Key Engineering Materials
ISSN: 1662-9795, Vol. 919, pp 108-120
doi:10.4028/p-x5552i

Submitted: 2021-07-19
Revised: 2021-11-16
Accepted: 2021-11-18
Online: 2022-05-11

Engineered Cementitious Composites for the Conservation of 20th Century Concrete Architectural Heritage

Antroula Georgiou[1,a*], Michalis Theodoulides[1,b] and Ioannis Ioannou[1,c]

[1]Department of Civil and Environmental Engineering, University of Cyprus

Panepistimiou Avenue. 2109 Aglantzia, Nicosia. P.O. Box 20537, 1678 Nicosia, Cyprus

[a*]ageorg44@ucy.ac.cy, [b]theodoulides.michalis@ucy.ac.cy, [c]ioannis@ucy.ac.cy

(*corresponding author)

Keywords: historic concrete, repair, strain hardening, fiber reinforced, cementitious composites

Abstract. Architectural heritage nowadays includes concrete structures constructed in the 20th century. These buildings are usually under-detailed, since the actual behavior of reinforced concrete at the time of their construction was not clearly understood, whilst building codes incorporating seismic resistance design, especially in seismic prone areas, did not exist. This inevitably led to inefficient design and consequently to severe damages in many historic concrete buildings during past seismic events. This paper explores the use of novel Engineered (Fiber Reinforced) Cementitious Composites (ECCs), with strain hardening abilities in tension, for the repair and strengthening of old sub-standard reinforced concrete columns, focusing on their confining and shear strengthening potentials. The experimental results show that, when replacing the reinforcement cover with fiber reinforced ECCs, the fibers bridge tensile cracks, limiting their opening and increasing their resistance against volumetric expansion, ultimately leading to increased amounts of energy dissipation. ECCs may thus by used in the repair of historic concrete structural elements.

Introduction

Historic Concrete Structures. Concrete structures constructed in the 20th century were usually under-detailed due to their experimental nature, the lack of knowledge in reinforced concrete (RC) mechanics at the time of their construction and the absence of building codes and standards for seismic resistance design [1]. These, along with the poor quality of the materials used for the construction of historic concrete structures, have led to severe damages or even to collapse during past seismic events [2]. Local deficiencies that lead to brittle damages in historic concrete structures are usually related to sparce stirrups, the lack of confinement in joint regions, low strength concrete and steel, and insufficient lap splices [3]; corrosion of the reinforcement and other moisture related processes also affect the durability of historic concrete structures [4]. At global level, soft stories are one of the main problems historic modernist structures face, due to the low lateral stiffness of slim members, resulting in high lateral sway imposed by earthquakes [5]. It is worth noting that early concrete was prepared on site, in small quantities, and was cast without the use of compaction equipment [6].

The preservation of historic concrete structures requires that no significant changes are implemented during their retrofit, especially in terms of geometry of their structural elements. At the same time, EC8-Part 3 [7], which is the normative document that describes the assessment and retrofit procedures for substandard structures against seismic loading, excludes historic structures.

Engineered Cementitious Composites (ECCs). These novel materials introduce the use of short randomly oriented plastic fibers in order to allocate strain hardening properties to the mix design in tension. Furthermore, ECCs exclude the use of coarse aggregates, in order to minimize the possible crack initiation areas, but may incorporate recycled waste materials, such as fly ash or silica fume, to minimize CO_2 emissions, whilst at the same time increasing the strength and/or workability of the end-product.

Even though most of the published research regarding ECCs refers to the use of the materials with regards to the design of new structures, some preliminary research results suggest the use of ECCs as promising repair materials for historic concrete structures, due to their ability to trap interface cracks and prevent spalling or delamination [8]. Initially, the use of ECCs for repair practices involved research on overlays, usually bridge decks [9]. The results showed that existing substrate cracks were arrested within the ECC material, allowing great deflections to occur by the opening of multiple cracking with relatively small crack width. The proper amount of fibers to be incorporated in the mix design should reflect each matrix, in order to achieve best performance and workability. Another potential repair use of ECCs involves the application of an additional layer of the material at the bottom of beams; bending tests carried out after this application showed failure of the compressive zone after very high deflections, good bonding with the substrate, and no delamination under repeated loading [10–13].

ECCs have also been developed for wet mix shotcreting [14] in small thicknesses of 45 mm on vertical surfaces and 25 mm on the overhead; these have been successfully used for the repair of beams that exhibited significant difference to their plain concrete counterparts. In that case, the plain mix repaired beams failed suddenly, in contrast to the strain hardening cementitious composite (SHCC) repaired beams that displayed multiple cracking, deflection hardening and energy dissipation. Additionally, the use of a repair layer around beams was compared to the patch repair method, for shear dominant members, indicating a substantial increase in strength and ductility of RC beams after peak load [15].

For the case of existing damaged or pre-damaged RC columns, ECC jacketing appears to be a suitable repair/retrofitting technique, especially in terms of shear [16–18] under reversed cyclic loading. Gholampour et al. [19] studied the effectiveness of confinement of core samples repaired with layers of ECC, whereby the core material had the same compressive strength with the ECC material. The effectiveness of ECC repair jacketing in low strength concrete members, which is the usual case in historic concrete structures, has nevertheless not been tested until now; therefore, more research is needed for quantifying the effectiveness of this technique. In this framework, the relation between the compressive strength of low strength historic concrete with ECC confinement and the jacketed system's final strength, in comparison to the properties of the jacket material and dimensions, is hereby investigated.

Methodology

The retaining and repairing, rather than replacing, poses a challenge when historic reinforced concrete elements are concerned. While in regions without earthquakes, preventive techniques (such as the use of water-repellent materials, or the adoption of electrochemical methods, such as re-alkalization of concrete, or cathodic protection of reinforcement [20]) may be adopted, in the case of structures under-designed for lateral loads, more active measures have to be undertaken. This is especially true in cases where, in addition to seismic actions, the building materials have been significantly weathered. Furthermore, repair materials should have lower modulus of elasticity, compared to that of the original concrete, in order to reduce the risk of damage to the latter (ACI Committee 546, 2006 [21]).

Historic concrete, in its earliest forms, was produced and designed by patented systems, such as the Hennebique (1892) [22], which are now considered obsolete. Reproducing the same materials and techniques is, thus, not an option, since both the raw material (cement, aggregates, steel) properties and the structural members geometry and detailing have changed. In this case, the conservation approach should aim at *retreatability* (i.e., the repair material should not preclude or impede further treatment in the future) [23,24]. Retreatability replaces the previously used term *reversibility*, which originated from art conservation and was deemed unsuitable for building conservation [24,25].

This research assesses the use of ECC jacketing on historic low strength concrete, through cover replacement. Initially, a historic case study structure (Fig. 1) built in accordance with the Hennebique patented system in Cyprus, with reinforced concrete structural members and load bearing masonry walls, was investigated and assessed under seismic loading. The seismic assessment revealed the structural deficiencies of the case study building structural members. The properties of the original concrete material were then used to define a new, equivalent low strength concrete to be subjected to repair. An ECC material was prepared by testing Polyethylene (PE) fibers of different lengths and surface characteristics; this was used for the repair jacketing of the low strength concrete. The experimental program consisted of a series of tests (compression, tension, split, bending) for the characterization of the materials designed and produced in the lab, and two types of repaired cores under compression, one to define the confinement effect of the jacket and the second to determine the axial load of the final retrofit practice.

Figure 1: Aerial photo of the case study building.

In-situ investigations. An extended in-situ investigation was performed, aiming initially at the verification of the geometry of the structural members. Since only some of the original construction detailing drawings were found, comprising mainly the slab reinforcement, a rebar detector (PROCEQ) was used to (i) verify the slab reinforcement in relation to the original drawings, and (ii) detect the steel reinforcement, rebar cover and diameter in the beams and columns. The detection of the reinforcement position was also used to determine the locations for the non-destructive rebound tests (EN 12504-2) and the possible positions for core sampling of concrete (EN 12504-1) [26]. The number of core samples had to be limited, due to the fact that the building is listed. For this reason, core samples were taken only from a column, a single location at the basement ceiling slab and another location at the ground floor roof slab (Fig. 2).

Figure 2: Left: Core sample taken from basement ceiling slab with reinforcement embedded in it. Middle: Core sample taken from column. Right: Location of core sampling from column.

The cover to the reinforcement was established both by the use of the PROCEQ rebar detector and from one of the samples taken from the slab that cut through a steel rebar (Fig. 2), as well as from in-situ observations of the columns that suffered from cover delamination and the reinforcement was thus visible. The concrete cover of the longitudinal bars was in the order of 20 mm. The longitudinal reinforcement of the columns, based on the exposed element (Fig. 3) and on a series of measurements with the rebar detector was found to be in the order of 5/8” (15.875 mm), since inches were used at that time for bar sizing, while no stirrups were used to confine the longitudinal bars (besides some thin wires to hold them in place during casting). This is in agreement with detailing plans found in the literature [27].

Figure 3: Cover delamination and rebar corrosion on exposed column.

Laboratory investigations. The following tests were carried out in the lab on the concrete specimens collected in-situ: (a) dry mass, density and porosity, by vacuum assisted water absorption, and (b) uniaxial compression (EN 12390-3 [28]) (Fig. 4). The samples showed low variability in the test results, even though concrete at the time the building was constructed was manually mixed on site in small batches. The average apparent density was found to be 2192 kg/m^3, while the open porosity was 18.3%. The average compressive strength was 15.21 MPa, resulting from samples with aspect ratio 1:1 (i.e., equivalent to mean cube strength), with the lower value of 13.92 MPa obtained from the roof slab, and the maximum of 17.11 MPa obtained from the column sample. The maximum (natural) aggregate size from the samples tested was recorded as 52 mm, though most samples included aggregates of much smaller diameter. Visually, the mix design showed no apparent voids or cracks, even though at the time there were no mechanical means for concrete compaction.

Figure 4: Tests on concrete. Left: Specimens for porosity measurement in the vacuum vessel. Middle: Testing apparatus for concrete compression. Right: Failure of concrete specimen in compression.

The concrete properties and detailing, the raw materials and the mix design are not in agreement with today’s practice included in Design Codes: the diameter and shape of the natural aggregates, the low strength of the cement used at the time, the mild steel rebars without ribs, the lack of stirrups and the small dimensions of the cross-section are all against current seismic design provisions and concrete standards. These render any attempts to reproduce exactly the original concrete material and members not feasible. Furthermore, the structural assessment of the existing column members showed that, in the event of an earthquake, these will fail in a brittle shear manner, compromising the stability of the porches they support.

Materials Used for the Experimental Investigation of the Repair Jacketing

Design of reference low-strength concrete (LSC). Even though reproducing exactly the same concrete mixture as the original one was not feasible, due to the different properties of the raw materials available today, a mix design (LSC) with similar compressive strength and density to the original concrete found in the structure under study was prepared: i.e., target cube compressive strength 15 MPa and target density ρ=2192 kg/m^3. This ensured the "compatibility" of the two mixtures. To achieve this, EN 1766 [29] was used, along with the American Concrete Institute (ACI) *mix design* proportioning method [30]. According to EN 1766, Concrete Type MC (0.9) was chosen, with a mean compressive strength at 28 days of 15±5 MPa for cubes and 12±5 MPa for cylinders. This mix should contain 195 kg/m^3 of cement, 10 mm maximum aggregate size and a water:cement ratio of 0.9±0.05. The mix proportions for the sand and coarse aggregate were calculated with the ACI method, but the cement (Ordinary Portland Cement, OPC 32.5) to sand ratio was set at 1:3, in order to replicate the mix proportioning used at the time of the construction of the case study building, that varied between 1:2:4 to 1:3:6 (cement:sand:coarse aggregate) [6]. The final mix proportions are summarized in Table 1.

Table 1:Mix designs for Low Strength Concrete (LSC) and ECC repair material

Sample	Cement	Water	Coarse aggregates	Sand A	Sand B	Silica fume	Fibers
LSC	1	0.9	7.75	1.55	1.55	-	-
ECC	1	0.375	-	0.395		0.083	2%

Repair material. A type of Strain Hardening Fiber Reinforced Cementitious Composite (SHFRCC) or ECC was chosen to be used as repair material for the historic case study building concrete columns that show cover delamination, corrosion of reinforcement and lack of stirrups/confinement. ECCs have the ability to arrest cracking through the action of the fibers bridging the cracks. High Tenacity Polyethylene (PE) fibers of 12 mm length were used; these were provided coated by the supplier. The length and surface characteristics of the fibers play an important role in the tensile strength, crack-bridging effect and ductility in tension of the end-composite [31]. PE fibers have a hydrophobic surface, thus a very low bond strength is exerted between the fiber and the surrounding matrix. In this case, pullout may lead to strain softening effects. In order to increase the bond, the provider of the fibers adopted in this study used a proprietary coating. The peak strain of the 12 mm High Tenacity Polyethylene fibers hereby used is 2.6%; their density and diameter are 970 kg/m^3 and 17.9 μm, respectively, their breaking strength is at 3000 MPa and their modulus of elasticity is 114 GPa.

Besides the fibers, the ECC mix design consisted of Ordinary Portland Cement (OPC) 52.5, silica sand with maximum grain size of 300 μm, and silica fume. The silica fume Grade 920 was provided by ELKEM Microsilica Cyprus. Silica fume is a recovered mineral component (RMC), the use of which has a high sustainability impact [32]. It can fill the gaps between cement grains and give mobility to the mix by allowing concrete to flow more easily when energy is applied to it, thus reducing segregation [33]. Furthermore, since silica fume has pozzolanic properties, it increases the strength and reduces the permeability of the final product [34]. The ECC mix design is shown in Table 1. PE fibers were added at a quantity of 2% by volume. The mixing order was as follows: (i) The dry materials (sand, silica fume, cement) were mixed together for more than 10 min, (ii) 90% of the water was added to the mix, which achieved self-compacting properties, (iii) fibers were added slowly to the mix in order to achieve proper dispersion, (iv) the rest of the water was added, along with a High Range Water Reducer (HRWR).

Mixing, Casting and Preparation of Specimens

The technique of replacing the cover of low strength reinforced concrete members with ECC materials has not yet been studied extensively, and the effectiveness of the confinement provided by the ECC has not yet been quantified. Another gap in the literature is the estimation of the final compressive strength of the jacketed member, which is related to the increase of the capacity of the original low strength concrete due to the confinement effect. In order to explore this subject, small cylindrical specimens of 100 mm diameter were prepared, confined with 25 mm cover of the ECC material (Table 2). The specimens were tested under uniaxial compression. Two sets of experiments were performed (Fig. 5): (a) one with compression only on the internal diameter low strength concrete core, to assist in defining the new confined strength and confinement provided by the ECC, and (b) one on the full final cross section of the jacketed cylinder. Low strength concrete specimens of the same size were used as reference. Three specimens were tested for each type of setup.

Table 2. Specimen dimensions before and after jacketing. Samples C-100/150 refer to the as cast non-repaired (reference) concrete samples, while samples R-C-100/150 refer to the repaired cylinders with final diameter of 100/150 mm; COMP. D_o refers to compression applied only to the internal core, while COMP. D_{col} refers to the samples where the load was applied to the full cross section of the member; D is the diameter and H is the height of the specimens before and after the repair

Sample	Type of loading	Material	Dim. before repair		Repair	Dim. after repair	
			D (mm)	H (mm)		D (mm)	H (mm)
C-100	COMP. D_o	C12	100	200	-	-	-
C-150	COMP. D_{col}	C12	150	300	-	-	-
R-C-100	COMP. D_o	C12/FRC	100	200	YES	150	200
R-C-150	COMP. D_{col}	C12/FRC	100	300	YES	150	300

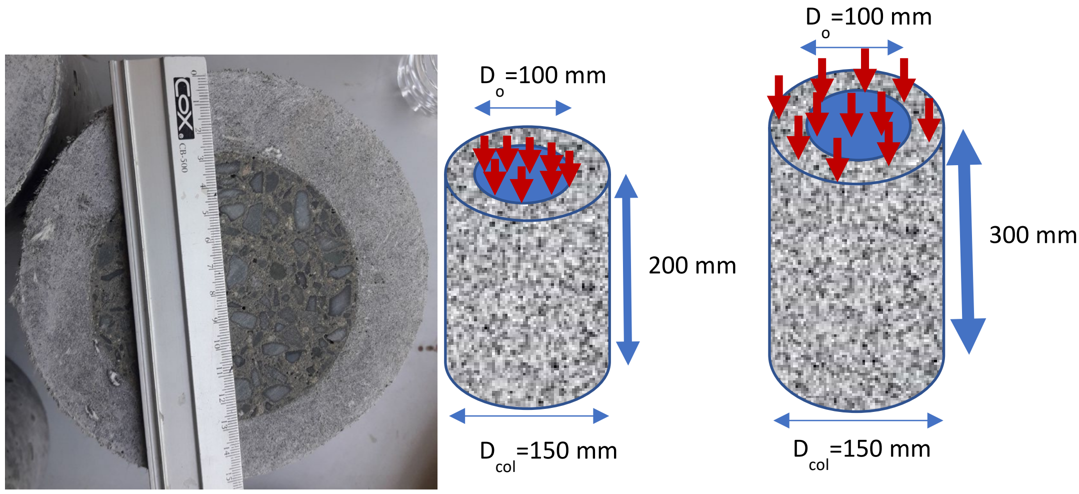

Figure 5: Left: Photo of a low strength concrete core confined with ECC. Middle: Setup A for confinement. Right: Setup B for jacketed member compressive strength.

In order to prepare the specimens, the low strength parts were first prepared with the use of cylindrical molds. After casting, the specimens were left to dry for 24 hours and they were then placed in a sealed container, covered with a wet burlap. One week later, the low strength cylinders were placed in the bigger diameter molds and the ECC was cast around them; compaction of the ECC was carried out with the use of a rebar. As with the original cylinders, 24 hours after casting, the new specimens were wrapped in wet burlap and placed in a sealed container until the repair material reached a curing age of 28 days.

Experimental Results and Discussion

Part A: Tests for the characterization of the materials

A.1 Low strength concrete. Tests were conducted on the LSC in order to acquire the compressive strength and indirect tensile strength of the material. The compressive strength and strain at maximum compressive stress, the split cylinder tensile strength, and the flexural strength under four-point bending are recorded in Table 3, together with the average values and standard deviations of the results. The stress-strain, both axial and lateral, under uniaxial compression, and the failure patterns are depicted in Fig. 6.

Table 3. Strength of LSC under compression (C), split (S) and flexure (B) tests

Specimen	f_{cmax} (MPa)	ε_o	Specimen	$f_{t,sp}$ (MPa)	Specimen	f_{fl} (MPa)
L1-C1	9.69	0.00445	L1-S1	1.195	L1-B1	2.101
L1-C2	9.32	0.00749	L1-S2	1.437	L1-B2	2.349
L1-C3	11.64	0.00460	L1-S3	1.569	L1-B3	2.200
Average	10.22	0.0055		1.40		2.22
Stand. Dev.	1.64	0.0020		0.09		0.11

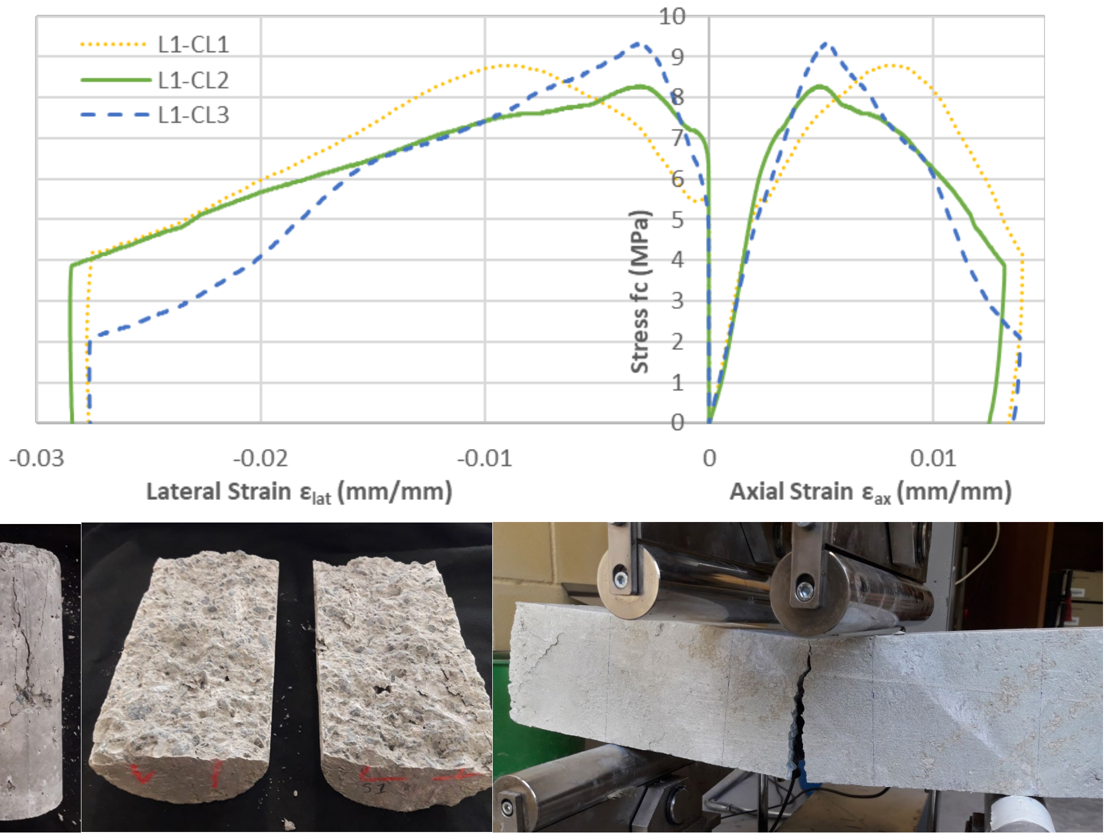

Figure 6: Top: Compressive stress-axial strain-lateral strain of LSC specimens. Bottom: Failure patterns under uniaxial compression (left), split cylinder (middle) and four-point bending (right) tests.

A.2 ECC jacket for repair. For the characterization of the behavior of the ECC jacket material, uniaxial compression, tension, split cylinder and four-point bending tests were performed, resulting in the stress-strain curves of Fig. 7. The ECC material exhibited strain hardening behavior, with an ultimate tensile strain prior to crack localization in the order of 1%. The uniaxial tensile stress obtained was ca. 2.5 MPa. The strain hardening behavior was extrapolated to the indirect tensile tests of split cylinder and four-point bending that also exhibited multiple cracking, large deformation capacity, increase of strength after first cracking and high energy dissipation. Additionally, in the uniaxial compression tests, failure was delayed with a shift of strain at peak load, and low lateral deformations, due to the confinement action of the fibers bridging vertical cracks; this is typical of strain hardening fiber reinforced cementitious composites [35].

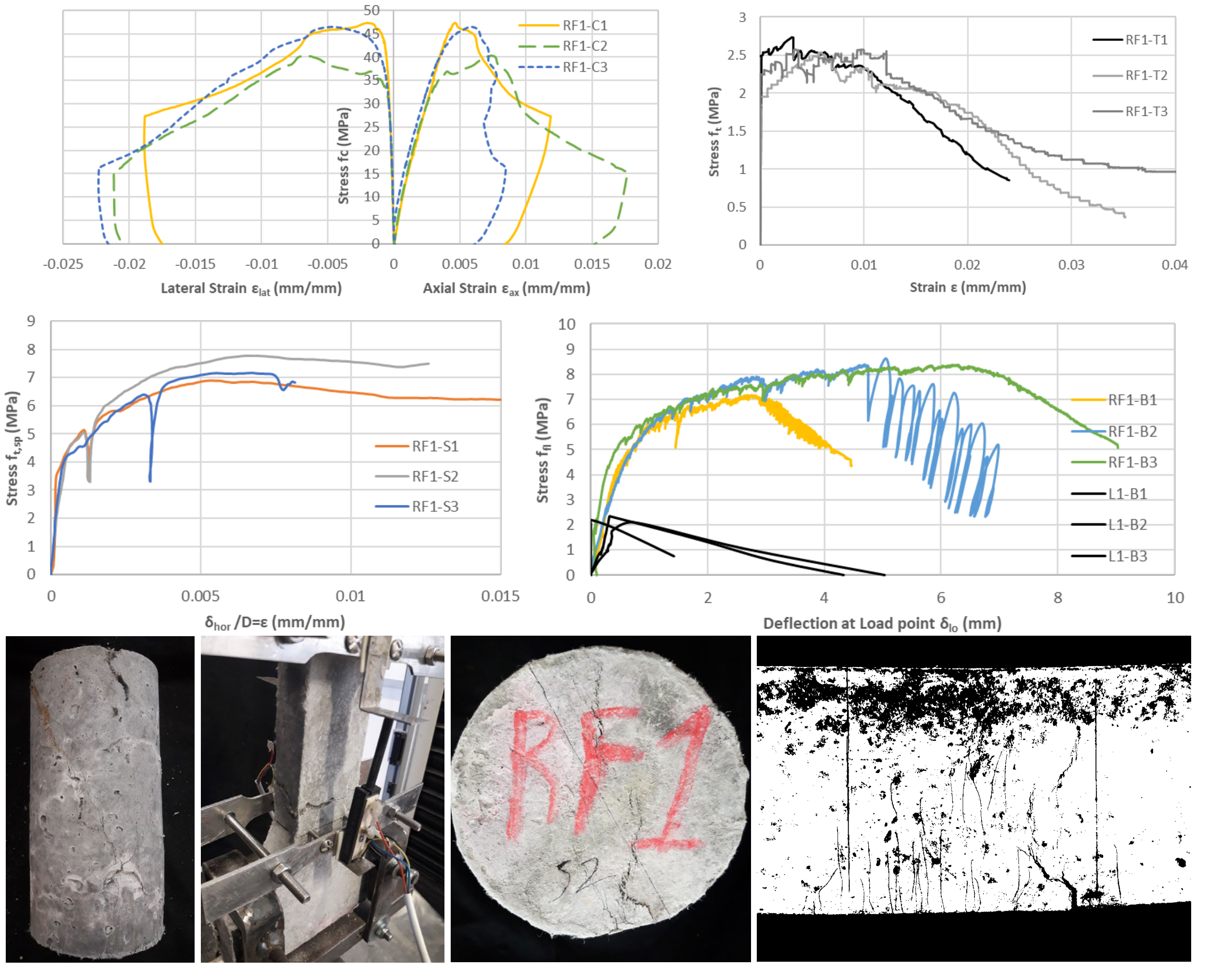

Figure 7: Top row: Compressive stress-axial strain-lateral strain (left) and uniaxial tension stress-strain curve (right) of ECC specimens. Middle row: Split cylinder stress-horizontal strain (left) and four-point bending stress-load point deflection (right) of ECC specimens. Bottom row: Failure patterns of ECC specimens.

Part B: Evaluation of the effect of confinement on the compressive strength of historic concrete

The confinement effectiveness on the compressive strength of the LSC was verified by comparing the results of similar cylindrical specimens (100x200 mm), with and without confinement, as shown in Fig. 8. The confined LSC compressive strength (f_{cc}) was double the relevant unconfined compressive strength (f_c) due to the restriction in lateral expansion provided by the ECC material. The strength of the confined concrete was calculated using the lateral stress (σ_{lat}), based on the Richart model for confined concrete [36]. The lateral stress imparted by the ECC, σ_{lat}, is related to the tensile split first cracking strength, $f_{t,sp,y}$, and the cover to internal core ratio, c/d_o:

$$f_{cc} = f_c + 4.1 \cdot \sigma_{lat}. \quad (1)$$

$$\sigma_{lat.} = 2 \cdot f_{t,sp,y} \cdot (c/d_o) \quad (2)$$

where $\sigma_{lat.}$=2.26 MPa, f_c=10.22 MPa, f_{cc}=19.49 MPa.

Therefore, the confined concrete strength may be calculated by Eq. 3:

$$f_{cc} = f_c + 8.2 \cdot f_{t,sp,y} \cdot (c/d_o) \quad (3)$$

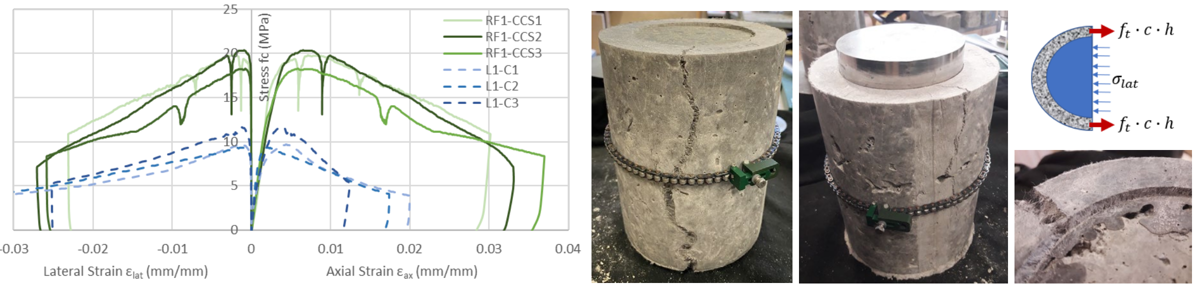

Figure 8: Compressive stress-axial strain-lateral strain of LSC confined with ECC (left) and failure patterns (right).

Part C: Evaluation of the compressive strength of jacketed historic concrete columns

Cylinders measuring 150x300 mm, consisting of an internal core of LSC with dimensions 100x300 mm and 25 mm ECC cover, were tested under displacement-controlled compression, with the load applied on the entire cross section. The compressive strengths of the confined specimens ($f_{col,jac}$) were equal to 3 times that of identical 150x300 mm cylinders of LSC (f_c). The stress-axial strain-lateral strain of the members is recorded in Fig. 9. The average values of compressive strength from the tests were used to calibrate an equation that can be used to compute the compressive strength of the ECC jacketed LSC members. The analysis used equilibrium of forces, as well as Eq. 3 for the confined LSC core strength (f_{cc}).

$$N_j = A_{cov} \cdot f_{c,ecc} + A_o f_{cc} = (A_{col} - A_o) f_{c,ecc} + A_o f_{cc} = \frac{\pi}{4}(D_{col}^2 - D_o^2) \cdot f_{c,ecc} + \frac{\pi}{4} D_o^2 \cdot f_{cc} \quad (4)$$

$$f_{col,jac} = \left(f_c + 8.2 \cdot \left(\frac{D_{col} - D_o}{D_o}\right) \cdot f_{t,sp,y}\right) \cdot \left(\frac{D_o}{D_{col}}\right)^2 + f_{c,ecc} \cdot \left(1 - \left(\frac{D_o}{D_{col}}\right)^2\right) \quad (5)$$

Where N_j is the ultimate axial load obtained during the test, A_{cov} is the area of the ECC confinement, $f_{c,ecc}$ is the compressive strength of the repair material, A_o is the area of the internal LSC core, f_{cc} is the strength of the confined LSC core, A_{col} is the total area of the member's cross section, D_{col} is the total diameter of the member's cross section, D_o is the internal diameter of the LSC.

As seen in Eq. 4 and 5, the compressive strength of the jacketed column is related to (a) the split tensile strength at the initiation of cracking, $f_{t,sp,y}$, and the compressive strength, $f_{c,ecc}$, of the ECC repair material, and (b) the ratio between the internal diameter and the jacketed column total diameter, D_o/D_{col}.

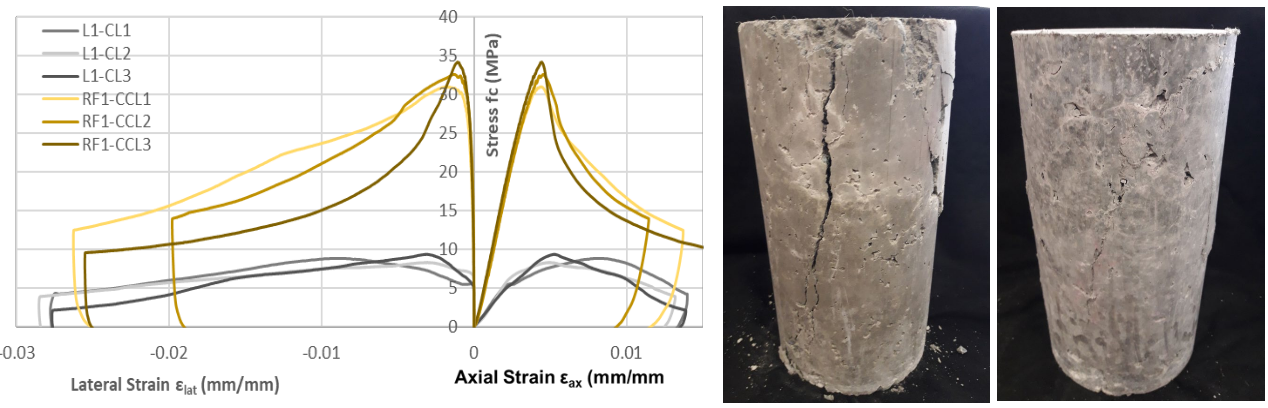

Figure 9: Compressive stress-axial strain-lateral strain of jacketed LSC member with 25 mm ECC (left) and failure patterns of LSC (middle) and jacketed (right) members.

Design of the jacket repair

The design of the repair of LSC members using ECC jacketing may benefit from the use of diagrams that relate the original member's compressive strength, the ratio of the jacket thickness to the jacketed column's final diameter and the resulting/required compressive strength of the repaired member. These three parameters may be plotted in diagrams for different LSC compressive strengths, as shown in Fig. 10 for the specific repair ECC material. The equation relating these properties is extrapolated by Eq. 6:

$$f_{col,jac} = f_{c,ecc} + 4.1 \cdot f_{t,sp,y} \cdot \left(\frac{D_O}{D_{col}}\right) + \left(f_c - f_{c,ecc} - 4.1 \cdot f_{t,sp,y}\right) \cdot \left(\frac{D_O}{D_{col}}\right)^2 \quad (6)$$

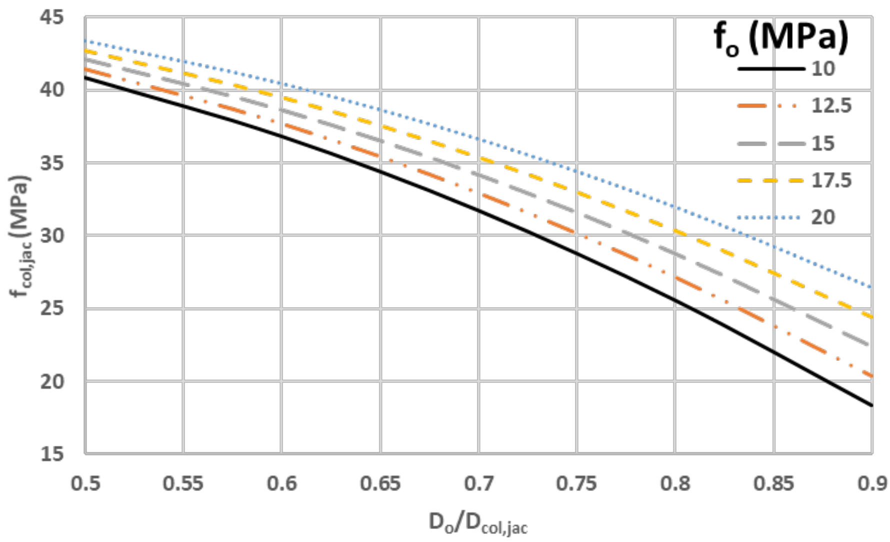

Figure 10: Simple diagrams for the calculation of the necessary $D_o/D_{col,jac}$ ratio in relation to the required compressive strength of the repaired concrete ($f_{col,jac}$) and the compressive strength of the original concrete (f_o).

Conclusions

Historic concrete structures are prone to deterioration and damage due to their intrinsic characteristics, which relate to the properties of the raw materials, the geometry of the members and the detailing of the reinforcement. Restrictions on the possible retrofit solutions require that the structural members' dimensions, and thus the original architectural form, should not be altered, while safety provisions, especially under seismic loading, require drastic increase in strength and ductility. This paper explored the effect of jacketing low strength historic concrete, by replacing the concrete cover with strain hardening fiber reinforced cementitious composites. This strengthening practice for low strength historic concrete appears to result in very effective confinement, even with small covers. The confinement effect, according to the experimental results, is related to the split tensile strength of the ECC material. Additionally, the compressive strength of the jacketed member is related to the properties of the ECC in tension and compression, and to the $D_o/D_{col,jac}$ ratio. Finally, simple equations and diagrams have been provided to enable the design for the retrofit of low strength historic concrete with ECC jacketing.

Acknowledgements

The research is part of the JPI Cultural Heritage research project "Conservation of 20th century concrete Cultural Heritage in urban changing environments" (CONSECH20). The authors would like to acknowledge funding by the Republic of Cyprus, through the Cyprus Research Promotion Foundation (Project P2P/JPICH_HCE/0917/0012). They would also like to thank AGBU for providing access to the structure under study for sampling and testing.

References

[1] H.A. Heinemann, Why historie concrete buildings need holistic surveys, Proc. Int. FIB Symp. 2008 - Tailor Made Concr. Struct. New Solut. Our Soc. (2008) 47. https://doi.org/10.1201/9781439828410.ch23.

[2] K.Q. Walsh, K.J. Elwood, J.M. Ingham, Seismic considerations for the Art Deco interwar reinforced-concrete buildings of Napier, New Zealand, Nat. Hazards Rev. 16 (2015) 1–21. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000169.

[3] S.J. Pardalopoulos, G.E. Thermou, S.J. Pantazopoulou, Screening Criteria to Identify Brittle R. C. Structural Failures in Earthquakes, Bull. Earthq. Eng. 11 (2013) 607–636. https://doi.org/10.1007/s10518-012-9390-7.

[4] G.P. Redondo, G. Franco, A. Georgiou, I. Ioannou, B. Lubelli, S.F. Musso, S. Naldini, C. Nunes, R. Vecchiattini, State of Conservation of Concrete Heritage Buildings : A European Screening, Infrastructures. 6 (2021) 1–15. https://doi.org/https://doi.org/10.3390/infrastructures6080109.

[5] R. Ferreira, C.S. Oliveira, SOFT-STOREY BUILDING IN LISBON : SEISMIC VULNERABILITY, (2019) 1–10.

[6] A. Georgiou, I. Ioannou, S. Pantazopoulou, Rehabilitation of 20 Th Century Concrete Heritage Buildings : the Case Study of the Municipal Market in Nicosia , Cyprus, (2019) 1–10.

[7] CEN. EN 1998-3, Eurocode 8 : Design of structures for earthquake resistance — Part 3: Assessment and retrofitting of buildings. European Committee for Standardization, Bruxelles 2004.

[8] Y.M. Lim, V.C. Li, Durable Repair of Aged Infrastructures Using Trapping Mechanism of Engineered Cementitious Composites, Cem. Concr. Compos. 19 (1997) 373–385.

[9] A. Kamal, M. Kunieda, N. Ueda, H. Nakamura, Evaluation of crack opening performance of a repair material with strain hardening behavior, Cem. Concr. Compos. 30 (2008) 863–871. https://doi.org/10.1016/j.cemconcomp.2008.08.003.

[10] A.E.H. Khalil, E. Etman, A. Atta, M. Essam, Behavior of RC beams strengthened with strain hardening cementitious composites (SHCC) subjected to monotonic and repeated loads, Eng. Struct. 140 (2017) 151–163. https://doi.org/10.1016/j.engstruct.2017.02.049.

[11] M.I. Khan, W. Abbass, Flexural behavior of high-strength concrete beams reinforced with a strain hardening cement-based composite layer, Constr. Build. Mater. 125 (2016) 927–935. https://doi.org/10.1016/j.conbuildmat.2016.08.132.

[12] M.K. Sharbatdar, J. Ayyubi, Flexural retrofitting of the damaged reinforced concrete beams by using HPFRCC, Sci. Iran. 27 (2020) 2680–2689. https://doi.org/10.24200/sci.2020.21737.

[13] S.K. Shin, J.J.H. Kim, Y.M. Lim, Investigation of the strengthening effect of DFRCC applied to plain concrete beams, Cem. Concr. Compos. 29 (2007) 465–473. https://doi.org/10.1016/j.cemconcomp.2007.02.005.

[14] Y. Kim, G. Fischer, Y.M. Lim, V.C. Li, Mechanical Performance of Sprayed Engineered Cementitious Composite Using Wet-Mix Shotcreting Process for Repair Applications, (2004).

[15] S. Kim, W. Park, Y. Jang, L. Feo, H. Yun, Crack damage mitigation and shear behavior of shear-dominant reinforced concrete beams repaired with strain-hardening cement-based composite, Compos. Part B. 79 (2015) 6–19. https://doi.org/10.1016/j.compositesb.2015.04.020.

[16] Y. Shao, C.W. Kuo, C.C. Hung, Seismic performance of full-scale UHPC-jacket-strengthened RC columns under high axial loads, Eng. Struct. 243 (2021) 112657. https://doi.org/10.1016/j.engstruct.2021.112657.

[17] M. Deng, Y. Zhang, Q. Li, Shear strengthening of RC short columns with ECC jacket: Cyclic behavior tests, Eng. Struct. 160 (2018) 535–545. https://doi.org/10.1016/j.engstruct. 2018.01.061.

[18] M. Kunieda, N. Ueda, H. Nakamura, Cyclic Response of Damaged Members Repaired By Different Types of Shccs, in: VIII Int. Conf. Fract. Mech. Concr. Concr. Struct., 2013.

[19] A. Gholampour, R. Hassanli, J.E. Mills, T. Vincent, M. Kunieda, Experimental investigation of the performance of concrete columns strengthened with fiber reinforced concrete jacket, Constr. Build. Mater. 194 (2019) 51–61. https://doi.org/10.1016/j.conbuildmat.2018.10.236.

[20] A. Macdonald, Susan; Gonçalves, Conservation Principles for Concrete of Cultural Significance, Getty Conserv. Inst. (2020) 30. http://hdl.handle.net/10020/gci_pubs/ conservation_principles_concrete.

[21] American Concrete Institute, Concrete Repair Guide., n.d.

[22] P.J. Reed, K. Schoonees, J. Salmond, Historic concrete structures in New Zealand: overview, maintenance and management, New Zealand, 2008.

[23] J.M. Teutonico, A.E. Charola, E. De Witte, G. Grassegger, R.J. Koestler, M. Laurenzi Tabbasso, H.R. Sasse, R. Snethlage, Group report: How can we ensure the responsible and effective use of treatments (cleaning, consolidation, protection)?, 1997.

[24] K. van Balen, I. Papayianni, R. van Hees, L. Binda, A. Waldum, Introduction to requirements for and functions and properties of repair mortars., Mater. Struct. 38 (2005) 781–785.

[25] H.A. Heinmann, Historic concrete: From concrete repair to concrete conservation, TU Delft, 1967. https://doi.org/https://doi.org/10.4233/uuid:987fafd0-cd76-4230-be0e-be8843cae08e.

[26] CEN. EN 12504-1, Testing concrete in structures — Part 1: Cored specimens — Taking, examining and testing in compression. European Committee for Standardization, Bruxelles, 2009.

[27] SALMOND REED, Historic Concrete Structures: A Maintenance and Management Handbook for New Zealand, Auckland, 2003.

[28] CEN. EN 12390-3, Testing hardened concrete, Part 3: Compressive strength of test specimens. European Committee for Standardization, Bruxelles, 2009,

[29] CEN. EN 1766, Products and Systems for the Protection and Repair of Concrete Structures. European Committee for Standardization, Bruxelles, 2017.

[30] ACI 211.1-91, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete., 2009.

[31] A. V. Georgiou, S.J. Pantazopoulou, Effect of fiber length and surface characteristics on the mechanical properties of cementitious composites, Constr. Build. Mater. 125 (2016) 1216–1228. https://doi.org/10.1016/j.conbuildmat.2016.09.009.

[32] A. Kanellopoulos, I. Ioannou, M.F. Petrou, Towards more sustainable and environmentally-friendly concretes: The use of silica fume, WIT Trans. Ecol. Environ. 120 (2009) 265–270. https://doi.org/10.2495/SDP090261.

[33] J.J. Chen, W.W.S. Fung, A.K.H. Kwan, Effects of CSF on strength, rheology and cohesiveness of cement paste, Constr. Build. Mater. 35 (2012) 979–987. https://doi.org/10.1016/j.conbuildmat.2012.04.037.

[34] M.Á. Sanjuán, C. Argiz, J.C. Gálvez, A. Moragues, Effect of silica fume fineness on the improvement of Portland cement strength performance, Constr. Build. Mater. 96 (2015) 55–64. https://doi.org/10.1016/j.conbuildmat.2015.07.092.

[35] A.V. Georgiou, S.J. Pantazopoulou, Experimental investigation on the confining effect of fibers in SHFRCC, Compos. Struct. (2017). https://doi.org/10.1016/j.compstruct.2017.09.110.

[36] F.E. Richart, A. Brandtzaeg, R.L. Brown, A study of the failure of concrete under combined compressive stresses., 1928.