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Simple off-the-shelf crack detector for small-scale centrifuge models

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Abstract

Reinforced concrete buildings represent the largest share of the world's building's stock. Although such buildings are usually designed to endure extreme loadings, their structural elements can deform and manifest cracks. Large cracks can point out problems related to structural health. For instance, hairline cracks can cause reinforcement corrosion. In addition, many existing cracks can be hidden by façade or can be difficult to determine due to inaccessibility to the structural element. Thus, many cracks cannot be easily detected by simple visual inspection of the building. Following the idea on how simple burglar alarm circuits and home security systems work we have proposed a sensor for monitoring occurrence of cracks in reinforced concrete buildings. The detector was experimentally tested in a centrifuge using a small-scale mock-up representing a real reinforced concrete system. This paper, inter alia, demonstrates scaling rules for centrifuges and how those rules are applied to a model used to mimic behaviour of real large scale reinforced concrete structures. Different small scale models comprising beams and slabs are made of gypsum mixtures. All the models were tested in the laboratories of the Faculty of Civil Engineering Osijek using a 0,40 m in radius centrifuge. The off-the shelf detector showed good potential in discovering crack occurrence on structural parts in buildings.

Introduction

Reinforced concrete buildings represent the greatest share of the world's building's stock and because of that are often subject of interest in civil engineering practise and scientific work. The biggest problem with reinforced concrete structures are extreme loads, such as strong earthquakes, large possible settlements, heavy equipment or machinery and other. Those loads can cause deformations like sagging and cracking which can easily be detected if they occur in visible places. Unfortunately, that is not often the case due to façade on buildings or the position of structural elements (e.g. foundations in the ground). Since deformations can cause problems such as reinforcement corrosion and eventually collapse of structure, it is crucial to detect and remedy them on time. With this in mind the aim was to find a simple, cheap and off-the-shelf detector that can be mounted on structural parts and monitor crack occurrence and avoid more severe damage and potential endangering lives. Following the idea on how simple burglar alarm circuits and home security systems work we have proposed a sensor for monitoring occurrence of cracks in reinforced concrete buildings. The hypothesis was that the process of crack occurrence is a small-scale equivalent of the door or window opening by an intruder. When doors or window is opened, the circuit will be open and thus the alarm will be triggered. The simple detector comprises one electrical circuit with a long-life battery and a LED light that will turn off when circuit is disconnected caused by excessive deformation of member to which the detector is attached. Literature review showed that similar sensors were designed earlier, mostly using electrical circuit principle. For instance, circuit with graphite lead connected to wires was used embedded in the cast-in-place soil-cement grid and then tested in large centrifuge (Tamura, Khosravi, et al. 2018). Another one (Chin, Rautenberg, et al. 2009), a bit more complex was designed using steel strip acting as a gage, to which the copper wire was glued. Two gages were then connected by copper strip so the conductivity was ensured, and when the crack occurs, deformation is determent by dropping of the voltage caused by breaking the copper strip. All the data was collected, and transferred to access points, so the whole construction was monitored from one centre. Those sensors were tested on a large-scale three storey RC construction. Also, another kind of sensor was proposed in (Morita, Noguchi 2008), using radio frequency identification connected to a brittle copper wire as switch. All data was monitored using antenna, scanner and personal notebook, which ensured detecting irregularities on time. The sensor was tested on steel specimen with notch on top, the specimen usually used for testing steel on fatigue.

The detector designed by the authors and described in this paper was experimentally tested in a centrifuge. A small-scale mock-up representing a real reinforced concrete system characteristic for Croatia was used as a vehicle for testing of the detector. More detailed description of small-scale mock-ups and the centrifuge is given in the following chapters of this paper.

The prototype and small-scale models for testing of the detector

The detector was tested using small-scale models based on a realistic reinforced concrete building which comprises slabs and shallow foundations. Dimensions of the slab were 540x280x42 cm. The slab was placed over two beams below longer edges. Beams had cross sections 28x20 cm. The foundation slab had plan dimensions of 215x270 cm. It was decided to make slab 20 cm thick in order to ensure crack development in a small-scale model. It was assumed that a building with two stories has a total mass of around 190 kN. It is important to stress that the structure does not correspond necessary to a real structure, instead it designed and used for purpose of testing of the crack detection device only.

The dimensions of the structural parts observed here were selected based on centrifuge limitations and following scaling rules described in (Madabhushi 2014).

The centrifuge (Figure 1) has radius of 0,40 m and capacity of 1000 RPM. The centrifuge can serve for testing models with a maximum volume of up to 8x8x8 cm placed inside a rigid basket. The basket has transparent window on one of its sides and a wireless camera used to track deformations. On the other side of the centrifuge arm, there is exactly the same basket placed for carrying a counterweight in order to minimize vibrations. This configuration of the centrifuge allows testing of small-scale models at acceleration of up to 450-*g*, with minimal cost and time. This allows us to test engineering system with dimensions of up to 36x36x36 m having up to 4,5 t.

Figure 1: Educational centrifuge at the Faculty of Civil Engineering Osijek

Structural parts described in this chapter were tested at acceleration of 400-*g* and they were scaled using scaling factors provided in Table 1.

Table 1: Scaling factors (Madabhushi 2014)

Quantity	Prototype/model
Length	$1/N$
Area	$1/N^2$
Volume	$1/N^3$
Density	1
Mass	$1/N^3$
Stress	1
Strain	1
Gravitation	N
Acceleration	N
Force	$1/N^2$
Young's modulus	1
Time	$1/N$

Material used for small-scale models

Due to the scaling rules, mixture for small-scale models has to be selected in order to well describe characteristic of real structural elements (Sabnis, White 1967). At first, cement mixture was found as a logical solution to use for simulating concrete in small scale models. However, it was shown that by reducing the model, tensile strength of cement rises causing model failing to simulate the behaviour of real concrete elements (Sabnis, White 1967). Besides, concrete requires constant and controlled curing period of up to 28 days.

It was shown in (Sabnis, White 1967) that gypsum mortar makes much better option for simulating small-scale concrete elements, with gypsum being cheaper than cement and requiring lesser curing period.

Three types of gypsum, all from different manufacturers (*Bifix*, *Lasselberger*, *Knauf*), were tested under compression (Figure 2) and tensile (Figure 3) force to decide which gypsum to use in the experiment. Each test was conducted three times, every time using different specimen. Literature review showed slightly greater strengths, probably due to them using high strength gypsum. In addition, (Sabnis, White 1967) showed that gypsum mortar mixed with sand represent concrete better than gypsum mortars without sand.

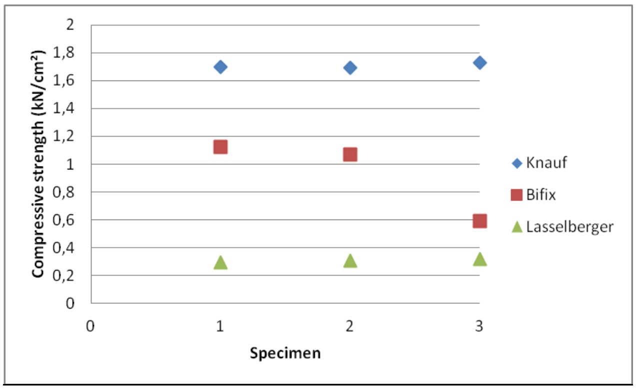

Figure 2: Compressive strength testing results

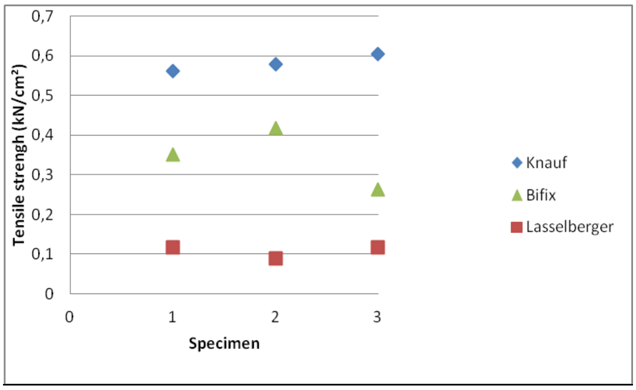

Figure 3: Tensile strength testing results

After all the tests were conducted we decided to make small-scale models using *Knauf* gypsum mortar without sand, with v/c ratio of 0,5. Models were made in Plexiglas moulds, previously covered with grease to ease removing models from them. Wrapping parts of the moulds in pieces of nylon also proved helpful with removing models from the moulds.

Small-scale models were used only to simulate crack development and their patterns in concrete structural parts. Thus the models were not reinforced in any way.

Description of small-scale structural parts

One way slab

Model of slab was 7,50 cm long, 3,90 cm wide and 0,6 cm thick, with two beams along longer sides with cross sections of 0,40x0,30 cm. The load on slabs was simulated by using two sets comprising thin steel plates glued together, forming the uniform load of around 80 g in weight. Before conducting the experiment in centrifuge, the model was placed on 4 small screws (1 cm long, with 0,5 cm in diameter). The screws were used to simulate supports and for better positioning of the model within the centrifuge basket with respect to the camera installed in the centrifuge.

Shallow foundation

The model of foundation was 3,75 cm long, 3,00 cm wide and 0,30 cm thick. A steel screw of total length of 2,9 cm and 1,6 cm in diameter, with two steel nuts added was placed in the centre of the slab to mimic the load coming from the column. The total weight of the steel screw with nuts was 65 g in model scale, which is 100 kN in prototype scale. The model was then placed on 5 cm of fine dry sand inside the basket of the centrifuge.

The operating principle of the detector

The detector can be assembled in several different ways, depending on the type of model that will be tested, material available and desired sensitivity of the detector. The main concept of the detector is based on the electrical circuit comprising a simple sensor connected in a series connection to a small 3V battery and LED light. The LED is supposed to turn off when the circuit is opened by cracking of the structural member that the detector is attached to through the simple sensor. Tested detectors by the authors differ mainly in material used to build the sensor through which the detector is attached to the structural part of the model, because it steers the sensitivity of detector:

1) The sensor can be made using thin copper wires connected to battery and LED light (Figure 4). The wire must be attached (e.g. glued) to the model so that it breaks together with the structural element. The placement of wires depends on where the cracks are expected.

Figure 4: The detector variant with copper wires

2) Graphite lead used in pencils can also be used for the purpose of making sensors (Figure 5). In this variant the copper wire of the circuit must be connected to the lead. The easiest way to form that kind of circuit is by wrapping the wire around the lead and then gluing the lead with wires on both sides on the model. The advantage of this approach is high brittleness of the lead, which makes it almost certain that circuit will open when member cracks even a little bit.

Figure 5: The detector variant with graphite lead on left hand side of the slab

3) Inside the circuit, copper adhesive tape can be soldered to copper wires, which are connected to the battery and LED light in series (Figure 6). Adhesive copper tape is easier to mount onto the model when compared to the variants with the glue. Problem with this variant of the detector is reduced breakability of copper tape compared to the other two materials used. The cooper tape should be cut in narrow stripes to better define its sensitivity.

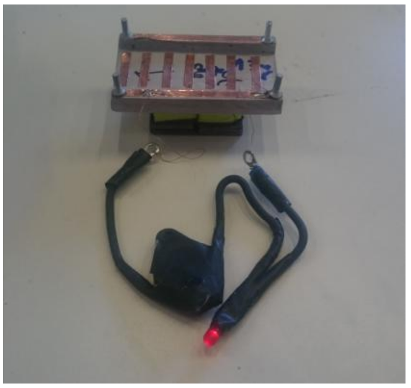

Figure 6: The detector variant with copper adhesive tape

The length of the sensors depends on the size of model to be tested and the place where the detector will be attached. Batteries can be placed onto the load acting as an additional load, beneath the model if possible, or even on the lever of the centrifuge.

Experiment in the centrifuge

Ready for testing, the detector attached onto the model was placed inside the basket of the centrifuge. Before starting the experiment the counterweight was precisely weighed so the whole system would be in balance during the experiment and to minimize vibrations. That requirement is mandatory during every experiment in the centrifuge. All tests were filmed with a wireless camera that allowed us to observe what was happening inside the centrifuge. Besides that, the camera allowed us to track the number of rotation per minute during each flight of the centrifuge. That way, as long as the LED light on the detector was on, we were certain that no crack occurred (Figure 7). Similarly, it was possible to detect the exact moment when the first crack occurs and when the collapse of the whole system takes place. Moreover, it was possible to later review again the whole experiment in slower pace

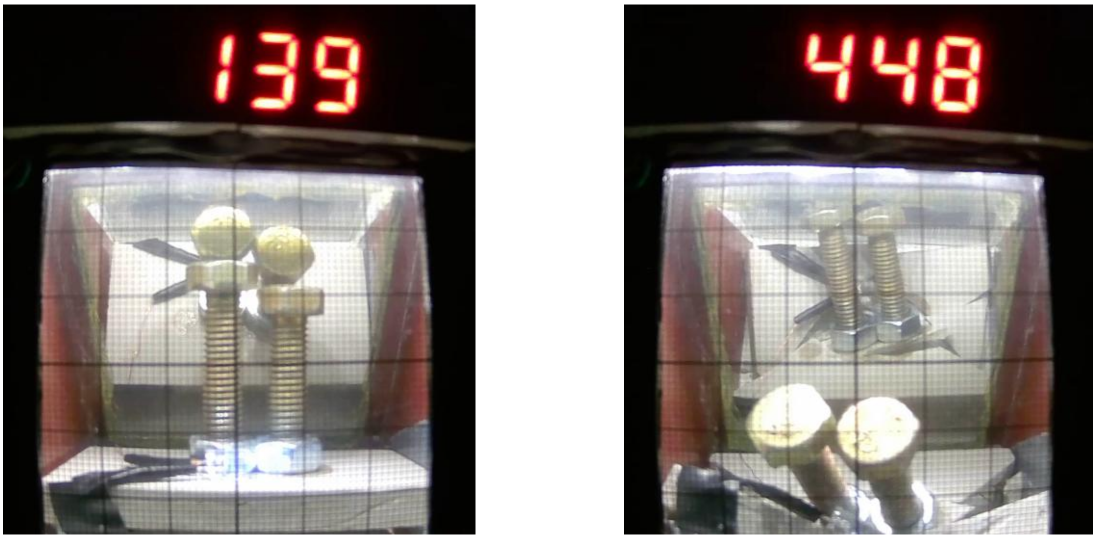

Figure 7: Model with the detector before (left) and after (right) the crack occured

However, the detector had not proved valid for foundation models, because the circuit had not broken even though the model did. The sensor has to be modified to be used in models like this one.

Conclusion

Reinforced concrete buildings represent the largest share of the world's building's stock. Although they are usually designed to endure extreme loadings, their structural elements can deform and manifest cracks, which can cause reinforcement corrosion. Many cracks can be hidden by façade or cannot be easily detected by simple visual inspection of the building. Following the idea on how simple burglar alarm circuits and home security systems work a sensor for monitoring occurrence of cracks in concrete buildings was proposed. The detector was experimentally tested in a 0,40 m radius centrifuge using small-scale models comprising beams and slabs made of gypsum mixtures representing real structural concrete parts. Three different types of material were used to make the sensor of the detector: I) cooper wire, II) graphite lead and III) adhesive cooper tape. The detector was tested on I) a small-scale one way slab over beams on longer sides and II) shallow foundation slab placed on a thick layer of dry fine sand. The detector proved useful for making experiments comprising small-scale slabs on beams. However, there were problems with the sensor attached to models of foundations placed on dry sand. In the later case, the sensor was not able to crack along with the model. Usually cracks occurred in places where there were no sensors. Since the tested slabs on sand were not reinforced we believe the sensor acted as the reinforcement and thus prevented cracking of the slab. The concept of the sensor for foundation slabs has yet to be improved.

Of the three versions of the detector, the one with the copper adhesive tapes proved to be the least effective. Although it was the easiest to attach to the model, it did not crack due to its large ductility. Both thin copper wires and graphite lead proved useful for purpose of making the crack detector, as they broke along with the member and thus fulfilled the idea and the starting hypothesis.

The detector can be modified to fit larger scale models and even full size structures. However, the detector should then be connected to a stronger and more resistant battery, along with more LEDs in different colours or placed in a specific order.

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