Vascular self-healing of a reinforced concrete beam under 4-point bending

P. Minnebo [1,a*], K. Van Tittelboom[2,b],N. De Belie[2,c] and D. Van Hemelrijck[1,d]

[1] Vrije Universiteit Brussel, Mechanics of Materials and Construction, Pleinlaan 2, B-1080 Brussel, Belgium

[2] Ghent University, Faculty of Engineering and Architecture, Department of Structural Engineering, Magnel Laboratory for Concrete Research, Technologiepark - Zwijnaarde 904, B-9052 Ghent, Belgium

[a]pieter.minnebo@vub.ac.be, [b]kim.vantittelboom@ugent.be, [c]nele.debelie@ugent.be, [d]danny.van.hemelrijck@vub.ac.be

*corresponding author

Keywords: vascular self-healing concrete, multiple self-healing

Abstract.
Self-healing materials are inspired on self-healing capabilities of living organisms. For plants, animals and people, the vascular system that distributes nutrients to all parts of the organism is also key for the self-healing capability. In a concrete element, a self-healing approach with an incorporated vascular system possess advantages towards repeatable self-healing and controlled placement of the self-healing system in the areas of interest. This study presents such a vascular system, which is designed to be accessible from outside of the concrete beam. Both clay and inorganic phosphate cement are compared as materials for the vanes of this system. The specimen contain steel reinforcement and are tested by means of 4-point bending, in order to obtain realistic conditions. Ease of construction and placement are discussed. From the experiments it can be seen that repeatable self-healing is possible, that the system is able to heal multiple cracks at the same time and that cracks can be sealed and mechanical properties restored.

Introduction

Concrete is prone to crack formation in its tensile zones, these cracks could cause durability problems in the future because they provide a gateway for hazardous liquids and gasses that deteriorate the concrete or cause the steel reinforcement to corrode. Self-healing concrete approaches aim to seal and repair these cracks autonomously in order to prevent durability problems. The vascular self-healing technique consists of a network, inside the concrete element, that allows a healing agent to flow into the crack at the moment of crack formation. It was introduced by Joseph et al. [1] and further investigated by other researchers such as Nishiwaki, Davies ,Sangadji and Schlangen [2]–[5]. A vascular system accessible from the outside, could provide new healing agent over the lifespan of the structure and allows to monitor when the healing process is activated (i.e. when healing agent flows). In this study, such a vascular system, accessible from the outside with two embedded containers is put inside a reinforced concrete beam which is tested by 4-point bending. The specimen are loaded three times to study the ability of a vascular system for multiple self-healing. During the experiments, strain fields on one surface are measured with digital image correlation.

Materials

The concrete specimen contain a vascular system, consisting out of a 3D-printed connection piece and container and out of tubes that are the vanes in the vascular system. Two materials for the tubes were used, inorganic phosphate cement (IPC) and clay. Inside the concrete beam, one (for the specimens containing the vascular system with IPC tubes) or for the vascular system with clay tubes two steel reinforcement bars are placed. The vascular system is filled with the healing agent right before loading, in total each specimen is loaded three times, except the reference which is loaded two times.

The concrete mix composition can be found in Table *1*. Two sets of experiments were conducted. One set with IPC tubes and one set with clay tubes, each with a reference sample without vascular system. For each test set, two reference beams and respectively three and four beams containing an IPC and clay vascular system were manufactured.

Table 1 Concrete composition

Component	Weight fraction (kg/m³)
Sand	670
Gravel 2/8	490
Gravel 7/16	790
CEM I 52.5 N	300
Water	150

Inorganic phosphate cement is a material that was developed at the Vrije Universiteit Brussel as a matrix material in cementitious composites. Cuypers [6] used it in her research on sandwich panels. IPC consisst out of a calcium silicate powder component and a phosphate acid based solution of metaloxides. After curing, the IPC material shows a high compression strength (i.e. 80-120 MPa) and a low tensile strength (i.e. 6-14 MPa). In Table *2* an overview of the material properties is given.

The clay consists of SiO_2 (77.6 %) and Al_2O_3 (18.3 %) (4.1% other materials). Initially, it is flexible and suitable for an extrusion manufacturing process. After curing at 1050 °C it becomes brittle. An overview of the clay material properties is given in **Fout! Verwijzingsbron niet gevonden.**.

The 3D-printed pieces, the connection and distribution piece, are printed in polyamide with the laser sintering method. Polyamide is a strong, flexible material, its properties can be seen in **Fout! Verwijzingsbron niet gevonden.**2. The container has a length, width and height of respectively 75 mm x 20 mm x 30 mm. The connection pieces have a height of 600 mm and the tubes can be connected at a height of 15 mm.

Table 2 IPC, clay and polyamide material properties

	Tensile strength [GPa]	**Compressive strength [MPa]**	**E-modulus [GPa]**	**Density [kg/m³]**
IPC	6-14	80-120	18	2000
Clay	18	/	22.8	2500
Polyamide	48	/	1.65	/

In Figure 1 the setup of the vascular system inside the concrete mold is depicted. The concrete specimen has a cross section of 100 mm x 100 mm and a length of 650 mm. The vascular system is 314 mm long. A steel rod with a diameter of 6 mm is placed at a height of 30 mm in the middle of the beam. The tubes of the vascular system are positioned at a height of 15 mm from the bottom of the beam, the connection pieces have three pedestals each of 10 mm prevent the vascular system to move to the bottom of the beam. Both containers can be accessed from the outside through the inlet on top of each container which sticks out of the concrete beam.

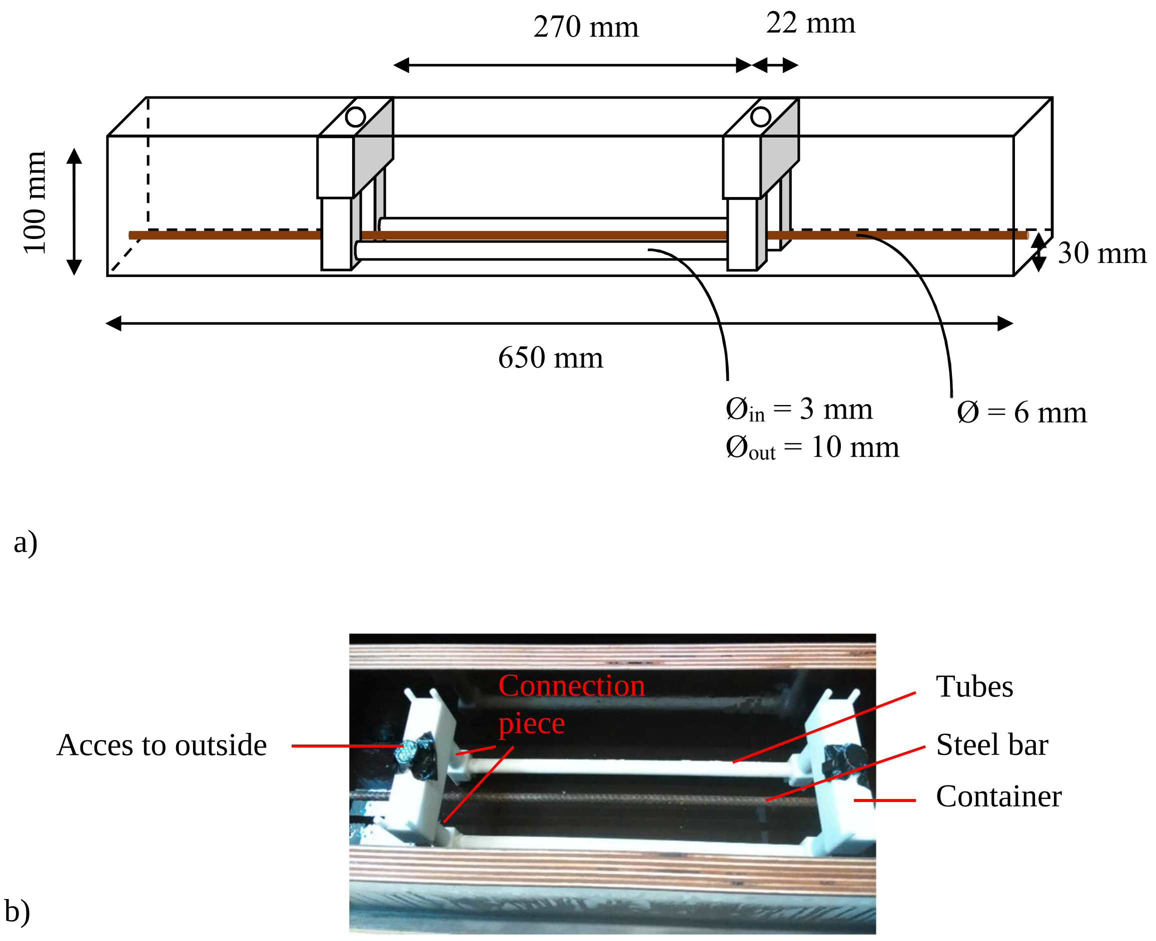

Figure 1 a) details of the concrete beam with one reinforcement bar and two tubes connected to the 3D-printed pieces on both sides. b) the vascular system in a concrete mold.

The healing agent is a one component polyurethane based injection resin, used to repair concrete cracks. It has a viscocity of 200 mPas (at 25 °C) and a density of 1075 kg/m³.

Experiments

The 4-point bending test is conducted at a speed of 2 mm/min with a span length of 600 mm between the lower supports and 200 mm between the upper supports. On the front surface of the beam, a speckle pattern is applied for DIC measurements and AE sensors fixed with tape on each specimen as can be seen on Figure 2. Each test was performed until an average crack width of 300µm was surpassed, measured by DIC. The containers, embedded inside the concrete beam, where each time filled with the healing agent right before loading.

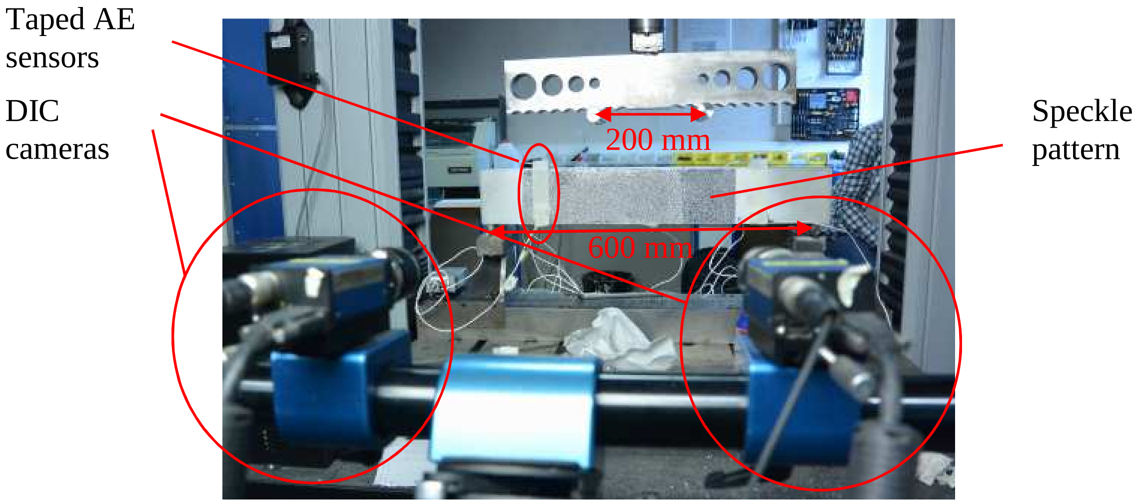

Figure 2 Experimental test, two DIC cameras are visualizing the speckle pattern on the frontside of the beam. Under the tape left and right on the beam, an AE sensor is positioned.

Digital image correlation is an optical technique that uses two CCD cameras and compares images of the speckle pattern in time. Calibration before the experiments allows to correlate the strain evolution on the surface during the experiment.

From the load curve, the stiffness is defined within the elastic region as

$$k = \frac{F}{\delta} \tag{1}$$

with **F [N]**: the applied force, **δ [mm]**: the associated displacement.

The healing efficiency is expressed as

$$\eta_{\text{stiffness}} = \frac{k_{reloading}}{k_{initial\ loading}} \tag{2}$$

Results

The stiffness and stiffness regain of the first set of specimens with an IPC vascular system can be seen in Table 3. In comparison with the reference beams, the stiffness is lower for the beams with a vascular system. This is due to the placement of the connection piece and container. It would be better for future research to put them at the extremities of the concrete beam. The stiffness regain of the vascular beams is significantly higher than the healing of the reference beams, respectively 106 % (at 2nd loading), 73 % (at 3rd loading) versus 43 % for the reference at second loading. The third loading results for each beam in a lower regain.

Table 3 Results of the IPC vascular system

	1st loading	2nd loading		3rd loading	
	Stiffness [N/mm]	**Stiffness [N/mm]**	**Healing efficiency [%]**	**Stiffness [N/mm]**	**Healing efficiency [%]**
Reference 1	13800	5103	37	/	/
Reference 2	13887	6717	48	/	/
Average	**13844**	**5910**	**43**		
Standard deviation	**62**	**1141**			
Specimen 1	8849	8202	93	6931	78
Specimen 2	7718	11795	153	6823	88
Specimen 3	12777	9370	73	6745	53

Average	**9781**	**9789**	**106**	**6833**	**73**
Standard deviation	**2168**	**1496**	**34**	**76**	**15**

The load-displacement curves of a representative specimen, specimen 1, are presented in Figure 3. The three black graphs show the loading and reloading of the specimen and the grey line shows the behavior of reference beam 2. Each load drop corresponds with the opening of a crack, as was confirmed by DIC measurements. In Figure 4 the DIC strain field can be seen at the moment of the first load drop of specimen 1 at the first loading cycle.

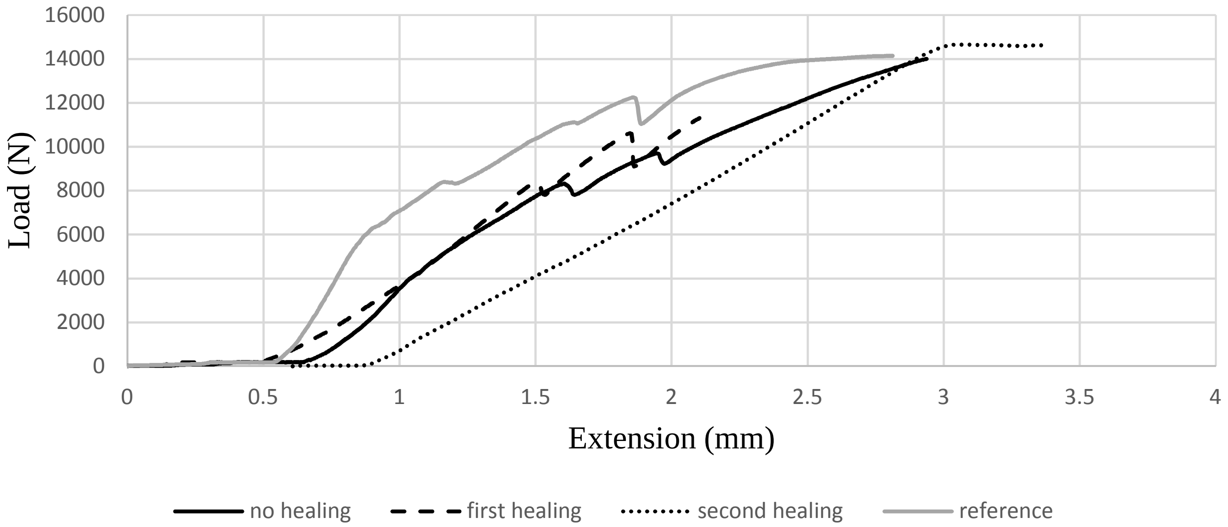

Figure 3 Loading and reloadings of a representative concrete specimen containing an IPC vascular system, specimen 1

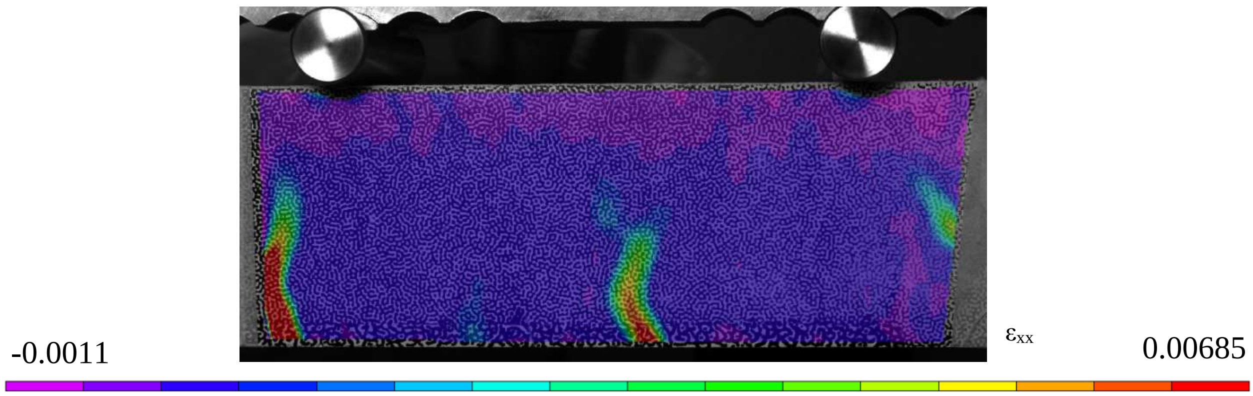

Figure 4 Strain field measured by the DIC software of the first loading of specimen 1with an IPC vascular system

In Figure 5 the strain field during the second loading is showed at the time of the first load drop, here it can be seen that the crack in the center of the beam of the first loading cycle stays closed and crack form on the sides of the beam at the moment of the load drop. Figure 6 shows the end of the second loading cycle, a total of four cracks are formed, the crack formed at the first loading cycle stays closed.

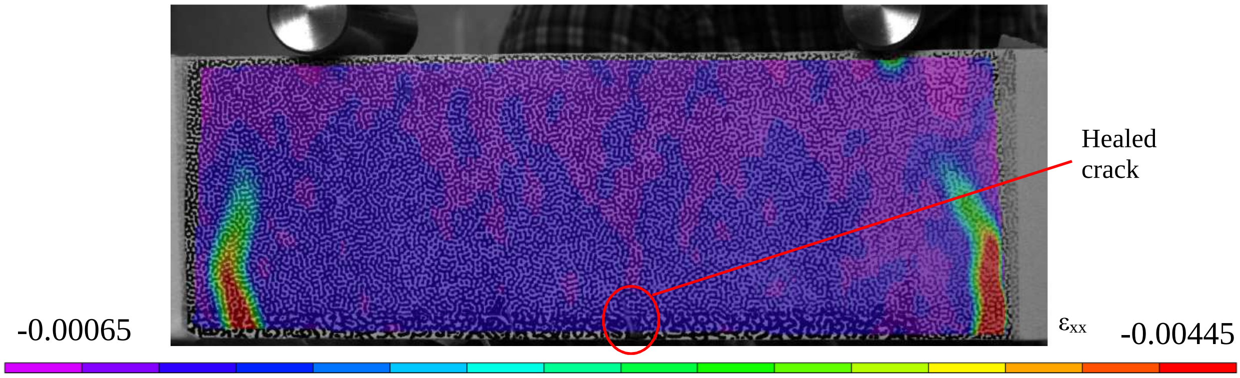

Figure 5 Strain field calculated by the DIC software of the second loading of specimen 1 with an IPC vascular system. Two cracks form along the sided of the beam, the crack from the first loading cycle stays closed

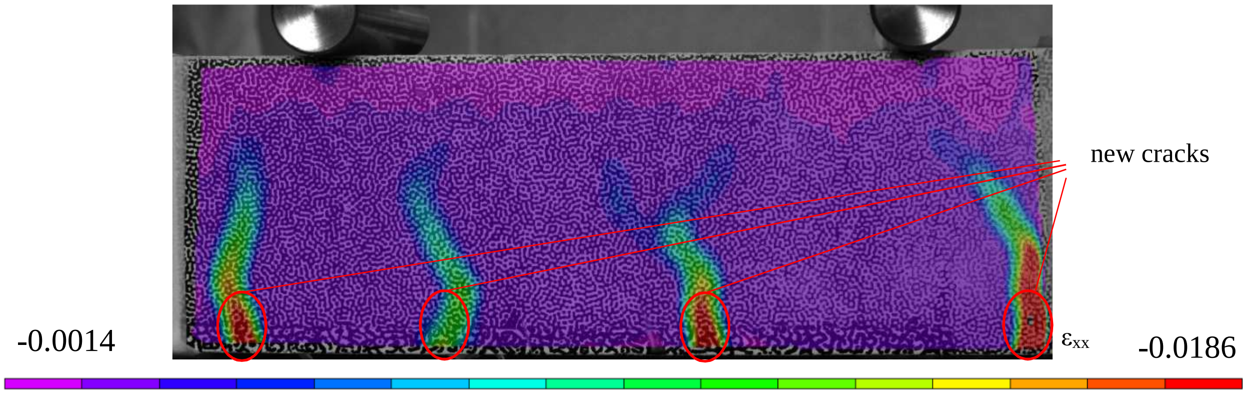

Figure 6 Strain field at the end of the second loading cycle, a total of four cracks is visible

In Figure 7, it is seen that at the third loading cycle all the cracks of the second loading cycle reopen, but the crack of the first loading cycle stays closed. The first healing, i.e. between first and second loading cycle, is more succesfull than the healing between the second and third loading cycle.

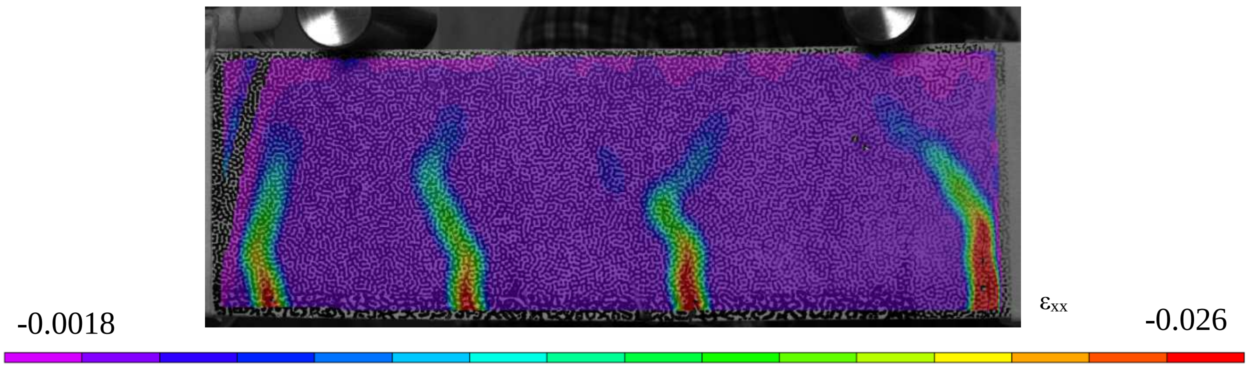

Figure 7 Strain field at the end of the third loading cycle

Further, a second set of experiments was conducted with concrete beams containing a clay vascular system. Like the IPC specimen, the clay vascular specimen are significantly weaker than the reference specimen. The healing efficiency of the clay vascular specimen is consequently bigger than the reference, respectivly 83 % (at 2nd loading), 61 % (at 3rd loading) versus 41 % of the reference at second loading. An overview of these results can be found in Table 4.

Table 4 Results of the clay vascular system

	1st loading	**2nd loading**	**3rd loading**

	Stiffness [N/mm]	Stiffness [N/mm]	Healing efficiency [%]	Stiffness [N/mm]	Healing efficiency [%]
Reference 1	24769	9479	38	/	/
Reference 2	20399	8716	43	/	/
Average	**22584**	**9098**	**41**		
Standard deviation	**3090**	**540**			
Specimen 1	21639	12873	59	11419	53
Specimen 2	12873	14592	113	8746	68
Specimen 3	17028	13248	78	9430	55
Specimen 4	15466	12587	81	10424	67
Average	**17118**	**13563**	**83**	**10005**	**61**
Standard deviation	**4343**	**852**	**20**	**1168**	**7**

On Figure 8, the load cycles of a representive specimen (i.e. specimen 3) are shown. The behavior of the beam containing a clay vascular system is similar to the reference beam. Each load drop corresponds with the opening of a crack, as was confirmed by DIC measurements.

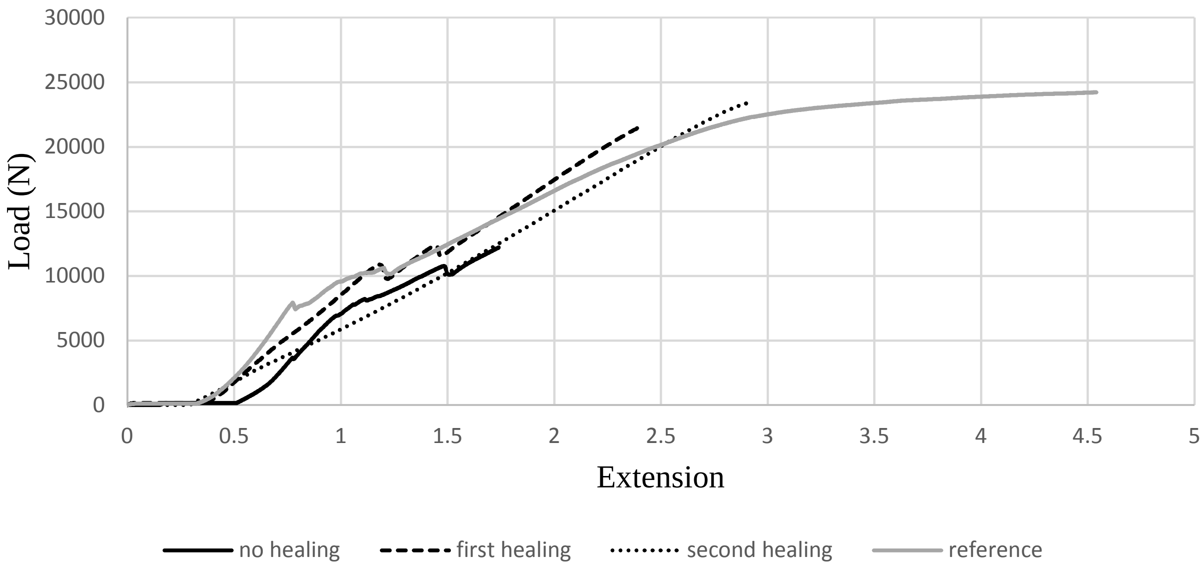

Figure 8 Loading and reloadings of a representative concrete specimen containing a clay vascular system, specimen3

From DIC it could also be seen that at each loading cycle, the same cracks open again. At first loading, four cracks (one on the left edge of speckle pattern) are formed, two between the span between the uppers supports and one at each side of the upper supports, near the position of the 3D printed distribution pieces Figure 9.

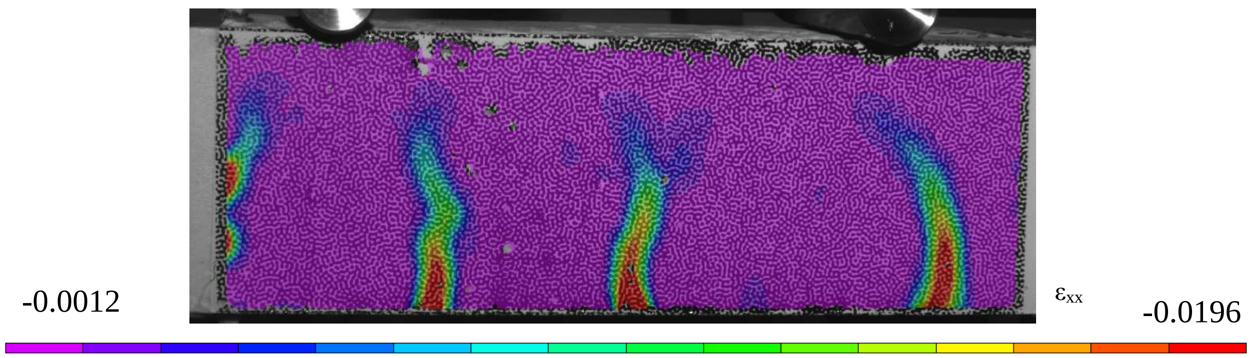

Figure 9 The strain field showing the cracks during the first loading

On the strain field of the second loading in Figure 10 it can be seen that indeed the same cracks reopen, they also reopen during the third loading Figure 11.

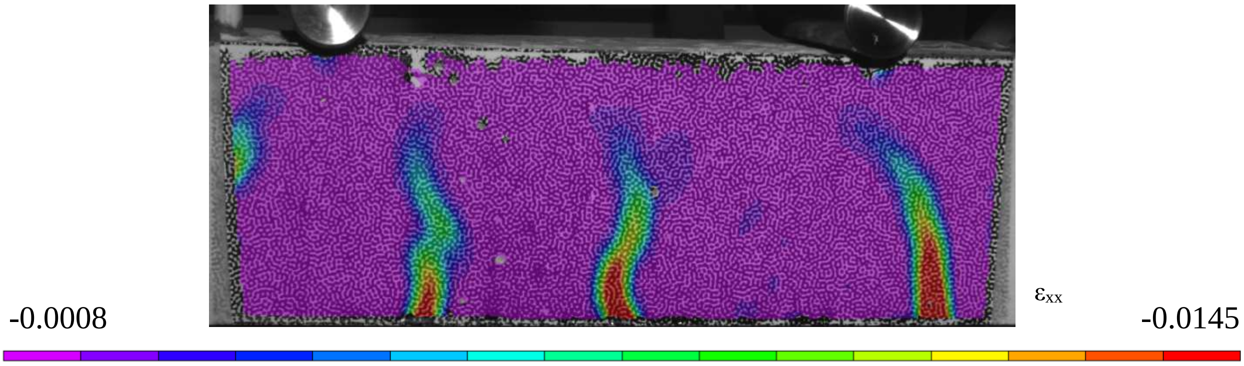

Figure 10 The strain field showing reopening of the cracks during the second loading

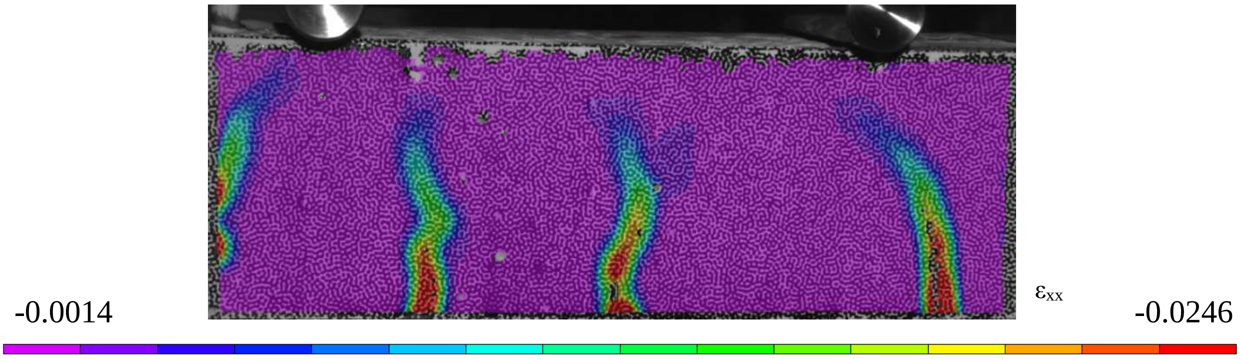

Figure 11 The strain field of the third loading, the same cracks open

Conclusion

The developed vascular system allows multiple self-healing. Both IPC and clay proved to be successful materials for the tubes. IPC showed a higher healing efficiency, 106 % at second loading and 73 % at third loading. The vascular system with clay tubes showed a lower healing efficiency of 83 % at second loading and 61% at third loading. In both cases the healing efficiency was higher compared to the reference which was 43 % for the vascular system with IPC tubes and 41 % for the vascular system with clay tubes. The reason for a diminished self-healing efficiency after each loading cycle is the clogging of the tubes. Future work will focus more on this aspect.

References

[1] C. Joseph, A. D. Jefferson, B. Isaacs, R. J. Lark, and D. R. Gardner, "Experimental investigation of adhesive-based self-healing of cementitious materials," *Mag. Concr. Res.*, vol. 62, no. 11, pp. 831–843, 2010.

[2] T. Nishiwaki, H. Mihashi, B.-K. Jang, and K. Miura, "Development of Self-Healing System for Concrete with Selective Heating around Crack," *J. Adv. Concr. Technol.*, vol. 4, no. 2, pp. 267–275, 2006.

[3] R. Davies, A. Jefferson, R. Lark, and D. Gardner, "a Novel 2D Vascular Network in Cementitious Materials," 2015, pp. 1–7, Concrete - Innovation and Design, fib Symposium Copenhagen 2015.

[4] S. Sangadji, “Porous Network Concrete: a bio-inspired building component ot make concrete structures self-healing,” Technische Universiteit Delft, 2015, PhD thesis.

[5] S. Sangadji and E. Schlangen, “Self Healing of Concrete Structures - Novel Approach Using Porous Network Concrete,” *J. Adv. Concr. Technol.*, vol. 10, no. 5, pp. 185–194, 2012.

[6] H. Cuypers, “Analysis and Design of Sandwich Panels with Brittle Matrix Composite Faces for Building Applications,” Vrije Universiteit Brussel, 2001, Phd Thesis.