 mm (compressive strength 15.7 MPa), and type S premixed mortar. Of the four groups, one group was assigned as the control group, and the remaining three groups were strengthened by applying the EDCC at one of three different thicknesses (5, 10 and 20 mm) on both sides of each wall (symmetrical strengthening). A summary of the walls and their ID is presented in Table 1. The designation of the strengthened specimens was XS-T-R where (XS) stands for the number of sides strengthened with the EDCC repair material, 2S for two-side strengthening. (T) indicates the thickness of the EDCC in mm, and (R) states the specimen number in its group; therefore, specimen 2S-05-3 was the third of the three walls strengthened with 5 mm of EDCC on each side. The specimens of Groups I and II were the same as those described by Kaheh et al. [8-9]. The properties of the masonry and the EDCC are presented in Table 2.

The walls were constructed on steel base beams equipped with three 200 mm high shear pins. The cores in the masonry that contained the shear pins were grouted only in their first course to prevent the wall sliding on the steel base beam during the tests. Before bolting the specimens to the load floor in the test frame, a special thin mortar was spread beneath the base beam to obtain a fixed boundary condition. The test frame is shown in Figure 1.

Table 1: Summary of Specimens

Group #	ID	Strengthening
Group I	C-1 C-2 C-3	None
Group II	2S-20-1 2S-20-2 2S-20-3	20 mm EDCC on each side
Group III	2S-10-1 2S-10-2 2S-10-3	10 mm EDCC on each side
Group IV	2S-05-1 2S-05-2 2S-05-3	5 mm EDCC on each side

Table 2: Masonry and EDCC Properties

Material	Samples	Compressive Strength (MPa)
Block	Block	15.7
Prism Group I	Three-high prism	16.9
Prism Group II	Three-high prism	17.2
Prism Group III, IV	Three-high prism	13.7
EDCC	Cylinder	45
		DTS*: 6.3 MPa

* Diametral Tensile Strength

Application of the EDCC

EDCC is a strain-hardening fiber-reinforced mortar with 1% polyester fibre (PET) and 1% polyvinyl alcohol fibre (PVA). The eco-friendly component is derived by replacing most of the Portland cement content (high energy intensity) with fly ash, which has lower energy intensity. The most cost-effective mixture-proportioning of the EDCC was determined through extensive experiments at the University of British Columbia [10-11].Table 3 shows the EDCC mix design used in this study.

Table 3: EDCC mix design [11]

Mixture	Cement	Fly ash	Silica fume	S/CM ratio[a]	W/CM ratio[b]	PET fibre (by volume)	PVA fibre (by volume)
EDCC	1	2	0.2	0.375	0.27	1%	1%

[a] S/CM: sand/cementitious material
[b] W/CM: water/cementitious material

The EDCC repair material was applied to the specimen surfaces layer by layer through hand application two weeks after the walls had been constructed. Prior to applying the repair material, the specimen surfaces were prepared by removing loose particles with sandpaper and spraying the surface water to help create good bond between the blockwork and the EDCC. After the EDCC had been applied, the specimens were cured for 30 days, being covered with wet burlaps overlain with plastic sheets.

Test Setup

Two kinds of tests were carried out on each specimen: in-plane quasi-static loading and in-plane free vibration tests at two levels of damage, resulting in three tests altogether. First, the walls were tested in the as-built, uncracked condition for in-plane free vibration. This was followed by applying quasi-static reverse cyclic loading to the walls, and finally, another in-plane free vibration test was performed with the wall cracked from the cyclic loading. The in-plane free vibration tests were thus carried out whilst there was no axial load on the specimens – the walls were free-standing cantilevers.

The procedure for free vibration tests was described in Kaheh and Shrive [9]. As can be seen in Figure 1, a cap plate was designed and connected to the top grouted course of each specimen through three 50 mm steel pins. The advantage of adding the cap plate to the test set-up was to allow connection and disconnection of the cap beam (see Figure 1) without damaging the specimen. The free-vibration tests could thus be easily executed before and after quasi-static cyclic loading. For a free vibration test, the cap plate was pulled with a cable so as not to crack the specimen, and the cable cut. The subsequent vibration was measured with laser displacement sensors and accelerometers. Data were acquired at a frequency of 6000 Hz during the free vibration tests. The free vibration tests were carried out on each specimen at two levels of damage: the first level was the uncracked condition, and the second was the cracked condition, which was caused by in-plane quasi-static shear loading to the same level of drift. The lateral displacement of the top of the wall was 7 mm at this point. The in-plane loading was stopped at the same level of drift for all specimens.

To test the specimens under quasi-static cyclic loading condition, the vertical actuators applied a low axial stress of 0.1 MPa to the specimen, as this is the order of magnitude of stress expected in a concrete block wall in a low rise building. The vertical actuators were programmed to maintain the same axial load throughout the test. This means the rotation of the top of the wall was not restrained, simulating the cantilever boundary condition dominant in the behaviour of walls in one-story buildings. The lateral loading was imposed with the horizontal actuator in a hybrid procedure of force- and displacement-control, as described in Kaheh et al. [8]. The cyclic displacement-controlled loading included sixteen stages with different amplitudes from 0.25 mm to 7 mm with a displacement rate of between 1 mm/min and 5 mm/min.

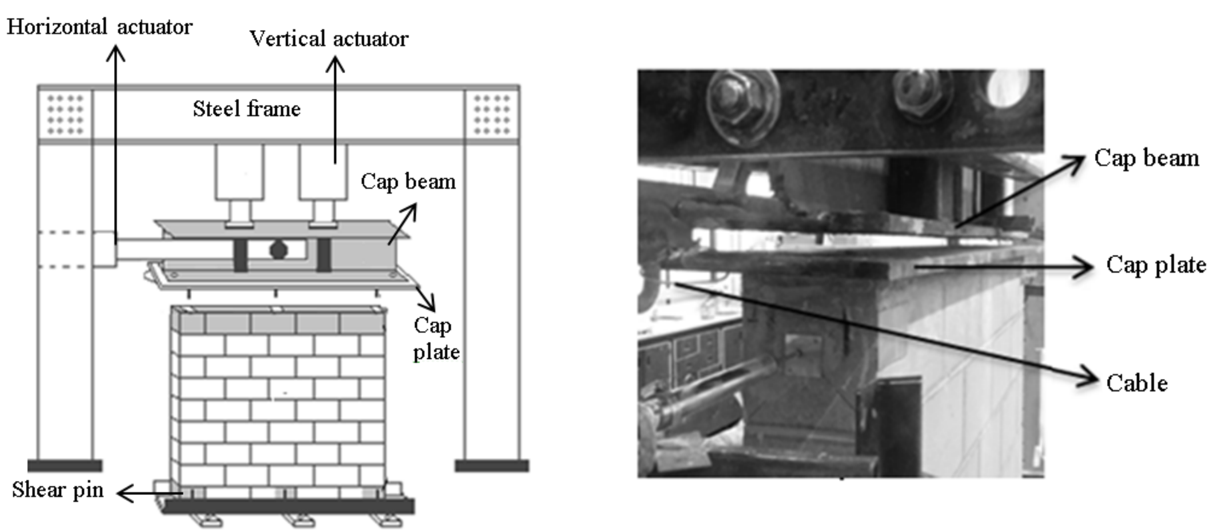

Figure 1: Test Setup for Quasi-static and Free Vibration Tests

EXPERIMENTAL RESULTS AND DISCUSSIONS

Quasi-static Cyclic Tests

The quasi-static cyclic test results for all four groups of specimens are summarized in Table 4, where V_{max} is the maximum lateral load and d_{vmax} is the corresponding displacement. The ultimate load resistance increased significantly in the strengthened specimens, compared to the control ones by 240%, 425% and 315% on average for Groups II, III and IV, respectively. Although the specimens in Groups III and IV were strengthened with thinner layers of EDCC than the walls in Group II, they showed better performance in many aspects such as load resistance, drift capacity, and stiffness degradation. The force-displacement hysteretic curves for specimens C-1, 2S-20-3, 2S-10-2 and 2S-05-2 are presented in Figure 2 for the quasi-static cyclic tests.

The EDCC with a thickness of 20 mm transferred a high percentage of the lateral load to the base without suffering any major cracking. Walls with this thickness of EDCC were observed to fail through vertical cracking of the webs of the blocks on the heel sides of the wall, as shown in Figure 3b. These cracks initially appeared in the web of the grouted core containing the shear pin when the specimen was being pushed from that side. This implies a tension-controlled failure as the wall was bent around the grouted core, with cross-wall bending causing splitting tension in the web. It was also noted that the base on which the walls were built bent up in the middle as this cracking developed. With this mode of failure, the tensile strength of the blocks used was one of the governing parameters that contributed to the in-plane behaviour of these specimens. This led to a high Coefficient of Variation (CV) in the ultimate resistance and ductility of this group of walls, about 22%. In an acceptable strengthening technique, the effect of the mechanical properties of existing materials on the achievement of the technique should be minimized. In addition, because the block failure was a result of the presence of the shear pins located in the first course, the predominant failure mode is expected to change to a rocking mode in the absence of shear pins. This is not a desirable failure in the case of seismic strengthening because of the minimal energy dissipation capability.

The specimens of Group III, where the thickness of the EDCC was decreased from 20 to 10 mm, showed more ductile behaviour than the specimens of Group II: d_{vmax} increased from 2.8 mm to 4.1 mm on average, an increase of almost 50 percent. A similar sort of increase was also observed in the ultimate load capacity with the peak load being 51.8 +/- 5.8 kN (compared to 33.4 +/- 7.2 kN for 20 mm Group II). These enhancements indicated that the 10 mm EDCC overlay was more involved during the cyclic loading, which led to a high drift capacity as a result of an increase in the number of micro cracks across the EDCC. Even though a better load distribution occurred in the strengthened specimens with 10 mm of EDCC on each side, the failure mode of specimens was the same as for those in Group II, web cracking, Figure 3c.

Table 4: Summary of Results for Quasi-static Cyclic Tests

Specimen			V_{max} (kN)				d_{vmax} (mm)				Failure mode
			Pull	Push	Ave (kN)	CV	Pull	Push	Ave (mm)	CV	
I	No EDCC	C-1	9.1	9.9	9.9	14.4 %	1.1	1.1	1.1	9.7%	RF(1)
		C-2	8.6	12.6			1.0	0.9			RF
		C-3	9.8	9.2			1.2	1.1			RF
II	20 mm EDCC	2S-20-1	34.0	22.3	33.4	21.5%	2.5	2.9	2.8	21.4%	BF(2)
		2S-20-2	29.0	33.5			2.5	4.0			BF
		2S-20-3	42.6	38.8			2.5	2.5			BF
III	10 mm EDCC	2S-10-1	48.9	49.3	51.8	11.2%	4.5	4.0	4.1	18.5%	BF
		2S-10-2	56.2	52.2			4.7	3.5			BF
		2S-10-3	60.3	44.0			5.0	3.0			BF
IV	5 mm EDCC	2S-05-1	39.9	42.0	41.2	9.6%	2.5	3.1	2.9	11.3%	EF(3)
		2S-05-2	47.6	35.8			3.3	2.9			EF
		2S-05-3	39.4	42.6			2.5	3			EF

(1): Rocking Failure, (2): Block Failed, (3): EDCC Failed

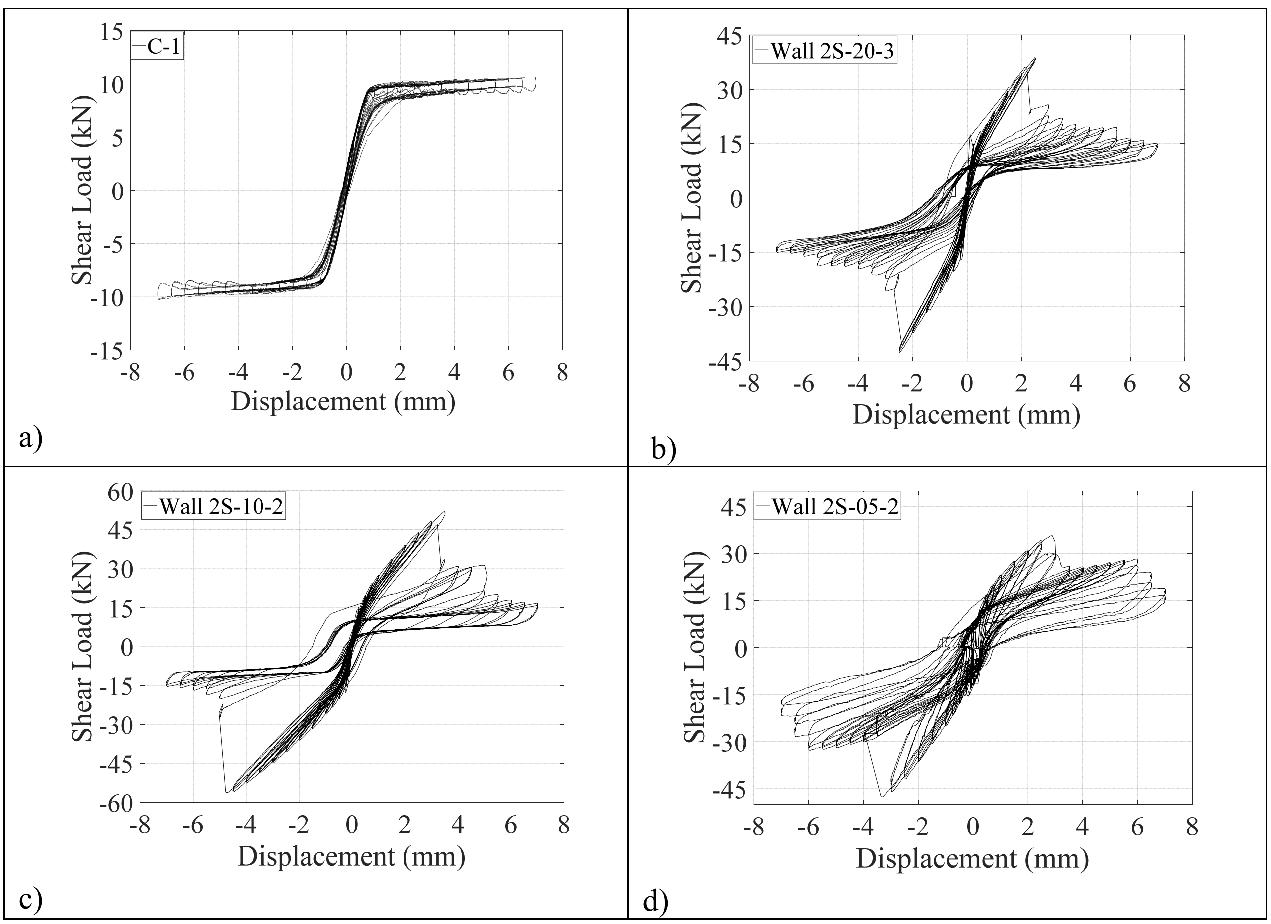

Figure 2: Hysteretic Curves (a) Wall C-1 (b) Wall 2S-20-3 (c) Wall 2S-10-2 (d) Wall 2S-05-2


a) Wall C-1


b) Wall 2S-20-3


c) Wall 2S-10-2

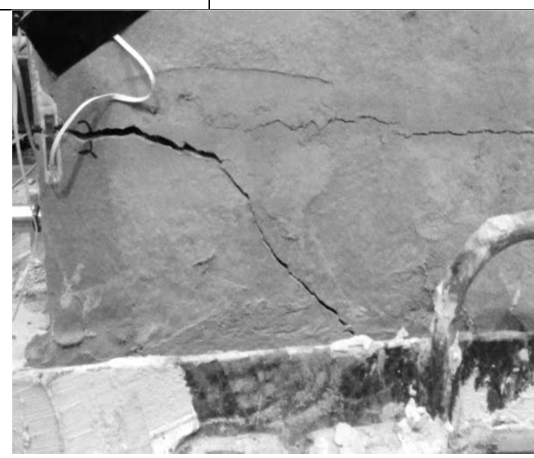
d) Wall 2S-05-2

Figure 3: Crack pattern (a) Wall C-1 (b) Wall 2S-20-3 (c) Wall 2S-10-2 (d) Wall 2S-05-2

The last three specimens were strengthened with a 5 mm layer of EDCC on each side, Group IV, with the aim of transferring the major cracking from blocks' webs to the repair material. As expected, the crack pattern changed, and damage was focused in the EDCC overlay across the first bed joint of the walls, Figure 3d. This meant that the EDCC was completely involved within the test and reached its ultimate tensile capacity. This was a desirable failure that increased the energy dissipation capacity of the specimens.

As may be seen in Figure 3d, the cracks propagated along two different paths for the specimens in Group IV. Initially, the cracks appeared at the level of the first bed joint of the wall when the top displacement of the wall reached around 3 mm. In following cycles, the cracks spread about 300 mm horizontally then took an inclined path to the base beam (black dashed-line). The onset of these cracks was concurrent with a drop in the peak load. Afterwards, the cracks started propagating in the middle third of the first bed joint, and moved towards the end edges (white dashed-line). The maximum lateral load reached 41.2 +/- 4.0 kN and the corresponding displacement 2.9 mm on average, with a CV of 11.3 %.

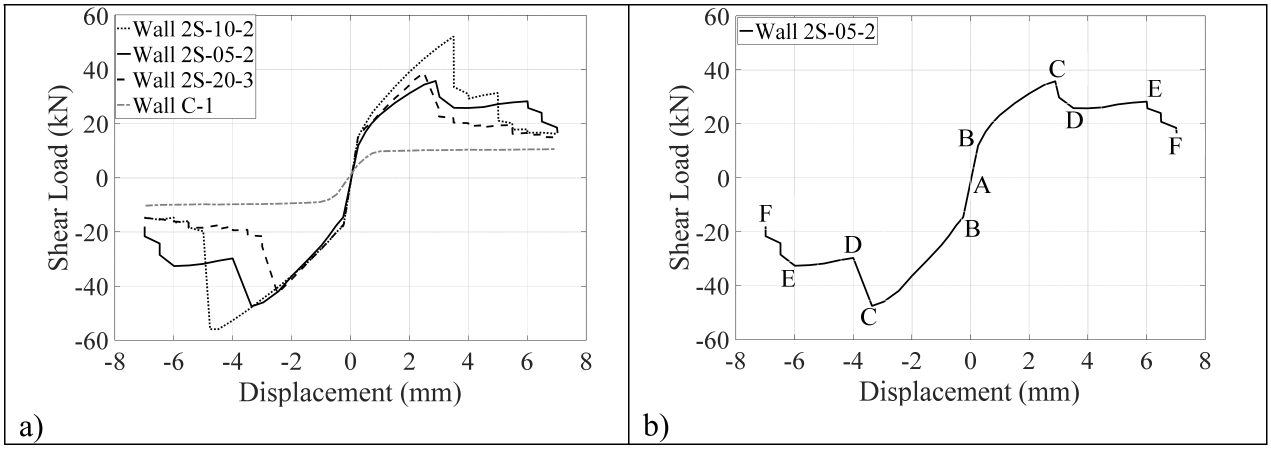

Figure 4: Envelope of Hysteretic Loops

The force-displacement envelopes diagram for walls C-1, 2S-20-3, 2S-10-2, and 2S-05-2 are shown in Figure 4. For all control walls, the lateral load reached its maximum with an approximately constant stiffness followed by a rocking failure. However, a different scenario can be observed in the envelope diagrams for strengthened specimens: a strain-hardening behaviour occurred before the maximum lateral load resistance was reached.

As to post-peak behaviour, Group IV (5 mm EDCC on each side) exhibited the best performance between the three strengthened groups of walls. The stiffness degradation of these specimens occurred more gradually, as may be seen in Figure 4a for wall 2S-05-2 compared to wall 2S-20-3 and 2S-10-2. Moreover, in all walls of Group IV, a different behaviour occurred after the first drop in the shear load. As can be seen in Figure 4b, the lateral load dropped from point C to D after reaching its maximum, which was the onset of cracking. Afterwards, the load started to increase again from point D to E so that the minimum corresponding displacement at point E was 6 mm. This kind of behaviour was a consequence of the gradual propagation of the cracks in the EDCC repair material, which was only observed in the specimens with the 5 mm EDCC layers.

Free Vibration Tests

Viscous-based damping was used to determine the dynamic characteristics of the walls because reasonable estimates can be obtained even though the effects of coulomb friction damping are more significant in cracked states. Viscous damping has the effect of lengthening the natural period from the undamped period to that of the damped period, Equation 1. However, the difference is negligible for specimens with a damping ratio below 20% [12]: therefore, for the subsequent discussion $T_d = T_n$ and $\omega_n = \omega_d$.

$$T_d = \frac{T_n}{\sqrt{1-\zeta^2}} \tag{1}$$

where ζ is the viscous damping ratio; T_n undamped period; and T_d damped period.

Table 5: Summary of Results for Free Vibration Tests

Specimen		Natural Frequency (Hz)		Reduction%
		Uncracked	Cracked	
Control No EDCC	C-1	26.2	23.3	11%
	C-2	37.7	18.0	52%
	C-3	37.3	26.4	29%
20 mm EDCC	2S-20-1	-	24.4	
	2S-20-2	63.5	33.4	47%
	2S-20-3	106.1	23.2	78%
10 mm EDCC	2S-10-1	109.6	33.6	69%
	2S-10-2	98.67	30.7	69%
	2S-10-3	106.7	33.6	69%
5 mm EDCC	2S-05-1	106.7	12.4	88%
	2S-05-2	-	17.5	-
	2S-05-3	105.2	12.8	88%

The results of the free vibration tests are presented in Table 5. The application of the EDCC increased the frequency of vibration of the specimens significantly in the uncracked state, which varied between 98 and 110 Hz, excluding specimen 2S-20-02. This means the natural frequency was approximately the same in the walls strengthened with the three different thicknesses of the EDCC (5, 10 and 20 mm). Thus, the natural period of the strengthened specimens appears to be independent of the thickness of the EDCC in the undamaged state. According to Equations 2 and 3, the natural frequency of a system with distributed mass and elasticity is related to the ratio of stiffness to mass [12], which remained virtually unchanged in the strengthened specimens.

$$f_n = \frac{\omega_n}{2\pi} \tag{2}$$

$$\omega_n{}^2 = \frac{\tilde{k}}{\tilde{m}} = \frac{\int_0^L EI(x)[\ddot{\varphi}(x)]^2\,dx}{\int_0^L m(x)[\varphi(x)]^2\,dx} \tag{3}$$

where ω_n and f_n are the natural frequency of vibration; k is the stiffness; *EI(x)* is the flexural rigidity; *m(x)* is the mass of wall per unit length; and $\varphi(x)$ is the shape function.

As expected, the natural frequency of vibration was less in the damaged than the undamaged state for all walls. The decrease in the natural frequency level could be attributed to the degree of damage. For instance, the natural frequency dropped by 88% for the walls in the Group IV as a result of the significant number of micro and macro cracks in the EDCC overlay. According to the data collected from the accelerometers mounted perpendicular to the direction of vibration, the out-of-plane mode shape was not excited in any of the walls strengthened on both sides during the in-plane free vibration tests. This is distinctly different to the walls strengthened on only one side, as described in Kaheh and Shrive [9].

CONCLUSION

Tests were carried out on four groups of three specimens to investigate the effectiveness of the EDCC repair material on the in-plane shear response of concrete block walls. One group was selected as the control group, and the remaining three groups were strengthened through applying the repair overlay at one of three different thicknesses (5, 10 and 20 mm) on both sides of the specimens. The specimens were subjected to two kinds of tests: in-plane free vibration and quasi-static cyclic loading. The free vibration tests were carried out before and after the quasi-static loading to assess the effect of damage on their dynamic response. From the test results, the following conclusions can be drawn:

1. In all strengthened specimens, the lateral load resistance and ductility was increased significantly compared to the control walls. The specimens with 20 mm EDCC on each side had the lowest increase in strength and ductility; while the specimens of Group III (10 mm EDCC) had the greatest increase in those parameters.
2. Damage was focused on the concrete blocks in the specimens with 10 and 20 mm EDCC on each side (web cracking), with no macro cracks being observed in the applied EDCC. However, in the specimens with 5 mm EDCC on each side, cracks occurred in the repair overlay, which led to better post-peak behaviour, and lower stiffness degradation as a consequence of the gradual crack propagation.
3. Block failure, which occurred in the specimens of Groups II and III, is not a desirable failure mode.
4. From the test results in this study, the most cost-effective thickness of EDCC for strengthening plain hollow concrete block masonry walls with low axial stress appears to be 5 mm on each side. This thickness is identified by taking into account all determinative parameters, including load resistance, ductility, post-peak behaviour, cost and preparation time.
5. The frequency of vibration of the strengthened specimens was enhanced significantly in the uncracked condition. Despite the different thicknesses of EDCC for specimens of groups II, III and IV, the percentage increase of the natural frequency remained unchanged. The natural frequency increased from about 34 Hz in control specimens to about 100 Hz in the strengthened ones.
6. In the damaged (cracked) state, the specimens of Group IV with 5 mm of EDCC had the highest decrease in the natural frequency because of a higher level of damage in the EDCC of these specimens compared to those with thicker layers.

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