SEISMIC PERFORMANCE OF CONFINED RUBBERISED CONCRETE COUPLING BEAMS

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Abstract

Reinforced Concrete structural coupled walls have long been used in medium to high rise buildings as a primary lateral force resisting system for wind and seismic loads. When a wall system is subjected to large lateral actions, the coupling beams are required to transfer high shear forces and undergo large deformations, thus dissipating energy over the entire height of the wall by providing substantial deformation ductility. Therefore, the performance of the entire lateral resisting system depends on the deformation capacity of the coupling beams. This paper introduces a novel solution for the manufacturing of highly deformable coupling beams using confined rubberised concrete. Rubberised concrete utilises recycled rubber particles as replacement for portions of the fine and coarse aggregates. Although the inclusion of rubber in concrete can lead to a significant reduction in compressive strength (up to 90%) and stiffness, FRP confinement can be used to effectively regain or exceed the full structural strength of traditional concrete and enable higher deformability, ductility and energy dissipation capacity. Two half-scale coupling beams were tested under cyclic displacement reversals to examine the seismic performance of confined rubberised concrete structural elements. Each specimen comprised a coupling beam, with an aspect ratio of two, connected to two rigid blocks representing the shear walls. The main difference between the specimens was the reinforcement layout (flexural and diagonal reinforcement). The set up simulated the double curvature expected in coupling beams by providing passive restraints through two rigid links. The results of the experimental program are presented and discussed to assess the performance of the proposed novel solution.

Keywords: Confined Rubberised Concrete, AFRP, Fibre Reinforced Polymer, Coupling Beam, Coupled Wall

1. Introduction

Structural coupled walls are a typical structural system for resisting lateral loads in medium to high rise buildings. When subjected to seismic actions, part of the overall overturning moment is resisted by each of the coupled walls and part by the coupling action from the coupling beams at each level. This system has been widely used to control deflections in buildings and exhibits an excellent dissipation capacity, under seismic actions. However, its overall performance is highly dependent on the local deformation performance of the coupling beams.

Over the past decades, previous research on coupling beams has focused on improving the reinforcement layout. Paulay [1] proposed in 1974 a new layout consisting on a group of diagonal reinforcing bars crossing at the mid-span of the beam. This solution often requires the use of transversal confinement reinforcement around the group of diagonal bars to improve the compressive strength and deformation capacity of concrete, as well as preventing the buckling of the longitudinal bars. Since then, several studies [2][3][4][5] have confirmed its effectiveness and demonstrated an enhancement to the deformability and energy dissipation capacity of coupling beams. This has led current codes such as EC8 and ACI 318-08 to adopt this layout. Analyses of the available experimental data on coupling beams with confined diagonal reinforcement and aspect ratios below two shows that the average ultimate chord rotation is 4.3%. However, this rotation is far from the chord rotation demand expected in coupled wall systems in which chord rotations up to 10% were measured [7]. More recently, several researchers examined the use of High Performance Fibre Reinforced Concrete to reduce the confinement of the diagonal cages improving its constructability [7][8].

Rubberised Concrete (RuC), uses rubber particles recycled from end-of-life tyres as a replacement to portions of the conventional concrete mineral aggregates (fine, coarse or both). Including rubber in concrete negatively affects some of the concrete fresh and hardened properties. The main observed effect is a reduction of its modulus of elasticity and compressive strength, which can drop by up to 90% [9][10][11] for high aggregate replacement (>50%). Such a reduction was associated in the literature to: a) the high Poisson's ratio and low stiffness of rubber [12][13][14]; b) the non-homogeneity of the mix [10] and c) increment in air content and porosity [10], among others.

Despite the negative effects on some concrete mechanical properties, the incorporation of rubber leads to a higher ductility and energy dissipation capacity. After RuC reaches its peak strength (in tension or compression), the rubber crumbs contain crack growth, inasmuch as sustain larger levels of strain than the mineral aggregates. This prompts a gradual and ductile failure and allows for larger deformations when compared to traditional concrete [15]. RuC also presents better dynamic properties such us: i) large impact load capacity [16][17] ii) high vibrational damping [15][16][18][19] and iii) improved fatigue life [20] which makes it attractive for seismic and dynamic applications. However due to its low compressive strength most researchers have recommended its use for non-structural components [17][21][22].

Recently, limited studies have investigated the use of Fibre Reinforced Polymer (FRP) jackets to confine RuC [23][24][25]. However, in most of these cases, the amount of rubber replacement was too low to significantly alter its constitutive stress-strain behaviour from that of conventional confined concrete. Previous research from the authors [26][27][28] proved that using CFRP & AFRP jackets to confine RuC with optimised mix proportions and large rubber replacement recovers the compressive strength of RuC to structural levels while obtaining axial strains up to 7% (i.e. 20 times more than conventional concrete), thus making confined RuC (CRuC) suitable for structural applications.

This paper presents the results of an experimental investigation into a novel highly deformable coupling beam solution. The proposed solution utilises CRuC in order to enhance its deformability and energy dissipation capacity. The results of an experimental program on two half scale coupling beams with high shear deformation capacity (HDC) are presented and discussed to assess the performance of the proposed solution. The results of the tests indicate a better seismic performance of the proposed coupling beams, in terms of ductility, deformability and energy dissipation capacity when compared to a benchmark conventional RC coupling beam.

2. Experimental Programme

The seismic performance of HDC coupling beams was examined with two half-scale specimens (Fig. 1). Each specimen consisted of a coupling beam, with aspect ratio h/d=2, connected to two rigid blocks, which represent the shear walls. Both specimens differed in the reinforcement layout (flexural and diagonal reinforcement). The coupling beams were cast using an optimized mix [26], which minimizes the effect of including rubber particles on the fresh and hardened properties of concrete, while maximizing the rubber content. After curing, the specimens were wrapped with six layers of Aramid Fiber Reinforced Polymers (AFRP) using a wet lay-up technique. The fibres were oriented perpendicular to the coupling beam longitudinal axis. Fig. 2 shows the experimental set-up that was used to simulate the boundary conditions expected in coupling beams. The specimens were loaded in displacement control and subjected to a series of quasi-static cycles at increasing amplitude of maximum displacement. The response of the specimens was continuously recorded during the tests with linear transducers, strain gauges and Digital Image Correlation. Table 1 presents the mechanical properties of the materials from the uniaxial compressive and tensile tests. In Table 1, f_c is the maximum axial stress and ε_c is the strain at maximum stress for RuC obtained from compressive tests on three 100mm cubes; (f_y,ε_y) and (f_u,ε_u) are the yield and ultimate strengths and strains obtained from the tensile test of three samples per steel rebar diameter; f_f is the tensile strength; E_f is the modulus of elasticity; ε_{fu} is the ultimate elongation of fibre; and t_f is the thickness of sheet provided by the manufacturer.

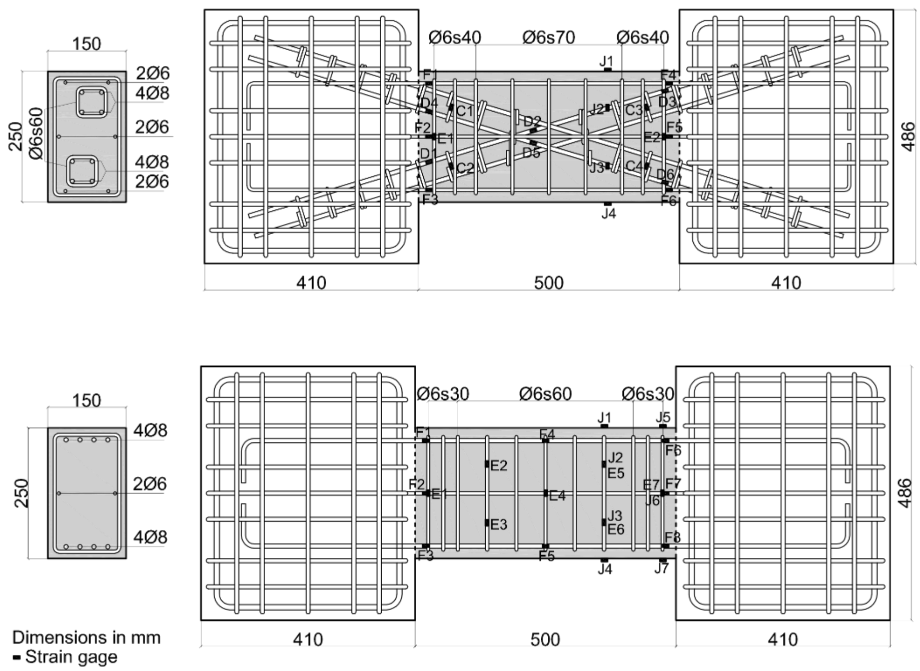


Fig. 1 – Specimen geometry and reinforcement layout

Table 1. Material Mechanical Properties.

RuC	Steel					AFRP			
f_c (MPa)	ϕ (mm)	f_y (MPa)	ε_y (με)	f_u (MPa)	ε_u (με)	f_f (MPa)	E_f (GPa)	ε_{fu} (%)	t_f
13.2	6	558	2730	620	10156	2400	116	2.5	0.2
	8	483	2532	560	14522				

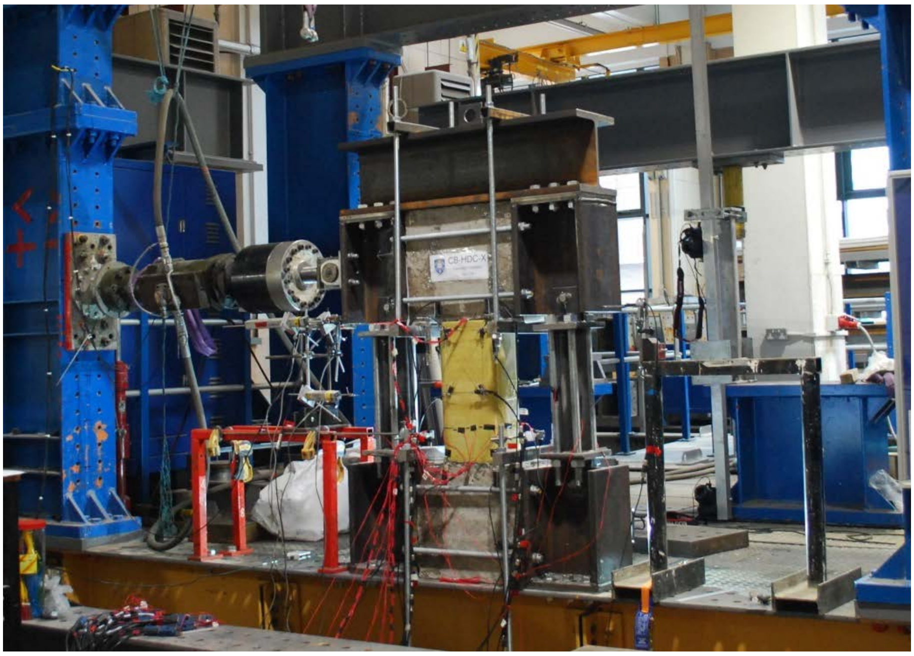
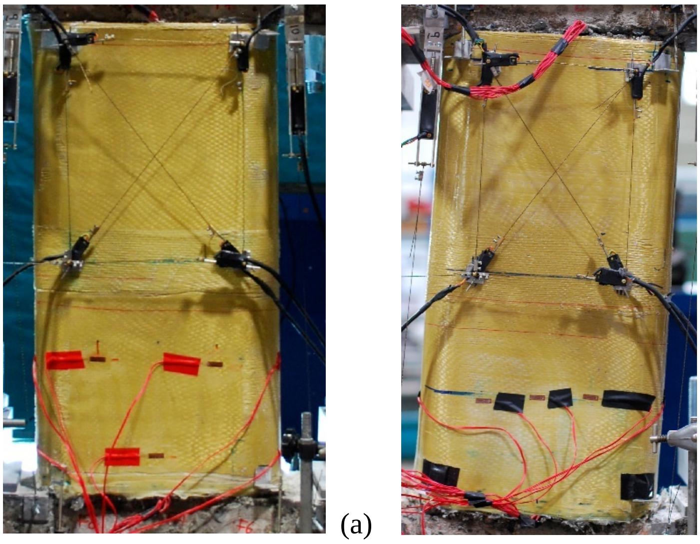


Fig. 2 – Test Set-up

3. Results and Discussion

All specimens had a predominant flexural response developing plastic hinges at the top and bottom along an approximate length of half the depth of the section, as can be seen in Fig. 3. Large flexural cracks at the wall-coupling beam interface were also observed which favoured shear sliding at final stages of the test. The main failure mode was crushing of the concrete within the compression zones due to excessive expansion of the FRP jacket at the wall to coupling beam joint.



(a) (b)

Fig. 3 – Failure modes (a) CB-HDC-X (b) CB-HDC-II

Fig. 4 shows the cyclic performance of the specimens in terms of shear force, V, versus relative displacement, δ. From these plots it can be observed that before yielding both coupling beams could sustain larger shear forces than predicted by current codes, and developed shear stresses of up to 4 MPa. In terms of deformation capacity, both coupling beams yielded at 1.4% chord rotation and reached an ultimate chord rotation of 8%, which was defined as the maximum chord rotation before a 20% drop in the load was recorded. After yielding, Specimen CB-HDC-X exhibited a better hysteresis response than specimen CB-HDC-II, with more stable cycles resulting into a high energy dissipation capacity. Table 2 summarises some of the key performance indicators for the tested coupling beams at both yielding (yielding chord rotation, θ_y , yielding shear force, V_y and secant stiffness at yield displacement, k_y) and ultimate limit state (ultimate chord rotation, θ_u and maximum shear force, V_{max}), as well as rotation ductility, $\mu=\theta_u/\theta_y$.

Table 2 – Main performance values

Specimen	θ_y (%)	V_y (kN)	V_{max} (kN)	θ_u (%)	k_y (kN/mm)	μ
CB-HDC-X	1.40	124.0	164.7	8.20	18.35	5.9
CB-HDC-II	1.41	127.2	148.2	7.90	17.26	5.6

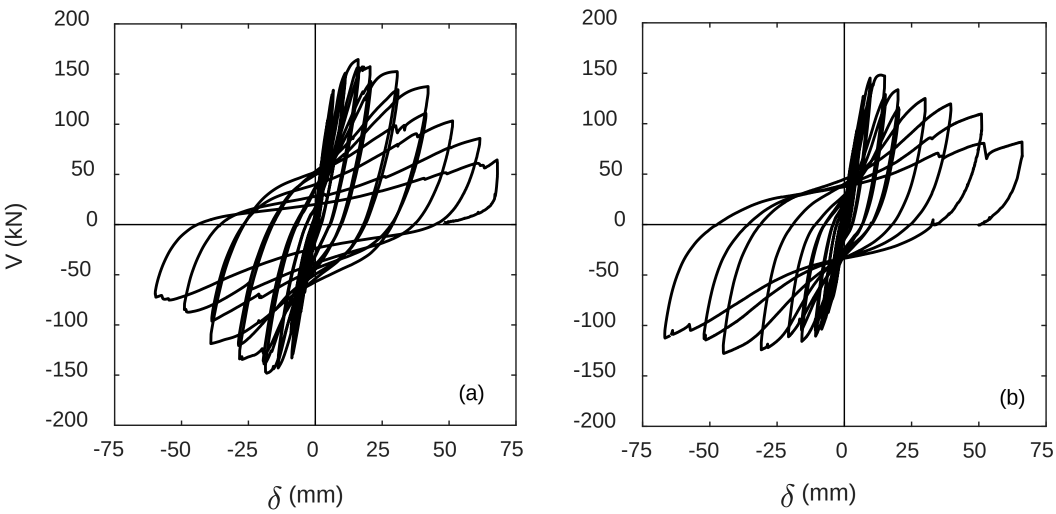


Fig. 1 – Force displacement hysteresis loop for (a) CRuC-X (b) CRuC-II

A comparison of the experimental results normalized by a benchmark conventional RC coupling beam is presented in Fig. 5. The performance of the reference beam was determined on the basis of experimental results available in the literature (i.e. θ_y≈1.5% and θ_u≈4%), as well as predictions of maximum shear strength given by Eurocode 8 and ACI 318-08 (e.g. $V=2A_{vd}\cdot f_y\cdot\sin\alpha$ = 88kN, where V is the predicted shear capacity, A_{vd} is the area of the reinforcement in the diagonals, f_{yd} is the yielding strength of steel and α is the angle of the diagonal with the longitudinal axis of the coupling beam). It can be observed that the CRuC coupling beams provide 1.5 times the shear resistance required in the codes. In terms of deformation, all beams presented similar yielding rotations to conventional coupling beams. With regards to the ultimate rotation, CRuC coupling beams almost doubled the deformation capacity of the reference beam.

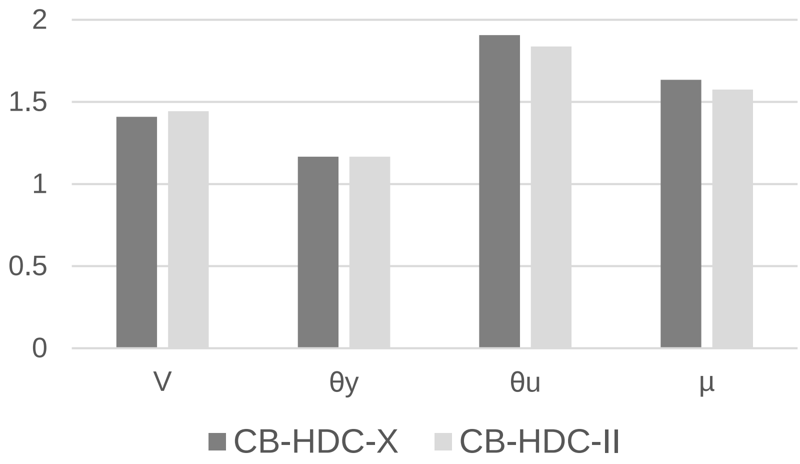


Fig. 2 – Key performance indicators normalized to design code predictions

4. Conclusions

This paper investigated an innovative solution for highly deformable coupling beams using Confined Rubberised Concrete, in which part or the total amount of mineral aggregate and sand is replaced by rubber particles recycled from end-of-life tyres. The feasibility of using this novel concrete for structural applications was proven with quasi-static cyclic experiments on two half-scale coupling beams. From the results presented, the following conclusions can be drawn:

- The Confined Rubberised Concrete proved to be feasible for structural applications enabling shear stresses of 4 MPa, comparable to those of conventional concrete, hence making this material suitable for structural applications.
- The coupling beams are characterised by a very stable hysteresis response with minimum pinching, and excellent energy dissipation.
- The coupling beams were able to withstand shear forces 1.5 times larger than those required in current codes, despite the low compressive strength of the plain Rubberised Concrete.
- The coupling beams developed ultimate rotations of up to 8% (i.e. 1.8 times larger than their conventional RC counterparts) before failure.
- The coupling beams showed a gradual failure enabling values of ductility up to 6.

5. Acknowledgements

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6. References

[1] Paulay, T., & Binney, J. R. (1974). Diagonally reinforced coupling beams of shear walls. Special Publication, 42, 579-598.

[2] Tassios, T. P., Moretti, M., & Bezas, A. (1996). On the behavior and ductility of reinforced concrete coupling beams of shear walls. ACI Structural Journal, 93(6), 711-720.

[3] Galano, L., & Vignoli, A. (2000). Seismic behavior of short coupling beams with different reinforcement layouts. ACI Structural Journal, 97(6), 876-885.

[4] Fortney, P. J., Rassati, G. A., & Shahrooz, B. M. (2008). Investigation on effect of transverse reinforcement on performance of diagonally reinforced coupling beams. ACI Structural Journal, 105(6), 781.

[5] Naish, D., Fry, A., Klemencic, R., & Wallace, J. (2013). Reinforced concrete coupling beams-Part I: testing. ACI Structural Journal, 110(6), 1057.

[6] Lequesne, R. D., Parra-Montesinos, G. J., & Wight, J. K. (2016). Seismic Response of Fiber-Reinforced Concrete Coupled Walls. ACI Structural Journal, 113(3), 435.

[7] Lequesne, R. D., Parra-Montesinos, G. J., & Wight, J. K. (2012). Seismic behavior and detailing of high-performance fiber-reinforced concrete coupling beams and coupled wall systems. Journal of Structural Engineering, 139(8), 1362-1370.

[8] Canbolat, B. A., Parra-Montesinos, G. J., & Wight, J. K. (2005). Experimental study on seismic behavior of high-performance fiber-reinforced cement composite coupling beams. ACI Structural Journal, 102(1), 159.

[9] M.K. Batayneh, I. Marie, I. Asi, Promoting the use of crumb rubber concrete in developing countries, Waste Manage. 28 (11) (2008) 2171–2176.

[10] Z.K. Khatib, F.M. Bayomy, Rubberized Portland cement concrete, J. Mater. Civ. Eng. 11 (3) (1999) 206–213.

[11] H.A. Toutanji, The use of rubber tire particles in concrete to replace mineral aggregates,Cement Concr. Compos. 18 (2) (1996) 135–139.

[12] Li, G., Stubblefield, M. A., Garrick, G., Eggers, J., Abadie, C., & Huang, B. (2004). Development of waste tire modified concrete. Cement and Concrete Research, 34(12), 2283-2289.

[13] Ganjian, E., Khorami, M., & Maghsoudi, A. A. (2009). Scrap-tyre-rubber replacement for aggregate and filler in concrete. Construction and Building Materials, 23(5), 1828-1836.

[14] Khaloo, A. R., Dehestani, M., & Rahmatabadi, P. (2008). Mechanical properties of concrete containing a high volume of tire–rubber particles. Waste Management, 28(12), 2472-2482.

[15] Hernandez-Olivares, F., Barluenga, G., Bollati, M., & Witoszek, B. (2002). Static and dynamic behaviour of recycled tyre rubber-filled concrete. Cement and concrete research, 32(10), 1587-1596.

[16] Atahan, A. O., & Yücel, A. Ö. (2012). Crumb rubber in concrete: static and dynamic evaluation. Construction and Building Materials, 36, 617-622.

[17] Topçu, I. B., & Avcular, N. (1997). Collision behaviours of rubberized concrete. Cement and Concrete Research, 27(12), 1893-1898.

[18] Najim, K. B., & Hall, M. R. (2012). Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. Construction and building materials, 27(1), 521-530.

[19] Xue, J., & Shinozuka, M. (2013). Rubberized concrete: A green structural material with enhanced energy-dissipation capability. Construction and Building Materials, 42, 196-204.

[20] Liu, F., et al., Mechanical and fatigue performance of rubber concrete. Construction and Building Materials, 2013. 47: p. 711-719.

[21] P. Sukontasukkul, C. Chaikaew, Properties of concrete pedestrian block mixed with crumb rubber, Constr. Build. Mater. 20 (7) (2006) 450–457.

[22] P. Sukontasukkul, Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel, Constr. Build. Mater. 23 (2) (2009) 1084–1092.

[23] Youssf O, ElGawady MA, Mills JE, Ma X. An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes. Construction and Building Materials. 2014;53:522-32.

[24] Moustafa A, ElGawady MA. Strain Rate Effect on Properties of Rubberized Concrete Confined with Glass Fiber–Reinforced Polymers. Journal of Composites for Construction. 2016:04016014.

[25] G. Li, S.-S. Pang, S.I. Ibekwe, FRP tube encased rubberized concrete cylinders, Mater. Struct. 44 (1) (2011) 233–243.

[26] Raffoul, S., Garcia, R., Pilakoutas, K., Guadagnini, M., & Medina, N. F. (2016). Optimisation of rubberised concrete with high rubber content: An experimental investigation. *Construction and Building Materials*, *124*, 391-404.

[27] Raffoul, S., Garcia, R., Escolano-Margarit, D., Guadagnini, M., Hajirasouliha, I., & Pilakoutas, K. (2017). Behaviour of unconfined and FRP-confined rubberised concrete in axial compression. *Construction and Building Materials*, *147*, 388-397.

[28] Raffoul, S., Escolano-Margarit, D., Garcia, R., Guadagnini, M., & Pilakoutas, K. (2019). Constitutive Model for Rubberized Concrete Passively Confined with FRP Laminates. *Journal of Composites for Construction*, *23*(6), 04019044.

