Open Eng. 2016; 6:548–553

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Smart Textiles for Strengthening of Structures

DOI 10.1515/eng-2016-0074
Received Mar 30, 2016; accepted Sep 06, 2016

Abstract: This paper presents results of mechanical tests on a prototype of an innovative structural strengthening in form of self-monitoring fabric. Smart textile employs carbon fibers conductivity for measuring strains while monitoring changes of electric resistance under increasing load. A general solution was tested in a series of calibrating tests on strengthening of small size concrete slabs. Promising results of simple specimen, has encouraged the research team to perform the next tests using mastered carbon fibre reinforced fabric. Main tests were performed on natural scale RC beam. Smart textile proved its efficiency in both: strengthening and monitoring of strains during load increase. New strengthening proposal was given 10% increase of loading capacity and the readings of strain changes were similar to those obtained in classical methods. In order to calibrate the prototype and to define range limits of solution usability, textile sensor was tested in areas of large deformations (timber beam) and as well as very small strains (bridge bearing block). In both cases, the prototype demonstrated excellent performance in the range of importance for structural engineering. This paper also presents an example of use of the smart strengthening in situ, in a real life conditions.

Keywords: strengthening of structures; smart textile; CFRP composites; Structural Health Monitoring; carbon fibers

1 Introduction

Traditional methods of structural strengthening of existing buildings, especially those subjected to complex loads (for example in seismic regions or in regions affected by mining deformations of subsoil) may cause structural failures, instead of protecting the structure. It was natural reason for the academia and industry to look how to resolve this problem. One of possible solutions was found in fibrous materials and textiles already used in other branches of industry such as FRP (Fibre Reinforced Polymers), SRP (Steel Reinforced Polymers) and TMR (Textile Masonry Reinforcement). High performance fibres have excellent mechanical properties suiting to needs of the construction and most of the research works within Structural Engineering focuses on those features. Observations from the solutions tested in Textile Engineering proved that these fibres may be useful for "sensoring". This feature seems to be underestimated by structural engineers, while other branches of industry dynamically use it in multifunctional smart textiles [1–4].

Most of the solutions for Structural Health Monitoring base on external monitoring systems and few recent smart solutions use optical fibres [5], though very rarely yet - high strength fibres themselves [6]. Most interesting solutions refer, however, to cables of bridges [7].

Therefore, a group of researchers from Silesian University of Technology (Poland) and Universidade da Beira Interior (Portugal) with industrial partners: FIDIA (Italy), FISIPE (Portugal) and Europrojekt (Poland) decided to undertake efforts in order to create a strengthening solution, which would be able to monitor itself using the features of fibres. Research programme called INSYSM (Intelligent Systems for Structures Strengthening and Monitoring) was founded by the European Commission [8].

This paper presents the overview of chosen results of structural tests on elements strengthened with CFRP (Carbon Fibre Reinforced Polymer) smart-textile, demonstrating the actual state of the solution.

Authors believe that such self-monitoring strengthening system could be particularly attractive to upgrade large structures with difficult access.

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* International Conference on Engineering 2015 – 2–4 Dec 2015 – University of Beira Interior – Covilhã, Portugal

Table 1: Mechanical and electrical properties of carbon tow used in the research.

Number of filaments	Diameter of filament [µm]	Tow fineness [tex]	Density [g/m^3]	Elongation at break [%]	Tensile modulus [GPa]	Tensile strength (GPa)	Single filament resistivity [µΩm]
24 k	7	1600	1.81	1.9	270	5.0	14
50 k	7	3200	1.80	1.6	253	4.0	15

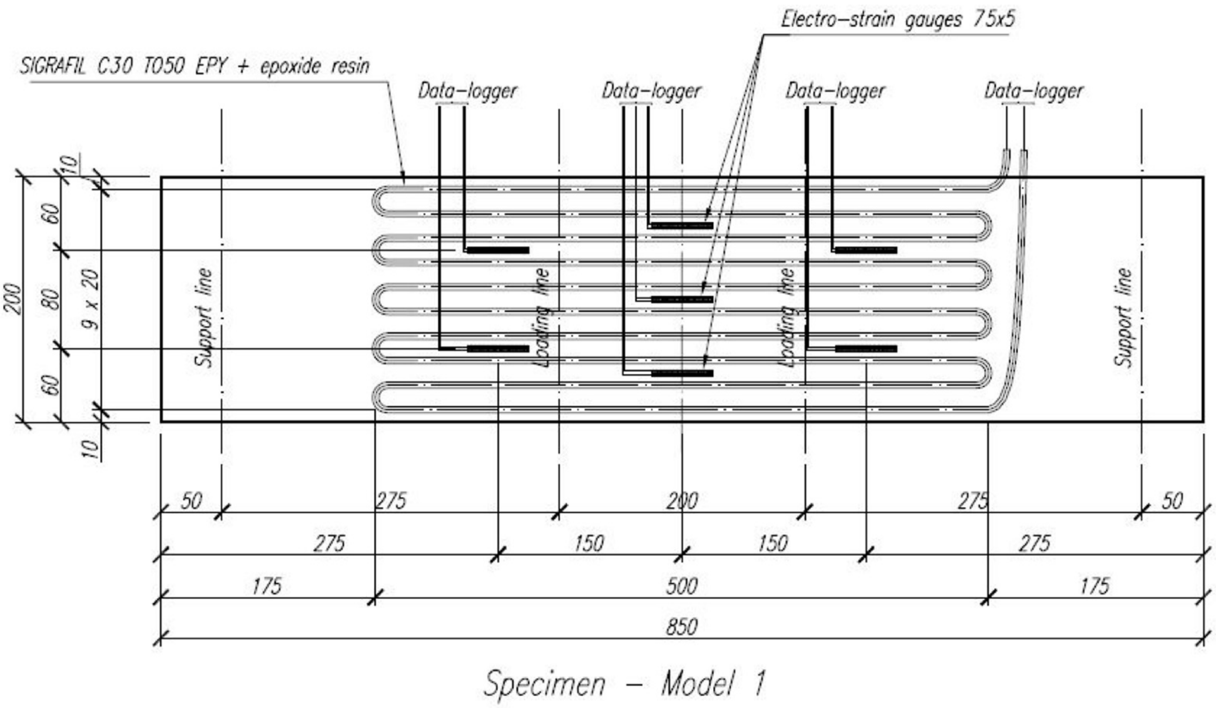

Figure 1: Scheme of the initial tests on specimens SP1 and SP2 equipped with the strengthening solution with the use of conductive carbon fibres [mm].

2 Initial tests on smart textile specimen

First tests on structural elements were preceded by numerous probes, checking and calibrating different solutions for smart textile, which would be able not only to upgrade structural capacity of the element but also measure low strains.

The monitoring of strain has been done by registering the changes in electrical resistance in conductive fibres while applying the load. The increase of the tensile strain was associated with the increment of relative electrical resistance in fibres.

The basic material for the strengthening smart-textile was carbon fibres – fibres, which is a common material in civil engineering and is characterized for its excellent conductivity.

The properties of the chosen types of carbon fibres are presented in Table 1.

The first attempt to verify the monitoring possibilities of carbon fibres were undertaken on small concrete slab specimens, strengthened with singular bundle of fibres and glued to the concrete surface with epoxy resin. For the control of real level of strains, specimens were additionally supplied with a set of strain gauges. The geometry of specimens is illustrated in Figure 1.

Results of tests proved the efficiency of the solution for both strengthening and monitoring of structural elements. The relation between strain and load increment was developed by similar path readings from the strain gauges (see Figure 2). Detailed description of initial tests and calibration procedure had been presented by Salvado *et al.* at [9]. The next step was to work on the prototype of sensing fabric.

Table 2: Properties of smart-textile specimens.

Specimen	Type	Thickness (cm)	Carbon fibre volume fraction	Total fibre volume fraction	Initial resistance (Ω)
1	24k carbon fibres	0.17 ± 0.048	0.12	1.6	7
2	24k/24k carbon fibres	0.17 ± 0.036	0.12	1.9	7

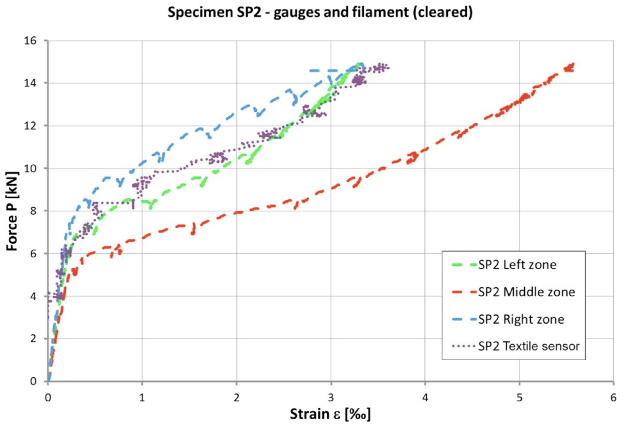

Figure 2: Strain-Load relationships for specimen SP2.

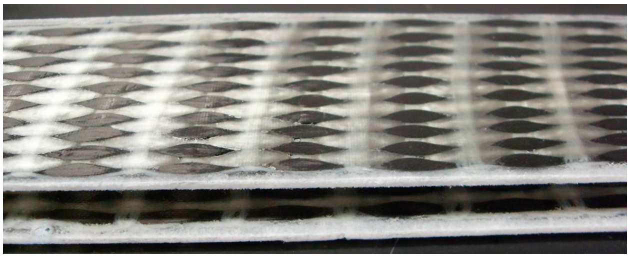

Figure 3: Carbon fibre smart textile specimen for strengthening of structures with function of real time strain monitoring.

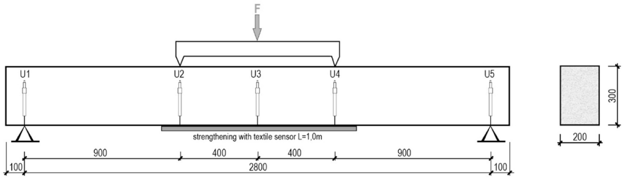

Figure 4: Scheme of the test on reinforced concrete beam with textile sensor.

The woven textile is a fabric made of carbon tow with continuous fibres separated by acrylic continuous fibres. Textile containing two types of fibres was joint together by cotton yarn (Figure 3). The woven fabric was fixed to the concrete surface with epoxy resin (density: 1110 kg/m^3). Table 2, highlights the properties of the fabric specimens.

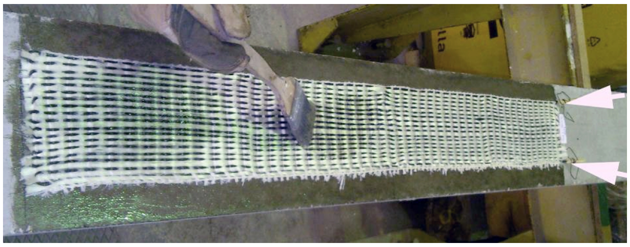

Figure 5: Application of textile sensor on the surface of reinforced concrete element.

3 Laboratory tests on full-scale strengthened RC element subjected to flexure

After successful trials on small elements, strengthening and self-monitoring smart-textile was tested on reinforced concrete element subjected to flexure. The simply supported beam was charged by pair of forces creating constant moment region of the length of 800 mm, as shown in Figure 4. The smart-textile with dimensions of 150 mm wide and 1000 mm long, was applied along the tensioned surface, in the zone of constant value of bending moments.

The technology for the application of smart textile prototype on the surface of a concrete element is analogous to the wet lay-up process of typical FRP sheets. For this case, typical epoxy resin was used (S&P Resin 55). The lamination process is demonstrated in Figure 5.

Initially, the electrical resistance of textile sensor fixed to concrete surface of non-loaded element was measured (see white arrows in Figure 5) given a value equal to 165.4 Ω. Then, a continuously load was applied using a hydraulic jack until the strengthened element failed. The element was additionally equipped with a set of strain gauges for strain control and a set of variable displacement transducers (U1 to U5) for deflection control. The purpose of conventional strain gauges was to enable calibration of readings from the smart-textile.

As the smart-textile was meant for self-monitoring strengthening solution, one of the goals of the test was

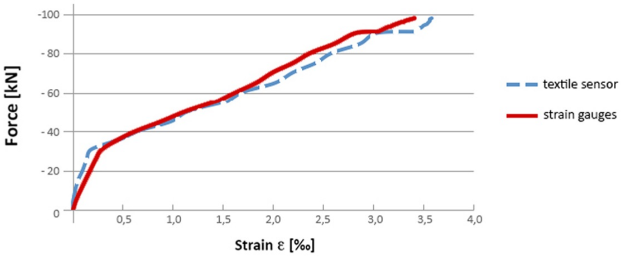

Figure 6: Comparison of average strain measured with the use of smart-textile prototype and system of typical strain gauges.

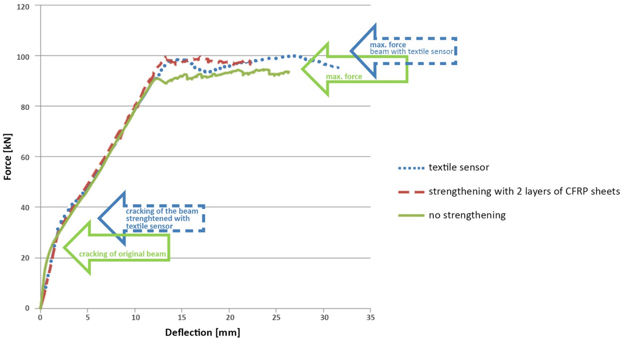

Figure 7: Comparison of Force-Deflection curves for beams with no strengthening, beam with textile sensor and beam strengthened with two layers of Carbon Fibre Reinforced Polymer sheets.

to check the mechanical performance and strengthening effectiveness. Results of the tests were compared with results obtained on reference elements without strengthening and with strengthening in form of regular CFRP commercial system.

The tests results were very promising. The most interesting outcome was the confirmation of the possibility of conducting precise strain monitoring by strengthening system. The deviations of readings from smart-textile and strain gauges do not exceed 5% and the character of the curves force-strain for both solutions are very similar (Figure 6).

The test served also to define the effectiveness range of strengthening system for structural upgrade of RC (reinforced concrete) elements. The behaviour of the model equipped with textile sensor was compared with the behaviour of a beam with no strengthening and with a commercial CFRP system (2 layers of sheets, with the same geometry as textile sensor).

Results of the comparison tests are presented in Figure 7, in the form of curves showing changes of deflection with increament of external load.

The obtained results are also very promising. The loading capacity of the beam strengthened with textile sensor increased by 10% in comparison to the model with no strengthening. First failures occurred on significantly higher level of external load.

Figure 8: Failure of RC beam strengthened with Carbon Fibre Reinforced Polymer smart-textile.

Figure 9: Tests on timber beam strengthened with textile sensor.

It should be noted that almost identical results (load at the first crack, failure force and deflection) were obtained while testing the beam with commercial CFRP strengthening.

Failure in both cases was caused by the delamination of FRP strengthening and concrete cover destruction in the zone of bond anchorage (Figure 8).

4 Tests on timber beam

Prototype of textile sensor had also been verified in conditions of large structural deformations, such as in timber elements. To obtain large deflections, a test using pine timber beam of 160 × 80 mm section was used (Figure 9). Similar configuration as in the case of RC beam (see Figure 3) regarding to the scheme, the geometry of the stand, the length of textile sensor and the layout of the strain gauges was employed. Expected deformations of the beam exceeded conditions of Serviceability Limit States, but the

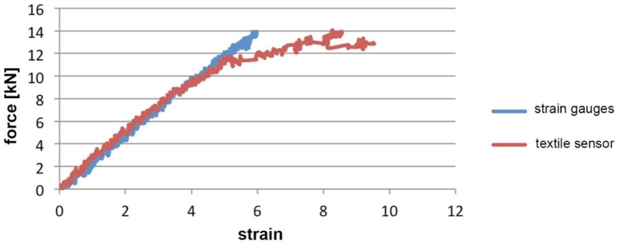

Figure 10: Results of tests on timber beam strengthened with textile sensor.

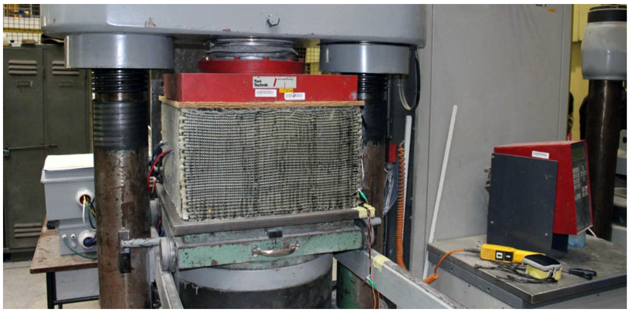

Figure 11: Compressive test on concrete bridge bearing block strengthened with textile sensor.

goal of the test was to check the behaviour of the prototype in extreme conditions.

Test proved excellent work of textile sensor in range of low tensile strains. Average reading obtained from strain gauges is almost the same as from textile sensor (Figure 10). Described test demonstrated problems of the prototype in monitoring of large elongations.

In general, as it was mentioned above, such large elongations and deflections do not meet requirements of Serviceability Limit States, thus the textile sensors would not be used in such conditions. Such test allows establishing limits of the range of new product usability. Phenomena of disrupted readings while large deformations shall still be analysed and described precisely and supported by results of further tests.

5 Laboratory compressive test on bridge bearing block

The calibration of textile sensor reading and defining the range of its usability required verification of the prototype under very low stresses. For this purpose, the tensile sensor was attached to a full-scale concrete block of bridge bearing (Figure 11). The block was then subjected to compressive forces and the strains were registered on the side surface of the element. Additionally, the test was meant to run for long term and it is still on-going. However, first results are proving high sensibility of textile sensor prototype in low-strain conditions (Figure 12). It is difficult at this moment to define the bottom edge of smart textile use and it requires further analysis.

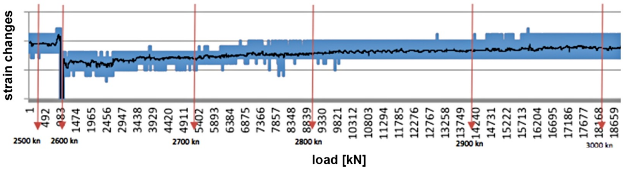

Figure 12: Results of the initial test of compression of bearing block: change of strain in function of compressive load increase.

Figure 13: Textile sensor applied in the concrete beam of hydroelectric power plant.

6 In-situ application of textile sensor

Prototype of the carbon fibre smart textile requires verification in real-life conditions. For this reason, it has been applied on concrete element of the building of a hydroelectric power plant. The building had been formerly destroyed during flooding and it is being upgraded. Due to expected large loads producing complex state of stresses, textile sensor was applied on the edge side of concrete beam that may be subjected to compression, vertical and horizontal flexure (Figure 13).

Process of building rehabilitation has not been completed yet; monitoring readings from textile sensor will be collected in all phases of the upgrade and at the end of planned works.

7 Conclusions

This paper presents all the phases of the calibration of a smart textile prototype for structures strengthening and monitoring. Carbon fibre-made fabric bonds two excellent features of this material – high strength and conductivity; therefore, it attracted attention of structural engineers. Conductivity of carbon fibres was used for monitoring the strains, by registering the changes of electric resistance while deformation of structural element.

This feature has been initially checked in the test of measuring deflections of small concrete slabs in which a single tow carbon fibre was glued. It proved the potential of this solution. In the next step, textile sensor was applied on a RC beam subjected to flexure. This test has shown high efficiency for the prototype for both features: strengthening and self-monitoring of structures.

In order to establish the limits of the prototyped solution usability range, the tests were performed in areas of large (deflection of timber beam) and very small (compression of concrete bridge bearing block) deformations. It demonstrated high sensibility of textile sensor to low deformation and disruption of readings for large deformations. In both cases, further tests and analysis are required.

At the same time the self-monitoring strengthening will be tested in situ, in real life conditions.

Acknowledgement: The research programme referred to in this paper has been supported by INSYSM Project founded by the European Commission in the 7th Framework Programme Marie Curie Industry–Academia Partnership and Pathways (Project No. 251373).

References

[1] Schulte K., Baron Ch., Load and Failure Analyses of CFRP Laminates by Means of Electrical Resistively Measurements, Composite Science and Technology, 1989, 36(1), 1989, 63–76

[2] Wang X., Chung D.D.L., Continuous Carbon Fibre Epoxy-Matrix Composite as a Sensor of its Own Strain, Smart Materials and Structures, 1996, 5(6), 796–800

[3] Todoroki A., Yoshida J., Electrical Resistance Change of Unidirectional CFRP Due to Applied Load, JSME International Journal. Series A, 2004, 47(3), 357–364

[4] Giurgiutiu V., Health monitoring of Aerospace Composites, Academic Press, Elsevier, USA 2016

[5] Lau K.-T., Fibre-optic sensors and smart composites for concrete applications. Magazine of Concrete Research, 2003, 55(1), 19–34

[6] Mufti A.A., Neale W.K., State-of-the-art of FRP and SHM applications in bridge structures in Canada. Composites & Polycon, The American Composites Manufacturers Association, Tampa, FL USA, 2007

[7] Zhou Z., Zhang Z., Ou J., Applications of FRP-OFBG Sensors on Bridge Cables, Proceedings of the Smart Structures & Materials/NDE Joint Conference: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems (San Diego, USA), SPIE, 2005, 1–10

[8] INSYSM Project website: http://insysm.polsl.pl, 6.11.2016

[9] Salvado R., Lopes C., Szojda L., Araújo P., Gorski M., Velez F.J., Castro-Gomes J., Krzywon R., Carbon Fiber Epoxy Composites for Both Strengthening and Health Monitoring of Structures, Sensors, 2015, 15, 10753–10770