THE FIRST NOVEL WIRELESS IoT SMART FATIGUE SENSOR IN THE WORLD
(Patent No: US 8,746,077 B2)

DEVELOPMENT OF A NOVEL WIRELESS IoT SMART FATIGUE SENSOR FOR STRUCTURAL FATIGUE HEALTH MONITORING

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SUMMARY:

A Novel Wireless Smart IoT Fatigue Sensor for the prediction of fatigue residual strength of critical mechanical and structural components has been developed and patented. The sensor is applicable to all applications where structural health monitoring is critical and essential.

The sensor is as big as a postage stamp (but slightly thicker) and gets attached to the critical parts of the structure just like a strain gauge using appropriate adhesive. But unlike a strain gauge, the new fatigue sensor works without needing a battery, power source or a processor. Since fatigue is a slow process and takes long time to develop, it is very beneficial for a sensor to work without needing power. Obviously, power may be needed for communication purposes but power is consumed only during communication.

The smart fatigue damage sensor system is designed for early detection and prediction of the total cumulative fatigue damage level of the monitored structure and can wirelessly transfer the information by using an active LoRa technology or passive RFID integrated system.

The IoT fatigue damage sensor system has a specially designed geometry with multiple parallel oriented unidirectional, bidirectional or multi directional breakable R, U or V type notched beams having different fatigue lifetimes to predict not only unidirectional or bidirectional fatigue damage but also multidimensional cumulative fatigue damage level of structural or mechanical elements including composite structures.

The intelligent fatigue sensor system is made up mechanical sensor part, electronics unit and communication environment for the Internet of Things-(IoT). This way structural health state of railway systems, marine structures, pipelines, aircraft, offshore structures, bridges can be monitored.

It is foreseen that the new novel IoT Smart Fatigue Sensor will revolutionize the concept of fatigue design and also will revolutionize the fatigue inspection and predictive maintenance methodologies.

Since the distributed fatigue sensor network system is periodically or continuously monitoring the fatigue health state conditions of structures, the database of the sensor network system will be used for condition-based inspection, sensor-based maintenance management and development of new fatigue design tools for fatigue sensitive parts or locations.

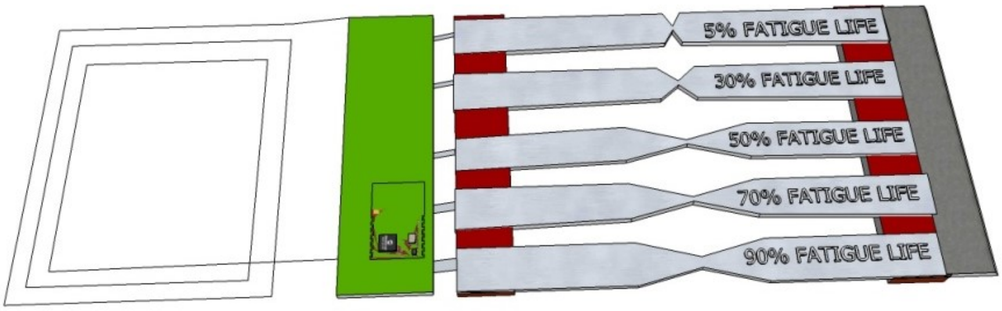

Figure 1-Battery free version of the RFID Fatigue Sensor powered by RF Power Loop **(Patent No: US 8,746,077 B2)**

The Figure-1 shows a sensor with 5 sacrificial beams members with fatigue life ranging from 10 % to 90 %. The 5% fatigue life mini-micro beam member is designed to be a 'self-check' mechanism and designed to fail quickly if installed properly.

Any sensor with 10 % finger not failing within reasonable time of installation is an indication of improper installation or faulty sensor. Failure-Fracture detection of the mini beams is done by sensing continuity of current passing through the beams. Since the current passing through the beam is in micro amps range, there is very little self-heating effect. Additionally, the current passes over the sensor only during reading of the sensor, so for that reason self-heating effect is negligible.

The fatigue relationship a combination of the sensing strain and notch effects together are two important critical design parameters defining the number of cycles (lifetime) breaking-fracturing the beams under fatigue cycling loads. For the optimal design of the sensor, five to seven parallel beams are considered optimal with different fatigue lifetimes changing from 10% to 90%.

Figure 2 shows the general system model and the sensing concept of fatigue damage of a mini beam considered in the design of the fatigue sensor. The fatigue design parameters are the length, the thickness and the notch effect (constant) of the sensing beam. It is expected that the designed and applied fatigue sensor will be mimicking the strain behavior and the lifetime of the real structure. The lifetime of the beams will be designed with different life cycles 10% N, 25% N, 50% N, 75% N, 90% N, which are always lower than the lifetime cycles (N-Lifetime of Real Structure) of the real structures or mechanical systems

THE IoT SMART FATIGUE DAMAGE SENSOR AND DISTRIBUTED FATIGUE STRUCTURAL HEALTH MONITORING NETWORK SYSTEM FOR RAILWAY SYSTEMS

The smart fatigue sensor is designed with multiple parallel beams which are sensitive to the different levels of fatigue damage. The beams of the sensor are designed to be sacrificial and designed to fail prematurely but progressively as the sensor goes through the same fatigue cycles as the structural member it is attached to.

The beams have 'Engineered R-U-V Type Notches' with special length and thickness geometrical parameters which are designed to fail after going through precise number of fatigue cycles. There are two versions of the fatigue sensor; active one with a battery version and positive one which works by harvesting RF power coming from a reader.

Active version with battery uses Lora or similar 'low power sensor networking' to interrogate the sensor about the state of breakable fingers. The sensor nodes relay information from one node to the other to communicate with the master node. Lora is a well-known low power communication network used for sensor communication. There are other networks like Sigfox, NBIoT, Zigbee, BLE or Wifi. All these networks work similar to Lora and can work with the new fatigue sensor.

The passive version of the sensor works without battery. This type is powered by RF power emitted by the interrogation wand. Interrogation distance of RFID type devices depend on both transmitter power and the coil size of the receiver. This application requires high power transmitters since metal surfaces shield and reduce the power received by the receiver. These types of sensors need to be interrogated using readers which are either mobile or stationary with respect to the sensors.

The sensor needs to be customized for the specific base metal of the structure. Since fatigue characteristics are based on SN characteristics of the underlying metal, the sensor has to be manufactured from the same metal as the structure. The sensor is typically manufactured using nontraditional Micro Manufacturing methods.

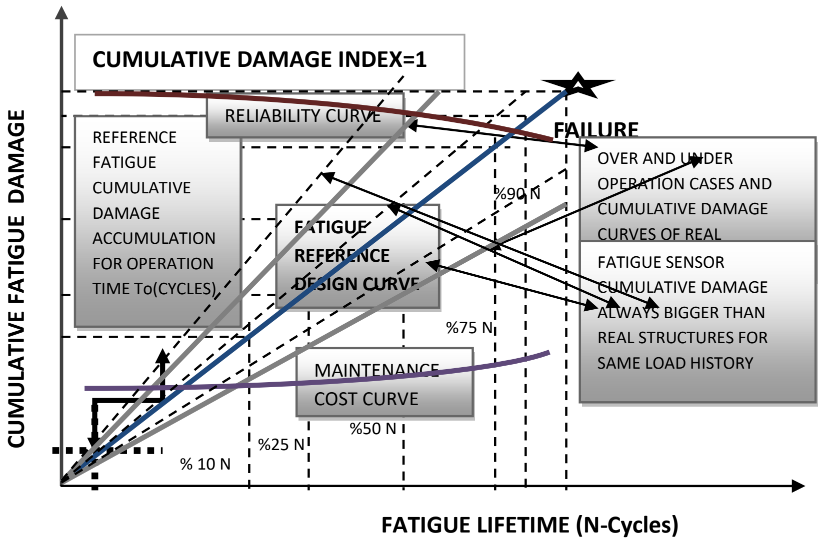

Figure 2- Comparisions of the Fatigue Sensor Based Structural Health Monitoring and Conventional Fatigue Design Cumulative Damage Index Curve

Since fatigue sensor is connected to electronics which has memory, it can hold information about fatigue as well as other critical information about the pars such as:

- ◊ The operational lifetime history of each fatigue critical component or location.
- ◊ The fatigue properties of the critical part.
- ◊ Type of fatigue cracks
- ◊ Maintenance history & the fatigue maintenance history of each critical location or component
- ◊ Fatigue sensitive details of the structure
- ◊ The component manufactured time, the manufacturer of the part
- ◊ The ID number of the component, the part and critical connections.
- ◊ The part expected scheduled repair time
- ◊ Part material properties, the part redesign needs and design modification or revision.
- ◊ Part connection properties (high stress locations, stress concentrated regions, rivet, welded, lap joints etc.)
- ◊ Parts repaired or replaced, the parts expected service lifetime, the parts crack lengths and many more useful information of structures.

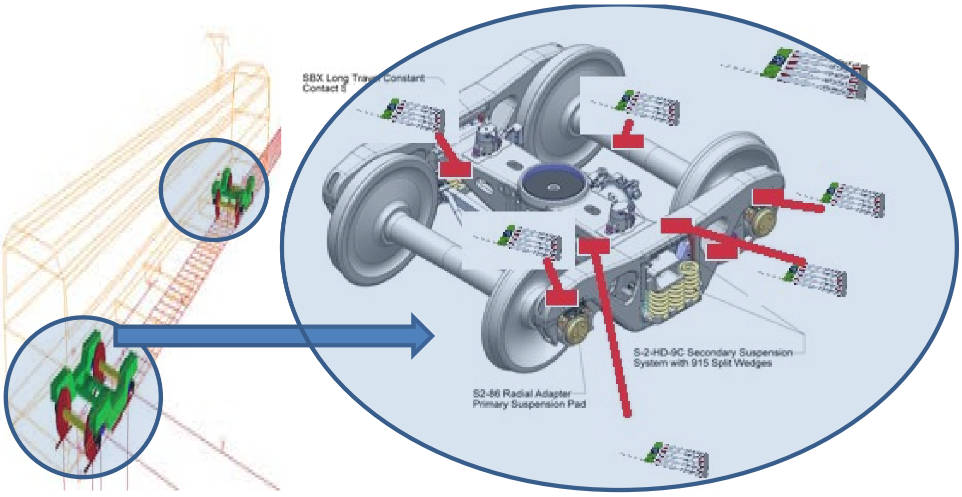

Figure 3-a- Possible critical locations of railway systems (Rails, Bogies, Axles, Wheels etc.)

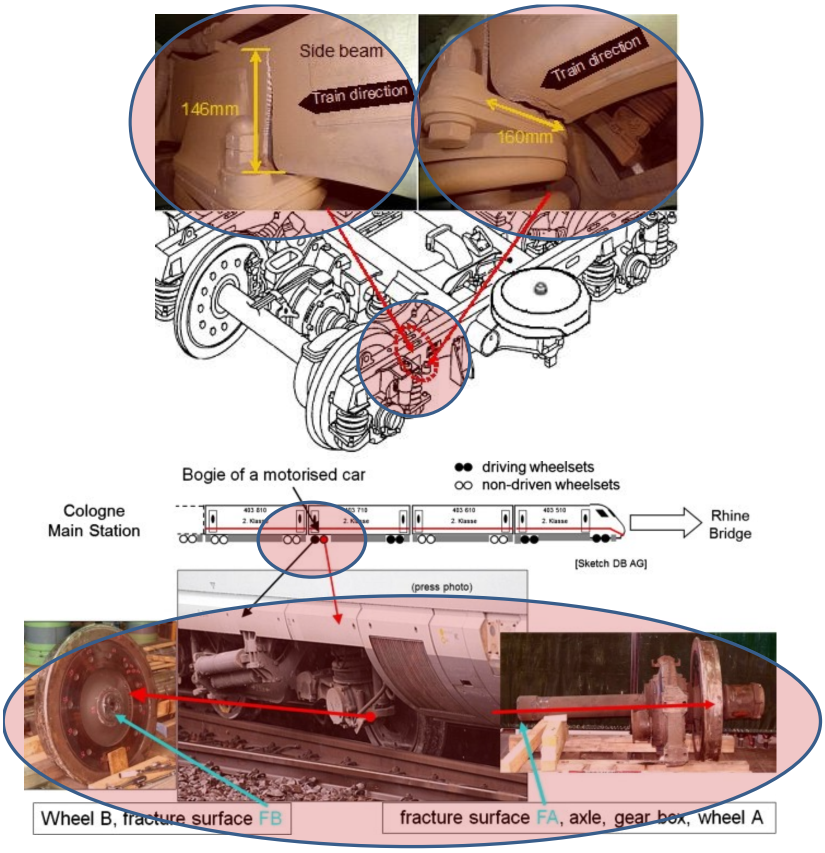

Figure 3-b- Fatigue sensor Applications

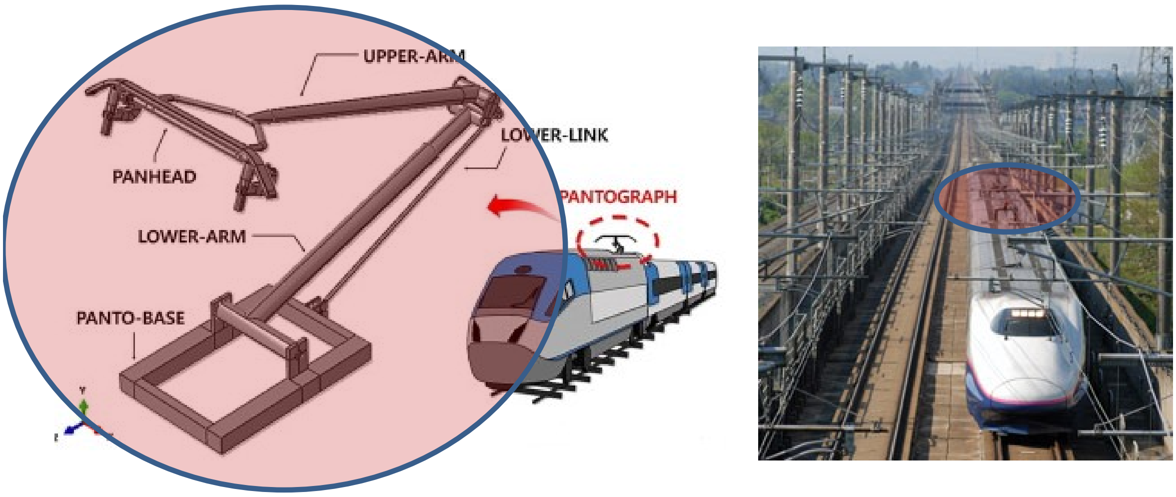

Figure 3-c- Fatigue Sensitive Details of Railway Systems (Pantograph, Rails, Bogies, Axles, Wheels etc.) and The Smart Fatigue Damage Sensor Applications

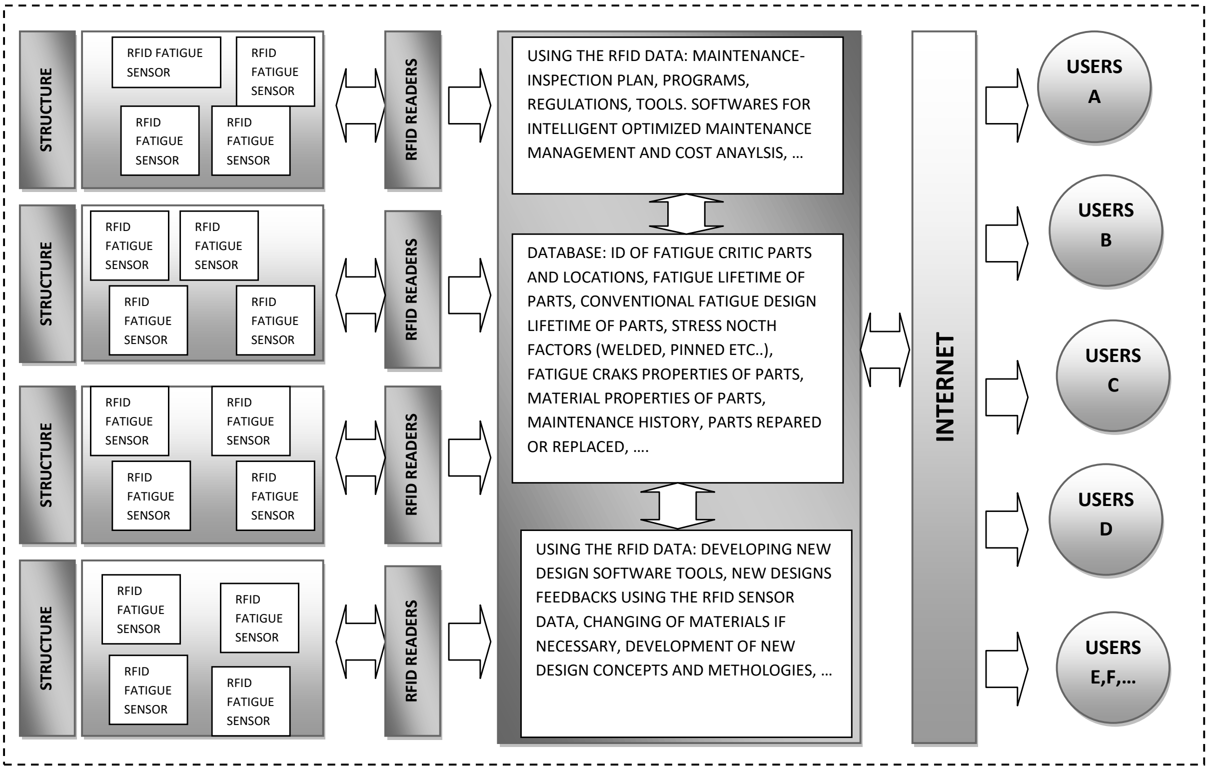

Figure 4- IoT system model of the Fatigue Sensor for (Fleets or Unit based) Fatigue Monitoring of Railway Systems

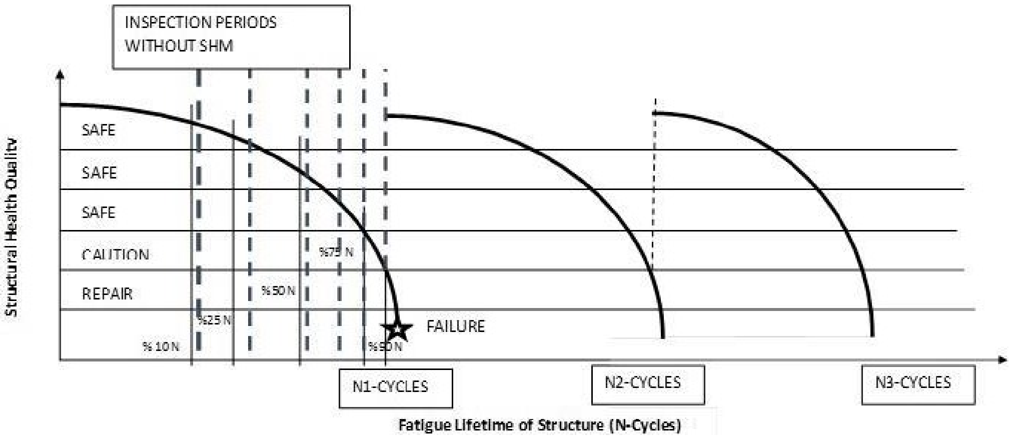

Figure 5- Structural Health Quality- Fatigue Lifetime (N) Curve- Strain Based Fatigue Life Cycles %10 N, %25 N, %50 N, % 75 N, %90 N and Extension of Lifetime of Structures with SHM Fatigue Health Sensor System

The fatigue sensor based Structural Health Monitoring and Maintenance Strategy is based on the periodic or real-time sensor information to optimize maintenance resources. The Fatigue Sensor System collects the operational lifetime history of each fatigue critical component or location, the fatigue properties of the critical part, the maintenance or fatigue maintenance history of each critical location or component, the fatigue sensitive details of the structure, the component manufactured time, the manufacturer of the part, the ID number of the component, the part and critical connections., the part expected scheduled repair time, the part material properties, the part redesign needs and design modification or revision, the part connection properties(rivet, welded, lap joints etc..), the part repaired or replaced, the part expected service lifetime, the part crack length and many more useful information of structures. The required maintenance decisions and the health state of critical parts of structures are given according to the RFID Fatigue Sensor Network data. The RFID Fatigue Sensor network information is mandating, the time of the fatigue damaged parts or locations should be repaired or replaced.

Therefore, the proposed IOT RFID Fatigue Sensor based Intelligent Predictive-Condition Based Maintenance Model is a very efficient and effective strategic system since it increases service life it increases the reliability of the parts monitored and it reduces maintenance and operational expenses.

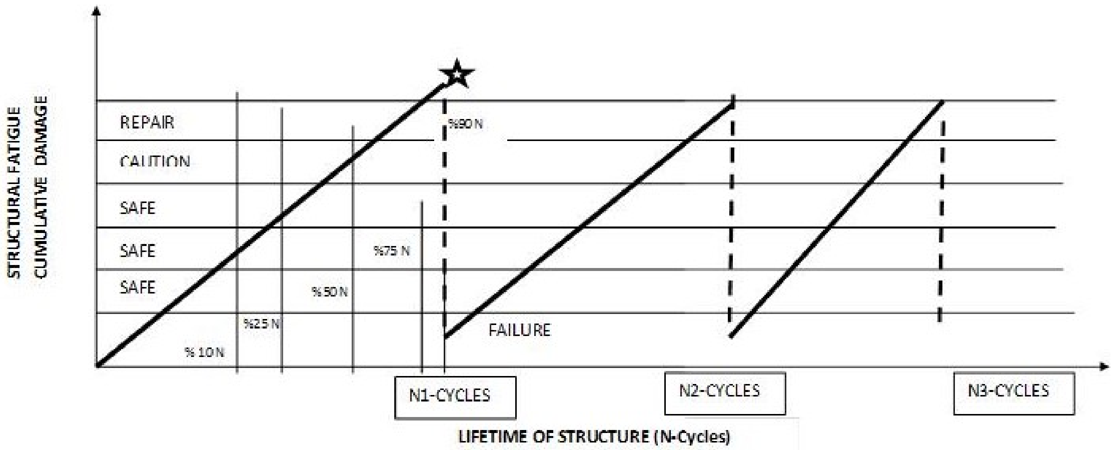

Figure 6- Structural Fatigue Cumulative Damage Level- Fatigue Lifetime (N) Curve- Strain Based Fatigue Life Cycles %10 N, %25 N, %50 N, % 75 N, %90 N and Extension of Lifetime of Structures with SHM Fatigue Health

DESIGN PRINCIPLES OF THE FATIGUE DAMAGE SENSOR FOR STRUCTURAL HEALTH MONITORING OF STRUCTURES

In the Fatigue Sensing Sensor Model (Figure-7), the linear damage accumulation rule (Miner Rule) and the Stresses-Cycles relationship of the fatigue life curve Stress(S)-Life(N) and Strain(e)-Life(N) are used to design and predict the remaining fatigue life of structures.

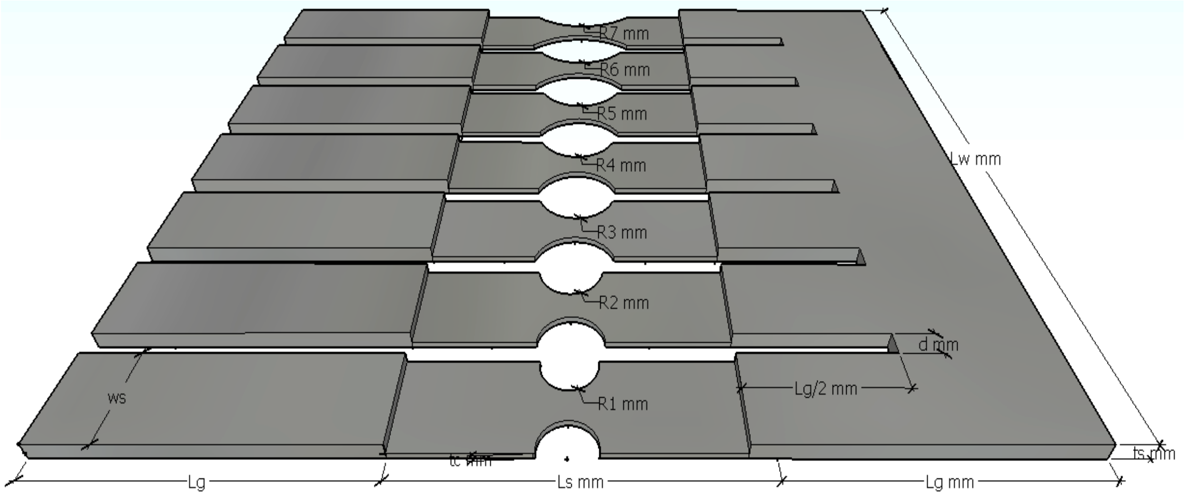

Figure 7 a - The Proposed Stress-Life Based Fatigue Damage Sensor with 7 Mini Beams, the total fatigue lifetimes (A BEAM-%10 N, B BEAM %20 N, C BEAM %30 N, D BEAM %40 N, E BEAM %50 N, F BEAM % 70 N, G BEAM %85-90 N)

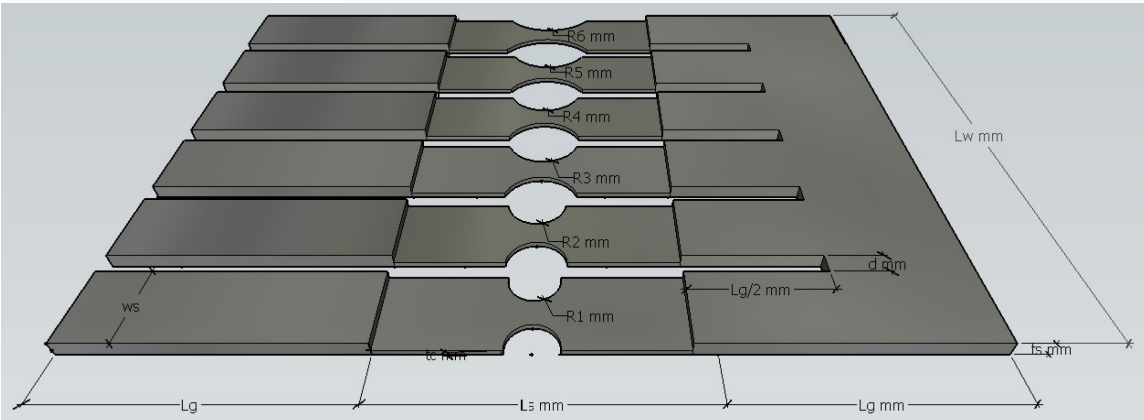

Figure 7 b - The Proposed Stress-Life Based Fatigue Damage Sensor with 6 Mini Beams, the total fatigue lifetimes (A BEAM-%10 N, B BEAM %20 N, C BEAM %30 N, D BEAM %50 N, E BEAM % 70 N, F BEAM %85-90 N)

The strain magnification factors $(K_{tnG})(K_{tnF})(K_{tnE}), (K_{tnD}), (K_{tnC}), (K_{tnB}), (K_{tnA})$ in the center of the mini sensor beams are the most critical design parameter to predict the remaining life of structural components. The generalized the Kohout and Věchet (K-V) stress-life or strain-life fatigue curve will also be used to design of the fatigue life time of the sensing beams in the different strain (magnification) levels.

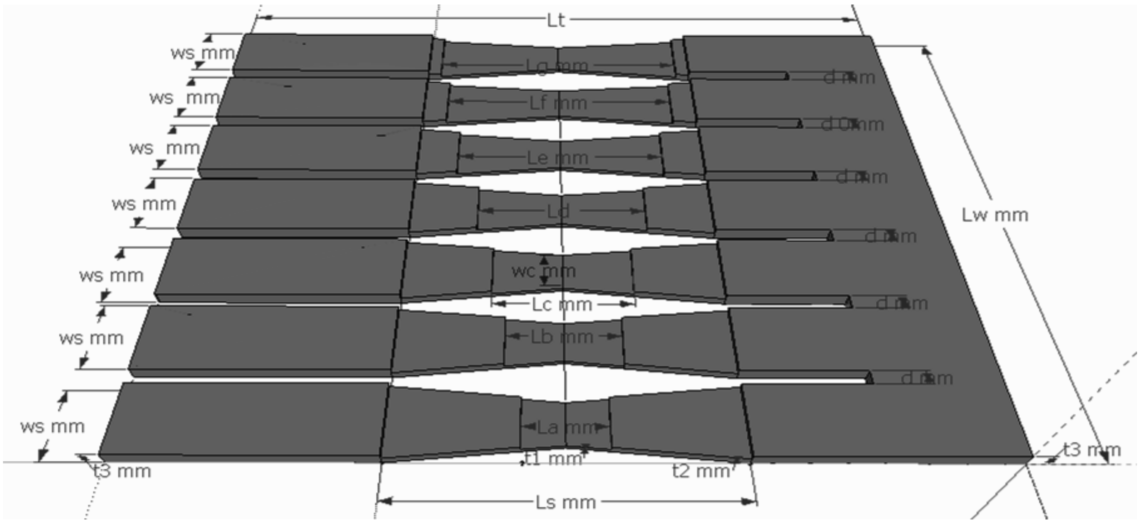

Figure 7 c - The Proposed Stress-Life Based Fatigue Damage Sensor with 7 Mini Beams, the total fatigue lifetimes (A BEAM-%10 N, B BEAM %20 N, C BEAM %30 N, D BEAM %40 N, E BEAM %50 N, F BEAM % 70 N, G BEAM %85-90 N)

The stress magnification factors $(K_{tnG})(K_{tnF})(K_{tnE}), (K_{tnD}), (K_{tnC}), (K_{tnB}), (K_{tnA})$ in the center of the mini sensor beams are the most critical design parameter to predict the remaining life of structural components. The generalized the Kohout and Věchet (K-V) stress-life fatigue curve (Figure 8) will also be used to design of the fatigue life time of the sensing beams in the different stress (magnification) levels.

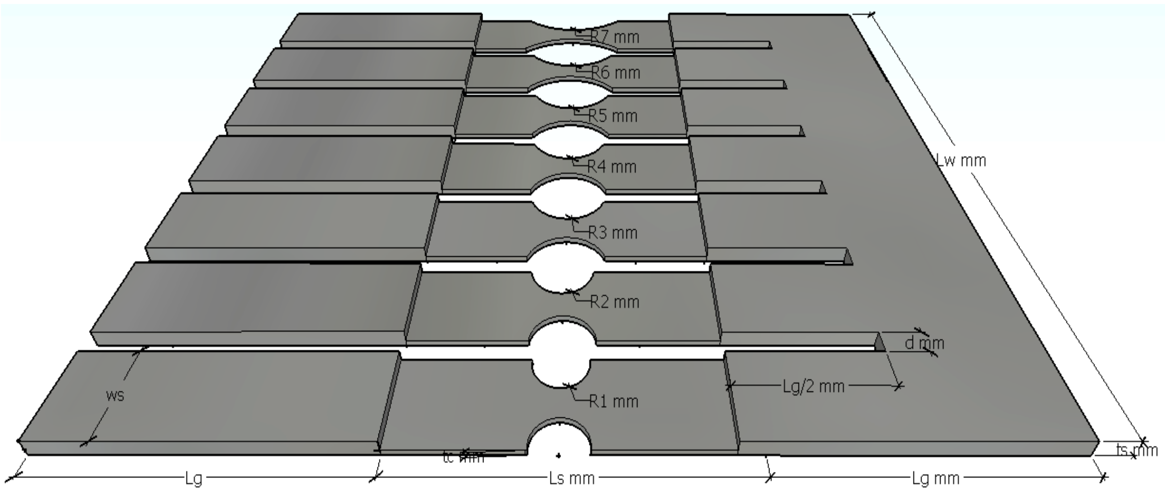

Figure 7 d - The Proposed Stress-Life Based Fatigue Damage Sensor with 7 Mini Beams, the total fatigue lifetimes (A BEAM-%10 N, B BEAM %20 N, C BEAM %30 N, D BEAM %40 N, E BEAM %50 N, F BEAM % 70 N, G BEAM %85-90 N)

Fatigue Stress and Life Cycles relationship of materials is represented by the S-N curves. The total stress range due to fatigue is known but it is difficult to separate the total stress range into two different low and high cycle fatigue regimes, therefore a combined low-high cycle equation model (Figure 8) can be more efficient and effective for design of FATIGUE DAMAGE SENSOR. Kohout-Věchet proposed a new generalized FATIGUE-LIFE (S-N) equation. The mathematical model representing the S-N fatigue curve combines two components of high and low-cycle fatigue regimes as shown in Figure 8. The most important parameters in this model are the slope of the curve, stress range, the fatigue life cycle and the fatigue limit.

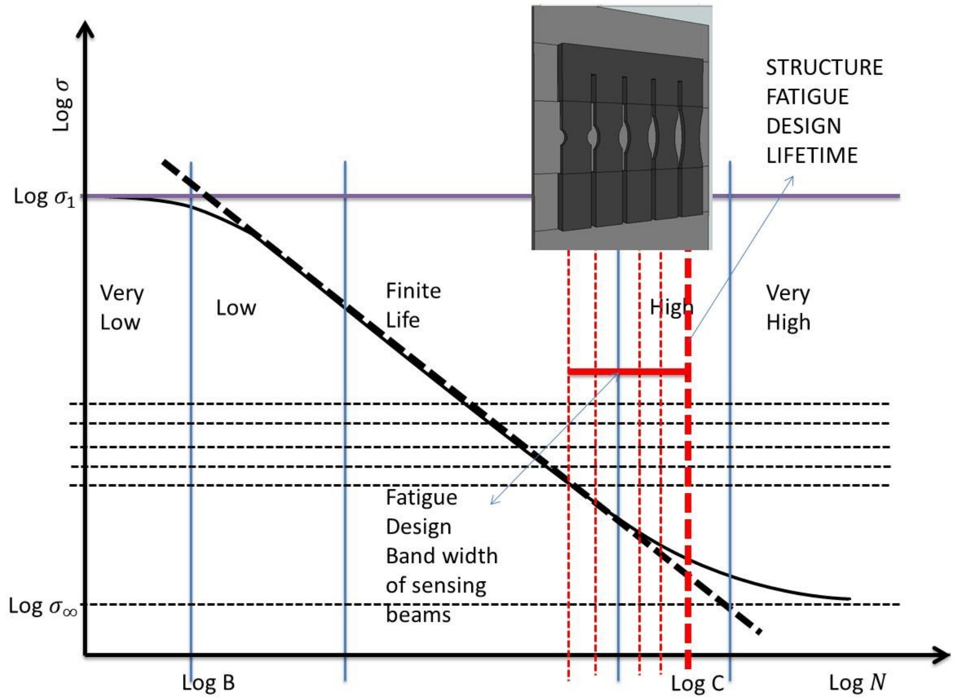

Figure 8- The Kohout and Věchet generalized S-N Fatigue Curve and Design of Fatigue Sensor for Remaining Life Prediction

The cumulative damage theory uses the S-N fatigue curve to calculate the total damage by using a stress cycle with an alternating stress. The cumulative damage rule assumes that a stress cycle with an alternating stress in a material. causes a measurable permanent damage D It also assumes that the total damage caused by a number of stress cycles is the summation of damages caused by the individual stress cycles.

The Kohout-Vechet (K-V) equation representing the finite (fatigue lifetime) design region is mathematically formulated as, $\sigma = a\left[\frac{(N+B)C}{N+C}\right]^b$. In the system model, the stress range (σ) as an independent variable is a function of the number of cycles(N). In this equation, a, b: Material Constants (Basquin parameters) of the S-N curve, σ_∞: Infinite fatigue life, σ: Stress Range, N: Number of Cycles, B: Tensile Strength Related Constant, C: Equation Constant.

The cumulative damage Miner Rule (Figure 10) assumes that a stress cycle with an alternating stress produces a measurable permanent damage. It also assumes that the total damage caused by a number of stress cycles is equal to the summation of damages caused by the individual stress cycles. According to the Miner rule, the stress levels and usage cycles two important parameters are a function of the linear fatigue damage accumulation D. At a constant stress amplitude level, the fatigue damage accumulation increases proportionally with the used cycles and the fatigue life is shorter at higher stress amplitude levels (Low Frequency) and longer at lower stress amplitude levels (High Frequency).

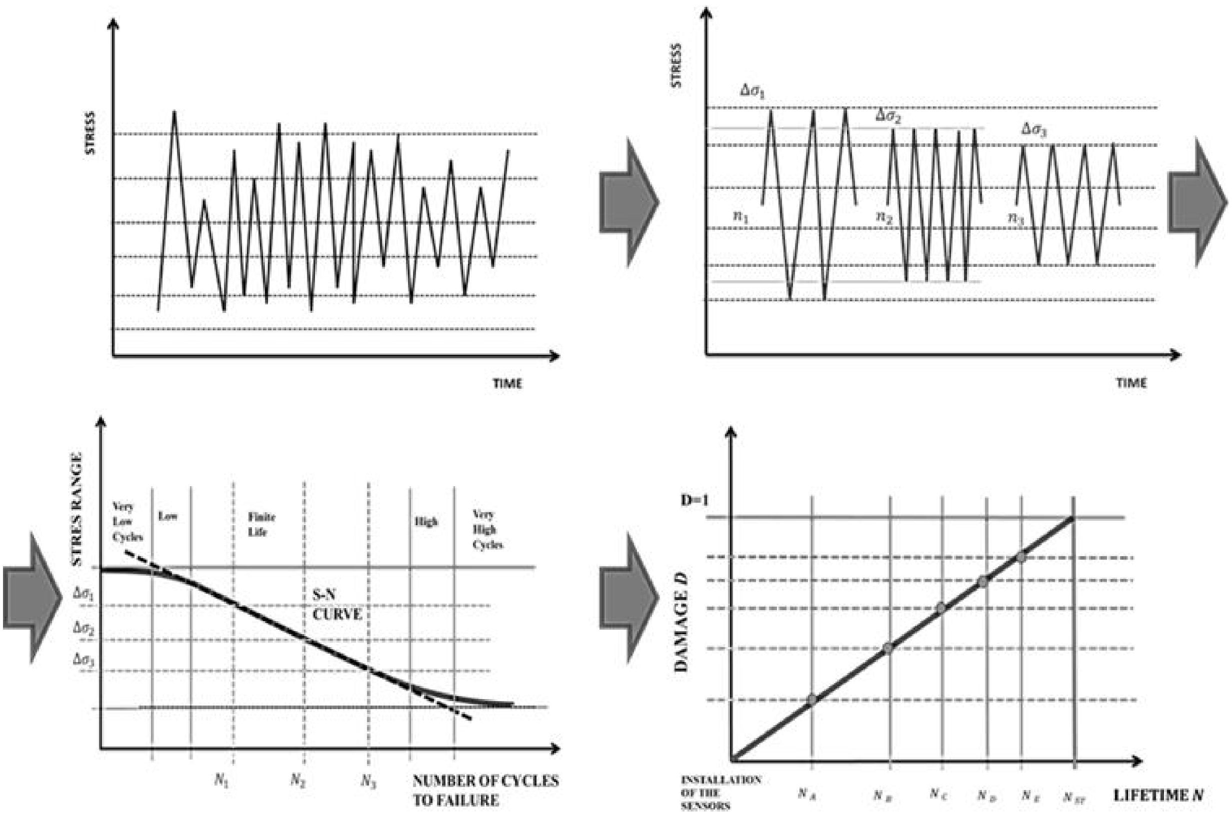

Figure 9 - The Miner Fatigue Damage Rule for Remaining Life Prediction of Structures

By using the Miner Fatigue Damage Accumulation rule (Figure 9)., the total fatigue lifetimes (A BEAM-%10 N, B BEAM %20 N, C BEAM %30 N, D BEAM %40 N, E BEAM %50 N, F BEAM % 70 N, G BEAM %85-90 N) of each sensor beam normalized to the total fatigue life (*N*) of the structure with different fatigue damage stress levels can be found. The normalized damage levels of the fatigue sensing beams comparing the damage of the structure in this case are D=0.10, D=0.20, D=0.30, D=0.40, D=0.50, D=0.70, D=0.85-0.90 (Figure 10). When the sensor beam A with %10 of N-(Total Life of Structure) fails, it will show that the remaining life of the new structures is the %90 N of the total life of structure and the damage level of the structure in this case is D=0.1. When the sensor beam B with %25 of N-(Total Life of Structure) fails, the remaining life of the structure is the %75 N-the total life of structure. When the sensor beam E with % 85-90 of N-Total Life of Structure fails, the remaining life of the structure is the %10 N-the total life of structure.

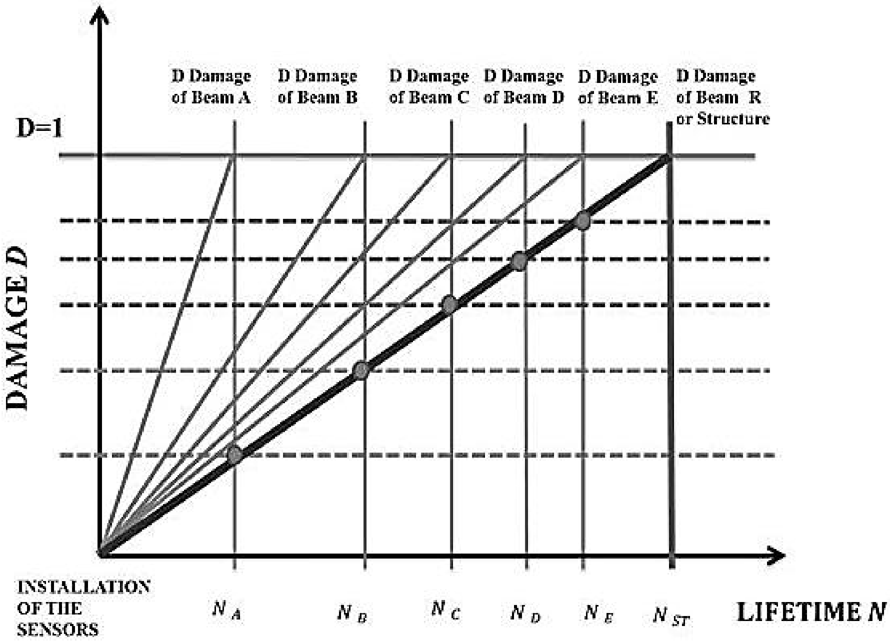

Figure 10- The Miner Fatigue Damage Accumulation Rule to Predict the Remaining Life of New Structures by using the Sensor with Different Life Cycles and Different Stress Levels

For the remaining life prediction of the old structures by using the Miner Rule (Figure 11), a 7 (seven) sensitive sensing beams(A,B,C,D,E,F,G) with Different sensitive intervals of Life Cycles

A BEAM-%10 N, B BEAM %20 N, C BEAM %30 N, D BEAM %40 N, E BEAM %50 N, F BEAM % 70 N, G BEAM %85-90 N

can be considered to predict the remaining life of the current used structures. The usage-past damage D_p and its consumed life cycle N_p of the current (old) structure are also considered in the design of the sensor for the remaining life prediction of the structure.

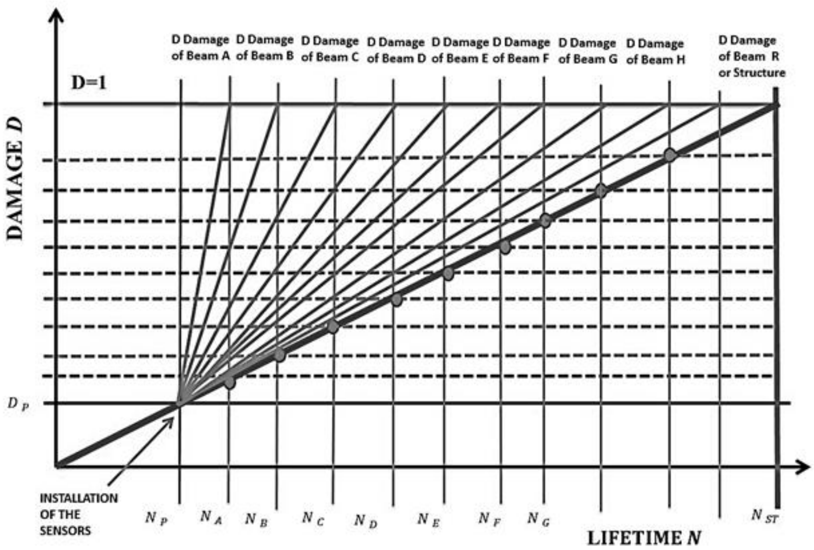

Figure 11- Miner Fatigue Damage Accumulation Rule to Predict the Remaining Life of Old Structures by using the Fatigue Sensor with Different Life Cycles Different Stress Levels

In general, stress magnification factor $K_{tst} = 1$ is used for the specimen of the Fatigue Stress-Life (N) Curves. In this case the stress magnification factors of the sensor beams as a function of their life cycles,

The fatigue stress magnification of 7 different sensor beams;

$$(K_{tst})_{\%100} < (K_{tnG})_{\%85-90} < (K_{tnF})_{\%70} < (K_{tnE})_{\%50} < (K_{tnD})_{\%40} < (K_{tnC})_{\%30} < (K_{tnB})_{\%20} < (K_{tnA})_{\%10}$$

The fatigue life of 7 different sensor beams;

$$(N_{tst})_{\%100} > (N_{tnG})_{\%85-90} > (N_{tnF})_{\%70} > (N_{tnE})_{\%50} > (N_{tnD})_{\%40} > (N_{tnC})_{\%30} > (N_{tnB})_{\%20} > (N_{tnA})_{\%10}$$

The fatigue life of the mini beams (A, B, C, D, E, F, G) with fatigue different life cycles %10 N, %20 N, %30 N, %40 N, %50 N, %70 N, %85-90 N is defined by the critical notch stresses of the mini sensor beams as depending upon the magnitude of the stress concentration factor (K_{tn}). The structural stresses in critical nothed sections of mini beams will be used for design of sensing beams to predict the remaining life of structures as a function of the fatigue lifetimes of the sensor beams normalized to the total fatigue lifetime (N) of the structure. In this case the stresses in the critical notched sections

$$(\sigma_{st})_{\%100} < (\sigma_{nD})_{\%85-90} < (\sigma_{nC})_{\%70} < (\sigma_{nE})_{\%50} < (\sigma_{nD})_{\%40} < (\sigma_{nC})_{\%30} < (\sigma_{nB})_{\%20} < (\sigma_{nA})_{\%10}$$

As it is known, Fatigue Stress and Life Cycles relationship of materials is represented by the S-N curves. The total strain-stress range due to fatigue is known but it is difficult to separate the total strain-stress range into two different plastic and elastic components, therefore a combined low-high cycle equation model (Figure) can be more efficient and effective. Kohout-Věchet proposed a new generalized S-N equation. The mathematical model representing the S-N fatigue curve combines two components of high and low-cycle fatigue regimes (Figure 2). The most important parameters in this model are the slope of the curve, stress range, the fatigue life cycle and the fatigue limit.

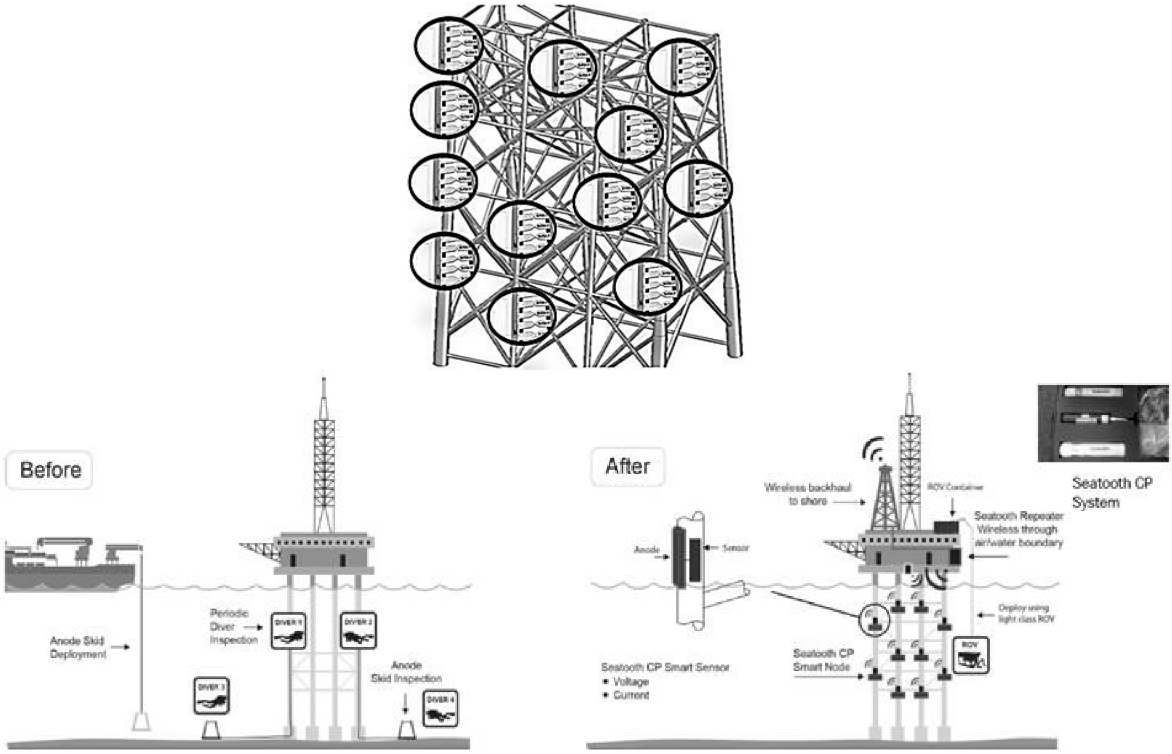

Figure 12- Marine application of the IoT Fatigue Sensor and distributed Sensor Network System on Large Fatigue Critical Oil Platform Structures for IoT Structural Fatigue Monitoring

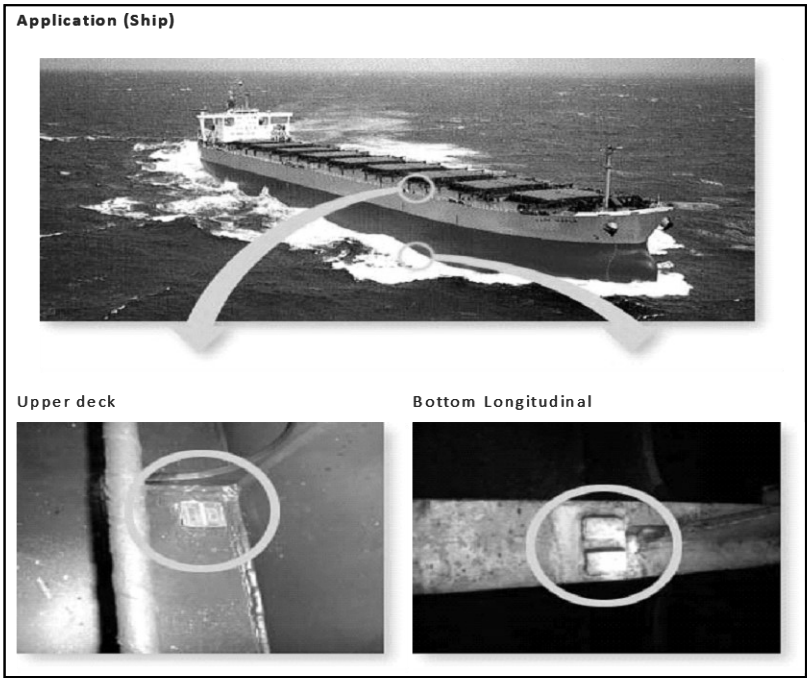

Figure 13- IoT System model of the fatigue sensor application for (Fleets or Unit based) fatigue monitoring of marine vessels

CONCLUSIONS

A novel wireless enabled smart Structural Fatigue Damage Sensor and IoT integrated wireless smart fatigue sensor network system for fatigue health monitoring of the state of critical parts was developed and patented in several countries. The smart RFID fatigue sensor is designed to be attached to the surface of hot spots of structures by a special super bond very similar to strain gage attachments. The fatigue sensor is mimicking the strains-stresses encountered by the structural member during its entire lifetime and gives a live indication of remaining lifetime in a wireless manner depending upon the level of the fatigue cumulative damage indexes as outlined previously.

It is also well suited to aircraft, shipping and bridge applications. The sensor keeps track of fatigue build up by using sacrificial fingers inside. A specially designed geometry used for fabrication of the internal fingers ensures fingers break at 10, 25, 50, 75 & 90 % of the expected lifetime of the structural member.

Wireless capability makes it easy to monitor the progress of expected lifetime without getting near the sensor. Typically structural members are replaced when they reach 90% of their expected lifetime before catastrophic failure occurs. The Proposed Fatigue Sensor System will increase not only the ‘Safety and Reliability’ but also Increase the expected service lifetimes of very large-complex and expensive engineering structures.

The system is also capable of monitoring fatigue cracks in hot spots of structures. A Smart Predictive-Condition Based Maintenance System Model was developed for not only for a single Complex Structural Unit but also a Complex Complete Fleet System to reduce Maintenance and Management Costs while increasing Safety and Reliability of Fatigue Critical Parts of Structures.

Advancement of the current microprocessor and IoT communication technologies opened up a new and exciting opportunity for the new sensor. This is called “Edge Computing” and with this, the sensor becomes an independent entity. In this mode there is no need to interrogate the sensor periodically. The sensor electronics periodically monitor the state of the sensor internally and only reports the data when there is change. This, will further reduce power requirements of the sensor modules and reduce the network traffic. We believe this will open up new application scenarios for IoT monitoring.

Among the key achievements of the Fatigue Sensor, one of the most important is the extension of expected lifetime or the service lifetime (the Fatigue Lifetime) of Critical Structures around two-three times of standard designed life when an Intelligent Sensory Predictive Lifetime Design Methodology is applied to fatigue critical structures instead of conventional strain gage design model methodology.