AXIALLY LOADED CONCRETE AND REINFORCED CONCRETE ELEMENTS STRENGTHENED WITH HPFRCC

DAUGEVIČIUS Mykolas [1], VALIVONIS Juozas [2]

Abstract

Compressed concrete and reinforced concrete elements were strengthened with high performance fiber reinforced cementation concrete (HPFRCC) jacket. Jacket of HPFRCC confines lateral deformations of ordinary concrete and enhance behavior of compressed elements. Totally 12 elements were tested, 6 off witch were strengthened with HPFRCC jacket (3 concrete elements and 3 reinforced concrete). Longitudinal and transversal deformations increased then jacket of HPFRCC was added. Ultimate longitudinal and transversal deformations of strengthened concrete elements increased 2 and 3.06 times and deformations of strengthened reinforced concrete elements respectively increased just 1.445 and 1.07 times. Experimentally was determined that the best strengthening effect obtained on ordinary concrete elements. Resistance of these elements increased about 3.5 times. Whereas resistance of reinforced concrete strengthened elements increased 2.947 times.

Keywords: HPFRCC, residual confinement, strengthening, mixture law.

1. Introduction

Composition of concrete can be damaged if structure elements are exposed in harmful environment. Degradation of concrete composition influences decrease of effective cross section, element stiffness and increase of deformations. Damaged structure element must be retrofitted. Compressed elements can be strengthened with wrapped FRP composite or new layer of concrete can be molded. If composition of concrete damaged or cross section decreased, confinement with FRP is not very suitable because confinement usual increase concrete resistance [1, 2, 3] but not stiffness. Molded additional layer of high performance fiber reinforced cementitious concrete (HPFRCC) increases the strength of not only the item but also ensures stiffness due to changes in cross-sectional characteristics. Transversal deformations of high strength concrete jacket increases respecting with the weaker internal concrete expansion under axial loading. Tensile strength of high compressive strength

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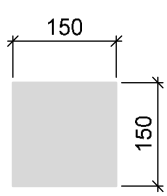
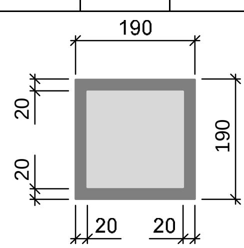
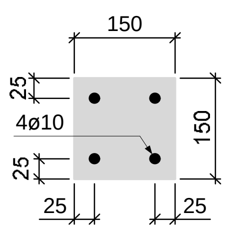
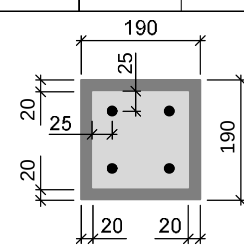
concrete usual remains very small in comparison with compressive strength. However if steel fibers are used, then deformability under tension of high strength concrete increases and ductility of structure elements increases too [4, 5]. Additional layer of HPFRCC can be not only molded but sprayed too [6]. But sprayed layer of HPFRCC usually thinner than molded layer. Then additional layer of HPFRCC added this means that load carrying capacity must increase. However experimental research of strengthened columns with prefabricated panel made from steel fiber reinforced cementitous composite showed that ductility increase more than resistance then thickness of confinement increase [7]. Confinement of compressed element with ferrocement jacket showed that modulus of deformations of such elements changes marginally but mostly resistance and ultimate deformation increase [8]. Buckling of longitudinal steel bars can cause spalling of protective layer of concrete and decrease resistance of reinforced concrete elements. External layer of high ductility cement can delay buckling of longitudinal steel bars [9].

Super position principle is used for calculation of concentrically compressed elements. However lateral deformations can reach ultimate tensile strength of jacket before the ultimate compressive strength will be reached. Therefore experimental study was conducted in order to determine influence of HPFRCC for strengthened concrete and reinforced concrete element. Determined resistance compared with the calculated from the super position principle.

2. Samples and characteristics of materials

Rectangular cross section specimens divided in two groups. Firs group consist of three concrete elements and three strengthened concrete elements (table 1). Second group consist of three reinforced concrete elements ant three strengthened reinforced concrete elements (table 1). Elements were strengthened with external layer of high performance fiber reinforced cementitious concrete (HPFRCC).

Tab.1: Characteristics of compressed elements

Concrete elements						Reinforced concrete elements					
C1	C2	C3	CH4	CH5	CH6	RC7	RC8	RC9	RCH10	RCH11	RCH12
											

Cylinders, cubes and prisms were compressed in order to predict compressive strength of materials. Dimensions and mechanical parameters of compressed samples presented in table 2 and 3. Flexural strength of materials was predicted with four point bending test on prismatic samples (table 4). Tensile strength was predicted from tensioned dog bone samples. Cross-section of these samples were 100x100 (table 5).

Tab.2: Strength of compressed samples

Sample	Material	Strength, MPa	f_{cc}/f_c	Standard deviation	The coefficient of variation
Cube 100x100x100	HPFRCC	111,5	-		
Cube 150x150x150	Concrete	35,6	3,17	1,18	3,31
	HPFRCC	112,7		3,56	3,16
Cylinder 150x300	Concrete	32,4	3,48	0,6	1,8
	HPFRCC	112,9		1,5	1,33
Prism 40x40x160	HPFRCC	105,4	-		
Prism 100x100x400	Concrete	27,3	3,93		
	HPFRCC	107,3			

Tab.3: Modulus of elasticity

Sample	Material	Modulus, GPa	E_{cc}/E_c
Prism 100x100x400	Concrete	32,7	1,16
	HPFRCC	37,8	
Cylinder 150x300	Concrete	29,9	1,15
	HPFRCC	34,5	
Prism 40x40x160	HPFRCC	42,48	-

Tab.4: Flexural strength

Sample	Material	Strength, MPa	fcc/fc
Prism 100x100x400	Concrete	3,57	4,45
	HPFRCC	15,9	

Tab.5: Tensile strength

Sample	Material	Strength, MPa	fcc/fc
Prism 100x100 (cross-section)	Concrete	2,28	2,1
	HPFRCC	4,78	

Reinforced concrete elements longitudinally reinforced with four steel bars and diameter of each bar was 10 mm. Tensile strength of longitudinal bars was 683 MPa and modulus of elasticity 189 GPa. Shear reinforcement was used near the ends of specimens.

3. Preparation of specimens and test setup

Preparation of the surface before the strengthening influences resistance of strengthened element. New layer of HPFRCC must have perfect bond with ordinary concrete and it has if surface is prepared properly. If bond with ordinary concrete is not warranted then external layer like in compressed layered element can buckle. Also if ordinary concrete is very weak shear stresses can damage perfect bond between HPFRCC and concrete. Resistance of strengthened element then external layer undergoes buckling is lower. Therefore in order to ensure perfect bond, surface of concrete was treated with high pressure water spout. Surface of stone aggregates were cleaned from sand and cement stone. Also aggregates of sand were removed up to 1 centimeter depth. So, uneven surface with protrusions of stone aggregates were formed (Fig. 1). Before application of HPFRCC surface of concrete was moistened.

Fig. 1: Surface of specimens after treatment

Before testing horizontal surface of samples was smoothened with high strength mortar and external load was transferred centrically over the whole surface. Tested samples were loaded according to the load control method up to the concrete crushing was reached. Longitudinal and lateral deformations were measured on all sides of specimens (Fig. 2). Length of measuring base respectively was 200 mm and 100 mm.

Fig. 2: Arrangement of transducers

4. Experimental results

Strengthened elements becomes layered after HPFRCC was applied. Strengthened element is composed of different materials which has different parameters of elasticity. Modulus of elasticity of strengthened concrete element it is possible to predict by mixture law:

$$E_{c.cc} = E_c \cdot V_c + E_{cc} \cdot V_{cc}. \tag{1}$$

Here E_c - modulus of elasticity of ordinary concrete; $V_c = A_c / A_{gros}$ - ratio of concrete cross section with cross section of strengthened element; E_{cc} - modulus of elasticity of HPFRCC; $V_{cc} = A_{cc} / A_{gros}$ - ratio of HPFRCC cross section with cross section of strengthened element. So taking in to account predicted moduli of elasticity of materials and ratios of cross sections, modulus of elasticity of strengthened element:

$$E_{c.cc} = 29.9 \cdot \frac{0.0225}{0.0361} + 42.48 \cdot \frac{0.0136}{0.0361} = 34.64 GPa.$$

Experimentally determined moduli of elasticity of strengthened concrete elements are presented in figure 3. Trend lines of stresses and deformations curves correspond 40 % of maximal stresses.

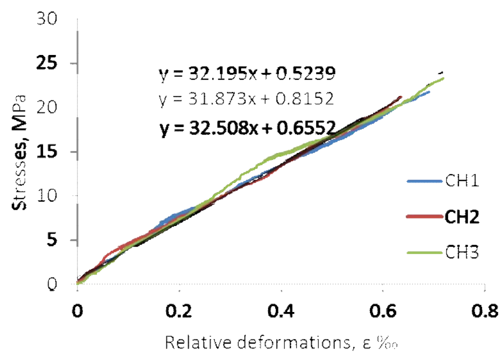


Fig. 3: Moduli of elasticity of strengthened concrete elements

Different materials elasticity influenced deformability of strengthened elements. longitudinal and lateral deformations of strengthened elements were smaller at the load level which correspond resistance of not strengthened element. Curves of load and relative deformations of tested elements are presented in figures 4, 5, 6 and 7. Longitudinal deformations of strengthened concrete elements are 2.6 times lower than in concrete elements near the ultimate state. Lateral deformations of these elements were 11.6 times lower. Respectively longitudinal and lateral deformations of strengthened reinforced concrete elements were 3.56 and 27 times lower.

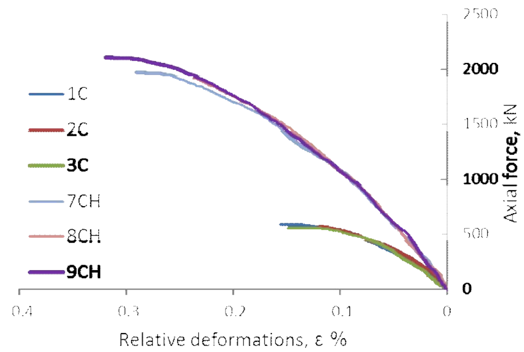


Fig. 4: Longitudinal relative deformations of concrete and strengthened concrete elements

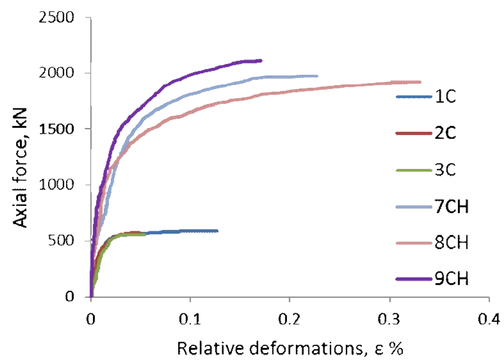


Fig. 5: Lateral relative deformations of concrete and strengthened concrete elements

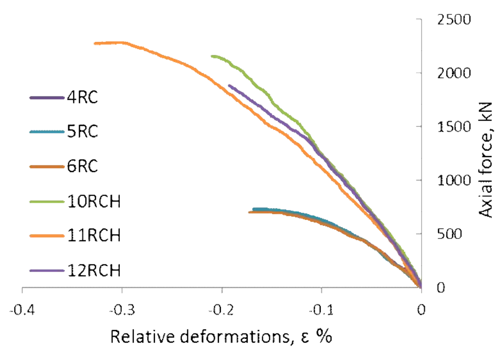


Fig. 6: Longitudinal relative deformations of reinforced concrete and strengthened reinforced concrete elements

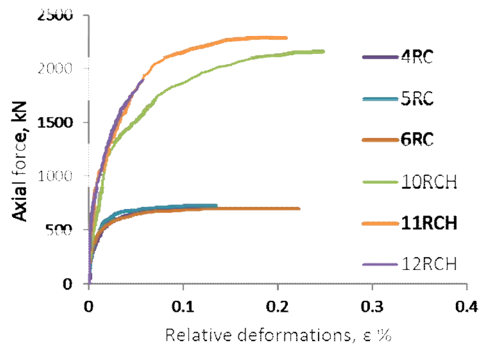


Fig. 7: Lateral relative deformations of reinforced concrete and strengthened reinforced concrete elements

Inclination of curves (in figures 4, 5, 6, 7) of strengthened elements at the beginning of loading period depends mainly from two factors. Firs factor is different modulus of elasticity. Second factor is different Poisson ratio. Experimentally predicted Poisson ratio of HPFRCC material differs from concrete material (figure 8). Poisson's ratio of the HPFRCC material is bigger, so from the beginning of loading external cover from HPFRCC provides confinement for internal concrete. When the evolution of plastic deformations of compressed concrete starts inclination of curves of strengthened elements changes marginally. But when the ultimate deformation of tensioned concrete is reached internal concrete layer expand mortally. At this moment cracks exists in the external layer of HPFRCC. Material of HPFRCC possesses residual tensile strength which provides for internal concrete residual confinement. Then the effect of residual confinement is reached increase of external load is significant and transition of curves of lateral deformations changes to horizontal position.

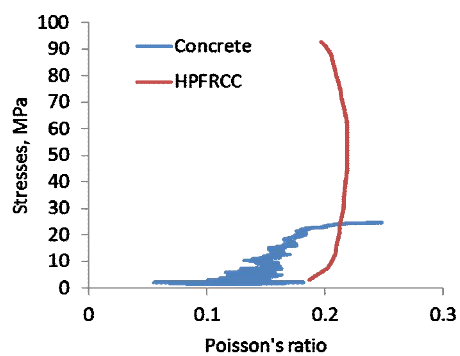
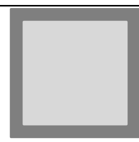
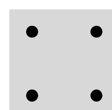
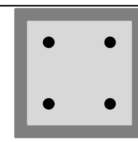


Fig. 8: Poisson's ratio of concrete and HPFRCC material

Deformability of strengthened concrete element with HPFRCC it is possible to divide in stages. First stage all materials work elastically. Second stage evolution of plastic deformations in internal concrete starts, but external layer of HPFRCC works elastically. Third stage plastic deformations are developing in all layers. Fourth stage expansion of internal concrete starts because composition of concrete damaged. Fifth stage cracks opens in external layer of HPFRCC and residual confinement effect start till failure of strengthened element.

Failure character of strengthened elements shows that all layers works together till failure. It is possible to hear how grows cracks before failure and failure is brittle. Experimentally was determined that the best strengthening effect obtained on ordinary concrete elements. Resistance of these elements increased about 3.5 times. Whereas resistance of reinforced concrete strengthened elements increased 2.947 times. Experimentally determined and calculated resistance values are presented in table 6. Compressive strength of HPFRCC material was evaluated from prismatic elements 40x40x160.

Tab.6: Experimentally determined and calculated values of resistance

Experimental values											
Concrete elements						Reinforced concrete elements					
C1	C2	C3	CH4	CH5	CH6	RC7	RC8	RC9	RCH10	RCH11	RC12
590 kN	572 kN	557 kN	1975 kN	1992 kN	2107 kN	710 kN	732 kN	705 kN	2155 kN	2286 kN	1887 kN
573 kN			2001.3 kN			715.7 kN			2109.3 kN		
											
Calculated values											
$N_R=A_c \cdot f_c$			$N_R=A_c \cdot f_c+A_{cc} \cdot f_{cc}$			$N_R=A_c \cdot f_c+A_s \cdot f_s$			$N_R=A_c \cdot f_c+A_s \cdot f_s+A_{cc} \cdot f_{cc}$		
573.1 kN			2006.5 kN			766.9 kN			2193.1 kN		

Minimum value of the coefficient of variation of resistance is obtained from reinforced concreter and concrete elements. Respectively these values are 2.01 % and 2.88 %. The coefficients of variation of strengthened elements increase. The coefficient of variation of strengthened concrete elements is 3.55 % and 9.64 % of strengthened reinforced concrete elements. Resistance results scattering presented in figure 9.

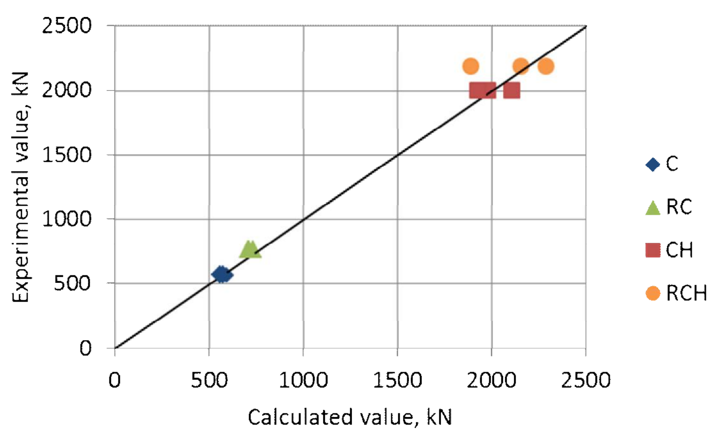


Fig. 9: Experimental values vs. calculated values

The increased scattering of resistance of strengthened elements could influence uneven distribution of strong concrete layer thickness. Because concrete surface could be unevenly treated. Scattering of resistance results of strengthened reinforced concrete elements are the biggest. Additionally longitudinal reinforcement could influence scattering of results. Ribbed steel bars were used for reinforcement. Acting of shear forces in concrete and steel bars interface lead the splitting of the protective layer of concrete. And expansion of internal concrete is more unpredictable.

5. Conclusions

Modulus of elasticity of strengthened elements changed when HPFRCC material was applied. It is possible to predict modulus of elasticity by mixture law.

Deformability of strengthened elements divided in to stages. Residual tensile strength of HPFRCC material provides residual confinement effect for internal concrete at the last stage. Increase of load carrying capacity then the effect of residual confinement starts is significant. Resistance of the strengthened elements dependent not only from increased cross section of the element, but also from the residual confinement effect.

Bond of concrete and HPFRCC, degradation of composition of the internal concrete, buckling of longitudinal steel bars, spalling of protective concrete layer influences the reliability of the strengthened element.

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