Carbon-based printed strain sensor array and wireless measuring system for application to Structural Health Monitoring

D. Zymelka\textsuperscript{1,2*}, K. Togashi\textsuperscript{2,3} and T. Kobayashi\textsuperscript{1,2}

\textsuperscript{1}National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8564, Japan
email: daniel.zymelka@aist.go.jp
\textsuperscript{2}NMEMS Technology Research Organization, Tokyo 101-0026, Japan
\textsuperscript{3}Next-Generation Electronics Department, Research & Development Center, Dai Nippon Printing Co., Ltd., Wakashiba Kashiwa, Chiba 277-0871, Japan

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ABSTRACT

We demonstrate a printed strain sensor array for applications to structural health monitoring (SHM). The unit sensors in the array were made of inexpensive carbon-based materials that were screen printed on a flexible thin substrate. The sensors were designed to operate at various temperatures so that they can be used in any season of the year. Each array was equipped with a specially designed wireless measuring system that enables an automated and remote strain measurements on the analyzed bridges. The strain analysis with the developed device was based on a comparative analysis of data registered by the unit sensors and their transformation into a strain distribution. The sensor arrays were attached to a highway bridge and their functioning was verified periodically along the last two years. Moreover, we demonstrate an experiment where short-term remote measurements were performed automatically every 30 min within several days. The collected data show that the sensors can accurately detect cracks and can withstand a continuous long-term exposure to various weather conditions and strains during normal traffic on highway bridges.

1. Introduction

In spite of the recent progress in the development of various measuring systems for applications to SHM, currently, the monitoring of transportation infrastructure still relies mainly on a traditional visual inspection. The overall high cost (sensors, hardware, installation process) of the available monitoring methods limits their widespread use. In practice, the cost of the entire sensors system determines a scale for the monitoring of a bridge or whether this bridge is monitored or not. On the other hand, the increasing amount of civil infrastructure and the aging of existing infrastructure requires their regular inspection and maintenance. Therefore, modern devices for the SHM, besides their high reliability and connectivity, should be inexpensive and widely available. In order to drive down the overall costs of the monitoring systems and to expand their use, the implementation of cost-effective materials and fabrication methods is important.

In this paper, we are focusing mainly on measuring system for SHM that use resistive strain sensors. The conventional strain sensors are typically made of materials characterized by very low temperature sensitivity, such as constantan (copper-nickel alloy). However, the use of such sensors in the framework of SHM is limited to their relatively small size. To overcome this problem, a concept of a sensors array composed of conventional strain gauges bonded one-by-one to the same substrate was demonstrated\textsuperscript{[1,2]}. On the other hand, the authors reported the high fabrication cost of their device. The overall cost of such an array can be reduced significantly if all the strain sensors are fabricated by printing methods using

\* Corresponding author.

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cost-effective materials. Printing technology has been already demonstrated as a suitable method for the fabrication of electronic components in various applications\textsuperscript{[3-5]}. The main advantage of printable devices is their low cost and the possibility of rapid and large-are manufacturing. Recently, we demonstrated a concept and functioning of a screen printed strain sensor array\textsuperscript{[6-8]}. The reported results showed its potential suitability for monitoring of bridges, especially for cracks detection or monitoring of already existing cracks. In this work, we report a long-term evaluation of the printed strain sensors array attached to a highway bridge and we demonstrate a specially developed wireless measuring system that enables automated remote monitoring of bridges.

2. Materials and Methods

2.1 Sensors

The sensors were screen-printed using a carbon-based paste (Asahi Chemical FTU-16R) on a 50-µm-thick poly(ethylene naphthalate) (PEN) substrate. The substrate with conductive lines and electrodes was prepared by the chemical etching of a copper-PEN laminate. The copper layer was 16µm thick and was attached to the PEN substrate by hot pressing. After the printing, we used a convection oven to cure the sensors at 150 °C for 30 min. In this work, we used two different layouts for the sensor array. A schematic illustration of the developed devices is shown in Fig. 1. In the first one (type “A”), the unit sensors were arranged into a regular array 4x4. The second one (type “B”), had a pattern of 25 strain sensors and an integrated temperature sensor chip. The shape of the unit sensors and the layout of the copper electrodes were specially designed in such a way that after the printing, the sensors form a full-Wheatstone-bridge circuit. The proposed design enables an effective compensation for temperature variations. We have provided the detailed information concerning the fabrication process and characterization of the printed sensor array in our previous reports\textsuperscript{[6-8]}.

![Figure 1](image)

\textbf{Figure 1.} Developed sensor arrays. “Type A” with a regular 4x4 sensors pattern, “Type B” with 25 strain sensors and an integrated temperature sensor chip.
2.2 Measuring system

Two types of measuring systems were used. In the initial state of this research, the measurements were performed using a 24-bit data acquisition system (National Instruments NI-9238) connected to a NIcDAQ-9188 chassis. This system was used to record data that are shown in Fig. 3(a) and Fig. 3(b). The only drawbacks of this measuring system were its portability and price. It was relatively large and was required for every sensor array. This makes its practical use for SHM very expensive. Thus, in the framework of this work, a specific data acquisition system capable for high accuracy and remote measurements was developed. This system was composed of a set of transmitters that were wirelessly connected to a receiver. One receiver was capable to operate simultaneously with up to 5 transmitters. Each transmitter was equipped with 25 channel voltage measuring system and resolution of 24-bit (ADC). The entire system was controlled by a computer with specially prepared software. During measurements on the bridge, data were automatically collected at a scheduled time and sent to a server, analyzed and displayed as a strain distribution. The schematic illustration of the wireless measuring system is shown in Fig. 2.

![Figure 2. Schematic illustration of the wireless measuring system.](image)

3. Results and discussion

3.1 Long-term reliability

In this section, we show data that demonstrates the long-term reliability of the developed sensor array. In this experiment, we used the sensors array type “A” (see Fig. 1). This sensor type was design and used in the initial part of this work and thus was installed as a first on the highway bridge. Although the array has been modified later (to type “B”), we decided to continue the long-term evaluation with the type “A”. There is no difference between the design and fabrication process of the unit sensors in both types of sensor arrays, thus the results on the long-term evaluation of the sensor array type “A” reflects the performers of the type “B”.
The sensors were installed on a girder of a highway bridge (Fig. 3) in March 2016. The bridge is located in one of the largest cities in Japan and is continuously exposed to various strain levels. In order to evaluate the long-term performance of the sensors, the measurements were carried out periodically. Figure 4 shows a part of the collected results for the last two years. All the graphs demonstrate the typical strain levels during the normal traffic. When comparing the data collected, it is seen that the amplitude of the measured strain and thus the performance (sensitivity) did not change. All the sensors were fully operational and thus are still being used for their further evaluation.

**Figure 3.** Developed sensors array (type “A”) attached to a girder of a highway bridge.

**Figure 4.** Long-term reliability of the developed strain sensor array. The graphs demonstrate typical strain levels recorded on the highway bridge.
3.2 Automatic remote monitoring of strains on the highway bridge

The developed sensor array was intended to be used in short-term dynamic strain measurements performed at any time and in any season of the year. In the previous section, we demonstrated its proper operation for at least 2.5 years. However, the specific design of the array (the layout of the sensors) was intended to use the developed device for cracks detection or monitoring of already existing cracks. In this section, we demonstrate strain analysis recorded when the sensors were attached to a concrete pier of the bridge.

The concrete piers are rigid and, in contrast with the metal girders, do not reveal easily measurable strains because of the normal traffic. However, as demonstrated in Fig. 5, the analyzed pier had a crack near the passage (an opening in the pier). In this work, this crack was used to evaluate the developed devices in terms of their suitability for practical applications in SHM. The sensor array (type “B”) was attached on the pier so that one line of the sensor within the array covered the crack. Note that the sensor array was attached on a curved surface. This demonstrates one of the main features of the flexible printed electronics. The sensors can be attached to non-planar surfaces like arcs or columns.

The sensor array on the pier was connected to the wireless data acquisition system as shown in Fig. 6. Strain measurements were performed automatically every 30 minutes. The duration of each measurement was set to 60 s, however, the duration of measurements and their frequency can be freely changed, depending on the application. The output signal from all 25 sensors was analyzed with the use of the developed software and presented in a form of the measured strain distribution.

The resulting strain map (Fig. 6) shows accurately the crack location in the concrete pier. The results confirm a proper operation of the developed measuring system.

Figure 5. Sensors attached directly on a crack found in a concrete pier. Because the sensor array was printed on the flexible substrate it could be easily installed on the curved surface.
3. Conclusions

In summary, we showed that developed carbon-based strain sensors that were arranged in the form of an array can be used for monitoring of civil infrastructure. The sensors can withstand at least 2.5 years being continuously exposed to various strains and weather conditions. The collected results show their proper operation, the crack in the concrete pier was detected and localized accurately. Thanks to the implemented printing method, the layout and size of the sensor array can be modified easily and scaled up by changing the printing pattern. Moreover, due to their flexibility, they can be attached to non-planar surfaces like arcs or columns. The specially prepared data acquisition system enables remote control and automated measurements from any place with access to the internet. The measuring system is portable, more compact and less expensive than most commercially available data acquisition systems. The low fabrication cost and good performance of the entire device make it very promising for its future practical applications.

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References