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HIGH-RESOLUTION SENSING SHEET FOR DAMAGE DETECTION BASED ON LARGE AREA ELECTRONICS

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ABSTRACT

Deep concern raised over the future of ageing infrastructure identified a need for reliable yet affordable Structural Health Monitoring (SHM) technologies. Damage detection and localization represent particular challenge, as the structures feature large size and localized damage can occur in large number of points. Early-stage damage detection and localization requires continuous sensing over large surface area, and with high spatial resolution (e.g. centimeter-scale resolution). Traditional sensing technologies are either limited by high cost and insufficient spatial resolution, or rely on complex algorithms that are challenged by varying environmental and loading conditions. This paper demonstrates the need for direct sensing, where anomalies are sensed at close proximity via a dense array of sensors. The hypothesis is that by substantially increasing the sensor response to local anomalies, direct sensing leads to greater robustness than current state-of-the-art approaches. To achieve this, our research presents such a technology based on Large Area Electronics (LAE) for direct sensing scalable to the level required for SHM and investigates how it could be applied in practice. A sensing sheet is manufactured based on LAE, which is capable of bonding to structural surfaces. Thin-film strain gauges and control circuits are integrated on the flexible electronics and deposited on a polyimide sheet that is possible to expand to large areas, allowing measuring and readout over a large number of sensors. In the first phase of this research, crack tests with thin resistive strain gauge sensors are utilized to identify the proper patterns (gauge length, distance, orientation, etc.) for the layout of sensing elements on the LAE sensing sheet, and indicate an average sensitivity of 0.0404 μm/με. Then a characteristic identification test is carried out to evaluate alternative designs for sensing elements based on thin film transistors, with an approximate sensitivity of 3.3 mV/με. Results of both tests are presented in this paper, demonstrating the feasibility and benefits of LAE and direct sensing approach for damage detection over large areas of structures.

KEYWORDS

Structural Health Monitoring (SHM), sensing sheet, Large Area Electronics (LAE), direct sensing, damage detection and localization.

INTRODUCTION

Civil infrastructure provide essential welfare in society. Therefore, they are invaluable assets that need to be preserved and well maintained. In order to achieve this goal, it is necessary to assess their health conditions. Structural health monitoring (SHM) is a potentially effective method for providing information about the true condition of the structural health if it can supply low-cost, reliable, and actionable sensing technologies for monitoring. SHM methods can facilitate early identification of potential structural problems and improve the optimization and preparation of appropriate maintenance procedures.

However, traditional sensing technologies are either limited by high cost and insufficient spatial resolution (Yao and Glisic 2012), or rely on complex algorithms that are frequently unreliable under varying environmental and loading conditions (Posenato et al. 2008). In particular, early-stage damage detection and localization is critical and it requires continuously monitoring over large surface areas of structures, and with a high resolution (e.g. centimeter-scale resolution). As a result, a direct sensing approach for reliable damage detection is proposed, in which dense array of sensors are integrated in a sensing sheet that is installed in direct contact with the potential damage areas and detects damage as an important variation in signal. This research introduces innovative sensing sheets based on Large Area Electronics (LAE) for direct sensing, which is scalable to the level required for SHM (Glisic and Verma 2011). Current research results demonstrate that the sensing sheets have the

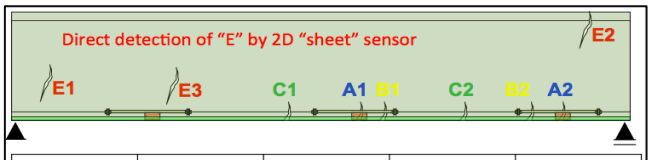
potential to overcome the robustness and reliability limitations affecting present SHM technologies.
This paper first introduces the main concepts of direct sensing approach, and then gives a brief description of LAE technology applied in SHM. Finally, current advancements in research and development are presented, including experiments and results that demonstrate the feasibility of LAE and the benefits of the direct sensing approach for damage detection over large areas of structures.

DIRECT SENSING APPROACH AND TWO-DIMENSIONAL (2D) SENSING

Materials fail at a point when the stress at that point exceeds the ultimate limit state. Strain is a parameter directly correlated to stress, and so any change in the stress field is reflected through a change in the strain field. In addition, the first signs of damage to a structure often have local character and occur in the form of strain-field anomalies. Typical examples are cracks and bowing in steel (which are early indicators of fatigue and loss of local stability), as well as non-structural cracks in concrete (which are early indicators of damage caused by frost, alkali-reaction, or corrosion in reinforced bars). These are reasons to adopt strain as the parameter of interest in this research and to create sensing sheets for strain monitoring.

In general, there are two main approaches for damage detection: (1) indirect sensing, and (2) direct sensing (Yao and Glisic 2012). The indirect sensing approach is based on measurements made by sensors that are not in direct contact with damage. The recorded data is analyzed using various classes of algorithms in order to ascertain crack detection and perform crack characterization. The advantage of this approach is the need for a relatively small number of sensors. However, the main challenge with indirect sensing is the need for sophisticated data-processing algorithms to achieve the spatial resolutions and detection localizations that are required in practical structural health monitoring (Posenato et al. 2008). The direct sensing approach is based on measurements made by sensors that are in direct contact with damage, and thus the damage is detected and localized directly as an unusual change in the output from the sensors affected by the crack. The advantage of this approach is its very high reliability in damage detection and characterization (Glisic et al. 2011; Glisic and Yao 2012); however, the challenge is that this approach requires a large amount of densely placed sensors, which can increase the overall cost and complexity of SHM.

Both direct and indirect sensing have advantages and challenges; however, with the development of new sensing technologies, low-cost direct sensing has the potential to become reality and to play an important role in damage detection and characterization. The research hypothesis is that by substantially increasing the sensor response to local anomalies, direct sensing leads to greater robustness than current state-of-the-art approaches. At present, three categories of sensors are commercially available (Yao and Glisic 2012): discrete short-gauge sensors, discrete long-gauge sensors, and continuous (1D) distributed sensors (or sensing cables). In addition, there is ongoing research in the development of continuous 2D sensors (sensing sheets, sensing skins, paints, self-sensitive materials, etc.). A schematic comparison between the damage detection capabilities of various types of sensors is given in Figure 1.



	Damage "A"	Damage "B"	Damage "C"	Damage "E"
Short-gage	Direct, reliable detection	*Indirect or impossible*	*Indirect or impossible*	*Indirect or impossible*
Long-gage	Direct, reliable detection	Direct, reliable detection	*Indirect or impossible*	*Indirect or impossible*
Distributed	Direct, reliable detection	Direct, reliable detection	Direct, reliable detection	*Indirect or impossible*
2D sensor	Direct, reliable detection	Direct, reliable detection	Direct, reliable detection	Direct, reliable detection

Figure 1. Schematic comparison between damage detection capabilities of short-gauge, long-gauge, distributed sensors, and 2D "sheet" sensor

This research focuses on the development of sensing sheets based on LAE, which could act as 2D-distributed sensors and function for continuous 2D strain measurements. Sensing sheets (Glisic and Verma 2011) have the capability to overcome the reliability and robustness limitations of current damage detection methods. This technology and its application in SHM are described in the next section. Figure 2 shows 2D strain measurements, illustrating how these provide a reliable modality for the detection and localization of cracks.

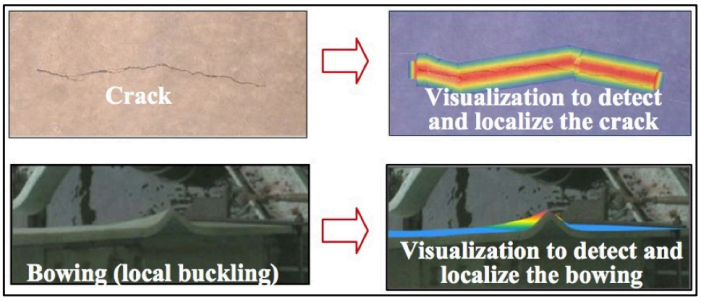


Figure 2. Illustration of the potential for direct damage detection using sensing sheets for 2D strain-field measurements. Left-side images show the damage, and right-side show the expected measurement (Glisic and Verma 2011)

LARGE AREA ELECTRONICS AND SENSING SHEETS

LAE is an emerging technology that allows a broad range of electronic devices to be integrated on low-cost plastic sheets (Arias et al. 2010; Someya et al. 2008). Through the use of micro-fabrication techniques, thin-film sensors have been demonstrated (including pressure sensors, vapor sensors, particle sensors, etc.). These sensors can be formed into dense arrays spanning large areas (i.e., tens of square meters).

LAE can potentially be a good tool for crack detection and characterization for large-scale structures (Glisic and Verma 2011). Current direct sensing techniques that are based on strain measurements either monitor cracks at one point or segment (e.g. short-gauge and long-gauge sensors), or in one dimension (1D, e.g., distributed sensors). LAE sensing sheets can be treated as a quasi-distributed sensor in two dimensions. While direct sensing would provide higher spatial resolutions and improve the localization of anomalies, the practical application of this method is limited by the need for a large number of discrete sensors and their deployment expenses. However, the use of large-area electronics can potentially overcome these obstacles. The concept of a sensing sheet and its application are shown in Figure 3.

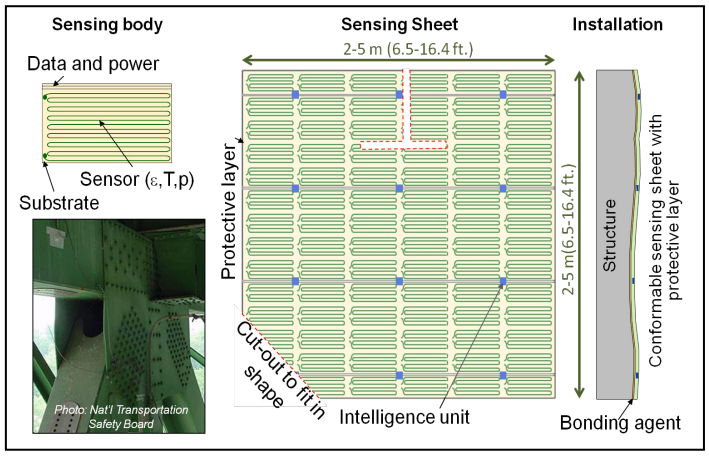


Figure 3. Diagram of the sensing sheet and its application

A sensing sheet consists of the following: (1) 2D distributed array of thin resistive strain gauges patterned on a polyimide substrate combined with functional LAE; (2) embedded integrated circuits (ICs) interfaced via non-contact links for sensor readout, data aggregation, and data analysis; and (3) integrated solar-energy harvesters and power converters on the large-area-electronics sheet to power the full system. The polyimide substrate will allow conformability to the surface of the monitored structure and resilience against outdoor conditions.

An important benefit of LAE is that it enables the integration of functional thin-film transistors (TFTs). This means that basic circuit functionality is available to facilitate readout from the large number of sensor channels. While these TFTs can provide basic functionality, the device-level characteristics that make them compatible with flexible, large-area substrates also severely limit their energy efficiency. Thus, large-scale processing over the sensor channels is not viable. Standard electronics technologies (e.g., based on integrated circuits) have

achieved very high efficiency for instrumentation and processing due to nearly five decades of Moore's-law scaling. We are now exploiting the basic functionality of the TFTs to create specialized interfaces between the large-area sensors and a potentially large number of ICs for readout and processing purposes (intelligence unit). The individual sensors are read by embedded ICs with wireless and computational capabilities, taking advantage of wireless sensing and distributed data management. The protective layer is made of flexible photovoltaic, which provides the power needed for the functioning. Finally, the sensing sheet can be expanded with integration of other types of thin-film sensors (e.g., pressure, temperature, vibration, etc.), i.e., it can be provided with multi-sensing capability.

The insights pursued in this research are focused on two areas: (1) the use of LAE as a sensing technology and its functional TFTs to facilitate readout permits high-resolution monitoring and assessment over a physically large structure; and (2) the resulting resolution can greatly facilitate early detection and, as a result, improve detection reliability and robustness to provide actionable outcomes. Beyond sensing, LAE can introduce long-range interconnects. Due to the physical size of infrastructure, communication between sensor nodes over distances of several centimeters and up to several meters is necessary, and the power needed for transmission is an important concern. Wired interconnects, on the other hand, incur much lower power consumption. Thus, the long-range interconnects provided by LAE allows for the low-energy communication required over the large number of distributed sensors.

The sensing technology that can result from this consists of a dense array of 2D-distributed resistive strain sensors (at less than 1 cm spacing) on a thin plastic (polyimide) substrate. It can be bonded onto critical areas of a structure and provide early detection and localization of specific relevant types of damage. Based on the authors' experiences, the indicators are expected to provide direct correspondence with the 2D strain field, where damaged regions are typically expressed by several orders of magnitude in increased strain. As an example, a 0.1 mm crack detected by a sensor with a gauge length of 100 mm will induce an average strain change of 0.1/100 = 0.001 = 1000 με, which is too high to be masked by environmental influences or by monitoring-system noise. In addition, measurements from surrounding undamaged material will permit analysis of relative differences, improving the prospects of overcoming false positives (i.e., increasing specificity) as well as false negatives (i.e., increasing sensitivity).

Figure 4 shows the thin-film LAE circuits for sensor-array control, which is the functioning principle of how the system works as a 2D strain sensor, and collects signals and analyzes such information. The detailed electronic functioning is out of the scope of this paper, but the principle is simply described as follows. The power cable, IC, TFTs, and the sensor elements are integrated on a large-area substrate. The power excites the system, and then IC activates the TFTs. It sends pulse signals to the sensor elements in its group one by one, and lets each sensor measure the strain in its corresponding district. The IC functions as a scanning chain, and it scans the strain distribution row by row. After one row is finished, the system will go to next row. Four signals are required from the IC for both power and control in order to sequentially access the individual sensors.

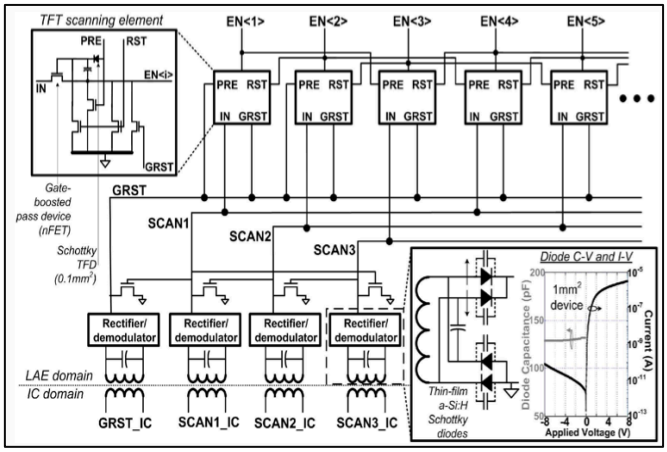


Figure 4. Thin-film LAE circuits for access control of multiple sensors (courtesy of Yingzhe Hu)

In summary, the sensing sheet can be manufactured based on LAE that combines high-performance ICs with flexible electronics, which is capable of bonding to structural surfaces. Thin-film strain gauges and control circuits are integrated on the flexible electronics and deposited on a polyimide sheet that is possible to expand to large areas. Signals are sent to ICs through non-contact couples, thus many ICs can be patterned with low-cost

sheet lamination, allowing measuring and readout over a large number of sensors.

PRELIMINARY EXPERIMENTS AND RESULTS

Several early-stage researches have been performed with respect to the capability and characterization of the LAE to act as a strain sensor, and these results can be found in literatures (Yao and Glisic 2012; Glisic and Verma 2011). Two additional tests that evaluate the sensitivity of thin resistive strain sensors to cracks and the sensitivity of sensing sheet configuration to strain using TFT as a strain sensor are presented in this paper.

Sensitivity of Thin Resistive Strain Sensor to Crack Opening

The main focus of this test was to examine the relationship between crack opening and measured strain for thin resistive full-bridge strain sensors. Full-bridge sensors were used because of their capability for differential sensing. This significantly improves robustness against noisy signals from external sources and helps avoid large sinusoidal baseline signals that would affect the AC readout scheme applied to the sensing sheet. Since the cost of manufacturing prototypical sensing sheets is very high, less expensive commercial strain gauges were used in this study. This simplification is justified because similar sensors will be patterned on the aforementioned sensing sheets in the future. This paper mainly focuses on cracks oriented perpendicular (90°) to the strain gauge, but other orientations were tested as well (0°and 45°).

In order to achieve repeatable results, all experiments were conducted in a controlled laboratory environment with the same preparation and testing procedure. Each experiment involved mounting a small artificially cracked concrete slab to a micrometer stage and bonding a commercially available full-bridge sensor (gauge length = 14.8 mm) over the crack. High-strength epoxy was used in both the concrete-stage interface and the concrete-sensor interface. The micrometric screw attached to the stage controlled and adjusted the crack width, and strain readings were taken by appropriate reading unit. Experiments were stopped either when the strain sensor was broken or when the measuring range of the reading unit was overpassed. A schematic view to the test set-up is shown in Figure 5.

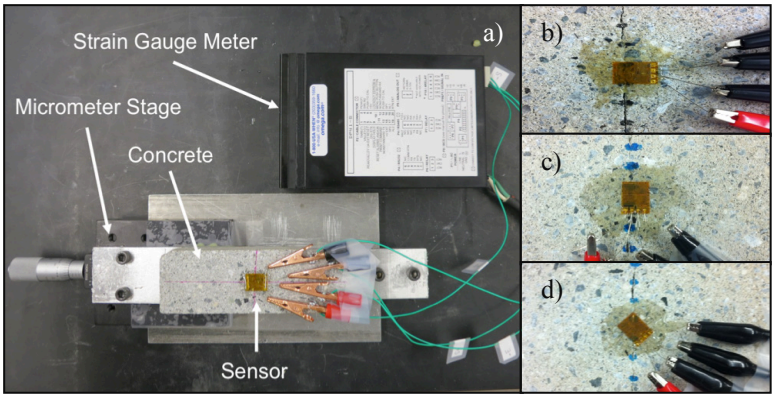


Figure 5. a) Top view to the test set-up, b) 90° test, c) 0° test, d) 45° test

At the beginning of each experiment, the micrometric screw was adjusted to the next closest increment of 25 μm. After ten minutes, the corresponding strain reading was noted and used as the base value for the experiment. The micrometer was then turned to the next 25 μm mark and the strain output was recorded after another ten minutes. This step was repeated until the reading unit either reached 14,000 με or overloaded, or the crack opening reached at least 350 μm. It was observed that while the first few strain readings (up to about 50 μm) stabilized within ten minutes, the rest of the readings followed the same general pattern of quickly reaching a peak strain value and then slowly decreasing for the rest of the time interval. By the end of the ten-minute interval, the strain was usually somewhat stable and not decreasing at a noticeable rate. This observation can be explained by several factors, including plastic creeping in the sensor film; stress concentrations near the crack; the epoxy in the sensor-concrete interface; and the effects of concrete deterioration at the crack edges. Lastly, at the end of each experiment, the micrometric screw was turned until the strain gauge ripped to ensure that the sensor-concrete bond was adequate and that the concrete at the crack edges did not deteriorate (since this could affect the strain measurements).

Systematic tests have been performed on 90° case, and results of ten tests are illustrated in Figure 6. For each test, strain change of the same order of magnitude is found for every crack opening increment, which indicates linear

relationship. The strain change (tension) measured by the sensor was very high for each crack increment, and the values ranged between several hundred to several thousands of microstrain, which is an order of magnitude higher than usual strain variations in structures due to live loads. The high sensitivity of the strain sensors to crack openings was thus confirmed by this test, and crack opening was successfully detected by the direct strain measurement. While all ten experiments produced nearly linear results, the large dispersion of gradients suggests that there are other factors besides crack growth that affect the strain response. The variation is probably due to the magnitudes of initial crack widths; stress concentrations at the edges of the crack; and the deterioration of the concrete from the epoxy. Also, it was difficult to keep all ten procedures completely identical even though the sample preparation was standardized. Thus, while the crack detection and localization using sensing sheets with integrated sensors is expected to be reliable, an estimation of the crack size would require additional statistical data analysis.

Three tests of 0° and 45° cases have also been taken, however, systmatic experiements are still needed to validate the funtioning principle of strain sensors in these situations. Preliminary results of theses two cases are also presented in Figure 6. Although the true principles haven't been completely verified, it could be seen that tests at 0° degree showed lower sensitivity and negative values (compression), while the tests at 45° showed an order of magnitude lower in sensitivity. This indicates that the strain sensor has a critical orientation in which it is insensitive to crack openings.

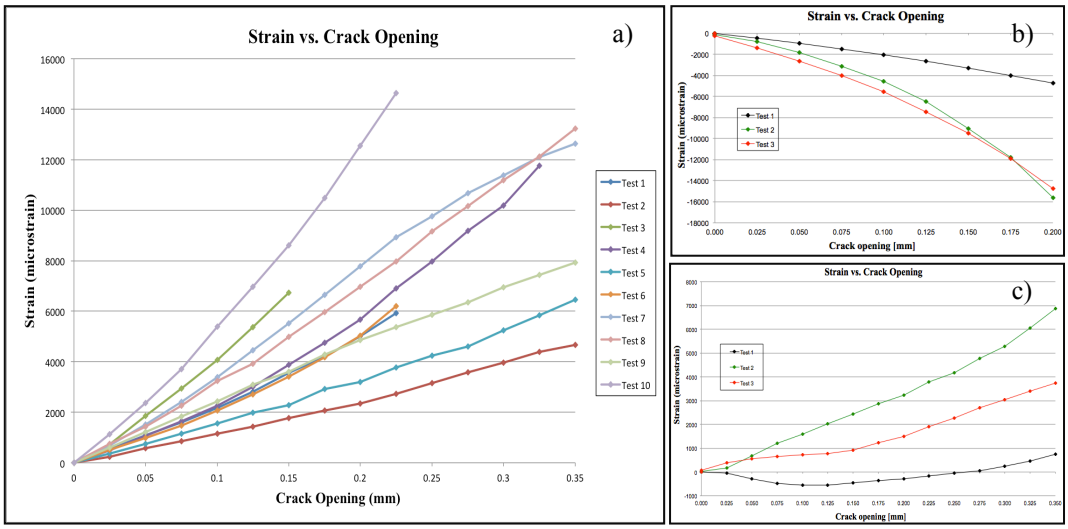


Figure 6. Results of strain gauge sensor under crack openings: a) 90° test, b) 0° test, c) 45° test

These behaviors are due to the arrangement of resistors within the full bridge sensor, as shown in Figure 7. Full bridge sensors consist of four resistors, two oriented at 0° and two at 90° (in Figure 7, R1 and R3 at 0°, R2 and R4 at 90°). The final value of measurement depends on the differences in measurement values registered by 0° resistors and 90° resistors. In 90° tests the 90° resistors are fully activated by crack opening while the 0° resistors are inactive (see Figure 7). The difference in measurement between 90° and 0° resistors is the largest and overall sensitivity is the highest. In 0° tests (see Figure 8), one 0° and one 90° resistor are activated and this explains lower overall sensitivity; in addition, the 90° resistor measures a larger value of strain than 0° resistor, and thus the overall change in measured strain is negative. For 45° tests (see also Figure 8) again one 0° and one 90° resistor are activated, but they both experience the same strain so their difference is close to zero. This explains why for this angle the sensor shows significantly lower sensitivity. In order to avoid ambiguity in data interpretation and to improve the overall sensitivity of the sensing sheet to cracks, an appropriate strain sensor pattern that considers the orientation of each individual sensor or an alternative design of the basic sensing element should be researched and developed in the future.

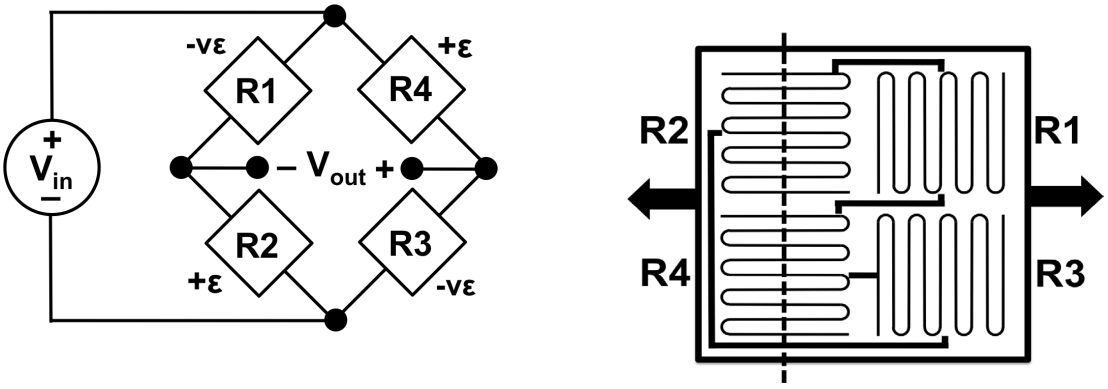


Figure 7. Left: configuration of the full-bridge sensor for axial strain. Right: the full-bridge strain gauge sensor oriented 90° with respect to the crack

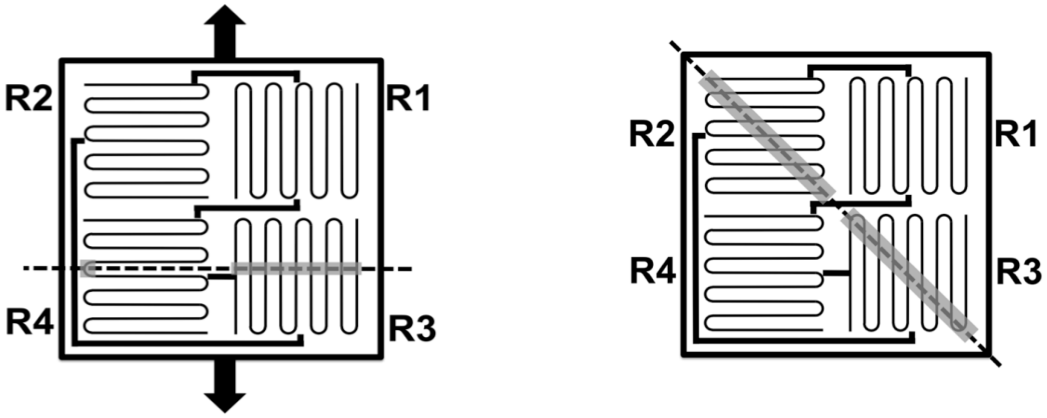


Figure 8. Left: sensor oriented 0° with respect to the crack; Right: sensor oriented 45° with respect to the crack. Gray areas of the sensing elements are affected by the crack

A statistical data analysis has also been carried out to explain the systematically experimental results in 90° tests. The purpose of such analysis is to statistically quantify the relationship between crack size and strain measurements. Therefore, the diagram is illustrated as crack opening versus strain, and the strain range is set up to approximately 5000 με. The left image of Figure 9 shows the portion of the results that is statistically analyzed.

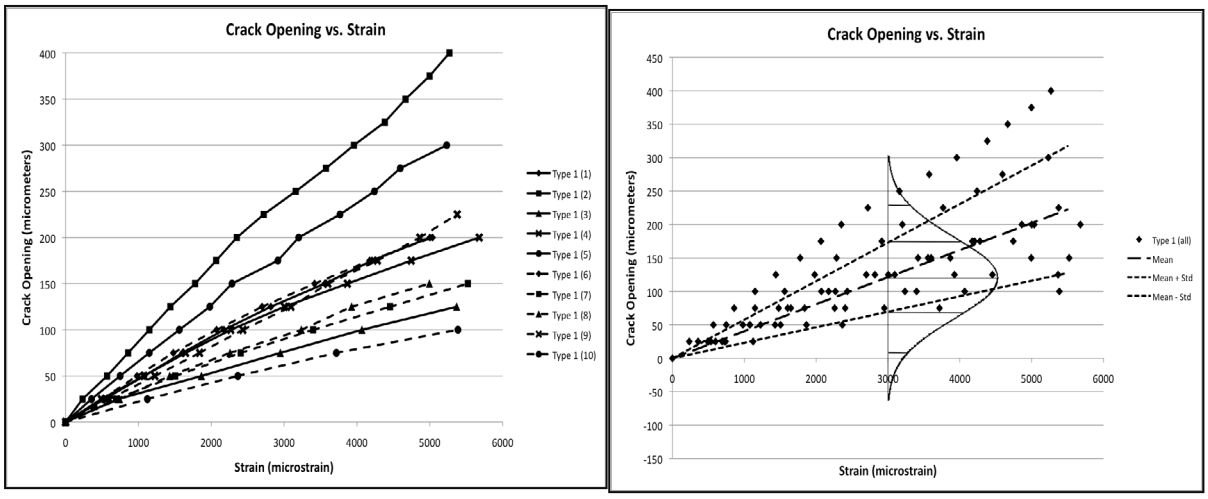


Figure 9. Left: 90° test results up to 5000 με; Right: the mean average relationship between crack opening and strain, plus/minus one standard deviation

To determine the mean relationship between crack opening and strain, the line of best fit for each experiment was found through linear regression. Then the mean and standard deviation of the ten slopes are calculated. The right image of Figure 9 displays the mean slope ± one standard deviation. The value of the mean slope is 0.0404 μm/με, and the slopes one standard deviation above and below are 0.0576 μm/με and 0.0232 μm/με, respectively.

The results of the statistical analysis have several important implications regarding the capability of full-bridge strain gauges for crack detection. Typical strain fluctuations in structures range between 60 and 100 με due to the effects of live loads. As shown in the right image of Figure 9, the mean slope of 0.0404 μm/με implies that a crack width of 4.04 μm (corresponding to 100 με strain) may be confused with live loads. However, the sensor can report strains higher than 5,000 με, which is an extremely large value when compared to the typical strain variations. Assuming that all changes in strain greater than 1000 με (an order of magnitude greater than the maximum strain from live loads) are the result of cracks, we can conclude that the electrical full-bridge strain gauge can, on average, reliably detect cracks with widths greater than 40.4 μm.

The slopes of the lines of best fit for each experiment seem to be normally distributed because four of the slopes are very close to the mean, while the other six slopes are above and below the average value. This suggests that the mean and standard deviation of the relationship between crack opening and strain can predict the width of a crack from a given strain output. For example, if the reading unit records a change of 3,000 με within ten minutes, we can conclude that the most likely value of the crack opening is 121.2 μm (see the right image of Figure 9). The Gaussian distribution also implies that there is a 68% chance that the width is between 69.6 and 173.1 μm and a 95% chance that the width is between 18 and 224.4 μm. This application of such analysis is particularly important in practical SHM, where we would have to completely depend on the changes in strain output to detect and characterize cracks. Consequently, the results confirm that cracks can be successfully detected and characterized by thin resistive strain sensors.

Overall, the results from above tests provide important implications for the development of the sensing sheet on the printed sensor arrangement. In Figure 3, the sensors in the sensing sheet are arranged in a regular pattern with straight rows and columns. However, since the full-bridge strain gauge is less sensitive to cracks in R1 and R3 as mentioned above, this means that there would be long strips of areas where cracks are less likely to be detected and accurately characterized (see the left image of Figure 10). However, it may be more appropriate to pattern the sensors in a staggered arrangement, as shown in the right image of Figure 10. In addition, it is analyzed that cracks oriented 45 degrees with respect to the sensor will not show any strain changes. With a staggered sensor arrangement, there is also a higher chance of crack detection for diagonal cracks, as shown in Figure 10. This observation contributes to the further research of appropriate layout of sensing elements in the LAE sensing sheets.

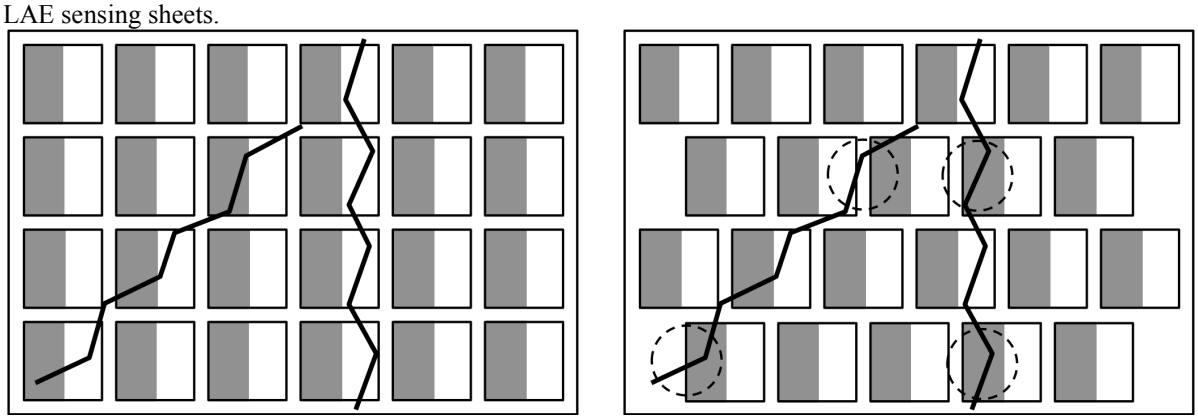


Figure 10. Left: a regular sensor arrangement has a higher probability of cracks being undetected. Right: a staggered sensor arrangement is more likely to detect cracks (circled areas). Gray areas are more sensitive

Characterization of LAE Configuration with TFT Strain Sensor

As an alternative design to thin resistive strain sensor, new type of strain sensor based thin film transistors (TFT) were researched. The TFT sensor is fully compatible with the sensing sheet design shown in Figure 4. The encoding parameter (output) from TFT strain sensor is voltage, while in engineering practice direct strain readout is preferred. For this reason, a characteristic identification test is performed to validate the strain-voltage relationship and to test TFT strain sensor sensitivity. The test setup is shown in Figure 11. A square steel plate

was installed as a cantilever beam, and both a TFT sensor and a thin resistive strain sensor were installed close to each other near the fixed-end. A lifting jack was used to raise the free-end of the beam and apply compression to both sensors, and five weights were used to lower the free-end of the beam and apply tension to both sensors.

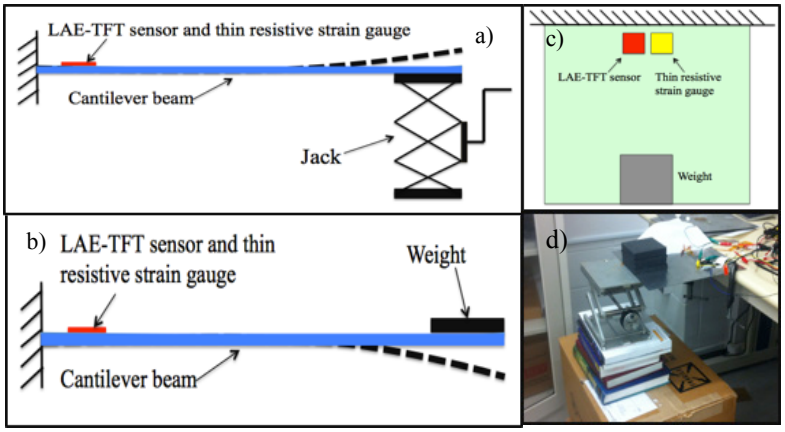


Figure 11. Setup of characteristic identification test for TFT sensor: a) compression test, b) tension test, c) top view of the set-up, d) side view of real experiment set-up

The compression tests were realized with the help of a lifting jack. When the handle of the jack was turned one round, it raised the free-end of the beam for a certain distance, which applied compression strain to both sensors. An oscilloscope recorded the TFT sensor output as a stable voltage, and a commercial reading unit as mentioned in previous section recorded the thin resistive strain sensor output. Compression tests ended untill the third round was applied. In tension tests, five weights were put cumulatively one on top of another at the free-end of the beam to generate tension strain in both sensors, and results were recorded the same way as compression tests. Tension tests ended until the fifth weight was added. Sample readouts from the oscilloscope for the TFT sensor are shown in Figure 12.

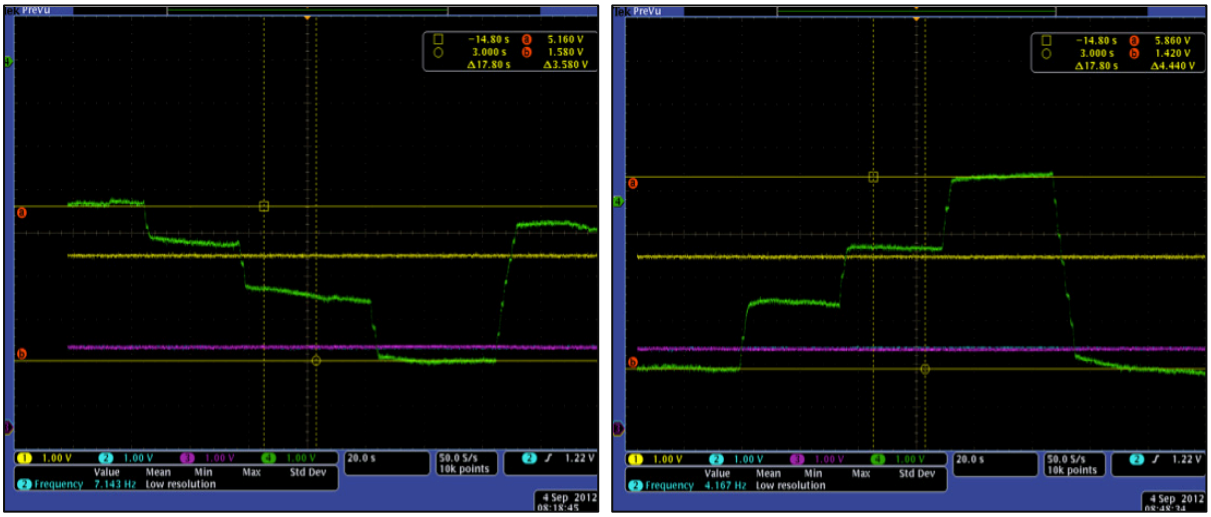


Figure 12. Sample readouts for the TFT sensor (voltage vs. time, output as shown by green lines) at different strain levels. Left: compression tests; Right: tension tests

Both tests were repeated three times and their results were plotted out in the same diagram, as illustrated in Figure 13. It was found that the output voltage has a linear relation with corresponding strain value (sensitivity of ~3.3 mV/με, with a calibration coefficient of ~0.3 με/mV). This indicates that TFT sensors behave linearly and are capable to measure strain directly with the above calibration coefficient. However, further tests are needed to assess the long-term stability of the sensor and its behavior when in contact with damage.

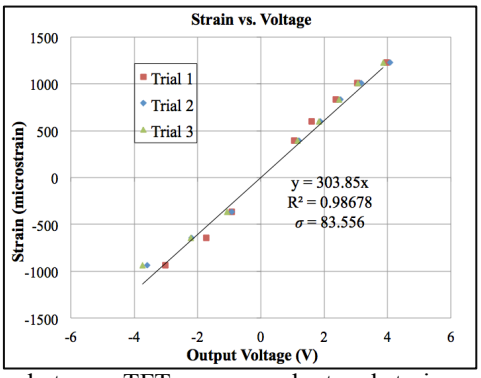


Figure 13. Relation between TFT sensor readout and strain gauge sensor readout

CONCLUSIONS

Direct damage detection is a novel sensing principle that could provide reliable, robust and low-cost SHM over large areas of structures. It may overcome the limitations of traditional sensing technologies that feature high costs and insufficient spatial resolutions, often relying on complex algorithms with questionable reliability in damage detection. The main concepts and motivations of direct sensing approach are presented in this paper.

The direct sensing principle is based on strain-field measurement using dense arrays of sensors embedded in sensing sheets enabled by a technology called large area electronics (LAE). A brief description of LAE and its applications in SHM are presented, and a prototype of sensing sheet and its functioning principle in 2D strain-field measurements are discussed. Two fundamental laboratory tests included an evaluation of the sensitivity of thin resistive strain sensors to cracks (with an average sensitivity of 0.0404 μm/με), and an evaluation of the sensitivity of novel TFT sensors to strain changes (with an approximate sensitivity of 3.3 mV/με). The results of both tests were encouraging and provided guidance for future research.

Sensing sheets based on LAE are still under development and results presented in this paper support the feasibility of such technologies. The authors believe that the distinct reliability, robustness, and low cost that these technologies can offer have the potential to transform SHM, vastly improving safety and reducing maintenance and life-cycle costs for civil infrastructure.

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