Sensing Sheets based on Large Area Electronics for Structural Health Monitoring of Bridges

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ABSTRACT

Damage characterization often requires direct sensing due to the localization of the anomalous behavior near the cracks. Direct sensing, however, is expensive because of the need to deploy a dense array of individual sensors. Sensing sheets based on Large Area Electronics (LAE) and Integrated Circuits (ICs) are a novel solution to this problem. Such sensing sheets could span several square meters, with a dense array of strain sensors embedded on a polyimide substrate along with the relevant electronics allowing for direct sensing while keeping the costs low. Current studies on LAE based sensing sheets are limited to laboratory experiments. This paper explores the question of suitability of the sensing sheets as a viable option for real-life SHM based on LAE and ICs. Results of laboratory experiments on an aluminum beam are provided to demonstrate the performance of sensing sheets in ideal conditions. Then, the sensing sheets are employed on a pedestrian bridge already equipped with fiber-optic sensors. The strain measurements from the sensing sheets and the fiber-optic sensors are compared and sources of differences are discussed.

Keywords: structural health monitoring (SHM), strain sensing sheets, large area electronics(LAE), long-term monitoring of civil structures and infrastructure, direct damage detection

1. INTRODUCTION

In the past decades, the use of structural health monitoring (SHM) for damage detection and optimal maintenance schedule has increased many folds. Damage in the form of cracks or excessive deformation is caused due to stresses in members exceeding the strength of material. However, currently it is not possible to measure the stress directly and hence strain becomes the parameter of choice to be monitored. Stress is correlated to the strain through modulus of elasticity and any damage due to high stresses is often identified well by the corresponding strain change. Crack initiation could be caused by many external sources such as mechanical effects (e.g. live and dead loads, fatigue), environmental effects (e.g. humidity, temperature, freeze-thaw cycles) and chemical processes(e.g. corrosion) could lead to cracks developing in the structure[1]. These cracks present themselves in various forms: transverse, longitudinal, slant, breathing, gaping, surface and sub-surface[1]. If the concerned structure is being monitored, cracks are often associated with sharp "jumps" in strains which could be captured by sensors either directly or indirectly.

Cracks are best identified when they cut across the sensors because of the large change in measured strain which cannot be attributed to electrical noise or environmental effects such as temperature or humidity[2]. Direct sensing is often carried out by discrete sensors (electrical, fiber-optic), distributed sensors (electrical, fiber-optic), wave monitoring sensors (acoustic emission, wave propagation) and eddy current sensors[3]. Discrete sensors can be further divided into short-gage and long-gage sensors. In similar circumstances long-gage sensors are preferred over short-gage sensors because of larger area covered leading to higher probability of damage detection. Direct

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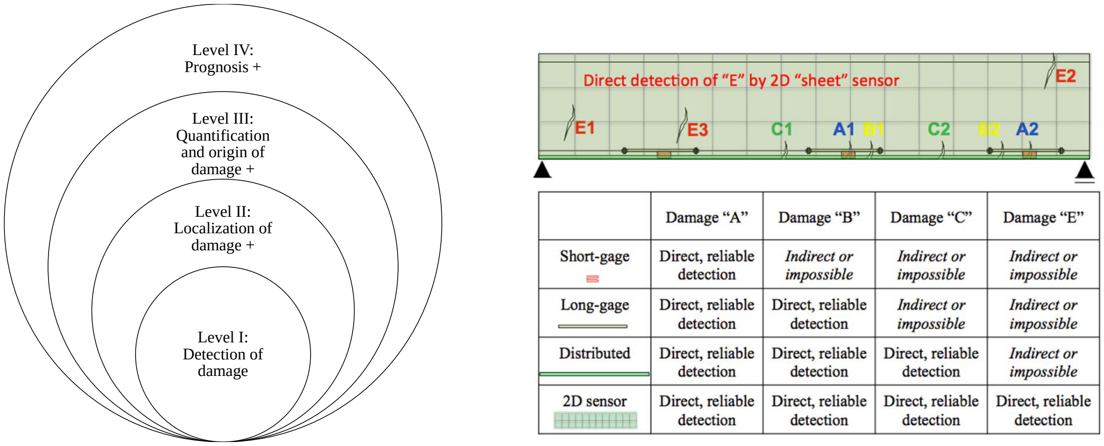
sensing is, however, costly as large numbers of sensors are needed if a comprehensive coverage of the structure's surface is required. Due to high cost and external constraints(such as safety in sensor deployment) it is often the case that indirect sensing is employed. Fewer sensors are installed and complex algorithms are used to identify, localize and quantify the damage. Indirect sensing is often classified into: (1) Model based and (2) Model free[1]. Analysis performed using finite element[4], modal characteristics[5], local stiffness reduction[6], spring models, flexibility matrix[7] and others come under the category of model based indirect sensing. With the rise of computational power data-driven or model free approaches have gained traction and include neural networks[8], fuzzy logic[9], principal component analysis (PCA)[2], genetic algorithms (GA)[10] and others[1]. Indirect sensing approach has shown great promise in laboratory experiments and few real-life applications but challenges of reliability in presence of environmental noises are still active areas of research.

The benefits of direct sensing make that approach ideal to achieve Level IV goals of SHM(Fig. 1). However one-dimensional sensors such as point sensors, short-gage, long-gage and distributed sensors can only detect damage if the cracks are very close to the sensors. Even a half-meter distance between the crack and the sensors could lead to inconclusive data analysis[3]. Two-dimensional sensors could help achieve the goal of providing extensive coverage of the structure while maintaining a low-cost. As shown in Fig. 1, these two-dimensional sensors do not suffer from the challenges of their one-dimensional counterparts. The benefits of two-dimensional sensors have encouraged multiple research works in this domain[12]. One of the earliest works developed large-area pressure sensors using organic field-transistors on plastic sheets[13]. These plastic sheets with rubber sensors could deform according to the shape of the object. Extensive research has been conducted using organic substrates. Printed electronic vapor sensors sensors consisting of three layers(polymer dielectric, nano-particle metal contacts, organic semi-conductor) were successful in identifying wine spoilage[14]. Oragnic semi-conductor based sensors have then been shown to successfully measure temperature and magnetic fields[15] . Carbon nanotube based sensing skins have been successfully implemented to measure strain and detect damage(crack and corrosion)[16,17] and distinguish between different types of damage in adhesively-bonded composites[18]. Improvements in sensing capabilities of the carbon nanotube based sensors have been reported by aligning the nanotubes using electric field[19]. To extensively cover the surface, paint based sensing techniques have also been advocated. Piezoelectric paint sensors have shown promise for fatigue cracks using dynamic sensing[20]. Successful work using composite coatings to measure underlying strains using non-contact optical measurements have been demonstrated[21], as is the use of photonic crystals for visually identifying strains[22]. Recent works have adopted strategies from human nervous system to implement sensing skins using conductive ink resistors and graphene-oxide capacitors[23] and created sensing concrete composites which could lead to the development of the smart structures[24].



	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. (a) Four levels of SHM (b) Advantages of two-dimensional sensors compared to short-gage, long-gage and distributed 1D sensors[11]

Researchers at Princeton University have developed a sensing sheet consisting of a dense array of resistive strain gage sensors[25](See Fig. 2). CMOS ICs are used in these sheets for sensor control and readout. Large-area electronics are combined with CMOS ICs for many-channel distributed sensing and data aggregation. This combination of CMOS ICs and LAE technologies is achieved using non-contact interfaces which allows for the sensing sheets to be scaled[26–28]. These electronics are printed on a polyimide sheet and it is expected that the mass production of such sheets would be approximately \$100 per m^2. Previous works using these sensing sheets have demonstrated successful fatigue crack detection[29] and explored optimal sensor arrangement for these sheets[30].

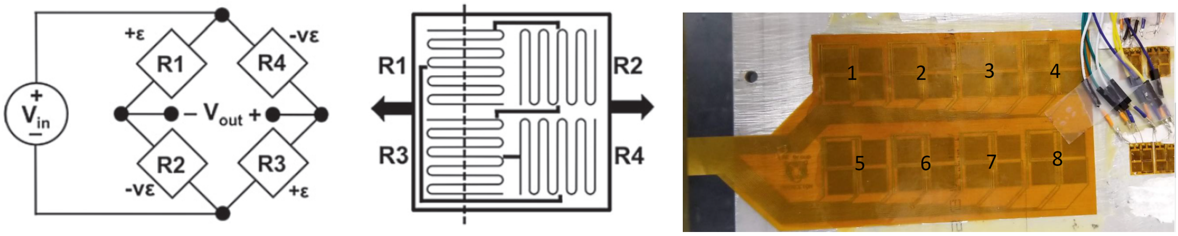


Figure 2. (a) Schematic of wheatstone bridge forming the basis of individual sensor[31] (b) Sensing sheet prototype deployed in laboratory along with sensor numbering

This paper focuses on the viability of the sensing sheets for real-life applications. Works discussed in the previous two paragraphs have used numerical simulations and laboratory experiments to demonstrate the success of those technologies. However, it is imperative to test any new technology on real structures as field conditions often vary from substantially from the laboratory setup. Environmental factors such as varying temperature and humidity can affect a sensing technology. For gaining acceptance in the industry for widespread use, laboratory testing is hence often not sufficient. In this work, the performance of sensing sheets is compared with that of fiber-optic sensors on a pedestrian bridge at Princeton University. The results demonstrate that sensing sheets could be used for monitoring of structures real-life structures.

The paper is organized as follows: Section 2 describes the Streicker Bridge at Princeton University campus with sensor installation. In section 3, the laboratory experiment and the sensing sheet set up at Streicker Bridge is elaborated. The results from laboratory and real-life tests are presented in section 4. Finally, the conclusions are presented in section 5 along with discussion on limitations and future work.

2. STREICKER BRIDGE

The sensing sheets described above was tested on a real-life structure, the Streicker Bridge at Princeton University campus. It is a pedestrian bridge, 104 meters long, connecting the east and west side of the university campus across Washington Road. The bridge is composed of a main span and four horizontally curved approaching legs. The side view of the bridge is shown in Fig. 3. Structurally, the main span is a deck-stiffened arch and the approaching spans are curved continuous girders. The bridge is supported by Y-shaped columns made of weathering steel. The deck and legs are made of reinforced post-tensioned concrete. Half of the main span and the southeast leg are installed with fibre-optic sensors and the bridge act as the on-site laboratory for the University's SHM*lab* research group[32]. During the construction phase, long-gage fiber optic sensors based on Fiber Bragg-Gratings (FBG) and Brillouin Optical Time Domain Analysis (BOTDA) were embedded into concrete at several locations (Shown in Fig. 4) on the southeast leg. The gage length of the installed FBG sensors is 60 cm. FBG sensors were reported to have higher accuracy compared to BOTDA sensors[33]. The installation of the sensors during the construction phase allowed to identify early age cracking in concrete which eventually closed.[34]

As it is pedestrian bridge with relatively low live loads, static measurements are collected at intervals of five minutes during active sessions. However, this rate could be adjusted as per requirement. To demonstrate the reliability of the sensing sheet for real-life applications, the sensors were glued to the lower surface of the deck in the proximity of the midspan of columns P12 and P13, labeled P12h13, see Fig. 4(a). Araldite 2012 was used for gluing as it provides the best strain transfer from the structure to the sensing sheets.[35]

Figure 3. (a) Elevation view of Streicker Bridge and (b) Elevation view of South-east leg

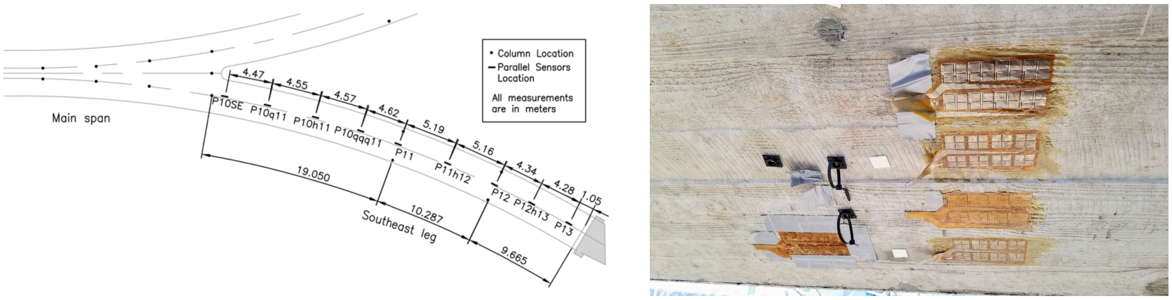


Figure 4. (a) Southeast leg sensors naming convention[32] (b) Sensing sheet glued on southeast leg

3. METHODOLOGY

In this section the experimental setup in the lab to demonstrate accuracy of the sensing sheets in ideal conditions and the setup at Streicker Bridge for real-life application are described. In the experiment, an aluminum beam of dimensions 169.3 cm × 25.4 cm × 1.0 cm (63.5in × 10in × 0.4in) was fixed at one end. A sensing sheet prototype was glued to its surface with the center at 37.5 cm (14.75in) from the fixed end. Different load conditions were created by using two bottles (B1 and B2) filled with sand, weighing 593.5g and 598.5g respectively. The bottles were placed near the free end with the axis of symmetry of the bottles being 2cm away from the free end. Setup with one bottle and the sensing sheet connection are shown in Fig. 5. The measurements (both in lab and outside) were carried out using a software written in MATLAB. Since strain can only be measured with

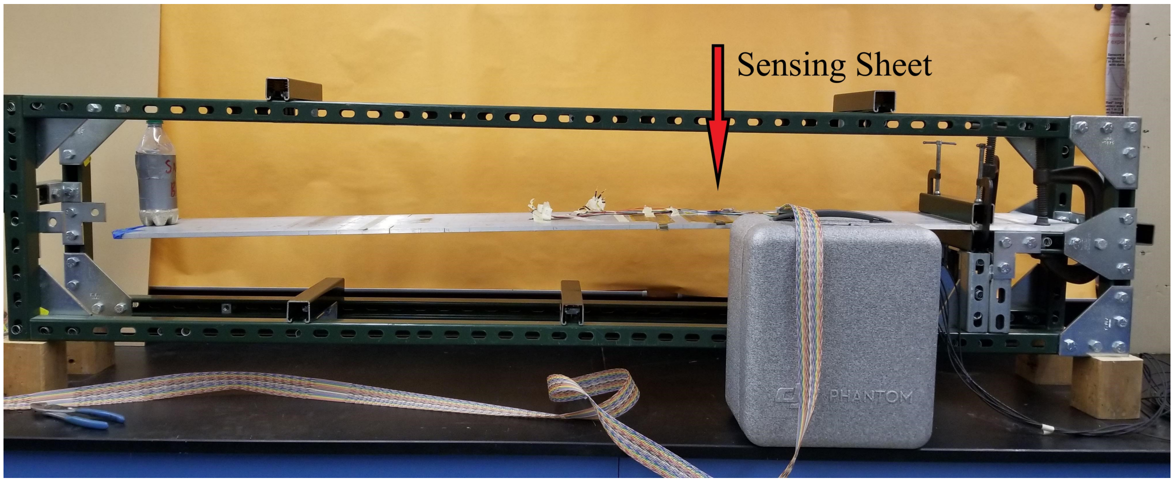


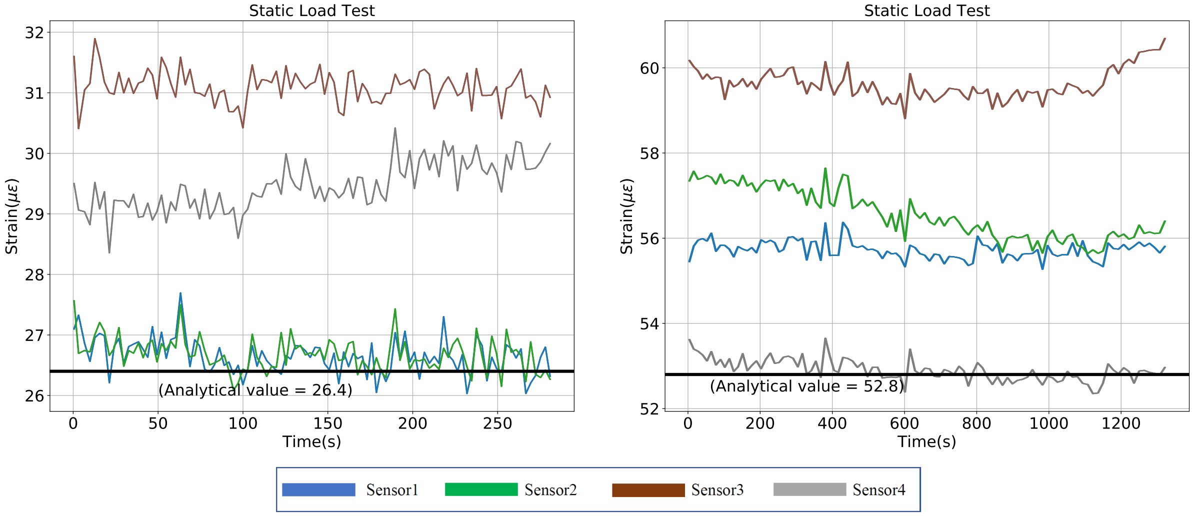
Figure 5. Cantilever beam with applied load using a bottle filled with sand.

respect to a reference, the baseline measurement was taken with the beam with no load. Hence, any strain measured would be due to the load applied by bottles(self-weight is not accounted). Two distinct measurements were conducted: (1) Only with bottle B1 (2) With bottles B1 and B2 placed simultaneously. The readings were started after the vibration induced due to the bottle placements was no longer noticeable. A fixed number of measurements were taken, allowing for the readings to be stabilized.

To test in real-life condition the sensing sheet was glued on the underside of the bridge around P12h13. Since Streicker Bridge has mostly pedestrian traffic, temperature change through the day is the major source of noticeable strain changes. Hence, these measurements were taken during the period of maximum temperature change of the day. The baseline measurements were recorded before the start of measurements. Thus, the dead load and all the existing live loads on the bridge correspond to zero strain. The readings were recorded for five hours and comparison was later made with the FBG sensors.

4. RESULTS

In what follows, the results from laboratory experiments and real-life testing are presented and discussed. In Fig. 6, the strain measurements from four different sensors in the sheet prototype are presented. Since, the setup is a simple cantilever beam the analytical solution was obtained. The analytical solution for each loading condition is shown by a constant black line for comparison.


Static Load Test

Static Load Test

Figure 6. (a) Static test with load B1 applied (b) Static test with load B1+B2 applied; Note: Sensor labels as in Fig. 2(b)

Fig. 6 shows that the sensing sheet is able to measure the theoretically predicted strain value. For the load B1 two sensors had measurements close to the theoretical prediction (Sensor1 and Sensor2) while for load B1+B2, Sensor4 measurements were very close. The maximum difference in values registered amongst the four sensors is $\approx 5\mu\varepsilon$. This difference can be attributed to the inherent accuracy of the sensing elements (resistors) used in the sensing sheet or to the non-uniform gluing of the sheet. It is important to note that such a deviation from theoretical value is acceptable as the "jumps" in strain in case of a damage is orders of magnitude higher. In Fig. 7, the mean measured value of each sensors and the standard deviation is plotted. The standard deviation bars show that the spread in each measurement is fairly small (in the range of $\approx 1\mu\varepsilon$). This is important for any sensing system as large deviations from the mean value could lead to misinterpretation of data.

The strain measurements from the Streicker Bridge are next presented. Fig. 8 shows strain measurements using the sensing sheet and the fiber optic sensor acting as the reference sensor.[36] The strain measured by the sensing sheet over a 5 hour period follows the FBG measurements very closely. The successful measurement of the strains verifies its real-life measuring capabilities for civil infrastructure projects.

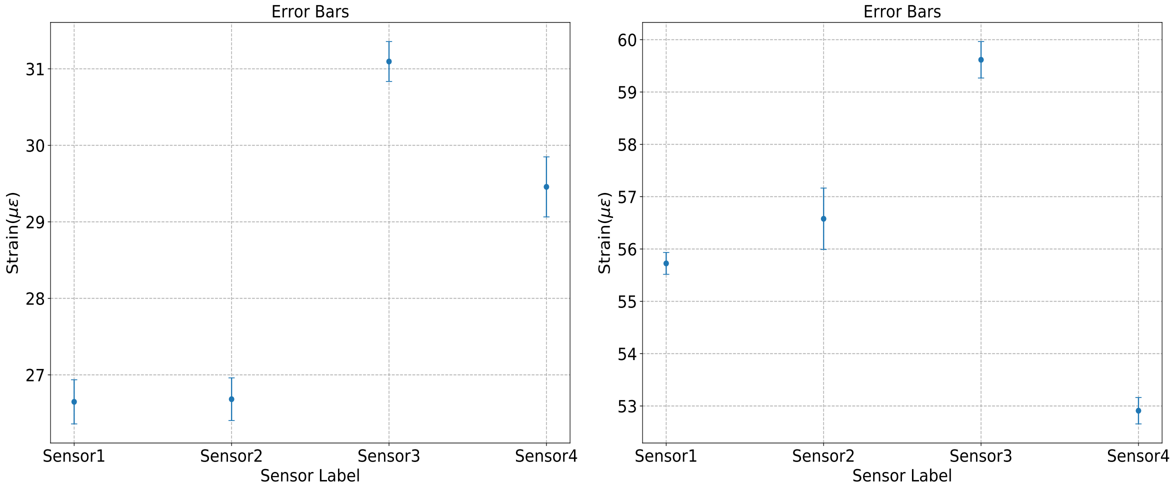


Figure 7. (a) Error bars for load condition B1 (b) Error bars for load condition B1+B2

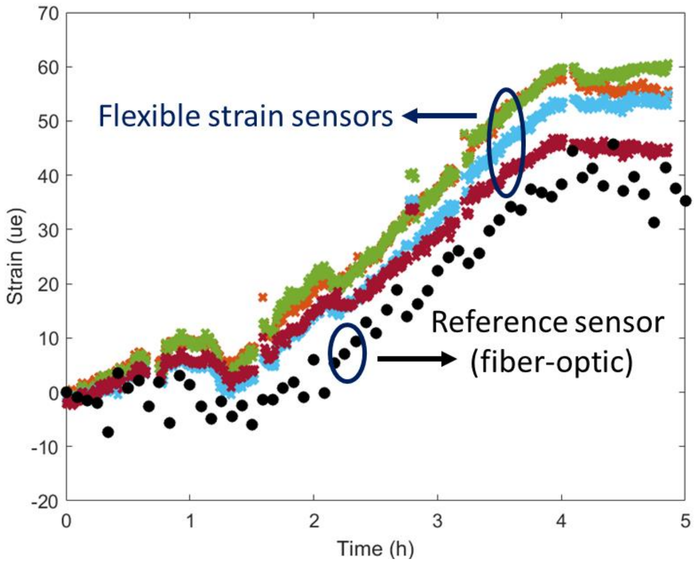


Figure 8. Comparison of strain readings using sensing sheets and FBG fiber-optic sensors[36]

5. CONCLUSIONS

Sensing sheets developed at Princeton University were tested for their applicability on real-life structures. These reisistive thin-film sheets were glued to the southeast leg of Streicker Bridge near the location of existing FBG fiber-optic sensors. The comparison of strain values measured by these two independent methods match closely indicating that sensing sheets are suitable for monitoring real-life structures. In addition to the real-life testing, laboratory experiments assessed accuracy measures of sensing sheets in ideal conditions.

Though these two-dimensional sensing sheets could make low cost direct sensing viable, a few limitations need to be overcome first. Limitations of the current design of the sheets includes its sensitivity to electrical noise. This could easily be overcome if a ground connection is available. Also, the current reading unit, which is connected to a laptop, could be replaced with ICs for reading and data processing. As already mentioned earlier, the choice of glue and gluing method can severely impact the strain transfer from the structure to the sensor. A self-adhesive sheet could posibly overcome this issue. Future works would focus on addressing these challenges as well as creating a wireless data collection and transmission system. This would enable 24-hour monitoring of the structure which is currently not possible. A power harvester system based on solar energy or mechanical vibration could supply enough electricity to make the wireless monitoring system a reality.

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