A Wireless Enabled Nondestructive Damage Tolerant Inspection Fatigue Sensor for Structural Health Monitoring and Prediction of Remaining Useful Fatigue Life of Aircraft Structures

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ABSTRACT

In this paper, a wireless enabled nondestructive evaluation (NDE) fatigue damage sensor for the structural fatigue health monitoring and prediction fatigue life of structural members of large engineering structures including spacecraft and aircraft structures is presented. The fatigue damage sensor has special designed smart sacrificial sensor beams for early fatigue damage detection and prediction. The smart predictive sensor can measure the state of damage levels and predict the remaining useful service life of structural components or locations for the fatigue life cycle management of structures. The wireless enabled nondestructive evaluation (NDE) fatigue damage sensor consists of mechanical and electronic units. The mechanical part of the fatigue damage sensor has special designed smart and predictive sacrificial beams with different levels of fatigue lifetimes normalized to the total lifetime of a real structure. The smart fatigue damage sensors attached onto the surface on a real structure is expected to have the same cyclic stress-strain loading behavior and the same cyclic stress-strain history for during the service life. The fatigue damage sensor having multiple parallel oriented mini or micro nondestructive fatigue damage measurement beams are designed to fail earlier than a real structure in the different predetermined fatigue lifetimes acting like a fatigue fusing system. The mechanical sensor beams designed with a special geometry and strain magnifying factors to break in the different progressive life intervals compared to the total service lifetime of a real structure. The electronic unit of the sensor can detect the fatigue failures of mini sensing beams and transmit the information wirelessly. The nondestructive IOT fatigue damage sensor directly measures the fatigue damage accumulation levels and the remaining useful lifetime of fatigue sensitive metallic and additively manufactured structural or mechanical members through the special designed fatigue damage measurement beams from critical points of the structure without using any algorithm. The smart structures instrumented with NDE fatigue damage for structural health monitoring (SHM) can provide real-time critical information on the status of the structure. Due to the nondestructive direct fatigue damage measurement nature of the sacrificial-breakable mini or micro electromechanical system (MEMS) sensing beams, the sensor provides real operational and progressive statistical fatigue damage data. The collected fatigue sensor data from the sensor network is quantitative and easy to interpret and understand without any further mathematical analysis. Since the wireless enabled fatigue damage sensor network through Internet of Things (IoT) technologies collect the real operational fatigue data remotely, the statistical fatigue damage sensor network data can be used for the prediction of lifetimes of structural members by using Machine Learning(ML) Algorithms such as Regression, ANN, RF.

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NONDESTRUCTIVE STRUCTURAL FATIGUE HEALTH MONITORING INSPECTION (NDI) SENSORS

Fatigue Damage and Life have a critical role in the design of fatigue critic structural and mechanical components. There are several different types of fatigue design methods are commonly used for the fatigue design of fatigue sensitive mechanical components or structures. All these techniques are based on some estimations and load assumptions. Any fatigue failure of one of the structural members of the system may lead to a devastating failure with serious consequences that cost life and properties. Therefore, the health conditions of the structural and mechanical elements suffering from cyclic dynamic stresses should be constantly monitored and the fatigue damaged parts should be replaced before the fatigue failure limit is reached. Steel bridges, ships, oil platforms, planes, helicopters, wind turbines, mega cranes, military portable bridges, railway structures, and marine ships are particularly considered vulnerable systems to this type of fatigue damage. Due to the importance of the fatigue subject, a great deal of time and effort has been put into developing fatigue sensors that can detect the level of fatigue damage and remaining fatigue life before any fatigue fracture failure occurs. Fatigue lifetime of materials is defined as the number of cyclic stresses that a sample can continue before any breakage. Fatigue of metallic type samples, ranging from very low to very high stress cycles, are represented mathematically by the Wohler curve which describes the relationship between the number of stress cycles and fatigue damage failure. Sinusoidal constant amplitude fluctuating dynamic loads are applied to tested samples that cause fatigue fractures of the material at a point that is logarithmically related to the number of cycles applied. What makes problems with fatigue difficult is that there is a high degree of randomness as its nature in fatigue measurement, even the damage level of fatigue is always changing a particular location of a particular piece. Many different mathematical models and theories have been developed to describe fatigue events in nature. Fatigue tests exhibit these random differences even if they are performed in highly controlled environments. Due to the empirical and stochastic nature of fatigue problems and the costly consequences of disaster failures, many researchers and inventors have studied this fatigue phenomenon. The latest technology in structural fatigue health monitoring includes the design and applications of electrical strain gauges, comparative vacuum monitoring sensors (CVM), electrical crack wires, crack-first fatigue sensors and electromagnetic foils. All these sensors are designed to detect the presence of fatigue cracks that develop throughout the life of the structure.

The majority of the fatigue damage Nondestructive Inspection(NDI) or Nondestructive Evaluation(NDE) sensors or the nondestructive inspection fatigue sensors [1-29] mentioned so far has been designed to detect the presence of fatigue cracks, all indicating a near-catastrophic event, whether chemical, optical or electrical. It is very important to have a fatigue damage sensor that gives a high indicator of fatigue before the crack occurs. The current design given in this study aims to achieve this with a unique approach. The current design monitors the current fatigue damage state of the structural element and estimates the remaining useful life (RUL), rather than trying to detect the presence of the fatigue cracks as required damage tolerance design approach by using NDI methods. The fatigue damage sensor passes the same fatigue life experience of the structural element or mechanical component from the beginning of its service life. When the lifetime of the actual tracked structure gets too close to the end of its remaining useful life, the critical sensor beam with 80-90 % N is broken and gives the alarm that the actual structural element is approaching the limit of its service life. The sensor is wirelessly enabled, which makes it possible to check the health status of the sensor as often as you want through.

THE NONDESTRUCTIVE DAMAGE TOLERANT ASSESMENT SMART IOT FATIGUE SENSOR SYSTEM MODEL

The smart fatigue damage sensor (Figure 1and 2) proposed in this system is designed with multiple parallel mini-micro sensor beams, each sensitive to different levels of fatigue damage and lifetimes. The sacrificial sensing beams of the sensor are designed as a fatigue fuse system. The mini sensor beams attached on the structure are designed to fail early in the different lifetimes but gradually while passing through the same fatigue cycles with the structural member. Sensing beams have "Engineered Strain Magnified Type Geometry" with special length, thickness and geometric strain magnified parameters designed to fail after a predetermined and incremental number of fatigue cycles. The fatigue sensor has two different versions, active and passive. The active version works with battery power and the passiveworks with RF power. The fatigue sensor with the battery uses Zigbee or similar low-power sensor network to check the sensor about the condition of breakable beams. Sensor nodes transmit information from one node to another to communicate with the master node. This type of active system model is shown in Figure 1. Zigbee is a well-known low-power communication network used for sensor communication. The battery-free sensor is shown in Figure-2. This type works with RF power emitted by the interrogation bar. The interrogation distance of RFID devices depends on both the transmitter power and the coil size of the receiver. This application requires high-power transmitters as metal surfaces protect and reduce the power received by the receiver. Such sensors need to be questioned (periodically) from time to time; for example, the aircraft enters the service hangar for regular maintenance intervals. In both active (Figure-1) and passive (Figure-2) versions of the sensors, the sensor weighs only a few grams, and the size varies from postage stamp to postcard as depending upon the requirements of location of the applications.

The IoT Smart Predictive Fatigue Damage Sensor used to measure the fatigue damage levels and the remaining lifetime of structures to monitor fatigue structural health monitoring. The Fatigue Structural health monitoring is a tool used to ensure the safety and soundness of structures. The Structural health monitoring uses the fatigue sensor data to optimize condition based predictive maintenance, decision optimization and optimize resources. The data that fatigue structural health monitoring systems acquire can help its users avoid structural failures. The IoT is a concept of exposing data generated from points of operational interest. The IoT fatigue sensor data is used to improve situational awareness by enabling visualization of important field parameters like fatigue damage. The IoT Structural Fatigue health monitoring is the process of monitoring or assessing the condition of a structure in order to gather information on its current state by using the predictive fatigue damage sensor data. The proposed technology is an integration of wireless transmission systems, sensors, analyzing tools, and GUI software. The system plays a key role in detecting damages using predictive maintenance, boosts safety of the structure, and enables automatic response, thus saving time and costs.

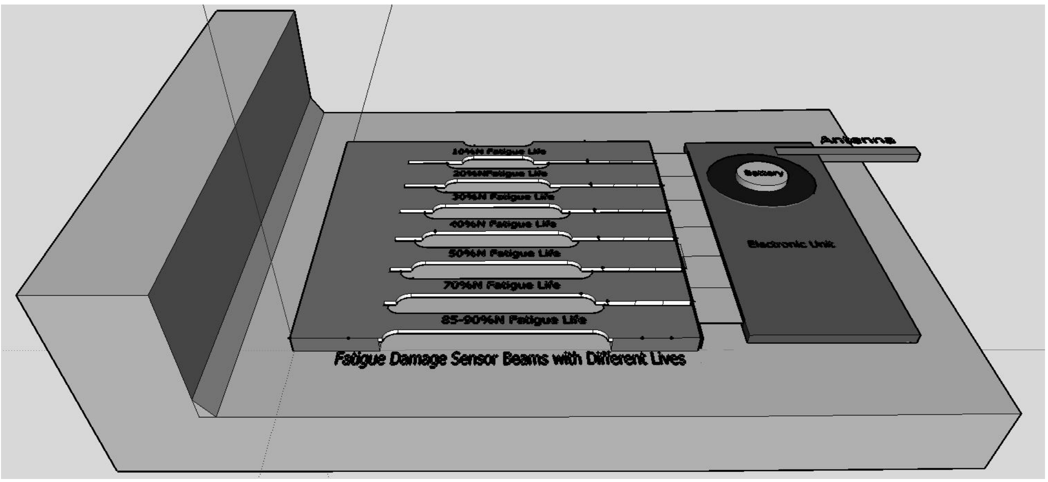

Figure 1. A general view of the Active(With Battery) Fatigue Sensor for Damage Tolerant Asessment IoT Smart Fatigue Damage Sensor (US Patent 8,746,077 B2)

Structural health monitoring applications require robust, reliable, and easy-to-read sensors to monitor the fatigue of structural members. An ideal Structural Health Monitoring System should have the following features: permanently mounted mini-micro sensors, optional or continuous status monitoring in real operational time, wireless transmission system to the central station, instant interpretation of sensor data, detection of unacceptable material damage in critical high-stress locations, material monitoring the growth of the damage in critical dimensions, growth forecast with a probable procedure, changes in the growth forecast for the actual damage status at the predicted intervals, estimation of the potential damage status in the near term and for life. All these qualities and expectations are unlikely to be included in a single structural health monitoring (Figure-3), but these are desirable features of the state-of-the-art ideal structural health monitoring system. There are many technical challenges to overcome ideal sensors. Ideally, the sensors used in structural health monitoring systems should be small (mini or micro sensors), low cost, lightweight, autonomously working without any power cord, robust, maintainable, repairable and easy to install, accurate, known possibility of fault detection (POD). It is easy to properly connect to the structure without causing any damage, suitable for wireless transmission to the central station, intensely distributed, measure local and system level response designed to measure relevant damage parameters. The above requirements are a summary of the expectations from ideal structural health monitoring sensors.

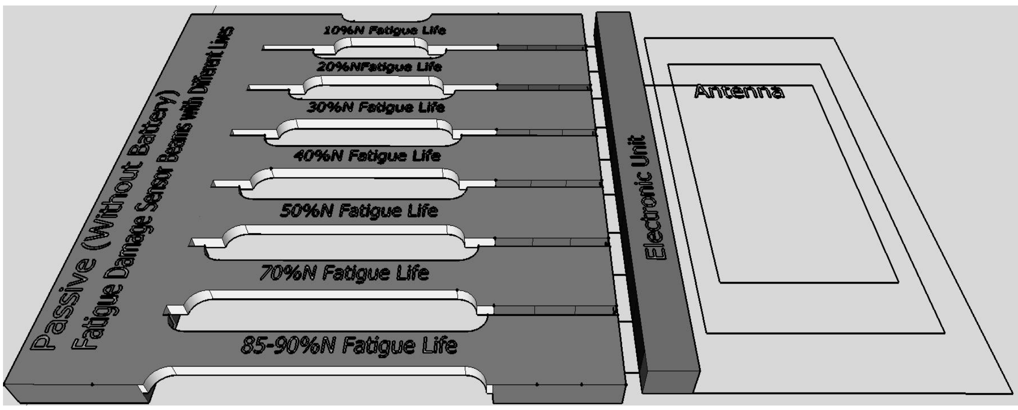

Figure 2. Passive (Without Battery) Version of the Damage Tolerant Assessment IoT Smart Fatigue Damage Sensor (US Patent 8,746,077 B2)

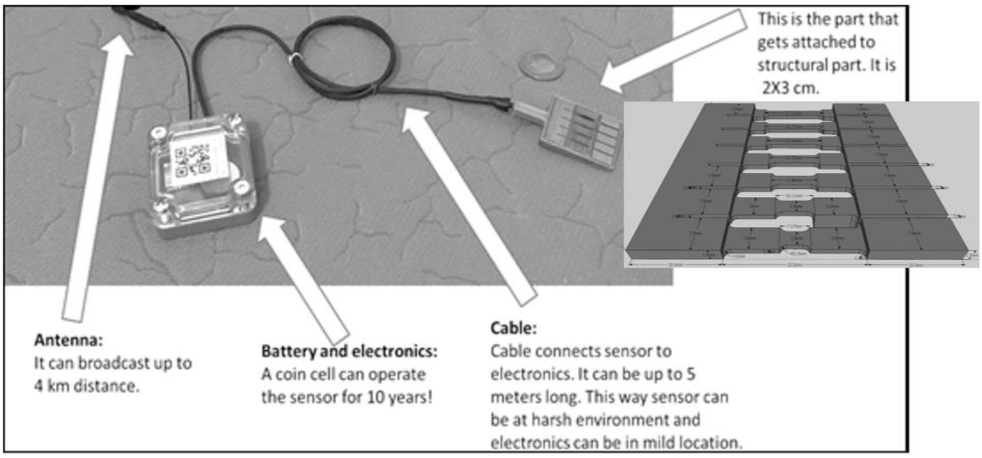

Figure 3. A general view of the active strain based IoT Smart Fatigue Damage Sensor (US Patent 8,746,077 B2) [29]

Figure 3 shows the scheme of the proposed strain based fatigue sensor system. As seen from Figure 5, the fatigue sensor system has between 5-10 different mini-micro beams designed for five-ten different levels of fatigue lifetimes (10% N, 20% N, 30% N, 40% N,50% N, 60% N, 70% N, 80% N, 85-90% N-Total Life of a real structure) and accumulated fatigue damage levels to predict the Remaining Useful Life (RUL) and the structural fatigue health monitoring(SFHM) of real structures.

DAMAGE TOLERANCE DESIGN AND NONDESTRUCTIVE FATIGUE DAMAGE SENSOR

Fatigue Damage Tolerance (safety by inspection) is a special field that evaluates the response of aircraft materials and structures under cyclic fluctuating stresses and strains. The Damage Tolerant Field focuses primarily on damage tolerant design criteria, nondestructive inspection(NDI), fatigue structural health state monitoring and life cycle management plans for critical aircraft components using the principles of materials science, fatigue, and fracture mechanics. Damage Tolerant Design is the maximum load carrying capability of an aircraft structure under fatigue loads until the damage is detected and measured by using nondestructive inpection techniques. The damage tolerant inspection model is shown in Figure-4. The maximum load carrying capability or the residual fatigue strength of an aircraft structure is a function of fatigue crack size and usage time in safely until reaching the fatigue failure. The important parts of damage tolerant design are fatigue and fracture mechanics analysis by using material properties and probabilistic damage evaluation methods.

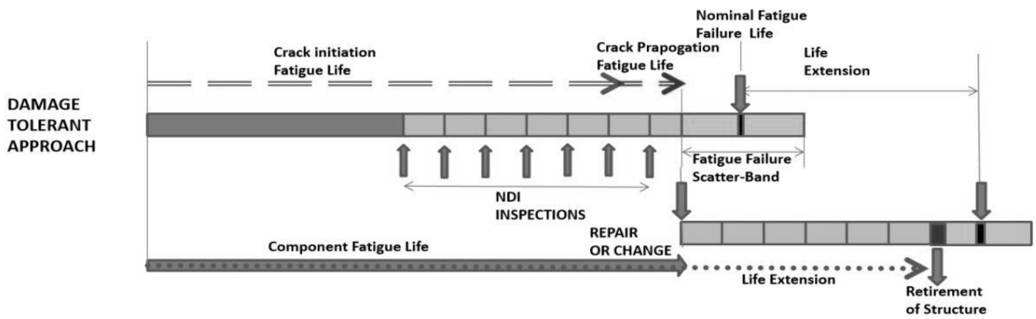

Figure 4. Damage Tolerant Approach and Structural Fatigue Crack Monitoring Using Nondestructive Inspectıon (NDI) Methods

DESIGN OF DAMAGE TOLERANT NONDESTRUCTIVE FATIGUE DAMAGE SENSOR

The proposed damage tolerant assessment fatigue sensor model and the sensor design parameters are shown in the Figure 5. The fatigue sensor system has seven different levels of fatigue lifetimes (10% N, 20% N, 30% N, 40% N,50% N, 70% N, 85-90% N). As seen from the Figure 5, the design parameters of the predictive fatigue sensor beams are the lengths of the beams ($L_A = L_B = L_C = L_D = L_E = L_F = L_G = L$), the thicknesses of the beams ($t_{A.B,C,D,E,F,G} = t$), the witdth of beams in the center ($W_C = W_{c,A.B,C,D,E,F,G}$), and the witdth of the beams in sides $W_s = W_{s,A,B,C,D,E,F,G}$.

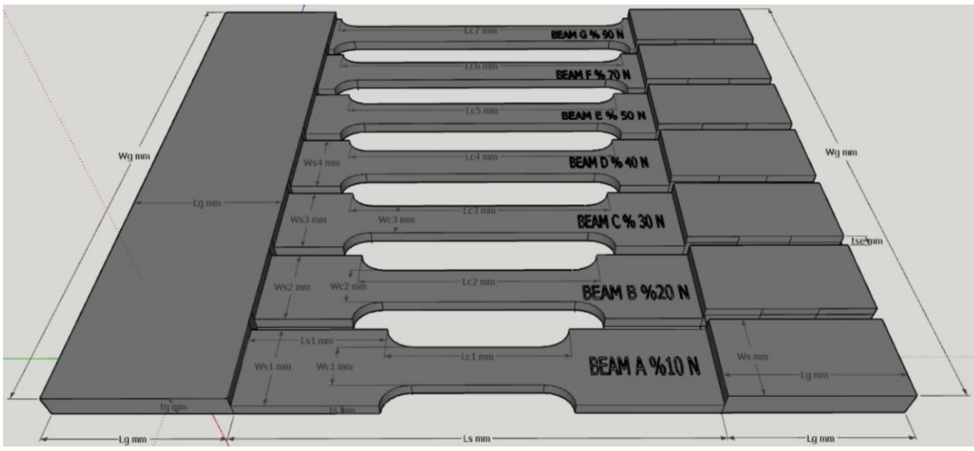

Figure 5. Design Parameters of the Nondestructive Strain Based IOT Fatigue Sensor

In the proposed system for several important reasons, the same material with the material of the structure is used for design of the fatigue sensor. The fatigue and mechanical properties of the sensor material must be same for the fatigue measurement performance of the sensor. The sensors are installed on the surface of the critical location of or part of a structure and a distributed sensor network system is established for the structural fatigue health monitoring. The loads coming onto structure and the sensor beams are same cyclic dynamic, thermal and vibratory loads effecting the fatigue lifetime of the structure. The sensor beams designed with strain magnifying effects are fractured in the progressive predetermined lifetime periods(Nf) as seen Figure-6 and the electronic part transfer this information to the center.

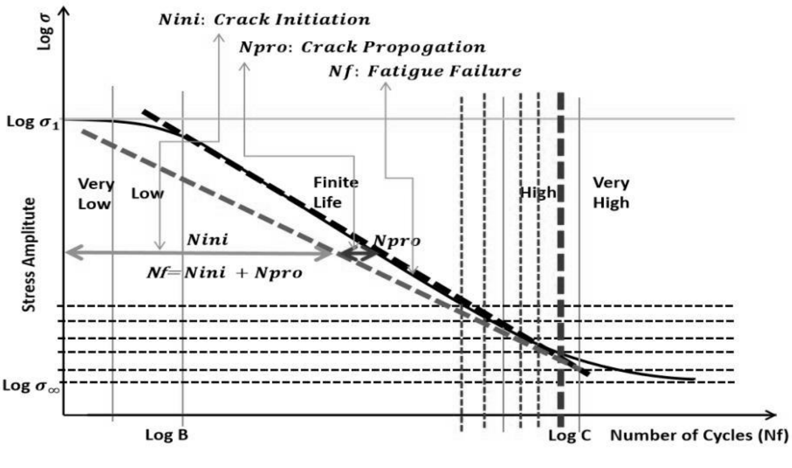

Figure 6. Fatigue Stress-Lifetime Curve and Crack Initiation and Crack Propogation Lifetimes for Damage Tolerant Assessment

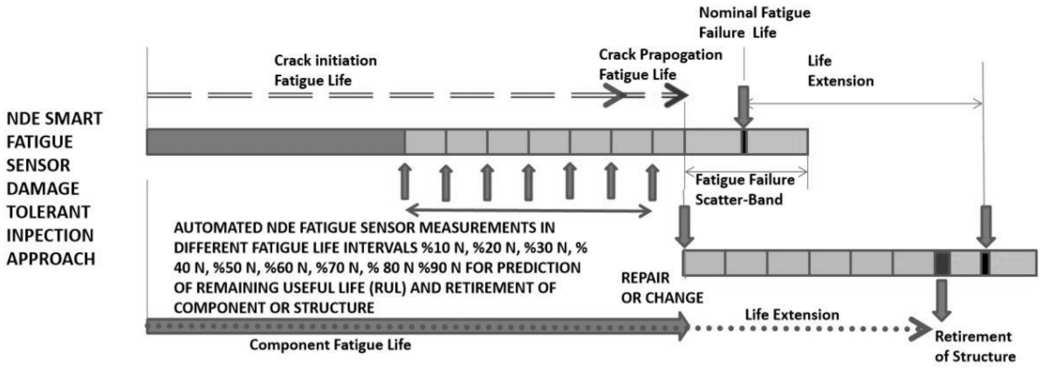

Figure 7. Smart IOT Fatigue Sensor and Nondestructive Evaluation(NDE) Fatigue Damage Sensor Measurements for Damage Tolerant Fatigue Life Monitoring

The nondestructive smart IOT fatigue damage sensor measures the current operational state of the structural or mechanical component and predict the remaining useful life (RUL) in different incremental and progressive fatigue lifetimes (10% N, 20% N, 30% N, 40% N,50% N, 60% N, 70% N, 80% N, 85-90% N-Total Life($N=N_{ini}+N_{pro}$) of a real structure) through Machine Leaning Methods as seen Figure 7, instead of trying to detect the presence of the fatigue cracks used in damage tolerance design approach by using NDI methods.

CONCLUSION

A novel strain based IoT Smart Fatigue Damage Sensor (US Patent 8,746,077 B2) [29]) has been designed, manufactured and tested for early fatigue detection and predicting the remaining life of critical mechanical or structural elements under cyclic loads before any fatigue failure occurs. The majority of the fatigue damage Nondestructive Inspection(NDI) or Nondestructive Evaluation(NDE) sensors or the nondestructive inspection fatigue sensors are designed to detect the presence of fatigue cracks whether they are chemical, optical or electrical detection based NDI sensors. It is very important to have a nondestructive fatigue damage sensor that gives a high indicator of fatigue before or after the crack occurs in a real structural fatigue damage state. The current design given in this study aims to achieve this with a unique approach by using predictive and sacrificial sensing beams by covering the fatigue crack initiation and propagation life periods of structural fatigue failures. The proposed nondestructive fatigue damage sensor monitors the current operational state of the structural element and estimates the remaining useful life (RUL) in different fatigue lifetime periods (10% N, 20% N, 30% N, 40% N,50% N, 60% N, 70% N, 80% N, 85-90% N-Total Life of a real structure), rather than trying to detect the presence of the fatigue cracks used in damage tolerance design approach by using NDI methods. The real sensor data can be used for the prediction of the remaining useful service life of structural elements through AI-Machine Learning(ML) Methods. The proposed Nondestructive Inspection Fatigue Sensor System is a very efficient and effective system for Condition Sensor Based SHM and Predictive Maintenance since it increases service life, safety and reliability and reduces maintenance and operating costs of fatigue critic structures.

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