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AIR HUMIDITY-INDUCED ERROR IN MEASURING RESISTANCE OF A CARBON FIBRE STRAIN SENSOR

M. GÓRSKI¹, R. KRZYWOŃ², S. KEKEZ³

The paper describes studies on the influence of humidity on the electrical resistance of a textile sensor made of carbon fibres. The concept of the sensor refers to externally bonded fibre reinforcement commonly used for strengthening of structures, however the zig-zag arrangement of carbon fibre tow allows for measuring its strain. The sensor tests showed its high sensitivity to the temperature and humidity changes which unfavourably affects the readings and their interpretation. The influence of these factors must be compensated. Due to the size of the sensor, there is not possible electrical compensation by the combining of “dummy” sensors into the half or full Wheatstone bridge circuit. Only mathematical compensation based on known humidity resistance functions is possible. The described research is the first step to develop such relations. The tests were carried out at temperatures of 10°C, 20°C, 30°C and humidity in the range of 30-90%.

Keywords: textile sensor, carbon fibre, strain error compensation, structural health monitoring

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1. INTRODUCTION

1.1. STRAIN GAUGE ERRORS AND COMPENSATION

There is no doubt, that the strain gauge after installation must be protected against mechanical, physical and chemical impacts. The total protection is possible only by the hermetic sealing. Unfortunately, this method can be easily applied to relatively small, industrial sensors. In construction engineering, the sensor is often part of the structure. Fibre Optic Sensors (FOS) [1-4] based on Bragg Grating (FBG) or Carbon Fibre Sensing [5] are good examples. The reading zone of such devices covers a large area. In such cases, an additional thick hermetic layer may be too expensive. Besides, due to its stiffness, it could also disturb the value of deformation measurement. For these reasons, the practical application of sensors requires the recognition of their characteristics under different operating conditions and the development of error compensation methods.

Between the potential sources of strain gauge errors are: the uncertainties caused by temperature variation [6, 7], including heating caused by excitation voltage [8], gauge factor variation [9], moisture and humidity effects [9, 10], lead wire effects [1], transverse strain sensitivity [7].

The sensitivity of the developed carbon fibre strain sensor to temperature and humidity found during the trial tests lead the authors to conduct a broader study of the influence of these factors. The paper will discuss their first part concerning the effect of humidity on the measured resistance.

1.2. STRAIN SENSOR BASED ON CARBON FIBRES

Strengthening of concrete structures with the use of externally bonded overlays based on high strength fibres is currently the easiest, fastest and very effective method of increasing the load-bearing capacity of building structures. Fibre reinforced composites, regardless of their superb strength to weight ratio, high specific stiffness, and significant chemical adhesion, they also have drawbacks, among which must be mentioned brittleness, unknown durability, stress rupture and in case of some fibres and resins sensitivity to certain environmental factors. The most popular carbon fibres have one more feature - they are electric conductors. The authors of this paper used this feature for the construction of a self-monitoring structural strengthening. Tests carried out on reinforced concrete, and timber beams confirmed the effectiveness of strengthening the structure

(comparable to one layer of laminated carbon sheet) and the simultaneous ability to measure strains in the strengthened zone [5].

Actually tested, the third generation of the sensor consists of wiggly lead continuous carbon fibre thread (zig-zag pattern typical for the majority of strain gauges). The thread is stabilized by fastening to the composite mesh matrix commonly used as a plaster reinforcement (Fig. 1a). Compared to the previously developed woven modifications [12], this construction allows the manufacturing of a sensor of any length under conditions of the building side. Glass fibre mesh stabilization reduces the risk of accidental short-circuiting during the assembly of the sensor. There is no need for additional separating acrylic threads. The parallel alignment of the carbon tow multiplies the length of the measuring base and thus improves the accuracy of the measurement.

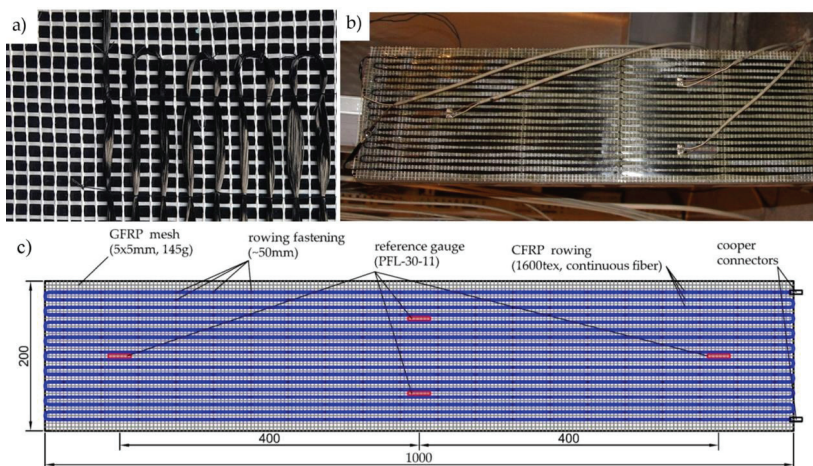


Fig. 1. The third generation of textile sensor: a) carbon fibre tow fixed to the composite mesh; b) sensor laminated on the concrete specimen; c) sample details.

1.3. EFFECT OF MOISTURE AND HUMIDITY ON THE GAUGE RESISTANCE

The construction of foil strain gauges assures relatively good resistance to the risk of errors associated with changes of humidity. The dominant view is that the effect of humidity should be concerned when long term measurement is planned, or environmental conditions may be unfavourable [7]. The influence of humidity usually results from the ingress of moisture and chance current flow between wires, which changes the nominal resistance of the gauge. Other factors may

be related to corrosion, changes in the local properties of materials [13], degradation of backing. Undoubtedly, the size of the sensor may influence the humidity error.

The development of self-sensing textiles for construction engineering is nowadays based mainly on the optical systems. Self-sensing fibres are in the initial stage of the research which mainly focuses on the short fibres dispersed in the matrix [14]. In the case of a textile sensor based on continuous fibres, some references can only be found in the studies on the humidity effects on the performance of temperature sensing fabric. Such researches [15, 16] show the relatively high sensitivity of textile sensors to relative humidity RH. The relative increase of resistance at the level of 20% is unacceptable when measuring a deformation of building structures. In the case of the developed textile sensor, this unfavourable phenomenon should improve the encapsulation of carbon fibres in the epoxy resin after the lamination process. Cured epoxies have dielectric properties. Thanks to that they are used for coating and encapsulating electrical circuits. Dielectric permittivity of epoxy resins is around 3÷6, their dielectric strength 120÷180 kV/mm and the volume resistivity 10¹⁹÷10¹² Ω/m [17]. Such a characteristic allows the movement of electrons along the carbon fibres. However, they can also be transmitted between the adjacent fibres. Transverse conductivity, in this case, depends mainly on the distance between the fibres, but could also be influenced by the shape or pre-treatment of fibres [18]. The transport of electron across an insulator gap is referred to as tunnelling. This process is sensitive to the gap width and height of the potential barrier to be penetrated [18].

The dielectric properties of epoxies can be degraded due to their permeability and absorption of water [17]. The absorbed water can promote electrolytic conducting between parallel bundles of carbon fibres, thus changing the resistance of the sensor. The aim of the research described in the further part of the paper is first of all to determine the scale of this phenomenon and possible consequences for the gauge error.

2. MATERIALS AND METHODS

2.1. TEST EQUIPMENT

The following test equipment has been used during the test:

- A UNI-MORS Climatic Chamber (LM 14/2012) with internal dimensions of 1.5 × 0.6 × 0.5 m, allowing temperature changes in the range of -30 to +90 °C and RH in the range of 20% to 95%.
- 64 channel Wheatstone bridge Z-TECH.

- Reference, foil strain gauges type PFL-30-11 (Tokyo Sokki Kenkyujo Co.), 30 mm long, gauge factor 2.13, gauge resistance $120 \pm 0.3 \Omega$.

2.2. PREPARATION OF THE TEST SAMPLE

After attaching the carbon fibres to the glass fibre mesh, the ready sensor was adhered to the concrete prism with dimensions of $1000 \times 200 \times 60$ mm (Fig. 1b). Two-component epoxy S&P Resin 55HP was used for this purpose. This specific adhesive is intended for fixing carbon sheets to various types of substrate. Wet lay-up technology was applied. First, the substrate was impregnated, then the sensor was placed, the carbon fibres were aligned and saturated with resin. The adhesive layer was levelled with a roller.

A single thread of conductive carbon fibre was delivered by the FISIPE Synthetic Fibre Company. The rowing consists of 24000 filaments (1600 tex). The tensile strength of carbon fibre is equal to 5000 MPa, modulus of elasticity 270 GPa and an ultimate elongation at break 1.9 %. Filament resistivity is equal to $14 \mu\Omega\text{m}$. The sensor has a length of 1 meter, contains 18 parallel threads, its initial resistance measured at the beginning of the test was equal to 254Ω .

On the surface of the sample, reference foil gauges were fixed in the arrangement shown in Figure 1c. Two groups of strain gauges were used to assess the impact of possible deformation of the sample and the type of surface (Fig. 2). The first group was placed on the sensor surface (RFGsens), the second on the opposite concrete surface of the sample (RFGconc).

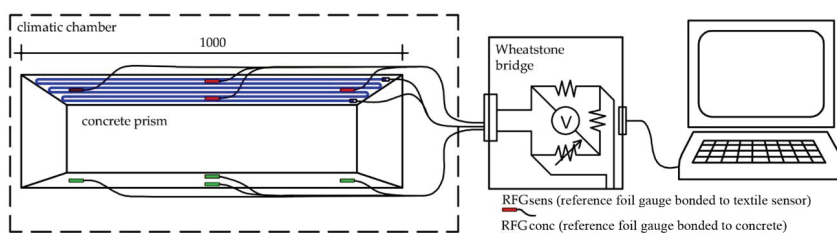


Fig. 2. Experiment set-up.

2.3. TEST PROCEDURE

To allow the samples to reach equilibrium with the surrounding environment, before the beginning of the test they were kept inside the climatic chamber for a minimum of 12 hours.

After placing in the climatic chamber, a control measurement was carried using a simple ohmmeter to check the initial resistance and to exclude accidental short circuit. Then the textile sensor was connected to the Wheatstone bridge, the chamber was closed, and the test started.

During the test, the actual humidity was verified by the chamber controller and at the same time resistance changes expressed by strain errors were recorded every 60 seconds through a computer connected to the Wheatstone bridge (Fig. 2).

An isothermal experimental cycle was applied, in which the temperature was kept constant, while the relative humidity (RH) was varied between 30% and 90%. Two types of such cycles were provided:

- stabilization of humidity at 60%, its increase to 90% and minimum 1-hour break for the stabilization of readings, decrease of humidity to 60% and 1-hour pause, then continued reduction of humidity by up to 30% and another pause to stabilize the measurement, return to the humidity of 60%,
- stabilization of humidity at 60%, its increase to 70% and minimum 20 minutes break and such an incremental increase up to 90%, then gradually reducing the humidity by 10% with breaks of 20 minutes, up to 30%, and similar return to a humidity of 60%.

Each described above cycle procedure was repeated at a constant temperature of +10 °C, + 20 °C and +30 °C.

3. RESULTS AND DISCUSSION

The test results for cycles with rapid change in the relative humidity are shown in separate graphs (Fig. 3 a-c). The chamber control system does not allow to determine the rate of humidity change, besides, change in resistance appeared with a certain delay to humidity. To demonstrate this phenomenon, the graphs are shown as a function of time and supplemented with the characteristics of humidity changes. The graphs also show averaged measurements made with the use of reference foil gauges placed on both sides of the sample (Fig 2). To estimate the magnitude of the error, resistance changes are shown in strain units calculated in accordance with specific gauge factors. This reflects the assessment of the error concerning the underestimated or overrated value of stresses. For example, for an average carbon fibre with a modulus of elasticity of approximately 190 GPa

and a strength of 2500 MPa, the strain of 1 ‰ means an error of 7% strength and even about 15% of the strain at which delamination failure may occur.

The graphs (Fig. 3 d-e) show the change in the strain error in the cycles of gradual variation of relative humidity. As in the previous graphs, the process of humidity changes during the test is shown below each graph.

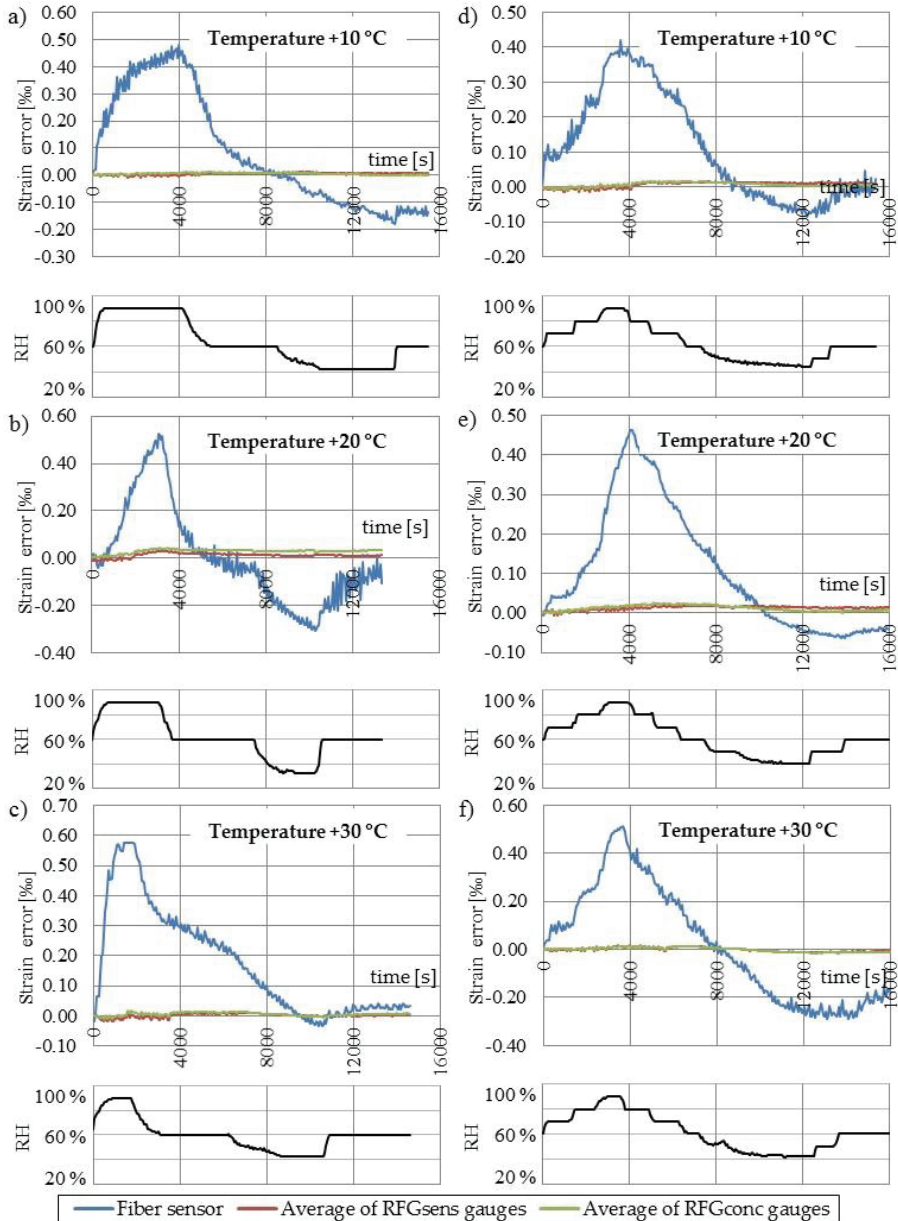


Fig. 3. Change of strain error: in the cycle of stabilized RH at 10 °C (a), 20 °C (b), 30 °C (c); change of strain error in the cycle of gradual variation of RH at 10 °C (d), 20 °C (e), 30 °C (f).

From the presented results, the following statements can be formulated:

- The largest recorded error in the form of strain error reaches almost 0.6‰ (Fig. 3c). In the diagnostics of CFRP composites, this means an error of around 5% of carbon fibre strength and 10% of strain, which often causes the failure due to delamination. These are significant values, especially for one cause of gauge error (humidity).
- The gauge error is higher in a humid environment than in a dry environment, which indicates the moistening as the primary cause of resistance changes.
- In the higher humidity, especially above RH 80%, the resistance decrease is more intense, which may result from the growing penetration of moisture into the structure of epoxy matrix and the formation of electrolytic solutions therein.
- At higher temperatures, the effect of humidity increases, the variance between temperatures +10 and + 30 °C reaches 35%. The probable reason for this phenomenon may be increasing of absolute humidity at higher temperatures or a change in permeability of epoxides.
- The change in the resistance is delayed respectively to the change in humidity. For an immediate change in humidity, the resistance stabilizes after at least one hour, although the time required for stabilizing the measurement depends on the scale of the humidity change. The cause of the delay may be the process of moisture exchange between the composite and the air.
- Due to the delay described above, the measurement at the end of the cycle, at 60% humidity, does not return entirely to the zero point.

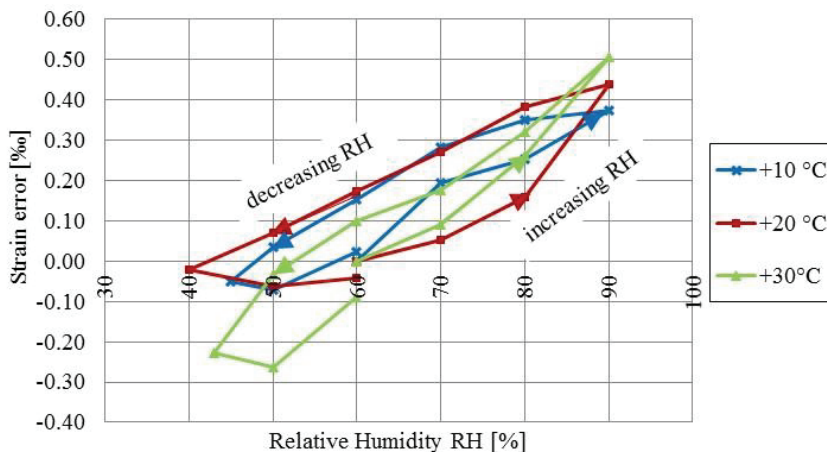


Fig. 4. Strain error vs relative humidity for cycles at 10 °C, 20 °C and 30 °C.

- At a similar rate of humidity change, the resistance decrease (indicated as an increase of strain error) is faster than its increase. This causes that the function of strain error vs relative humidity has a different course for the process of humidity rise and its decrease (Fig. 4). This means that a mathematical description of this change would also have to contain information about the direction of humidity changes. The analysis of the position of the functions in Fig. 4 also shows that the position of the cycle curves is the most similar at 30 °C. The cause may be the easier moisture exchange at a higher temperature, especially more intensive drying.

4. COMPENSATION MODEL

As shown in the previous chapter, the error of the textile sensor depends on both humidity and temperature. The measurement compensation model should take into account the impact of both factors. Due to the delay of the indication, this model should also take into account the situation of the increase or decrease in humidity. The proposed mathematical model is based on the curves shown in Figure 4. They could be estimated by the shifted and rotated ellipse (Fig. 5). In the Cartesian coordinates, the ellipse could be described by the following equation (4.1):

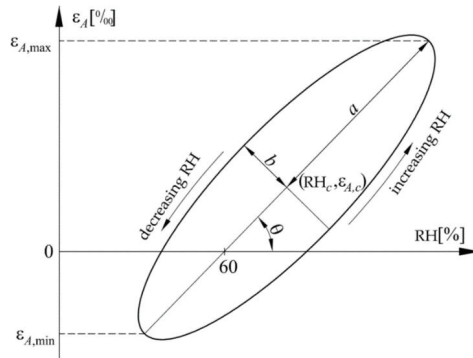


Fig. 5. Elliptical compensation model of strain error and relative humidity relation.

$$(4.1) \quad A \cdot RH^2 + B \cdot RH \varepsilon_A + C \cdot \varepsilon_A^2 + D \cdot RH + E \cdot \varepsilon_A + F = 0,$$

where main parameters are given as:

$$A = a^2(\sin \theta)^2 + b^2(\cos \theta)^2,$$

$$B = 2(b^2 - a^2) \sin \theta \cos \theta,$$

$$C = a^2(\cos \theta)^2 + b^2(\sin \theta)^2,$$

$$D = -2A \cdot RH_c - B \varepsilon_{A,c},$$

$$E = -B \cdot RH_c - 2C \varepsilon_{A,c},$$

$$F = A \cdot RH_c^2 + B \cdot RH_c \varepsilon_{A,c} + C \cdot \varepsilon_{A,c}^2 - a^2 b^2,$$

a – is the semi-major axis of the ellipse,

b – is the semi-minor axis of the ellipse,

$(RH_c, \varepsilon_{A,c})$ – are the center coordinates,

θ – is the inclination angle of the semi-major axis.

The major axis lies on a straight line that intersects the point $(RH\ 60\%, 0)$, which corresponds to the initial temperature of each test. The angle of inclination of this line corresponds to the inclination angle of the semi-major axis of ellipse θ . It can be described by the equation (4.2).

$$(4.2)$$

$$\varepsilon_A = \tan \theta (RH - 60[\%])$$

Table 1. Parameters of the ellipse on the basis of the test results.

Series of results	$\tan \theta$	θ [rad]	$\varepsilon_{A,\max}$ [%]	$\varepsilon_{A,\min}$ [%]	b_{above} [%]	b_{below} [%]	b_{average} [%]
10 °C	0.01055	0.01055	0.3737	-0.070	0.1599	0.1765	0.1682
20 °C	0.01103	0.01103	0.4394	-0.0638	0.1994	0.1808	0.1901
30 °C	0.01484	0.01484	0.5079	-0.2624	0.1143	0.1140	0.1142

The function (4.2) can be determined for each series of results using linear regression. Table 1 summarizes the results of these calculations. On the basis of the results presented in Table 1, the relationship between the angle θ and the temperature T can be expressed by the function (4.3). Similarly, the top and bottom vertex coordinates can be found. Maximum and minimum strain errors measured during tests at certain temperatures are listed in Table 1. Relations (4.4) to describe the influence of temperature on extreme strain error can be proposed from them.

$$(4.3) \quad \theta = 7 \cdot 10^{-12} \cdot T^6 + 0.0105,$$

$$(4.4) \quad \varepsilon_{A,\max} = 0.007 \cdot T + 0.3 \text{ [%]}, \quad \varepsilon_{A,\min} = -0.01 \cdot T + 0.03 \text{ [%]}.$$

The ellipse center lies in the midpoint of the path joining the maximum and minimum vertex. At the same time, this point lies on the major axis of the ellipse given by the formula (4.2), therefore:

$$(4.5) \quad \varepsilon_{A,c} = 0.5(\varepsilon_{A,\max} + \varepsilon_{A,\min}) = -0.0015 \cdot T + 0.165 \text{ [%]},$$

$$(4.6) \quad RH_c = \frac{\varepsilon_{A,c}}{\tan \theta} + 60 \text{ [%]}.$$

Length of the semi-major axis is equal to half the distance between vertexes. The length of the semi-minor axis expresses the largest distance of a point on the ellipse from the major axis. The values obtained during the tests and shown in Figure 4 are summarized in Table 1. For the average distance, the following equation for the semi major and semi-minor axis could be proposed:

$$(4.7) \quad a = 0.5(\varepsilon_{A,\max} - \varepsilon_{A,\min}) = 0.0085 \cdot T + 0.135 \text{ [%]}, \text{ and } b = -0.0027 \cdot T + 0.2115 \text{ [%]}.$$

On the basis of (4.3), (4.5), (4.6) (4.7) and (4.1), the equation of the ellipse for describing the compensation of effect of relative humidity RH on the magnitude of the error ε_A will be found. This

equation has two roots, the lower one describing the bottom part of the ellipse, thus the case of increasing humidity and the greater one which corresponds to the decrease of humidity.

5. CONCLUSIONS

The test results show that relative humidity significantly affects the measurement of deformations using a developed textile sensor. Reading error can be over twenty times higher than when using traditional plastic strain gauges. The sensor is particularly sensitive to the relative humidity increase in the range of 60÷90 %. Changes in resistance in a dry environment, for RH below 60% are several times smaller. Such properties clearly show that the reason for the resistance changes is too large permeability of the epoxy matrix and its moistening in the humid environment.

There could be noticed a delay in resistance changes in relation to relative humidity changes. This phenomenon refers more to the process of decreasing humidity, which means a faster process of moistening of the epoxy matrix than its drying.

The gauge error found during the tests in a humid environment is unacceptable in practical applications. Due to the delay in resistance changes, the mathematical calibration of the measurement may be unreliable, especially in the case of rapid changes in humidity (e.g. the following rain and drying with the sun activity). A useful improvement can be the application of a thin, impermeable protective layer on the surface of the sensor. Research on the implementation of such a layer will be the next step in the development of a textile sensor for simultaneous monitoring and reinforcement of the structure.

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ACKNOWLEDGEMENTS: The authors acknowledge the european union for financing the development of intelligent textile sensors (project 251373 fp7-people-2009-iapp—intelligent systems for structures strengthening and monitoring insysm) and the silesian university of technology (grant no bk-237/rb6/2018) for the financing of current research. The authors also acknowledge fisipe synthetic fiber sa, portugal and s&p reinforcement poland for the supply of carbon fibers.

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Tab. 1. Parametry elipsy określone na podstawie przeprowadzonych pomiarów.

WPLYW WILGOTNOŚCI POWIETRZA NA BŁĄD POMIARU REZYSTANCJI SENSORA ODKSZTAŁCENI WYKONANEGO Z WŁÓKIEN WĘGLOWYCH

Słowa kluczowe: *sensor tekstylny, włókno węglowe, kompensacja fałszywego odkształcenia, monitoring konstrukcji*

STRESZCZENIE

Kompensacja błędu pomiaru w tensometrii elektrooporowej ma istotne znaczenie dla dokładności mierzonych odkształceń. Wśród źródeł błędu zazwyczaj są zmiany temperatury, wilgotności, wahań stałej tensometru, przebieg ścieżki przewodzącej czy odkształcenia w kierunku prostopadłym. Już wstępne badania opracowanego przez autorów artykułu sensora odkształceń wykorzystującego włókna węglowe, jako przewodnik wykazały jego znaczną wrażliwość na zmiany wilgotności. Koncepcja sensora polega na wykorzystaniu laminatu zbrojonego włóknami węglowymi, tradycyjnie stosowanego do wzmacniania konstrukcji budowlanych, jako układu samo-monitorującego. Funkcja taka może być bardzo przydatna z uwagi na kruchość właściwości tego typu materiałów i gwałtowny proces zniszczenia. Uzyskanie wystarczającej czułości wymaga wężykowego ułożenia włókien węglowych, analogicznie do klasycznego tensometru elektrooporowego. Opisany w artykule sensor jest trzecią generacją rozwoju koncepcji, modyfikacja polega na zastąpieniu produkcji w procesie tkania przez stabilizację włókien na siatce kompozytowej. Zaletą tego rozwiązania jest ograniczenie niebezpieczeństwa przypadkowych zwarcie w wyniku nieprawidłowej laminacji sensora.

Ze względu na rozmiary sensora, który po wbudowaniu będzie stanowił fragment konstrukcji budowlanej, możliwa jest wyłącznie numeryczna kompensacja błędu pomiaru na podstawie funkcji matematycznych opisujących wrażliwość sensora na zmiany temperatury i wilgotności. W celu ich określenia przeprowadzono badania w komorze klimatycznej nieobciążonego sensora przyklejonego do próbki betonowej. Sensor wykonano z pojedynczej wiązki włókien węglowych o gęstości 1600 teks. Oporność pojedynczego włókna wynosi 14 $\mu\Omega$ m, co dla 18 wężykowo, równoległe ułożonych włókien na odcinku jednego metra daje oporność 254 Ω . Położenie wiązki ustabilizowano na siatce z włókna szklanego, a następnie przyklejono do prostopadłościenną próbkę betonową o wymiarach 1000 × 200 × 60 mm. Zastosowano żywicę epoksydową przeznaczoną do mocowania mat z włókien węglowych.

Sensor przed każdym testem umieszczano w komorze klimatycznej na przynajmniej 12 godzin w ustabilizowanej temperaturze badania i początkowej wilgotności RH 60%. W trakcie pierwszej serii badań utrzymywano stałą temperaturę i zmieniano wilgotność w cyklu RH 60%-90%-60%-30%-60%. Po osiągnięciu zadanej wilgotności utrzymywano ją do ustabilizowania pomiaru oporności. Tego typu cykle pomiarowe wykonano dla temperatur +10 °C, +20 °C and +30 °C. W drugiej serii badań zmodyfikowano cykl zmian wilgotności na bardziej łagodny, tzn: RH 60%-70%-80%-90%-80%-70%-60%-50%-40%-30%-40%-50%-60%, jednocześnie pominięto oczekiwanie na stabilizację pomiaru rezystancji.

Zmierzone w trakcie testów fałszywe odkształcenie pokazano na wykresach na rysunku 3. Badania jednoznacznie pokazują, że wilgotność w znaczący sposób wpływa na wartość pomiaru rezystancji i tym samym pomiar odkształcenia. Błąd ten jest ponad dwudziestokrotnie większy niż w tradycyjnych tensometrach foliowych. Największe zmierzone fałszywe odkształcenie wynosi aż 0,6‰. Dla kompozytu oznacza to błąd na poziomie 5% wytrzymałości włókna węglowego, a biorąc pod uwagę graniczne odkształcenie delaminacji błąd może sięgać nawet 10%. Błąd jest większy w warunkach podwyższonej wilgotności (dla RH 60÷90 %), niż w środowisku suchym, co wskazuje na zawilgacanie, jako główną przyczynę obserwowanych zmian rezystancji. W warunkach wysokiej wilgotności, powyżej 80%, spadek oporności elektrycznej jest bardziej intensywny, co może wynikać z wykraplaniem się na powierzchni wilgoci i powstawaniem roztworów elektrolitycznych. W wyższych temperaturach wpływ wilgotności na błąd pomiaru rośnie.

Różnica pomiędzy temperaturą +10 i + 30 °C sięga 35%. Przyczyną tego zjawiska może wyższa wilgotność bezwzględna lub zwiększona w wyższej temperaturze nasiąkliwość epoksydów.

Zmiana oporności jest opóźniona względem zmian wilgotności. Czas stabilizacji pomiaru oporności po zmianie wilgotności zależy od skali tej zmiany i może sięgać nawet jednej godziny. Przyczyną tych opóźnień jest efekt bezwładności związany z wymianą wilgoci próbki z otoczeniem. Dla podobnych zmian wilgotności wzrost oporności elektrycznej następuje szybciej niż jej spadek. Różnica ta jest mniejsza w wyższych temperaturach. Oznacza to, że opisująca go funkcja powinna niezależnie opisywać sytuację przyrostu i spadku wilgotności i jednocześnie uwzględniać wpływ temperatury.

Jako model matematyczny dla zależności błąd pomiaru odkształcenia – wilgotność zaproponowano funkcję pochylonej i przesuniętej elipsy. Parametry tej funkcji wyznaczono na podstawie analizy statystycznej wyników badań.

Poziom błąd pomiaru rezystancji (a w konsekwencji także wyznaczonego odkształcenia) jest nieakceptowalny w zastosowaniach praktycznych. Opracowany model kompensacji w zasadzie dotyczy wyłącznie sensora o geometrii zbliżonej do badanego. Dodatkowo problem stanowi opóźnienie zmian oporności względem zmian wilgotności, trudne do oszacowania zwłaszcza w przypadku szybko następujących po sobie zmian (np. naprzedniutki deszcz i słońce). Planowany, dalszy rozwój koncepcji sensora obejmie zastosowanie dodatkowej, szczelnej, elastycznej i cienkiej warstwy, uniemożliwiającej wnikanie pomiędzy włókna węglowe wilgoci i jednocześnie niezaburzającej pomiaru.

Received 21.10.2019 Revised 07.05.2020

