Carbon Fibre Sensor Networks as reinforcement for concrete and component monitoring

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ABSTRACT: One of the fundamental building blocks in the development of a sustainable urban environment is the ability to monitor the structural systems constructed in the urbanization process. In this study, we aim to investigate a new class of smart textile reinforcement for Textile Reinforced Concrete (TRC) structures with inherent sensing capabilities. The carbon fibre is used as the reinforcement as well as the sensor. The sensing capability aims to utilize the piezoresistive effect of carbon fibres within textile fabrics. The study demonstrates that by strain applied to the reinforcement, the electrical response of the carbon fibre changes. In correlation with the material properties, load and strain within the component can be detected. In this study, the concept and the electromechanical properties of fibres and textiles are experimentally demonstrated. Specifically, several structural-sensory fibre reinforcements are tested and monitored under mechanical loading condition. The results of the tests demonstrate the features of the sensory/structural technology; highlight its potential use as a basis for a structural monitoring system.

1 INTRODUCTION

There are several developments that require new building materials. To reduce the environmental impact, especially the carbon dioxide emissions, less concrete needs to be consumed. Tall buildings require lightweight façade solutions. The combination of Textile Reinforced Concrete as building material with integrated sensor offers a solution to these needs. Textile Reinforced Concrete uses high modulus fibres made of glass and carbon instead of the traditional steel rebar to reinforce the concrete element, see Fig. 1. Since the fibres eliminate the required need to coverage against corrosion, thin walled components up to few millimetres thickness are possible. Brameshuber et al (2006), Hegger et al (2008), Hanisch et al (2004), Curbach et al (2001), Janetzko et al (2007).

The textiles used to reinforce the TRC element are typically open mesh grids made of leno wovens or warp knitted fabrics, see Figure 2. In general, the fibre properties in terms of stiffness and strength are much higher compared to the concrete. Depending on the textiles used and the amount of fibres in relation to the matrix, the component properties are in between the properties of the fibre and the properties of the matrix.

The idea of the continuous Carbon Fibre (CF) Sensor is to make use of the electromechanical properties of the carbon thread for strain sensing. Carbon fibres are electrically conductive and change their conductivity related to strain. This idea, of using continuous carbon tows for sensing, has been first investigated by Wen and Chung (1999) and Wen et al. (2000). The conducted research extends this approach by using continuous CF sensors in order to create an inherent component health monitoring introduced in Goldfeld et al (2014, 2015a, 2015b).

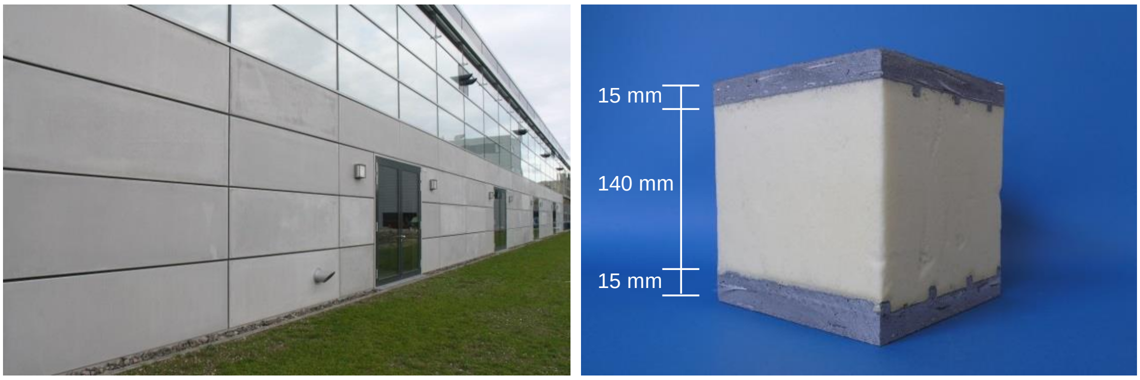

Figure 1. Façade of Innotex building (left exterior view, right cross section of sandwich structure)

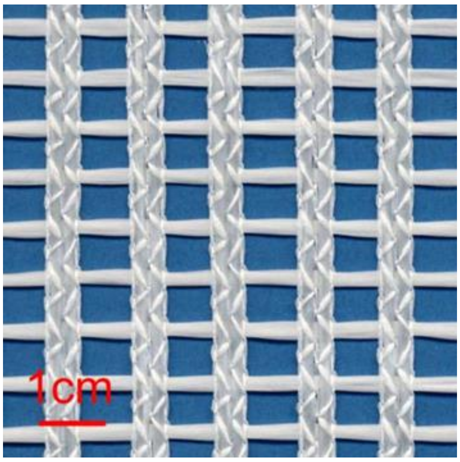

Figure 2. Open Tricot Weave Fabric

2 MATERIALS AND METHODS

2.1 Processing of carbon fibres

Carbon fibres can be distinguished by material properties and production process. Regarding the material, carbon fibres are distinguished by their precursor-material in Polyacrylnitril (PAN)-based fibres and Pitch-based fibres. The latter consists of an anisotropic graphite material with aromatic hydrocarbons with a higher value of orientation of the graphite-structure in the precursor than in PAN-fibres.

The precursor is stabilized through an oxidation process at 200-350 °C to prevent them from melting in the following carbonization. This increases the amount of carbon in the fibres from about 60 % after the stabilization up to 92 % by applying a temperature of up to 2000 °C. The carbonization removes hydrogen, nitrogen, oxygen and sulphur. In this step, graphite-structure oriented in fibre direction is formed.

To define the final properties of the fibres, a third process, the graphitization is added at temperatures from 1200 °C to 3000 °C. That way, the graphite-structure is further aligned through stretching the fibres, the density is reduced by the mentioned reactions and the amount of carbon is increased at about 95 %.

2.2 Mechanical properties

The temperature the carbon fibres are treated determines its mechanical properties. The mechanical properties can be distinguished by this process into two types. Fibres treated at 1200 °C (carbonized) are called high tenacity (HT) carbon fibres whereas carbon fibres treated at 2000 – 3000 °C (graphitized) are called high modulus (HM) carbon fibres. HT-fibres have a tensile strength of about 3 - 7 GPa and a Young's Modulus of about 180 - 350 GPa, HM-fibres have a tensile strength up to 3,1 GPa and a Young's Modulus from 400 to 800 GPa.

The fracture strain of Textile Reinforced Concrete is about 1 % until first cracks appear. The fracture strain of the reinforcement fibres has high influence on the component behaviour. The mechanical properties of the composite are a synergy of both, the matrix and the reinforcement. An increase of the fibres' Young's Modulus is not able to increase the properties of the composite in the same extent. The carbon fibres used in these tests have a fracture strain from 0.6 to 1.6 % and are hence in the same range as concrete. The different fracture strain and different Young's Modulus makes the suitable for different applications. The different fibre types enable the structural design on different levels.

2.3 Electrical properties of carbon fibres

The use of carbon fibres as sensor elements depends on two electrical properties; conductivity and piezoresistivity.

2.3.1 Electrical Conductivity

The electrical conductivity κ, is inverse of electrical resistivity ρ, of a given material. It can be calculated as a product of charge carrier concentration n, elementary charge e, and the mobility of the charge carrier u, of the material.

$$\kappa = \rho^{-1} = n \cdot e \cdot u \tag{1}$$

The electrical conductivity of carbon fibres increases with increase in Young's modulus as well as an increase in temperature.

2.3.2 Piezoresistive Effect

The piezoresistive effect is the change in resistance R, with change in applied mechanical strain ε. The ratio of relative change in resistance $\frac{\Delta R}{R}$, to strain is known as Gauge Factor (GF).

$$\frac{\Delta R}{R} = GF \cdot \varepsilon \tag{2}$$

The resistance is directly proportional to the length of the material L, and inversely proportional to the cross-sectional area A.

$$R = \rho \frac{L}{A} \tag{3}$$

The carbon fibre and composing the carbon fibre filaments have a circular cross sectional area. Considering n number of filaments, the Poisson's ratio ν, and strain ε leads to a relative change in resistance given by

$$\frac{dR}{R} = \varepsilon(1 + 2\nu) + \frac{d\rho}{\rho} - \frac{dn}{n} \tag{4}$$

Assuming there is no breakage in the carbon fibre, the number of filaments does not change, so the change in resistance becomes

$$\frac{dR}{R} = \underbrace{\varepsilon(1 + 2\nu)}_{Geometrical\,Effect} + \underbrace{\frac{d\,\rho}{\rho}}_{Piezoresistivity\,Effect} \tag{5}$$

As shown, the change in resistance depends on two terms, one due to the geometrical effect and the other due to the piezoresistivity effect.

The use of carbon fibre as a sensor requires a constant Gauge Factor value. However the GF value for a given material has different values lateral and perpendicular to the direction of strain. Hence the absolute GF depends on GF in the direction of strain GF_l and the Poisson's ratio as well as the ratio of GF_l and the perpendicular gauge factor GF_q.

$$\mathrm{GF} = GF_l\,(1 + \frac{GF_q}{GF_l}\nu) \tag{6}$$

2.4 Sample preparation

To test the electrical conductivity under mechanical load, the carbon fibre is clamped into a tensile testing machine. For preventing the fibres to break at a stress spike caused by the clamping a defined homogenous insertion of the force into the fibre is needed. Therefore, the carbon fibres are embedded in a suitable resin.

This is done by stretching the fibres with certain strength and fitted into silicon moulds of a defined size and measured free length between the clamping spots, see Fig. 3. The moulds are then filled with resin and cure for 24 hours. As the electrical properties are meant to be evaluated, there has to be a connection between the carbon fibre and the electrical testing device.

Clamping the fibres with conventional alligator clamp produces a lot of electrical noise while measuring which can be of larger scale than the signal from the carbon fibres. To avoid this effect, the connection point is placed in the embedded area. The carbon fibre and a copper-cored wire are brought together in a silver jacket and crimped together to apply a lossless connection compared to the resistance of the fibre. That way, the wires can be connected to the electrical testing device without moving joints.

The investigated fibres differ in filament count, linear density and tensile modulus. They are given in Table 1.

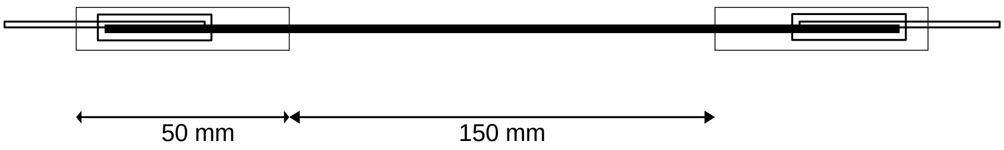

Figure 3. Sample preparation and free length

Table 1. Investigated fibres

	Filament count	Linear density	Tensile Modulus
Carbon Roving 1	24K, PAN-based	1600 tex	240 MPa
Carbon Roving 2	24K, PAN-based	810 tex	393 MPa
Carbon Roving 3	12K, Pitch-based	1560 tex	420 MPa

3 RESULTS

The results of the electro-mechanical response of the carbon fibres are shown in the Figures 4-6. The figures contain the resistance over strain of each type of fibre.

The first carbon fibre (see Table 1) has the highest strain and a linear proportion between resistance and strain up to 1,145 % of strain in average, see Fig. 4. The average Gauge Factor is 0,013079. It is noticeable that the standard deviation of the series is quite high and also the behaviour and starting point of the non-linear section is quite different.

The second carbon fibre (see Table 2) has much lower strain compared to the first and a linear proportion between resistance and strain up to 0,512 % of strain in average, see Fig. 5. The calculated average Gauge Factor of the second carbon fibre is 0,015454.

The third carbon fibre has medium strain compared to the first two and a linear proportion between resistance and strain up to 0,618 % of strain in average, see Fig. 6. The calculated average Gauge Factor of the third carbon fibre is the smallest compared to the other fibres with 0,012083. The following table summarizes the results.

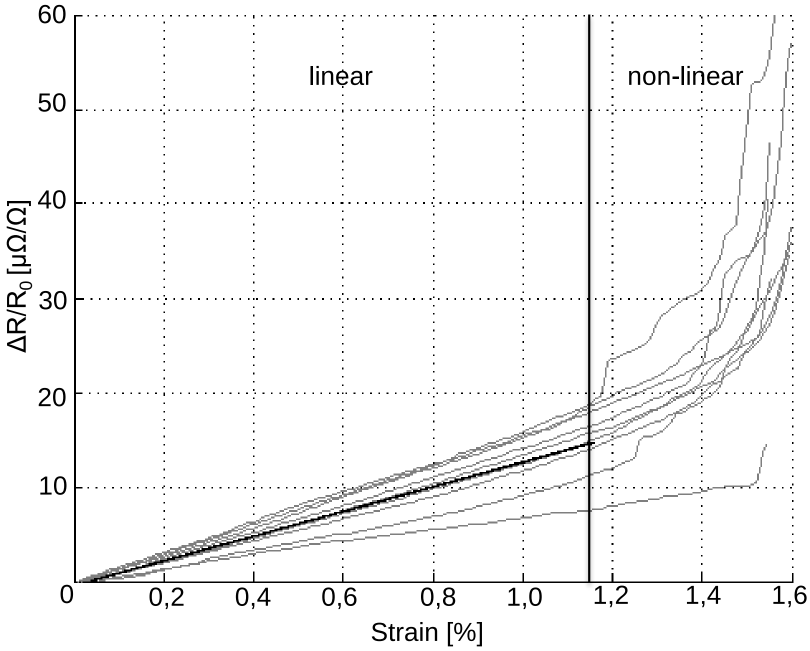

Figure 4. Strain-Resistance Diagram of Carbon Roving 1

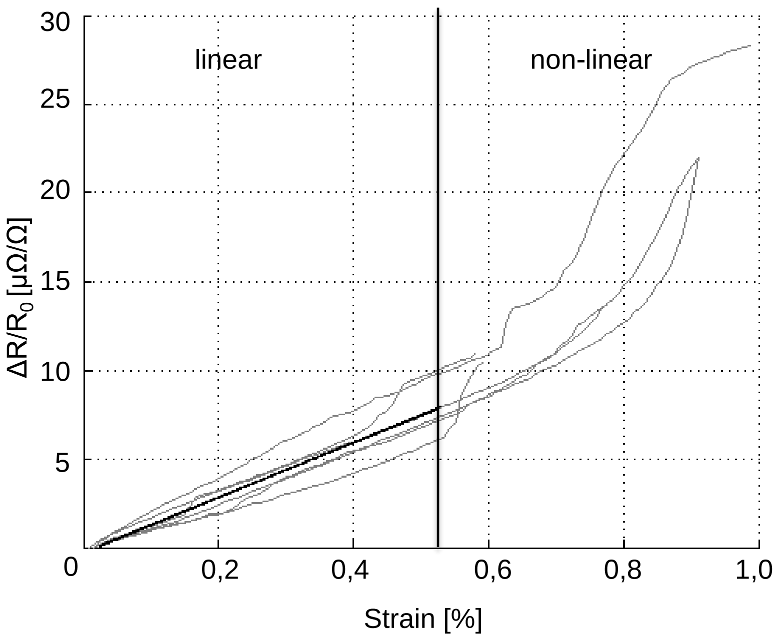

Figure 5. Strain-Resistance Diagram of Carbon Roving 2

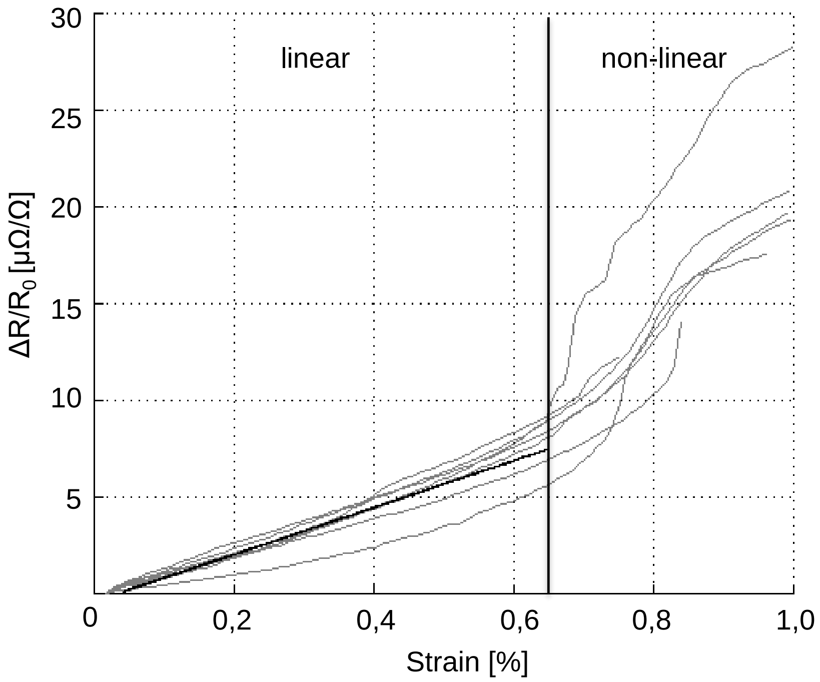

Figure 6. Strain-Resistance Diagram of Carbon Roving 3

Table 1. Investigated fibres

	Gauge Factor	Linear Strain
Carbon Roving 1	0,013079	1,145 %
Carbon Roving 2	0,015454	0,512 %
Carbon Roving 3	0,012083	0,618 %

3.1 Reproducibility Over Time

To check the reproducibility cyclic load was applied to the first carbon fibre. Within the test the carbon fibre sample was subjected to multiple cycles of strain values over a period of time, see Fig. 7.

It can be observed that the change in measured voltage is proportional to the change in applied strain. There is also a noticeable drift in the absolute values of measured voltage over time. However the relative change in voltage is seemingly constant for the corresponding change in applied strain.

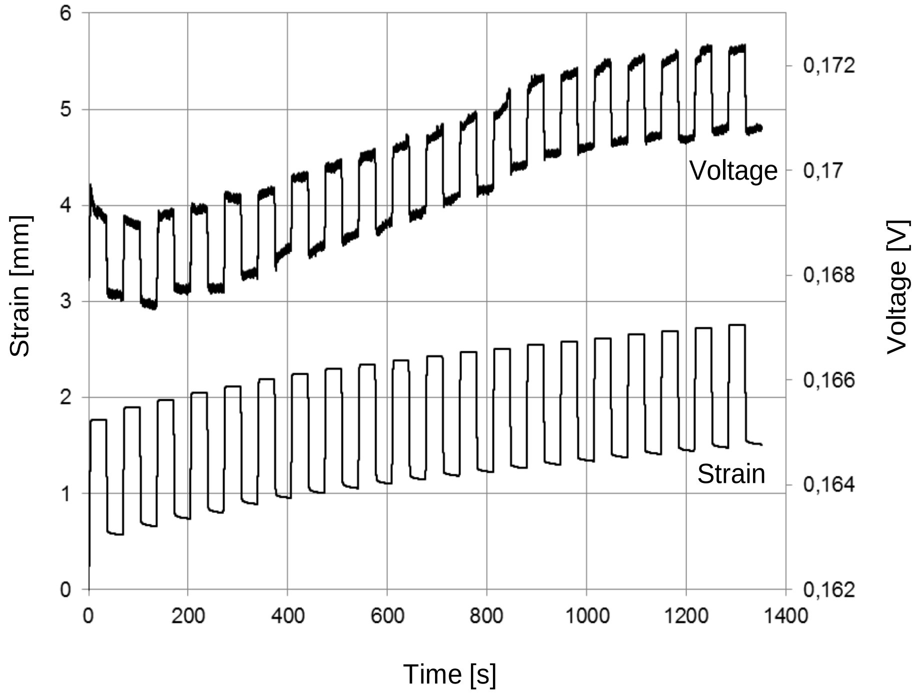

Figure 7. Change in Voltage and strain over time

4 CONCLUSIONS AND RECOMMENDATIONS

Although the carbon fibres differ in Young's Modulus and material the Gauge Factor is in a similar range between 0,012 and 0,016 for all types of fibres. Still the change in resistance is rather small and a lot of factors influence the sensor signal. The observed error in the signal could be attributed to the following factors:

1. Damage to the fibres due to mechanical fatigue;
2. Measurement inaccuracy which also may account for the noise due to constant movement of the electrical connections;
3. Temperature changes introduced into the material due to mechanical and electrical work.

All this influences do not cause sudden peaks, but cause a drift in the signal over time, which can be seen in Fig. 7. Since the relative change in the cyclic loading is repeatable proportional to the introduced strain, an improved measurement is the next step to utilize the fibres as sensor.

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