Approach to Health Monitoring of an Aircraft Structure with Resistive Ladder Sensors During Full Scale Fatigue Test

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7th European Workshop on Structural Health Monitoring
July 8-11, 2014. La Cité, Nantes, France

APPROACH TO HEALTH MONITORING OF AN AIRCRAFT STRUCTURE WITH RESISTIVE LADDER SENSORS DURING FULL SCALE FATIGUE TEST

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ABSTRACT

This paper presents an application of resistive ladder sensors for health monitoring of an aircraft structure. Cracks forming can affect significantly the integrity thus the use of methods which enable damage detection as early as possible is an important issue. The article presents novelty in approach to detect fatigue cracks in the early stage with use of Resistive Ladder Sensors. Additionally, measurement results for customized sensor are delivered, which is design and manufactured on site with conductive paint in DW (direct-write) technique. Moreover the article will present on-line diagnostics capability for the real aircraft elements (including shape complicated) as well as results of the damage detection from full scale fatigue test of turbo-prop military trainer.

KEYWORDS : *SHM, fatigue crack, crack gage, resistive ladder sensor, FSFT.*

INTRODUCTION

During flight, an aircraft is subjected to a wide spectrum of varying loads. Under the influence of those forces, stresses arise periodically, and irreversible changes in structure may occur. As a consequence, cracks are formed, which reduce the structural strength, and can affect the integrity significantly. For that reason, development of innovative and reliable monitoring methods is so essential for aerospace industry.

A crack length measurement method is very important in the investigation of the fatigue crack growth characteristics of a material and in the evaluation of the fatigue strength of a machine element. Many crack length measurement methods have been proposed. JSME (1986) recommended estimating the crack length from the opening or closing displacement of a crack. In addition, crack length can also be measured using optical microscopes, optical grid technology an acoustic emission method and an ultrasonic method. However, the methods proposed up to now require specific measuring devices and complex calculation processes for crack length, and are applicable to long cracks, i.e. several millimeters in length, not to small cracks shorter than 1mm in length or cracks with a high growth rate. In addition to the above-mentioned methods, a thin metal film, such as a crack gauge (e.g., KV-25B manufactured by Kyowa Co., SG-CP1 manufactured by Omega, CPA-02 manufactured by Vishay), has been used for crack length measurement and fatigue crack initiation detection.

The fatigue crack detection and its size determination is one of the basic aims for Structural Health Monitoring (SHM) system. Resistive Ladder Sensors provide a convenient, economical method of indicating the presence of a crack, and quantify its linear size in a predetermined location on a test part or structure. The sensor's structure and manufacturing process is similar to foil strain gauge one. Differences in shape of the measuring grid can be noticed, as it's designed as a number of conductive strands (paths) connected in parallel. The sensor needs to be permanently bonded to the structure in a hot-spot area. When the fatigue crack propagates under the sensor, it is causing a local deformation, and gradually tears the foil of the sensor. Along with the foil, permanent opening of a conductive strand occurs (Fig. 1). Electrical resistance is measured between the sensor's two terminals and any changes are affecting the output signal.

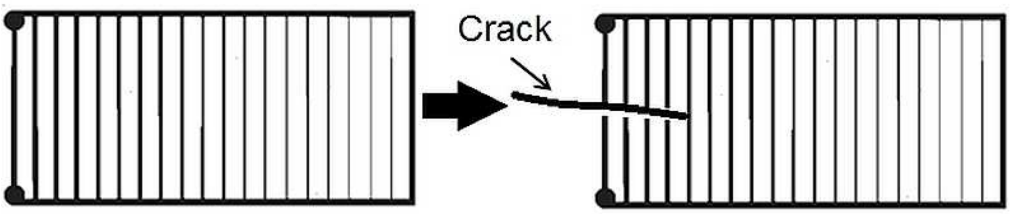

Figure 1. Resistive ladder sensor without / with propagating crack

Due to material properties of copper, the method at its early stage of development the method suffered from two serious limitations:

- the crack tip could progress considerably beyond the wire without breaking the strand;
- in areas of high cyclic strains, the wire might fail in fatigue without crack initiation in the structure (not confirmed in our test).

Nowadays, high-endurance materials are employed for measurement grid manufacturing (e.g. constantan). The sensor has a single cycle strain range of up to 3÷5 % with a fatigue life of greater than 10^7 cycles at ±2000 microstrain. The standard backing is an epoxy matrix. These gages can operate through the temperature range of –40° C to over +200° C.

1 Characteristics of Resistive Ladder Sensors

Electrical resistance R of a single strand of the resistive ladder sensor is expressed by the following equation:

$$R_{strand} = \rho \cdot \frac{l}{w \cdot t} \tag{1}$$

where l is length, w is width, t is thickness of the conductor. ρ is specific resistance of the conductor material.

The sensor is composed of several number of strands connected parallel. The basic electrical model is ilustrated on Fig. 2. For simplified ideal case, when a measuring grid has a simple shape with equal strand resistance, sensor's value R_{sensor} could be expressed by the equation:

$$R_{sensor} = R_{strand}/N \tag{2}$$

where N is a number of conductive strands.

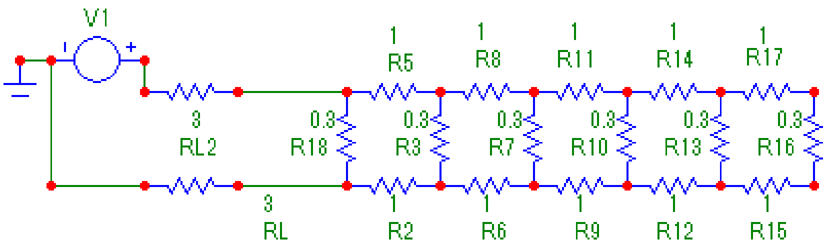

Figure 2. Basic electrical model of resistive ladder sensor

Unfortunately, it's quite difficult to determine an equation for a sensor, which has a variable strand length or width, because R_{strand} must be calculated separately for each small conductive element. Similar issue with sensor's equation occurs when terminals (place where measurement wires are soldered to the sensor) are located only near the first strand, not along whole sensor's ladder. For that reason, with more complex measurement grid shapes, direct data collection from the sensor is the best way to obtain resistance characteristics. Good approximation of the equation for complex grid shape sensor can be expressed by:

$$R_{sensor} = \prod_{i=1}^{N} R_i \, / \sum_{i=1}^{N} \prod_{j=1, j\neq i}^{N} R_i \tag{3}$$

where R_i is a basic resistance of the following conductive strand and i, j=1, 2, 3, …, N indexes of a strand.

2 FULL SCALE FATIGUE TEST

The reliability of Resistive Ladder Sensors was proven during laboratory tests conducted on a fatigue test machine. Both simple shape coupons, as well as real aircraft elements were used as specimen. After that, the implementation of these sensors on real aircraft structure was delivered to verify the measurement method.

As installation of such sensors on operational aircraft is very difficult due to strict regulations, so then the prototype system was prepared for the Full Scale Fatigue Test (FSFT) of PZL-130 Orlik TC II aircraft. PZL-130 Orlik is a turbo-propeller engine trainer aircraft used in the Polish Air Force for primary training . A modernization program, accompanied by a major change in the maintenance system (SEWST), was contracted by Polish MoD. SEWST is collaborative research-based activity undertaken by EADS PZL-Okecie (manufacturer) and Air Force Institute of Technology (AFIT).

One of the major program tasks is a Full Scale Fatigue Test (FSFT). The structure is loaded in a specially designed test rig (Fig. 3) by means of twenty actuators, which apply forces to the wing, fuselage, empennage and landing gear. The loading system is similar to the system used during the Full Scale Fatigue Test of the Pilatus PC9/A trainer aircraft. During the FSFT NDT inspections are planned periodically.

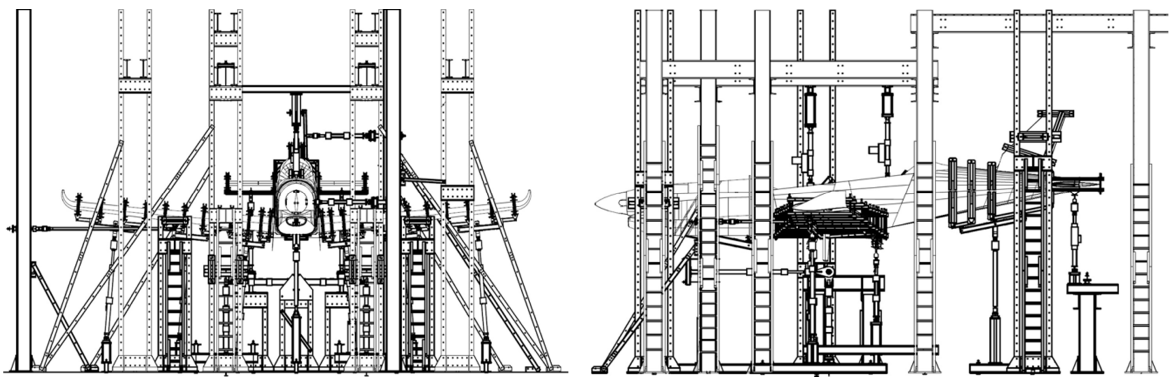

Figure 3. Test ring for Full Scale Fatigue Test

3 MEASUREMENT SYSTEM AND RESULTS

Several measurement nodes have been deployed in selected locations on the aircraft at present. The system components are: power unit with voltage stabilization, sensor in voltage-divider configuration, acquisition unit with 16-bit ADC and signal conditioning connected to industrial computer.

The sensing element is placed in a voltage divider (Fig. 4), between 100 Ω precision resistor and ground connection. In this way, the output voltage from the voltage divider is on a satisfactory level, and the sensor is protected against high input currents. DC power supply was used for voltage stabilization of +5 V DC. Signal conditioning unit and A/D converter card are combined together in National Instrument USB NI-6215 measurement card, with 8 analog input channels ±10 V and 16-bit ADC. The card was connected to PC computer via USB port with LabVIEW™ Signal Express software for data acquisition and display.

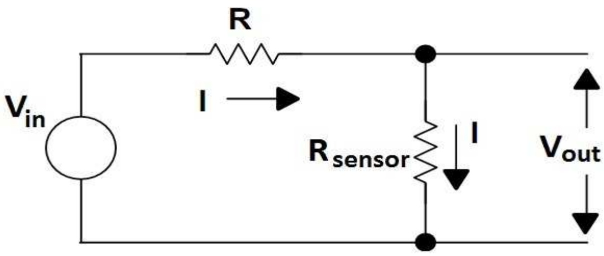

Figure 4. Signal conditioning for Resistive Ladder Sensor

System is designed to be telemetric, providing instant access to real-time data. Post-processing is performed off-line after compilation with some test parameters. But quick estimation of structure's condition can be carried out even from raw data.

The output signal from measurement system is expressed by the following equation:

$$V_{Out} = V_{In} \cdot [R_{sensor}/(R_{sensor} + R)] \quad (4)$$

where U_{out} is output divider voltage, U_{in} input voltage divider (from power supply), R is the resistance of higher arm of voltage divider and R_{sensor} actual sensor's resistance.

Table 1. Parameters of resistive ladder sensor

Measurement grid of the sensor		
Type:	TFDBP 1	TFDBP 3
Resistance:	1.8-35.0 Ω	2.5-36.0 Ω
Width:	10.0 mm	25.0 mm
Length:	50.0 mm	53.0 mm
Thickness:	60 µm	60 µm
Temperature range:	- 40 ÷ +200 °C	- 40 ÷ +200 °C
Single cycle strain range:	> 5% strain	> 5% strain
Material:	Constantan	Constantan
Thickness:	5µm	5µm
Carrier pad		
Material:	Modified epoxide-phenol resins	Modified epoxide-phenol resins
Width:	12.0 mm	30.0 mm
Length:	52.0 mm	55.0 mm
Thickness:	30 µm	30 µm
Insulation resistance:	> 100 MΩ	> 100 MΩ

The sensor of type TFDBP1 has nonlinear, logarithmic characteristic. Measurement grid is design as 20 strands with increasing length. Separation between strands is 0.5 mm, what guarantees good crack length quantification on limited area.

The sensor of type TFDBP3 has partially linear characteristic. It's composed of 73 conductive, equal strands with 0.5 mm separation. It's ideal for monitoring long, propagating cracks up to 50 mm.

Several sensors were installed on aircraft structure under FSFT test. Sensor in node W.15 (Fig. 5 - left) is located on center wing section, bottom skin in main spar near the symmetry axis. Fatigue crack started to propagate from the rivet. Sensor in node W.19 (Fig. 5 - right) is located on fuselage longeron near the canopy front lock. Fatigue crack started to propagate from a lock.

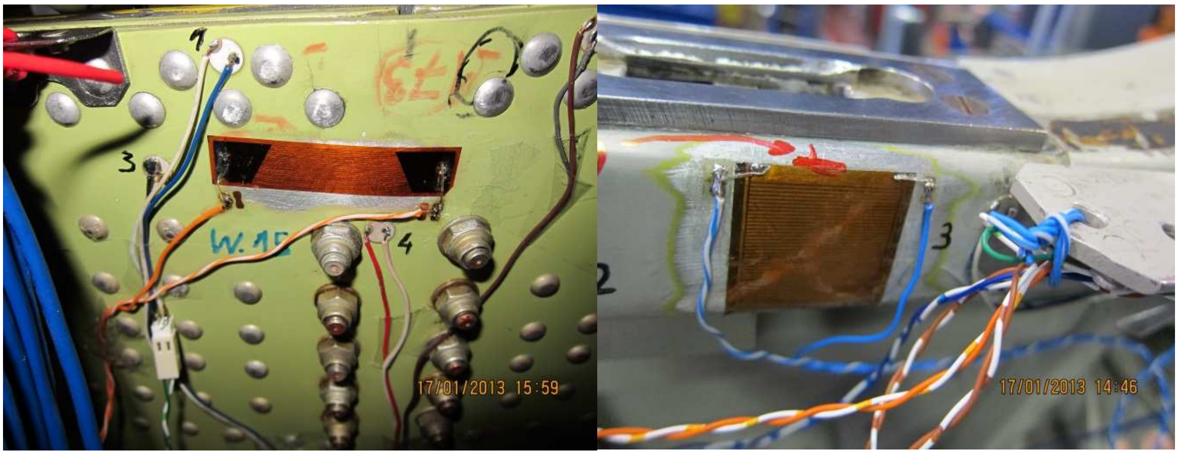

Figure 5. The view of measurement nodes for Resistive Ladders Sensor W.15 (left) and W.19 (right)

Measurement results from both, node W.15 and W.19 are illustrated on Fig. 6.

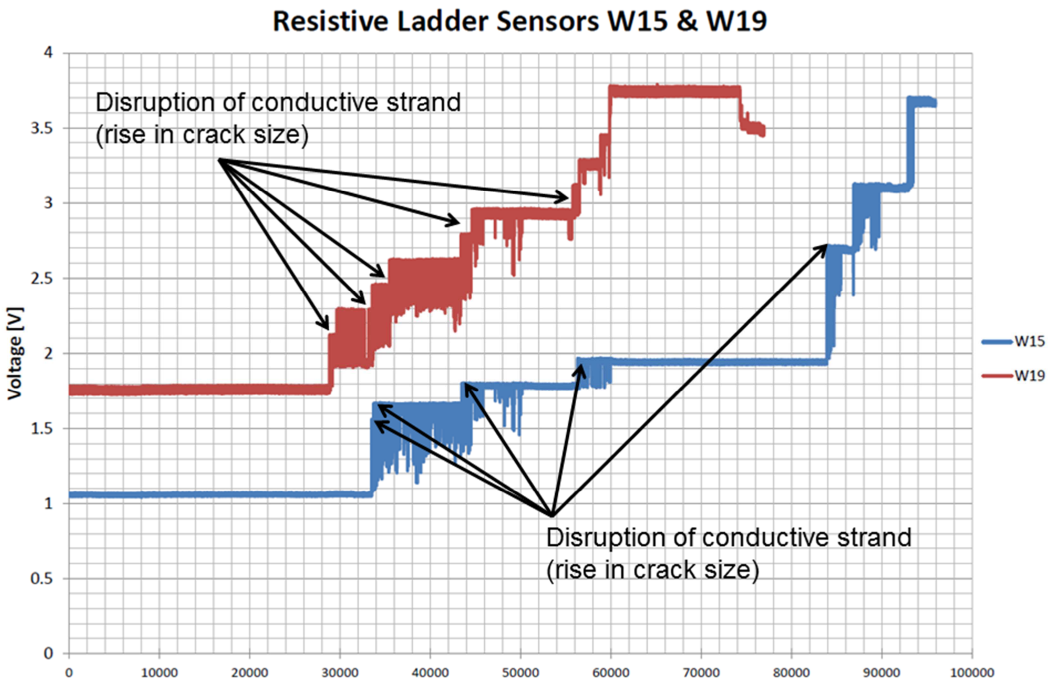

Figure 6. Results of Resistive Ladder Sensors during FSFT

Data is stable while the test object is under load and the correspondence of crack size and measurements is kept. Each increase in voltage rate indicates the growth of fracture on 0,5 mm. Some temporary alteration in measurement value can be noticed. It's caused by pauses in a test while conductive strands have tendency to reconnection at the begining of crack development. The same phenomenon have been already observed during laboratory tests on fatigue machine [4].

Although that fact could impose some limitations for off-line monitoring with Resistive Ladder Sensors as the indication of crack size could be saddled with large uncertainty. On the other hand, it has neglible influence for on-line monitoring, where data is collected in real-time when the test object is subjected to varying loads. It can be proven that relatively small stressforced need to occur to read crack size accurately.

4 CUSTOMIZED DW (DIRECT-WRITE) SENSOR

Due to access difficulties and bonding area limitations, the described ready to use RLS cannot be applied in some cases. For that reason, silver-based conductive layers were designed and manufactured as Customized Resistive Ladder Sensor (Fig. 7) and their preliminary tests were also conducted during FSFT. Those conductive layers were prepared in DW (Direct-Write) technique with use of brush.

Customized DW sensors can provide a novel and efficient method for crack initiation detection, and long term monitoring of fatigue cracks in aircraft structures. The conductive paint can be applied to the aircraft structure, and the measuring grid shape can be quickly and adaptively formed on in situ or can be pre-fabricated. That type of monitoring is becoming popular and usually called as 'smart' or 'sensing' coatings in general.

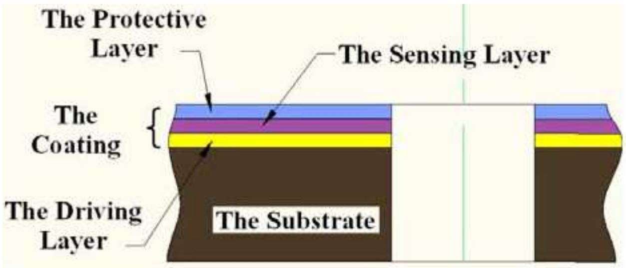

Figure 7. Schematic of Customize DW sensor

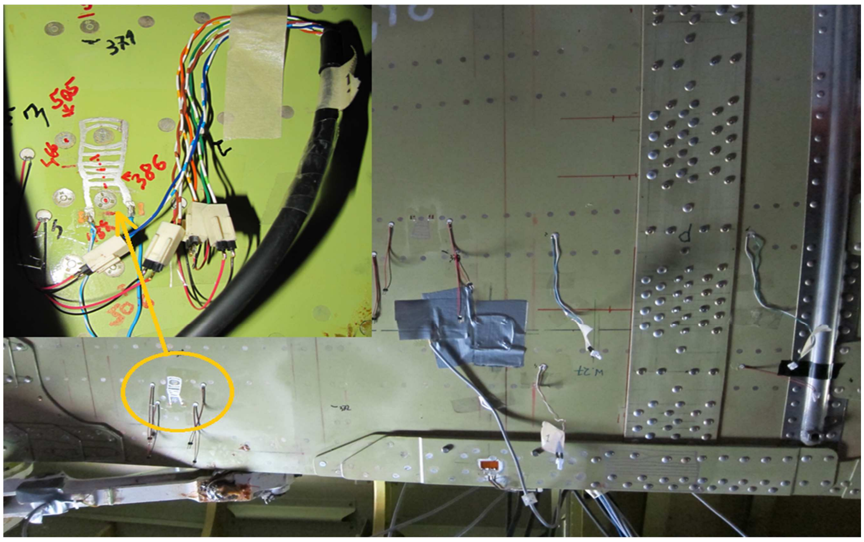

Figure 8 View of measurement node for Customized DW Sensor during FSFT

An example of Customized DW sensor is presented on Fig. 8. It's located on the bottom, central wing section. The crack propagated from nearest rivet, which is marked with red line. Measurement results for that sensor are presented on Fig. 9.

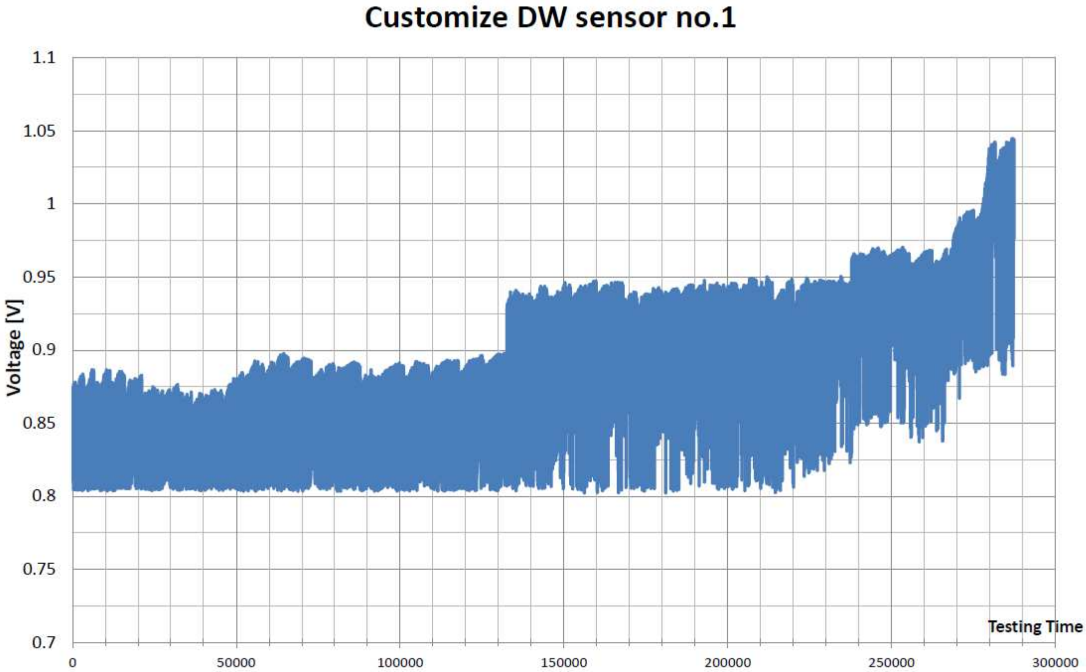

Figure 9. Results of Customize DW sensor during FSFT

The results are barely less stable than ones from prefabricated Resistive Ladder Sensors. Output voltage alteration is higher, about 50mV. However, typical voltage 'steps' can be observed on data chart, what corresponds to sensor's strand rupture and crack size propagation. On fig. 8 it's shown that 4 conductive strands are disconnected due to fatigue fracture, and measurement results confirm that.

It is worth to mention that data from the sensor were being gathered for over 4 months. Regarding that fact, the results are satisfactory as a long term monitoring technique. Fatigue crack was successfully detected on the early stage and it's length could be determined during propagation. The manufacturing process of measuring grid still need some upgrades but after overcoming that, Customized Resistive Ladder Sensors based on conductive paint could become low-cost, uncomplicated and easy-in-application crack detection and monitoring method in future SHM system. Since the conductive film is thin and can be applied directly on a monitored surface, a very small crack can change the electric resistance of DW strands.

5 SUMMARY

In the article the method for fatigue crack initiation detection using Resistive Ladder Sensors based on the changes in the electric resistance of the film due to crack growth or crack initiation was presented. Measurement system was prepared and examined during Full Scale Fatigue Test (FSFT) of military aircraft-trainer, providing long term monitoring process. The results were illustrated and discussed.

Moreover, due to access difficulties and bonding area limitations in some aircraft locations, the necessity of sensor's shape customization occurred. The novelty in approach of the design and manufacturing in site of sensors, based on conductive layers is delivered in the article. Both types of sensors have proven crack monitoring capabilities in pre-defined locations.

The article also provide on-line diagnostics capability for the real aircraft elements (including shape complicated) as well as results of the damage detection correlated with the NDI programme. Compiling sensor's data with addition parameters, e.g. operational time, local load and material features, the final system might reveal as a good tool for both, crack detection and basic short time prediction of structure condition.

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