A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor
and
Wireless SHM-RFID-IoT Smart Fatigue Damage SENSOR NETWORK
and
An Internet of Things-IoT Based Intelligent Predictive Maintenance Management System
(FOR TANKER-SHIP APPLICATIONS)

by

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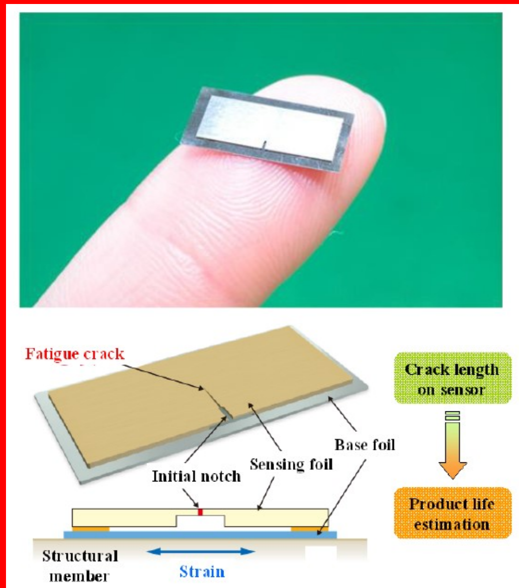
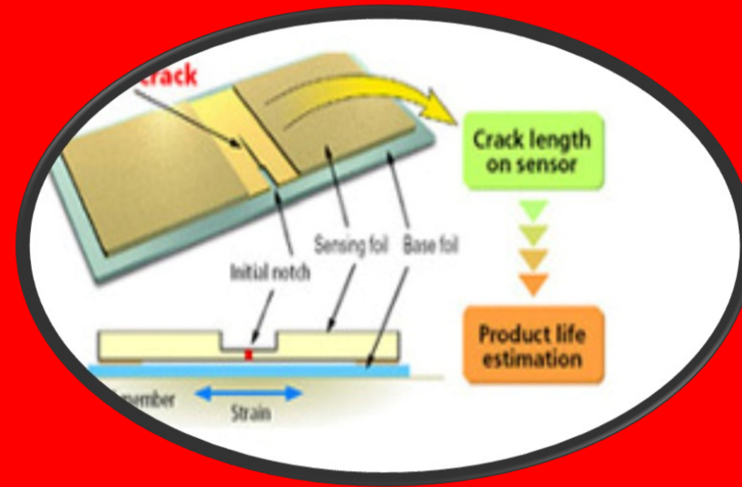
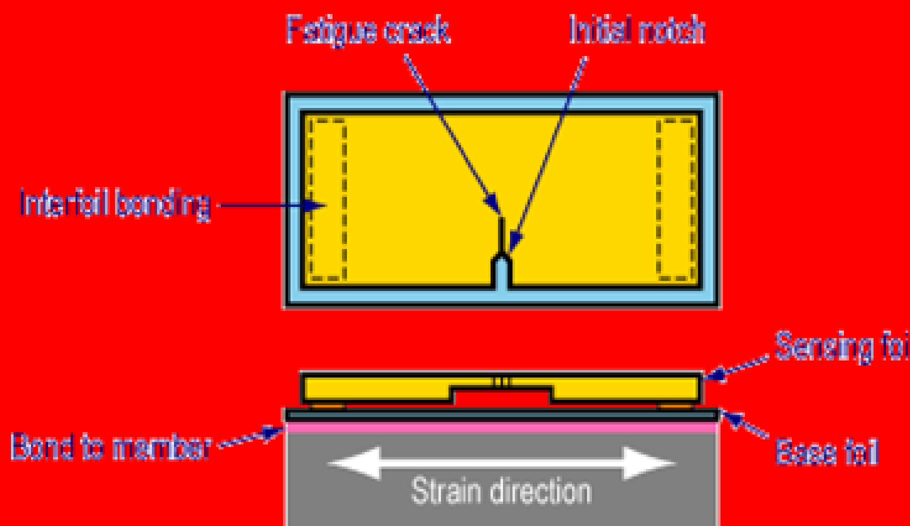
Conventional Fatigue Structural Health Monitoring with Monitas System (TANKER-SHIP APPLICATIONS)

- The structural health monitoring is a wide and fast developing area of engineering showing multiple developments and applications. One of them is the development and application of the Advisory Monitoring System (AMS) which is taking place within the Monitas Joint Industry Project led by MARIN. The AMS, referred to as the Monitas system, controls the fatigue lifetime consumption of FPSO hulls.
- The Monitas system shows and advises on fatigue lifetime consumption based on the fatigue design data, fatigue design tool, the monitoring data of global and local stresses, vessel motions, and the environmental and operational conditions.
- The Monitas system is an active system. It requires sensors, cabling, power, data acquisition systems and the Monitas software that translates Gigabytes of data into a concise advisory including explanation of possible differences between the design and actual fatigue lifetime consumption. In this respect the Monitas system advances the conventional Hull Monitoring Systems (HMSs) which are specified in present rules of different Class Societies. This is because the information provided by a HMS can at best be restricted to the value of fatigue lifetime consumption without exploring possible differences from the design values.





KAWASAKI FATIGUE DAMAGE SENSOR(FDS) FOR SHIP-TANKER APPLICATIONS



KAWASAKI FATIGUE DAMAGE SENSOR FOR SHIP-TANKER APPLICATIONS

Fatigue Monitoring System for Ships:
Hull structure's fatigue life monitoring system using fatigue sensors
Fatigue Damage Sensor

- Kawasaki Heavy Industries, Ltd. developed a compact and highly sensitive sensor, Fatigue Damage Sensor (FDS), which can be attached for fatigue damage monitoring in the vicinity of welding parts of structures exposed to fluctuating loads.
- On FDS, crack will propagate from the initial notch after receiving fluctuating strains on the structural members. The fatigue damage can be monitored by measuring its crack length on FDS using the fundamental characteristic of FDS; its crack growth rate is always constant independent of its crack length against the same strain fluctuating ranges. More accuracy results will be anticipated as compact Kawasaki FDS can be attached on the stress concentrating areas as close as possible.
- Comparing to the fatigue damage evaluation method by strain gauges, monitoring method by FDS is a simple and easy one with low-price. FDS application is growing day by day throughout bridges, rolling stocks, and so on in addition to ships.

KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

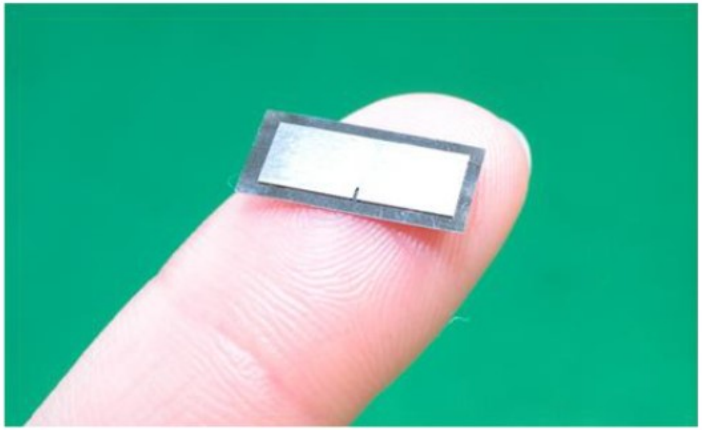
- **Ship-Tanker fatigue cracking has caused concern for the entire marine industry including operators, regulators and classification societies. In response to this concern, various researchers have been developing improved means for evaluating structural fatigue.**
- **The developed model a practical rationally-based fatigue design method which is sufficiently rapid and efficient to be a part of preliminary structural design. This is important because if fatigue is not adequately addressed at this stage, no amount of detail design will be able to correct or makeup for this inadequacy.**
- **The method consists of five basic steps: specifying a realistic wave environment, generating a hydrodynamic ship-wave interaction model, computing cyclic nominal stress due to waves and ship motions, using S-N data to predict fatigue life, and using structural optimization to resize the scantlings such that the desired fatigue life is obtained.**

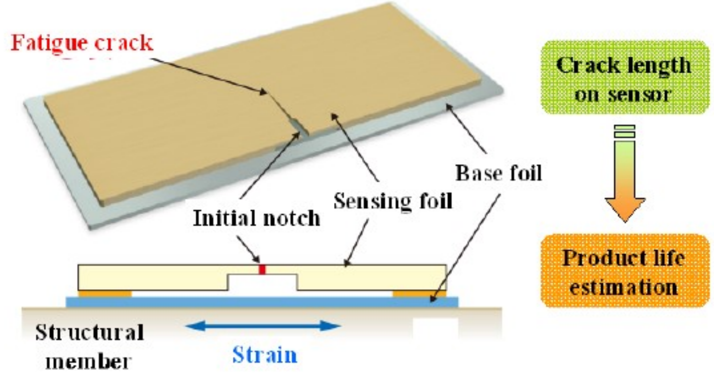
KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

- Knowledge of fatigue damage level with Fatigue Sensors is relevant for lifetime extension and assurance issues of ships and offshore structures, but also for sensor based smart rational planning of inspection, smart maintenance and repair management.
- Lifetime prediction with fatigue damage sensors moves a step closer to real fatigue lifetime of structures
- To measure cumulative fatigue damage level Kawasaki developed the Fatigue Damage Sensor (FDS).
- This sensor consists of a base and sensing foil. In the centre of the sensing foil a groove is formed to amplify strain and an initial notch is placed in the centre of this groove. An estimate of fatigue damage is found by measuring the length of the crack in the sensor.
- The main advantage of the FDS is that fatigue life can be monitored without the necessity of pulling cables or installing a data acquisitioning system. In addition, the sensor is very compact which means it can be installed closer to stress concentrations.

KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

- **Fatigue Damage Sensor was developed by KAWASAKI-JP. The Fatigue Damage Sensor (FDS) is shown in Figure FDS. It consists of sensing foil which is thinner in the central section in order to amplify strains. In the middle of this section an initial notch is introduced.**
- **When the FDS is attached to a structure it feels the same strain variations (albeit, amplified) as the structure and consequently a fatigue crack initiates and propagates from the notch tip depending on number and level of strain cycles.**
- **The crack propagation rate is relatively independent of the crack length. The crack length is proportional to the accumulated fatigue damage in the structure during the period after the sensor installation; hence the crack length is inversely proportional to the fatigue lifetime consumption.**





KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

- **This newly proposed fatigue life evaluation procedure using obtained factors is checked by comparison results of fatigue tests for a large structural model on which FDSs and strain gauges are provided simultaneously and to which random loads by assumption of storm patterns are applied under various mean stress levels. Practical application results of the FDS for an LNG Carrier for 5-year operation are discussed.**
- **A proactive safety management system for ship structures that quantifies the aging effect such as fatigue and corrosion on ship structural integrity, Hull Aging Management System (HAMS), is proposed as a new approach to the ship's structural surveys that have conventionally been done according to a more passive management system.**

Table 1 Principle dimensions of LNG VENUS

LNG tank type	Moss spherical four tanks
Class	NK (Nippon Kaiji Kyokai)
Length	288 m
Breadth	48.94 m
Depth	26.0 m
Designed drought	11.55 m

Source: MHI Technical Review Vol. 52 No. 1 (March 2015)

Fig.1 Overview of LNG VENUS

KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

- **In a proposed fatigue management system called the ‘Hull Fatigue Management System’ (HFMS) using Fatigue Damage Sensors (FDSs), it is an important problem to improve the prediction accuracy of hull fatigue life using the FDSs.**
- **The characteristics of the FDSs that are in use for fatigue life evaluation by monitoring structural members in ship structures are discussed in order to improve the prediction accuracy of fatigue life exposed to random wave loads such as storms under various loading conditions peculiar to ship structures. Factors affected by random loading against constant-amplitude loading and mean stress levels are introduced for the evaluation procedure using FDSs and confirmed by a series of fatigue testing and numerical simulations.**

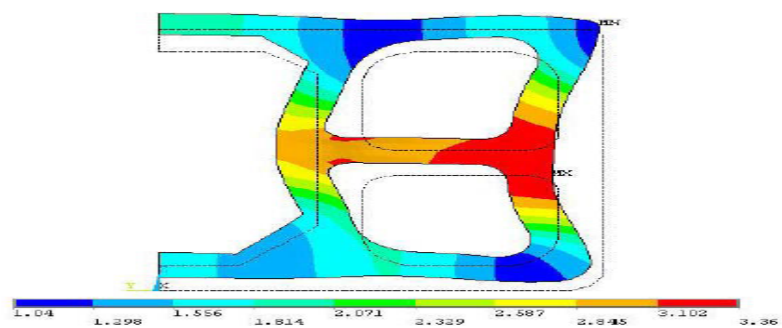


Fig. 6 Deflection pattern for the tanker with fully loaded condition

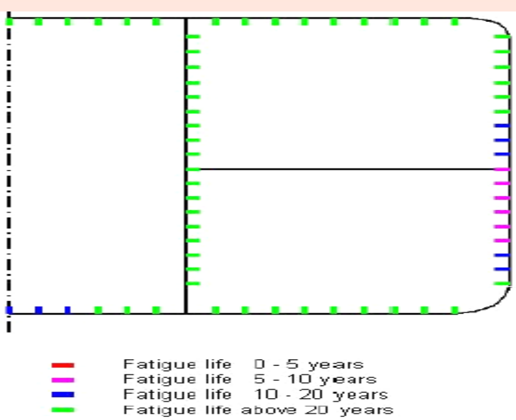


Fig. 9 Fatigue life at different longitudinal position of the section considered

KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

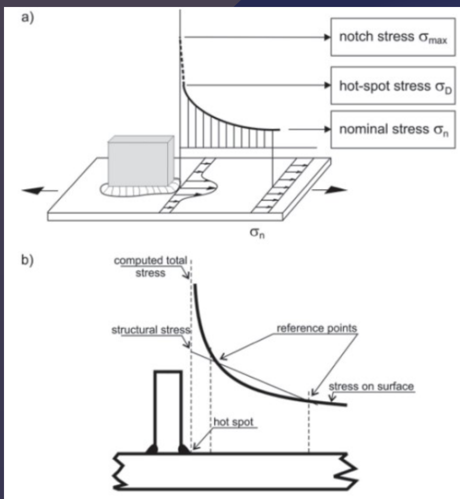


Fig. 14. Definition of structural hot- spot stress: a) stress representatives; b) determination of the hot-spot stress

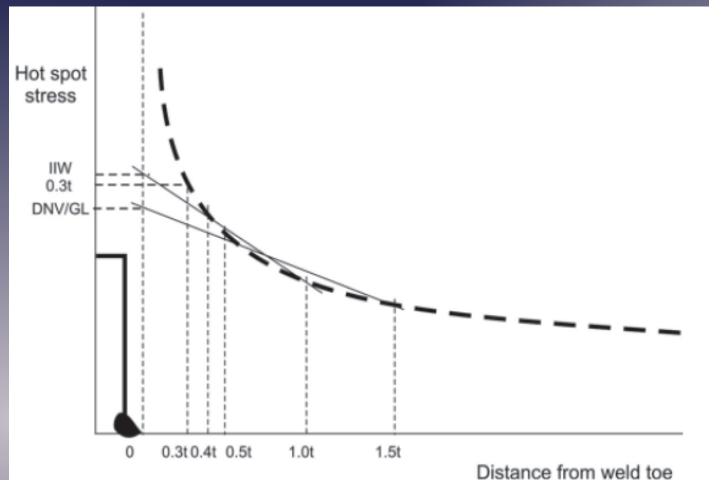
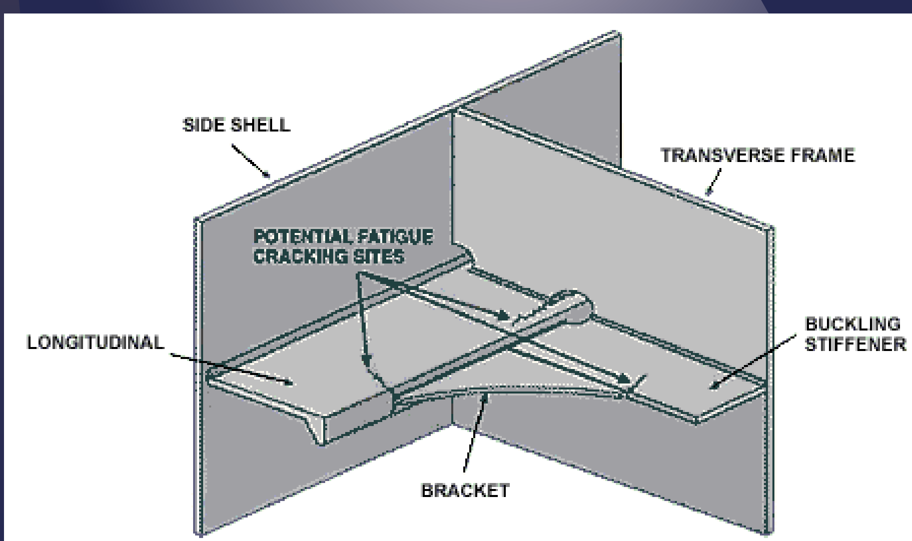
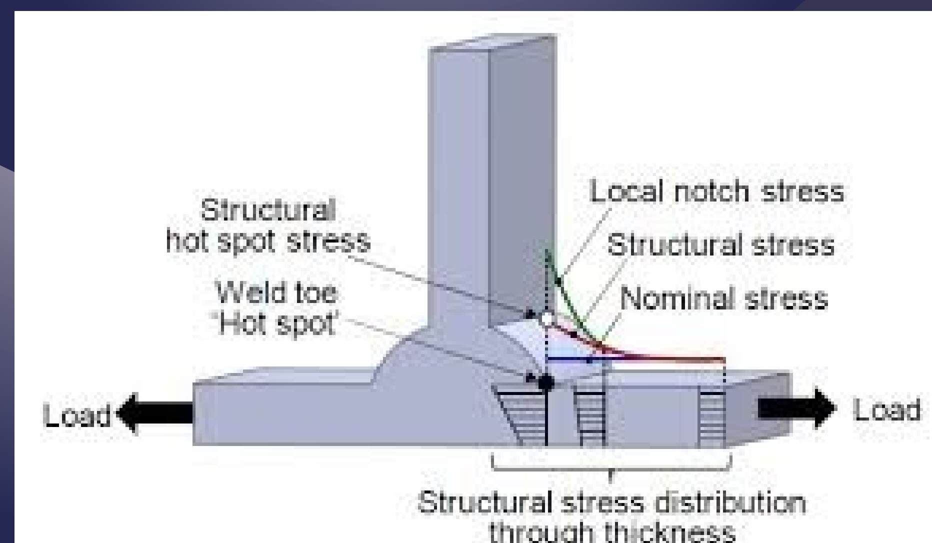


Fig. 15. Differences in obtained „hot-spot" stress values depending on the points chosen for extrapolation

Identify all the Fatigue Critical HOT SPOTS in SHIP STRUCTURES for the applications of Smart fatigue damage sensors in order to monitor the RESIDUAL FATIGUE STRENGTH





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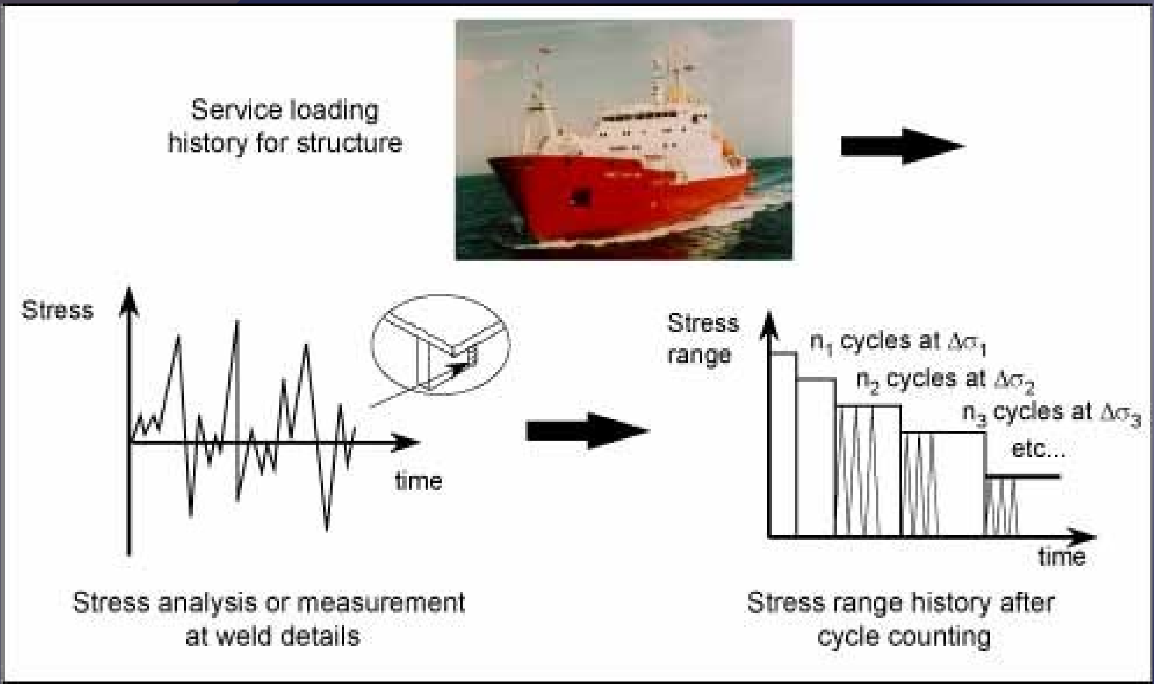


- **Elements and Factors of Fatigue Design for Ships**
- **Identify all the Fatigue Critical HOT SPOTS in STRUCTURES**
- **Install Fatigue Damage Sensors in order to monitor the RESIDUAL FATIGUE STRENGTH**

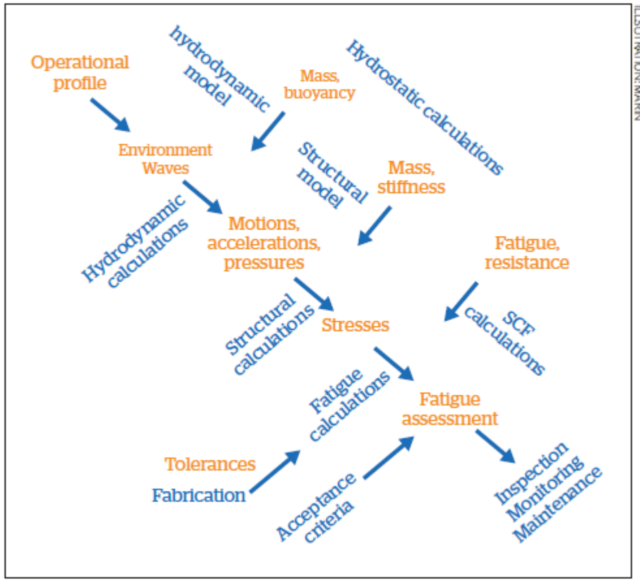


Figure 1. Elements of fatigue design

KAWASAKI JP Fatigue Damage Sensor(FDS) (TANKER-SHIP APPLICATIONS)

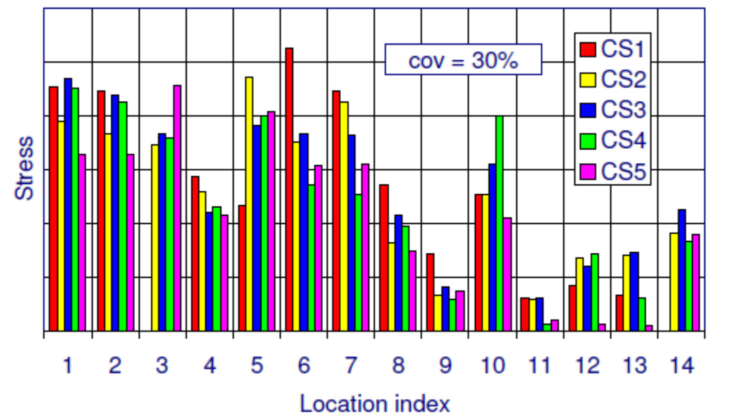


Figure 6. Stress prediction benchmark – stress results

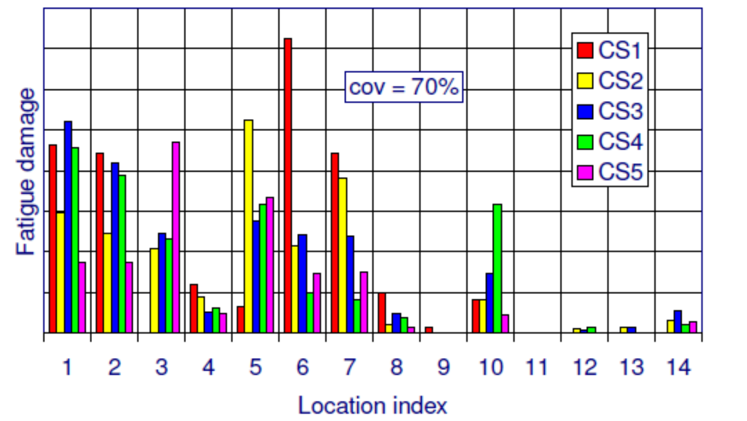


Figure 7. Stress prediction benchmark – lifetime results

Fatigue Critical HOT SPOTS in SHIP STRUCTURES for the applications of fatigue damage sensors FDS in order to monitor the RESIDUAL FATIGUE STRENGTH or CUMULATIVE FATIGUE DAMAGE INDEX

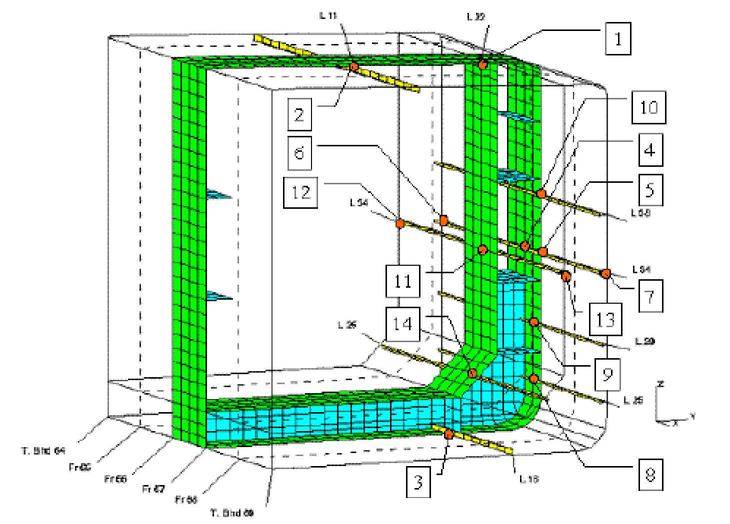
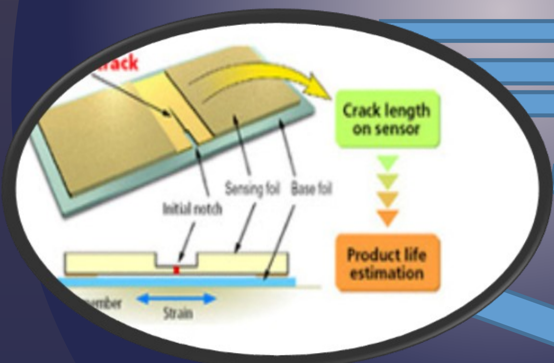


Figure 5. Stress prediction benchmark - structure

KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

STRUCTURAL FATIGUE DAMAGE MONITORING of different components of TANKER-SHIP SYSTEMS (welded, rivets, bolted, and other fatigue specific-sensitive elements) during normal service.



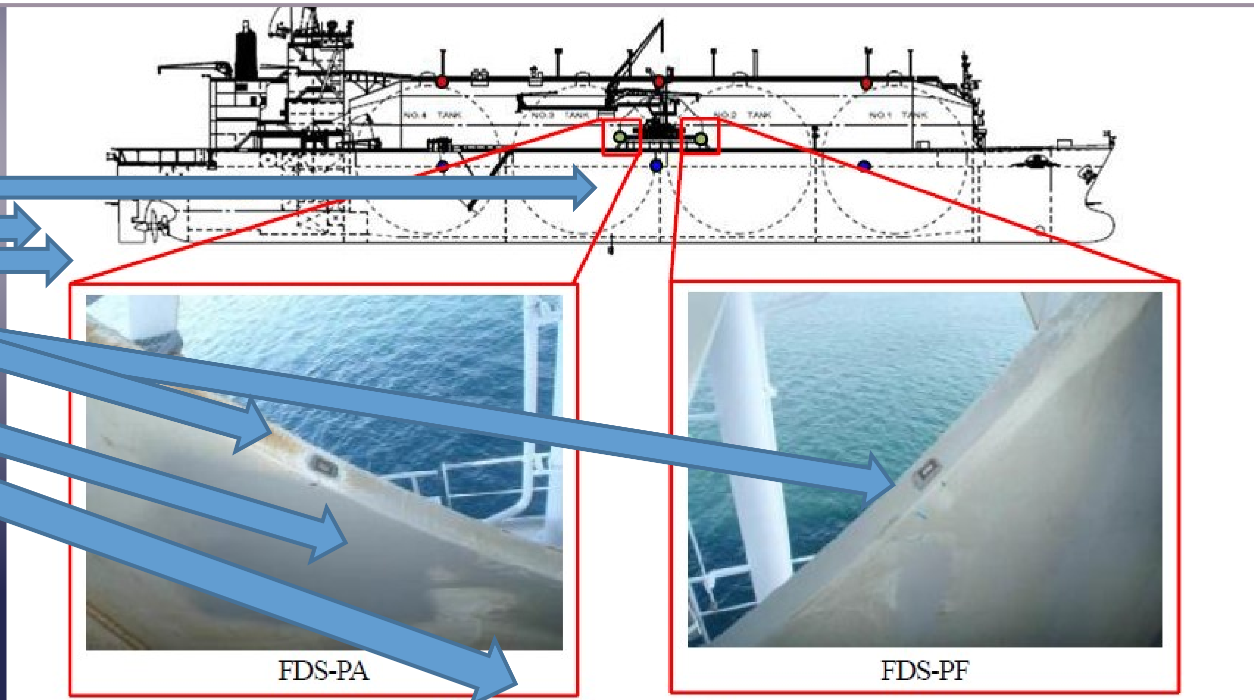


Fig. 8 Arrangement of FD sensor

SHM-RFID-IoT Smart Fatigue Damage Sensor

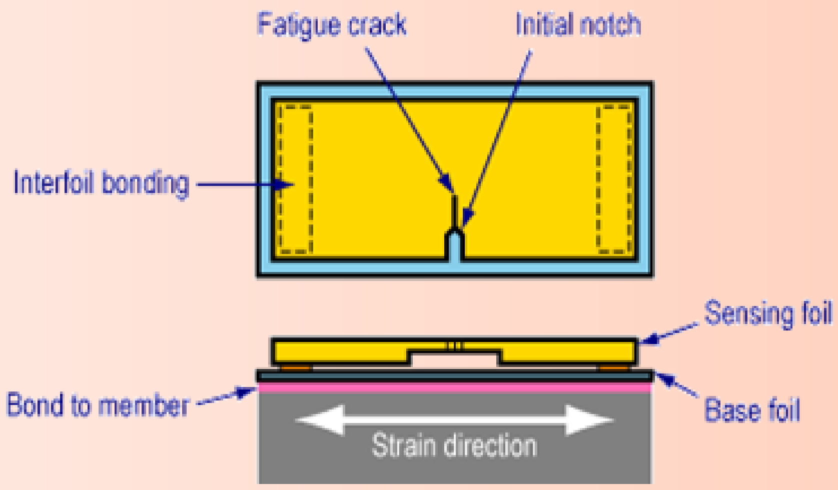
FATIGUE DAMAGE SENSOR-FDS APPLICATIONS FOR LNG CARRIERS

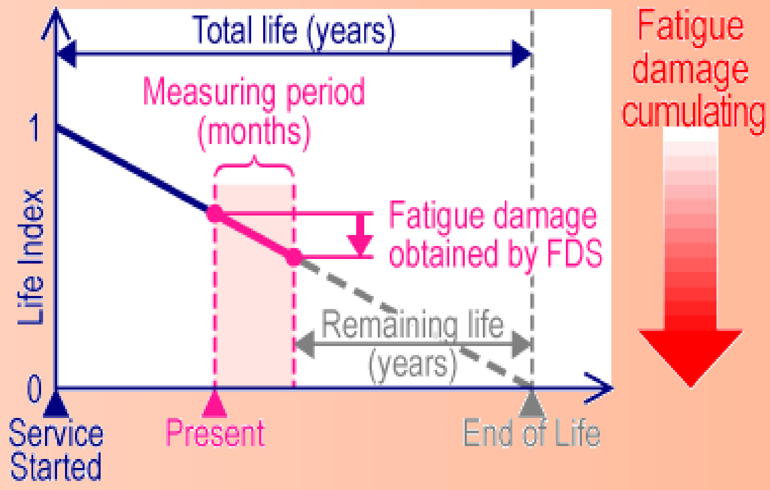
KAWASAKI JP Fatigue Damage Sensor(FDS) (TANKER-SHIP APPLICATIONS)

- **The FDS-KAWASAKI-JP sensor has been developed by Kawasaki. It is a passive sensor similar in size and installation to a conventional strain gauge. After the installation the sensor feels strains of the structure. These strains develop a crack in the sensor. The crack length is a measure of fatigue lifetime consumption.**
- **This paper describes the sensor and compares its readings with conventional fatigue assessment methods based on the rain-flow counting of measured strains.**
- **This presentation focuses on the first successful application of FDS to an FPSO. In general, the FDS is applicable to any structure. However, for the FPSO application the sensor has to be calibrated in order to take into account the characteristic stochastic nature of fatigue loading of marine structures subjected to action of waves. The beauty of the sensor is its simplicity and low cost.**
- **The disadvantage is that the crack length has to be read periodically. The presentation demonstrates that the FDS gives reliable results and is very attractive for direct assessment of fatigue lifetime consumption of vital structural elements of FPSOs. It gives guidance on application of FDS including preferred locations, installation procedure, and number of sensors per location and reading procedure.**

KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)

- **The fatigue lifetime evaluation using the FDS is explained in Figure FDS.**
- **First the sensor is installed. Then, after a certain time period the crack length, Δa, is measured. This corresponds to the fatigue damage, Ds, accumulated in the FDS.**
- **The relationship between Δa and Ds is known from laboratory tests of FDSs only. Finally, the accumulated fatigue damage in the welded joint, Dw, is estimated based on the relation between Ds and Dw. This relation is obtained from laboratory tests of FDSs applied on welded joints.**





KAWASAKI JP Fatigue Damage Sensor(FDS)
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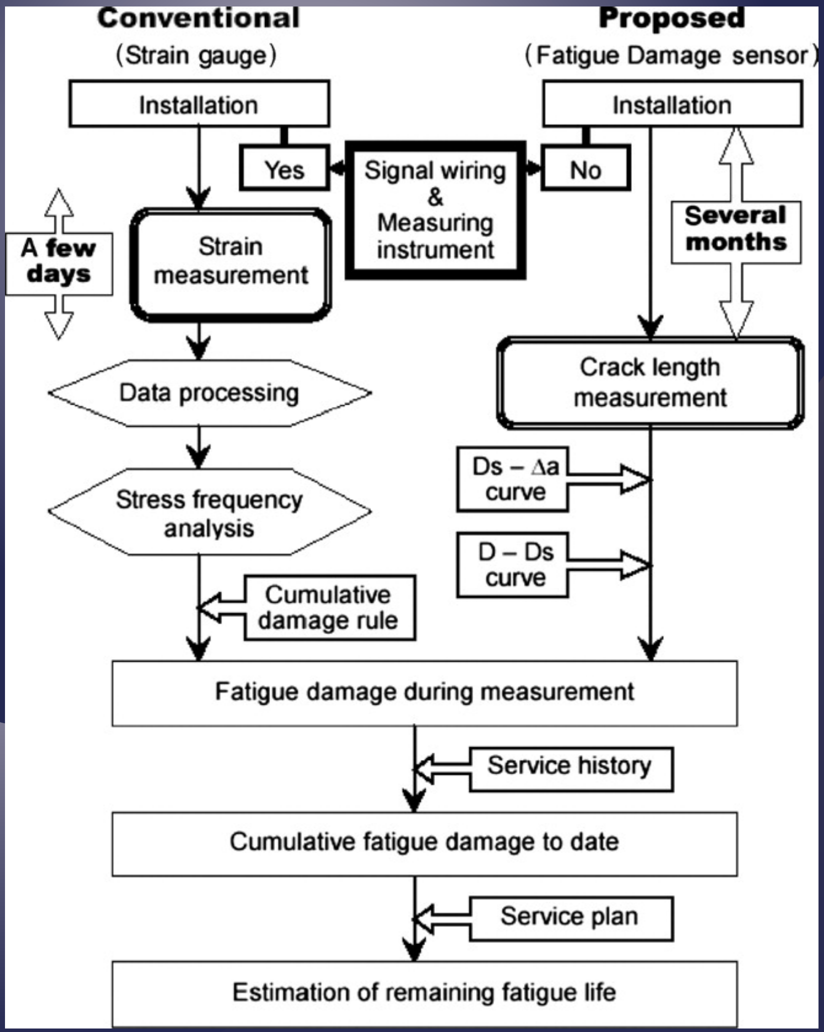
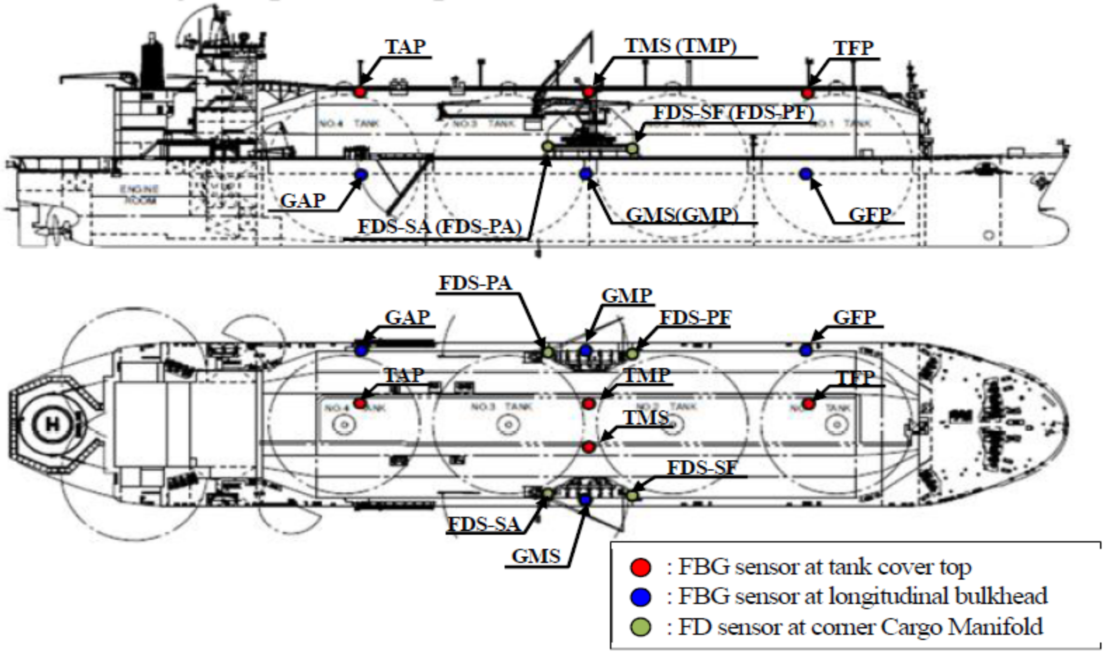


KAWASAKI JP Fatigue Damage Sensor(FDS)
(TANKER-SHIP APPLICATIONS)



a) FBG (Fiber Bragg Grating) sensor

TAP	Tank cover top at No.4 Hold (P-side)
TMP	Tank cover top at midship (P-side)
TMS	Tank cover top at midship (S-side)
TFP	Tank cover top at No.1 Hold (P-side)
GAP	Longitudinal BHD at No.4 Hold (P-side)
GMP	Longitudinal BHD at midship (P-side)
GMS	Longitudinal BHD at midship (S-side)
GFP	Longitudinal BHD at No.1 Hold (P-side)

b) FD (Fatigue Damage) sensor

FDS-PA	Corner of cargo manifold opening (P-side, Aft)
FDS-PF	Corner of cargo manifold opening (P-side, Fore)
FDS-SA	Corner of cargo manifold opening (S-side, Aft)
FDS-SF	Corner of cargo manifold opening (S-side, Fore)

Fig. 2 Arrangement of sensors for monitoring system

STRUCTURAL FATIGUE DAMAGE MONITORING of different components of TANKER-SHIP SYSTEMS (welded, rivets, bolted, and other fatigue specific-sensitive elements) during normal service.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor

(SHM TANKER-SHIP APPLICATIONS-SENSORS)

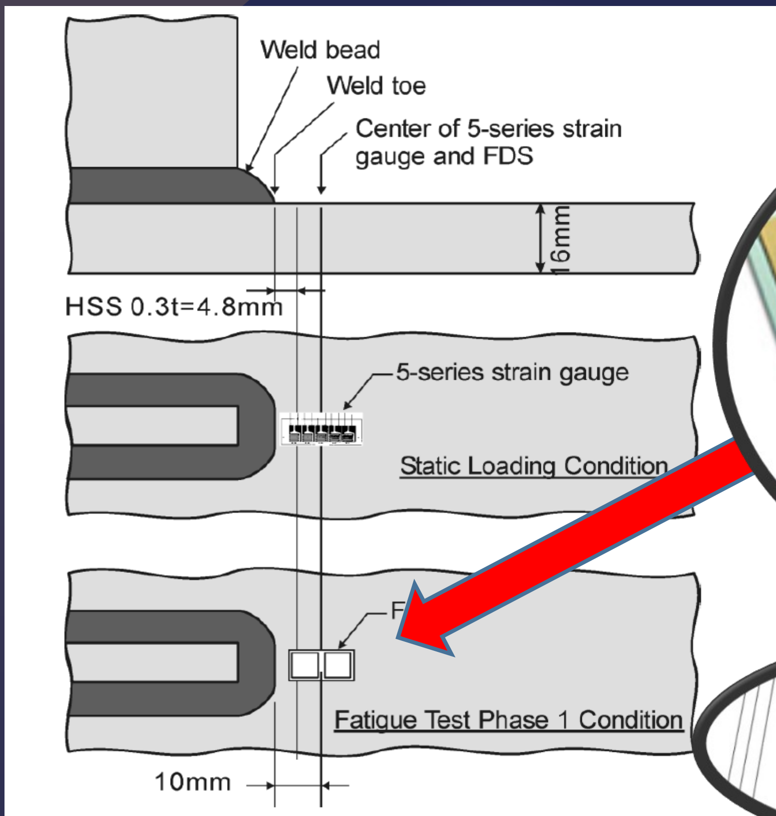
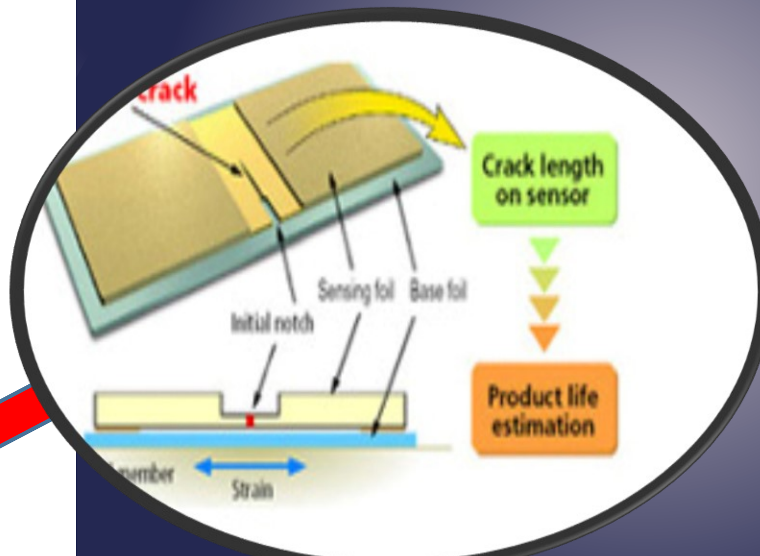
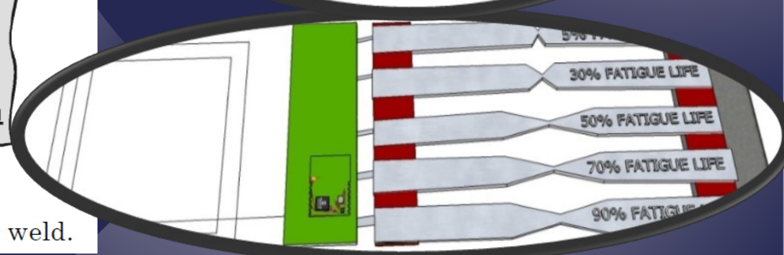


Fig.2.8 Location of strain gauge and FDS stuck near weld.



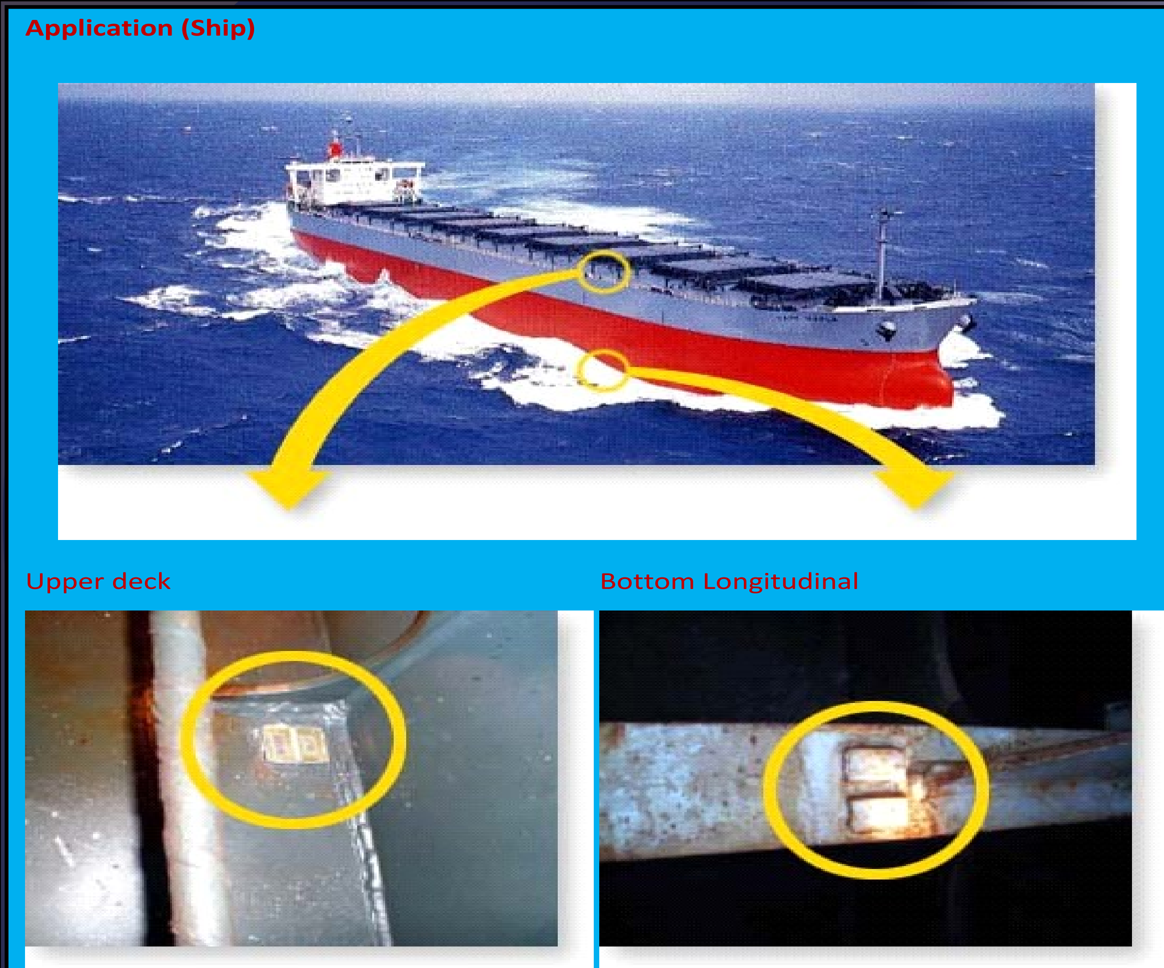


Identify all the Fatigue Critical HOT SPOTS in STRUCTURES for the applications of Smart fatigue damage sensors in order to monitor the RESIDUAL FATIGUE STRENGTH

CURRENTLY, NO FATIGUE SENSORS IN THE SHM SYSTEMS TO MONITOR RESIDUAL FATIGUE STRENGTH

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor

(SHM TANKER-SHIP APPLICATIONS-SENSORS)

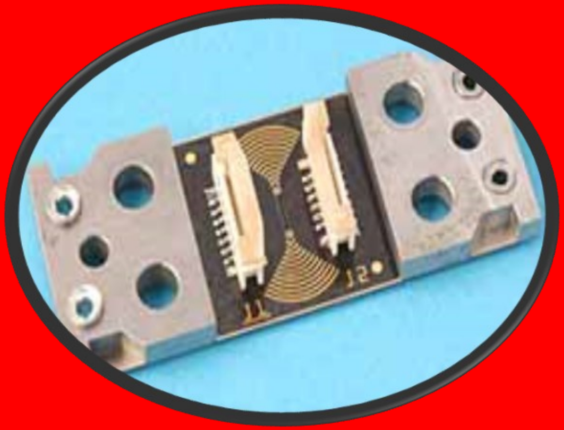


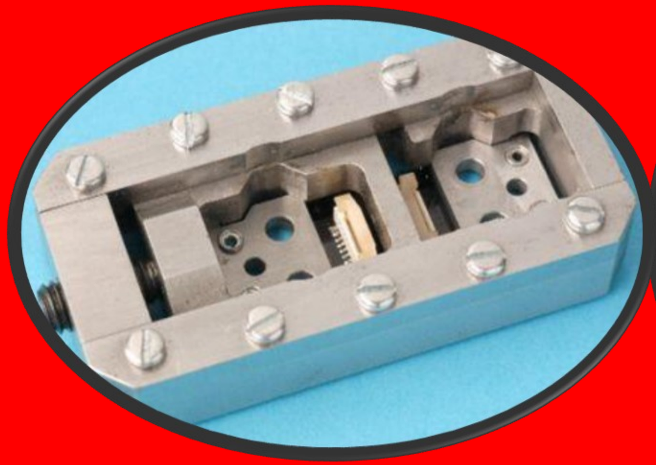
Kawasaki FDS is applicable to various steel structures

DISTRIBUTED SENSOR NETWORK FOR TANKER-SHIP SHM SYSTEM. FATIGUE SENSOR APPLICATIONS TO SHIPS: Fatigue sensitive regions, locations under high loads, predetermined and formerly known-experienced spots on the structures and mechanical components such as Riveted, Bolted and Hole Type Connections etc..

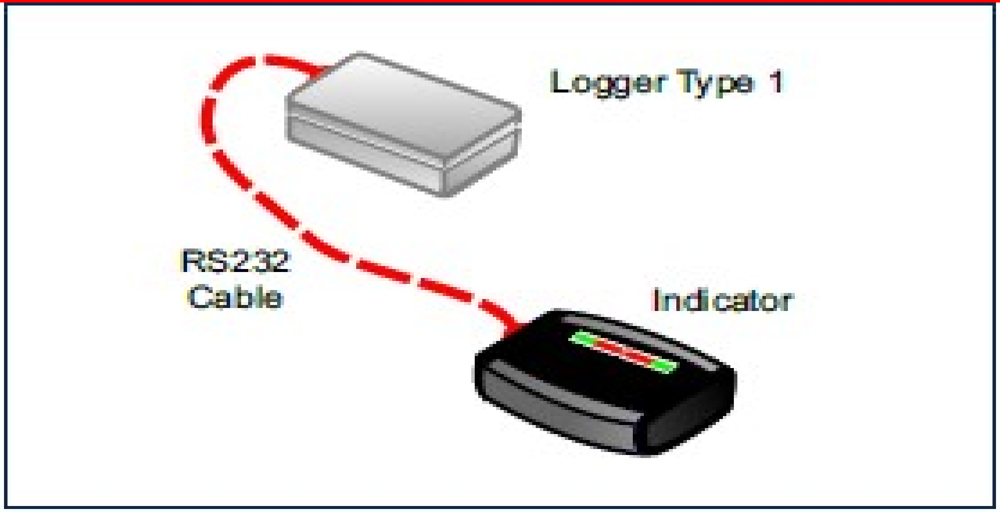
A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (TANKER-SHIP APPLICATIONS)

WIRELESS STRUCTURAL FATIGUE DAMAGE MONITORING AND FATIGUE DAMAGE DETECTION of different components of TANKER-SHIP SYSTEMS (fatigue specific-sensitive elements) during normal service.





THE CRACKFIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)



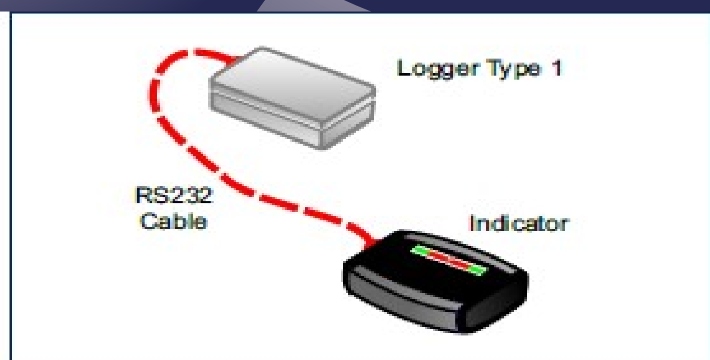
THE CRACKFIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

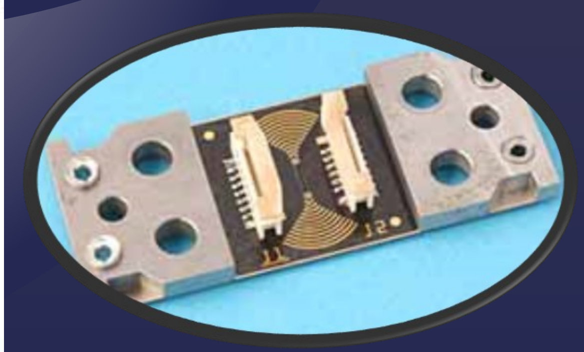
Monitoring System | CrackFirst™ Fatigue Monitoring

System Benefits

- Provides an accurate record or cumulative fatigue damage
- Indicates the portion of design life consumed
- Provides design and development engineers with valuable information
- Maintenance can be scheduled by usage rather than time
- Optimises operational efficiency

Fatigue sensitive regions, locations under high loads, predetermined and formerly known-experienced spots on the structures and mechanical components such as Riveted, Bolted and Hole Type Connections etc..



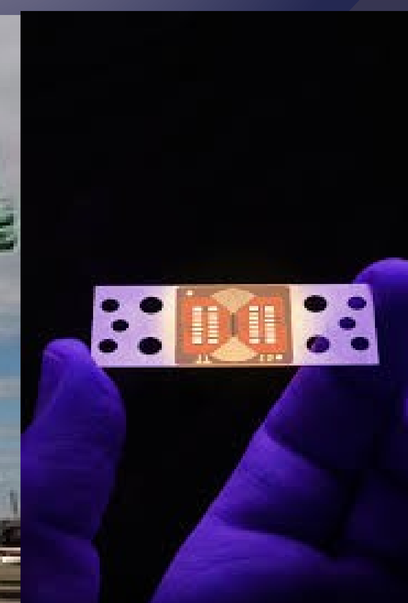


THE CRACKFIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

The CrackFirst™ fatigue monitoring.

- **Strainstall have been commissioned to install CrackFirst™ onto an INF 2 classified, multi-purpose cargo vessel.**

- **Strainstall have fitted four of its CrackFirst™ sensors onto the Atlantic Osprey cargo vessel operated by the International Nuclear Services (INS). Accurately measuring cumulative fatigue in the vessel's hull it ensures operational efficiency is optimised.**

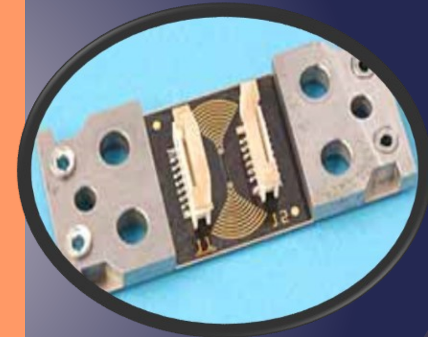


THE CRACKFIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

How it works:

CrackFirst™ is designed for use in welded steel structures. Consisting of a thin shim of material with a manufactured pre-crack at its centre, it is attached to the target structure close to a critical joint. Under the action of cyclic stress, the pre-crack extends in proportion to the cumulative fatigue damage for a welded joint subject to the same loading. The condition of the sensor then indicates the amount of design life consumed in the adjacent weld. This allows for maintenance to be determined by component usage rather than time so preventing unnecessary or tardy replacement work.

Optimising operational efficiency in this way, our system helps to ensure that this INF 2 classified vessel continues to transport its cargo of nuclear and non-nuclear materials unhindered by cumulative fatigue damage.



THE CRACKFIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

The CrackFirst sensor system is ideal for use by all industries in which fatigue of steel welded structures presents a structural performance concern.

At the heart of the CrackFirst system is a fatigue sensor, which, when installed on a welded steel structure, indicates the portion of the design life that's been consumed and enables engineers to estimate its remaining life. The sensors, when suitably located, are subjected to the same loading history as the structure and provide an accurate record of cumulative weld fatigue damage.

The sensor comprises a steel coupon attached adjacent to a critical joint. Stress cycles cause fatigue crack growth in the coupon that is detected electrically. For a typical fillet welded joint the sensor output gives the proportion of the fatigue design life that has been used.

The CrackFirst system was developed through the collaboration of TWI Ltd, FMB, Micro Circuit Engineering Ltd, UMIST and Caterpillar Peterlee (a division of Caterpillar (UK) Ltd) in a project funded by the DTI's LINKSensor and Sensor Systems for Industrial Applications programme.

The CrackFirst system is currently licensed by Strainstall, through whom the sensor system is available to end users.

THE CRACKFIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

- **The CrackFirst ™ is a new type passive fatigue damage sensor developed for fatigue critical locations pinned, welded or other stress concentration joints in steel structures.**
- **The sensor, which comprises a small steel shim containing a pre-crack, is attached adjacent to a critical weld detail. Under the action of cyclic stress in the member to which it is attached, the crack in the sensor extends by fatigue, giving rise to a change in the electrical output of the sensor.**
- **Interpretation of the output allows the cumulative damage in the target joint to be estimated, providing valuable information for assessing the safe remaining life of the structure.**
- **In order to assess the sensor's suitability for application to ship structures, a series of fatigue tests was conducted on steel plate specimens incorporating transverse welded stiffeners, with sensors attached adjacent to the welded joint.**
- **The specimens were fatigue tested to failure under constant amplitude loading in air. Sensor performance was compared with the fatigue test results for the joints and with the Class F fatigue design curve in UK design codes. The results demonstrate that the fatigue sensor system is suitable for fatigue critical joints (including welded) in steel and is capable of providing advance warning of the rate at which the design life is being consumed.**

THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

The Atlantic Osprey is an INF 2 classified multi-purpose general cargo vessel operated by the International Transport department of British Nuclear Group Sellafield Ltd. Originally built as a vessel carrier, she has a lift-on/off capability together with drive on capabilities via a stern door which, when open, becomes the access ramp for vehicles. The vessel (formerly known as the Arneb) was purchased by BNFL in 2001 and extensively refurbished to meet its operational requirements. She transports used research reactor fuel and MOX fuel and is also chartered to transport non-nuclear materials.

Strainstall were commissioned by James Fisher & Sons plc (shipping agents to BNFL) to install four CrackFirst™ sensors with enclosures onto the vessel. The CrackFirst™ sensor is designed for welded steel structures and consists of a thin shim of material attached to the target structure close to a critical joint. Under the action of cyclic stress in the structure, a fatigue pre-crack at the centre of the shim, introduced during manufacture, extends by fatigue crack growth. The sensor design is such that the extent of crack growth in the shim is proportional to the cumulative fatigue damage for a welded joint subjected to the same loading. In other words, the condition of the sensor indicates how much of the design life of the adjacent weld has expired and how much remains.

The CrackFirst™ sensors were required as part of the re-lifing of Atlantic Osprey, so that the chief engineer could set up regular checking of the sensors and record the sensor status displayed on the indicator provided as part of the fatigue monitoring system .

THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

- **The results obtained demonstrated that the sensors performed well in laboratory tests. It was established that the electrical output of the sensor system changed reliably throughout its life in twelve steps, *Fig.s*. As indicated in *Fig.*, failure of the final sensor track, i.e. the twelfth step change in its electrical output, corresponded closely with the Class F design S-N curve. In a structural monitoring application, with the sensor installed adjacent to a Class F detail, the twelfth step change in output would indicate that the structure or component had reached the end of its design life.**
- **At this point various actions could be considered, such as inspection and repair if necessary, increasing the frequency of inspection, retiring the structure from service or modifying the loading, etc. Since the sensor output is related only to the cumulative applied loading, it is not an indication of the condition of the joint itself. The target joint may or may not show evidence of cracking; the joints tested here survived significantly beyond the Class F design endurance (see Table). In applications where the decision is taken to extend the life, the failed sensor could be replaced to allow monitoring to continue.**

THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

- Because of the difference in angular misalignments, the metal-cored arc welded specimens experienced higher bending stresses than the HLA welded specimens. When plotted in terms of the local stress range at the sensor, Fig., it appears that sensors attached to the metal-cored arc welded joints had slightly greater endurance than sensors on the HLA welded joints. This suggests that the performance of the sensor, to some degree, depends on the loading mode. In situations where bending stress constitutes a large proportion in the total stress range the sensor life may exceed the Class F design curve, in which case, it may be cautious to base assessment on the life to separation of the eleventh track.
- As discussed earlier, successful application of sensors to a structure will require knowledge of the fatigue design, critical locations, stress direction, etc. In general, the requirements are similar to those for monitoring systems based on strain measurement, except that details of peak stress magnitudes and cyclic frequency are not required. Sensors should ideally be aligned with the direction of maximum stress range, so that cracking progresses straight across the sensor shim; however, the design allows for some deviation from the correct angle without loss of sensitivity. The physical dimensions of the sensor prevent its application to very small components.

THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

5. Conclusions

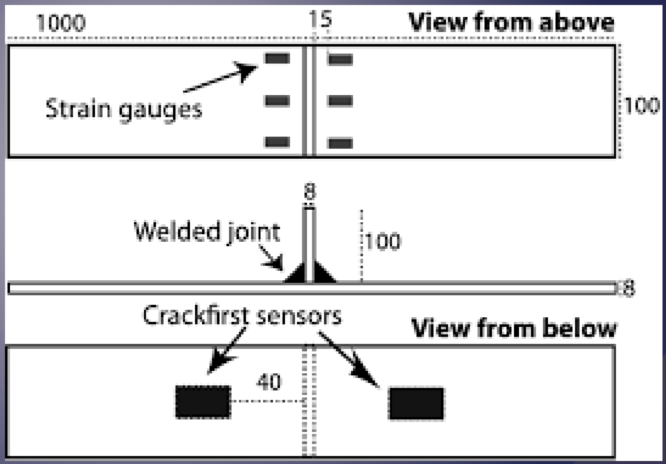
All sensors failed before the test specimens to which they were attached indicating that the sensors could be used to predict the failure.

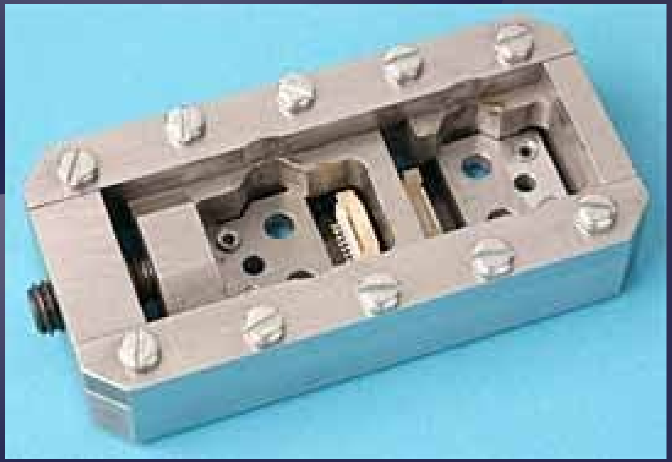
The sensor had a fatigue characteristic similar to the Class F design curve of BS 7608, and an approximately linear response to the number of cycles at a given stress range.

The sensor provided a reliable and sequential indication of design fatigue life consumed under cyclic loading.

Sensor attachment to the structure by a combination of CDW studs and epoxy resin adhesive gave satisfactory performance.

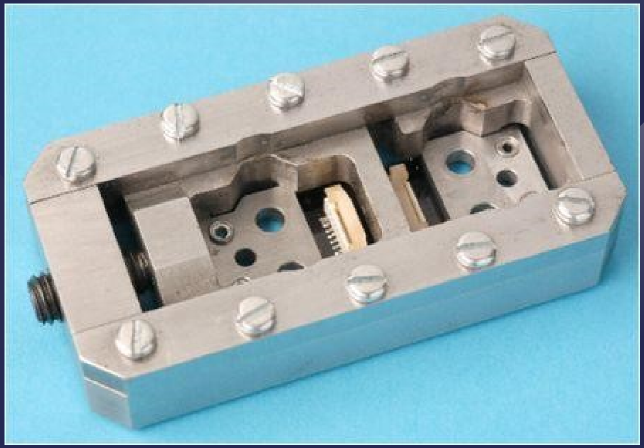
The fatigue endurance of the sensor, to some degree, depended on the loading mode. Sensors mounted on specimens subjected to a higher degree of bending stress gave marginally longer lives.

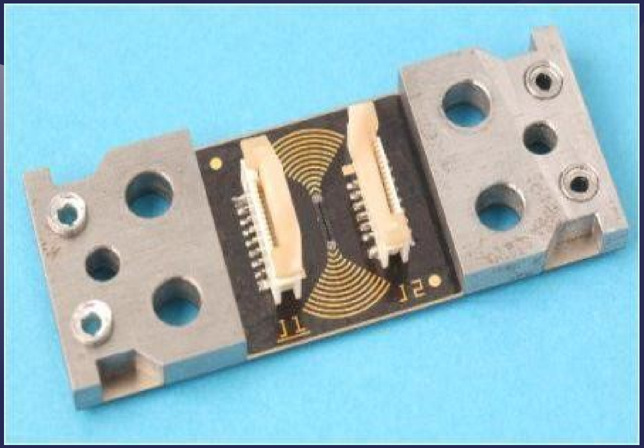




THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

- **The CrackFirst™is a fatigue sensor system for welded joints in steel structures, capable of providing advance warning of the rate at which the design life is being consumed.**
- **The CrackFirst™ sensor was designed for welded steel structures and patented in 1990. It consists of a thin shim of material attached to the target structure close to a critical joint. Under the action of cyclic stress in the structure, a fatigue pre-crack at the center of the shim, introduced during manufacture, extends by fatigue crack growth.**
- **The sensor design is such that the extent of crack growth in the shim is proportional to the cumulative fatigue damage for a welded joint subjected to the same loading. In other words, the condition of the sensor indicates how much of the design life of the adjacent weld has expired and how much remains.**





THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

- **There are several methods of powering and interrogating the sensor, which are based on the clients requirements.**

- **The simplest method is to interrogate the sensor using a multimeter. There is a known relationship between electrical resistance and crack length.**

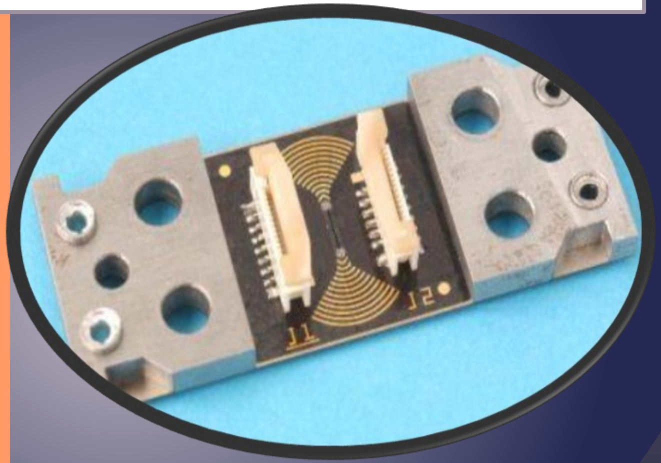
- **For remote location or more frequent checking, an on-board electronics unit regularly checks the sensor status and records in memory the date/time of each crack increment.**

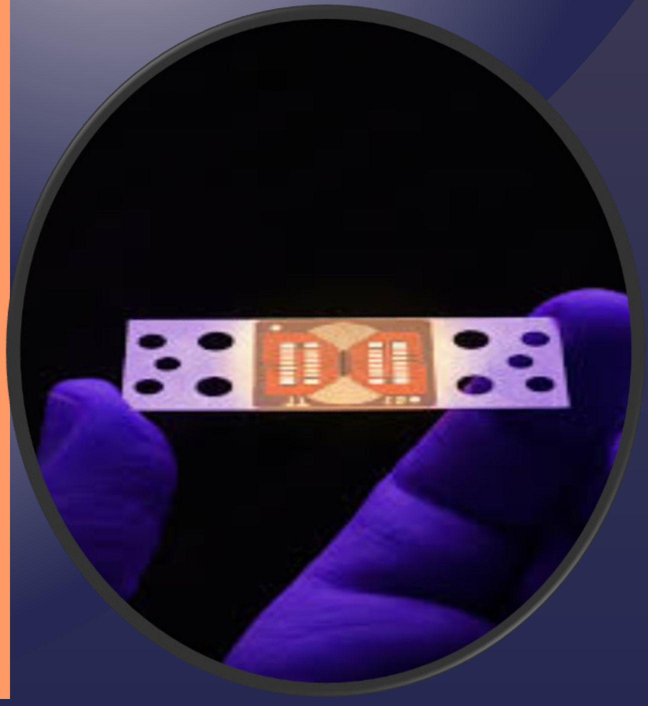
- **Sensor data can be downloaded to a laptop PC via a wireless link or to a datalogger.**

- **The power can be obtained from an on-board battery, a remote battery pack, the vehicles power or from a mains supply.**

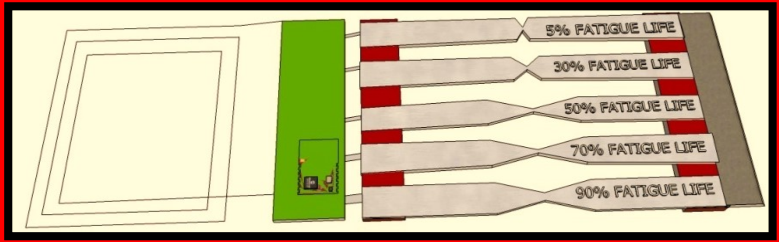
THE CRACK-FIRST FATIGUE SENSOR (TANKER-SHIP APPLICATIONS)

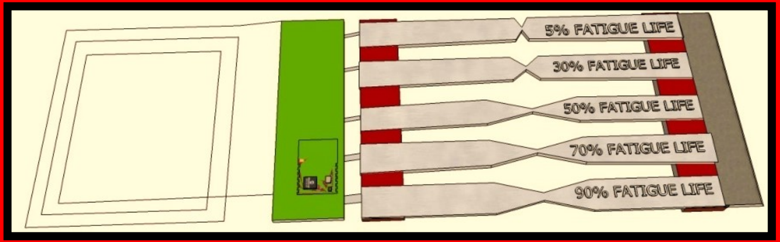
- The sensor comprises a steel shim 0.25mm thick, with openings at each end, and a central slit which acts as a starter notch for fatigue pre-cracking.
- It can be installed 10mm from the toe of a weld and is attached to a structure by a combination of threaded studs and adhesive bonding.
- In order to protect the sensor and the on-board electronics from mechanical damage and corrosion, a sealed enclosure is fitted over the entire installation area.
- The sensor is prestressed after installation using the rig shown in previous Figures. Data is expressed as a percentage of the design life for the appropriate joint class according to BS 7608.
- The CrackFirst™ system was developed through the collaboration of TWI Ltd, FBM, Micro Circuit Engineering Ltd, UMIST and Caterpillar Peterlee (a division of Caterpillar (UK) Ltd) in a project funded by the DTI's LINK Sensor and Sensor Systems for Industrial Applications Programme



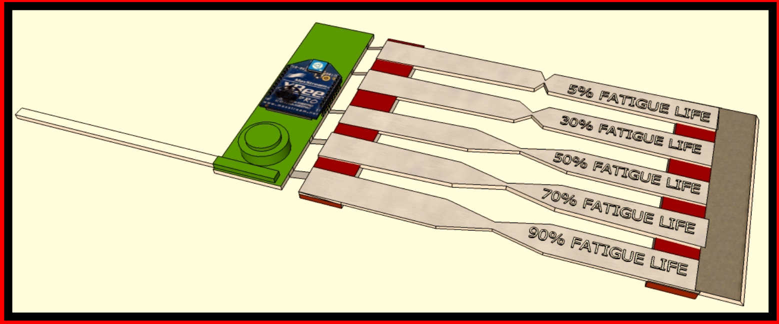


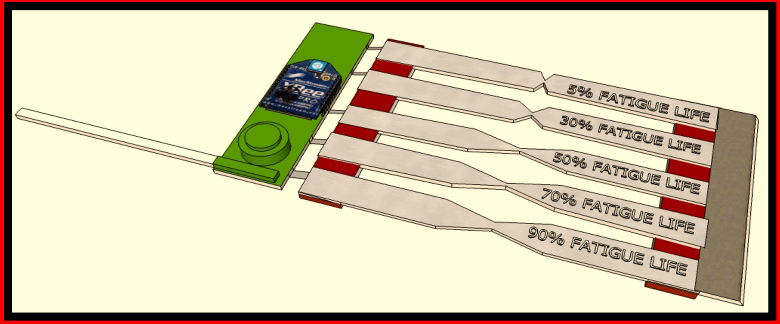
Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor





- **A Novel Smart RFID Fatigue Damage Sensor aiming to the prediction of fatigue residual strength of critical mechanical and structural components for Structural Health Monitoring has been DEVELOPED and PATENTED (Patent N0. US 8,746,077 B2).**
- **The proposed smart sensor system is designed for early detection and estimation of the structural health cumulative fatigue damage level and wirelessly transferring the information using an active or passive RFID integrated system.**





A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (TANKER-SHIP APPLICATIONS-WELDED JOINTS)

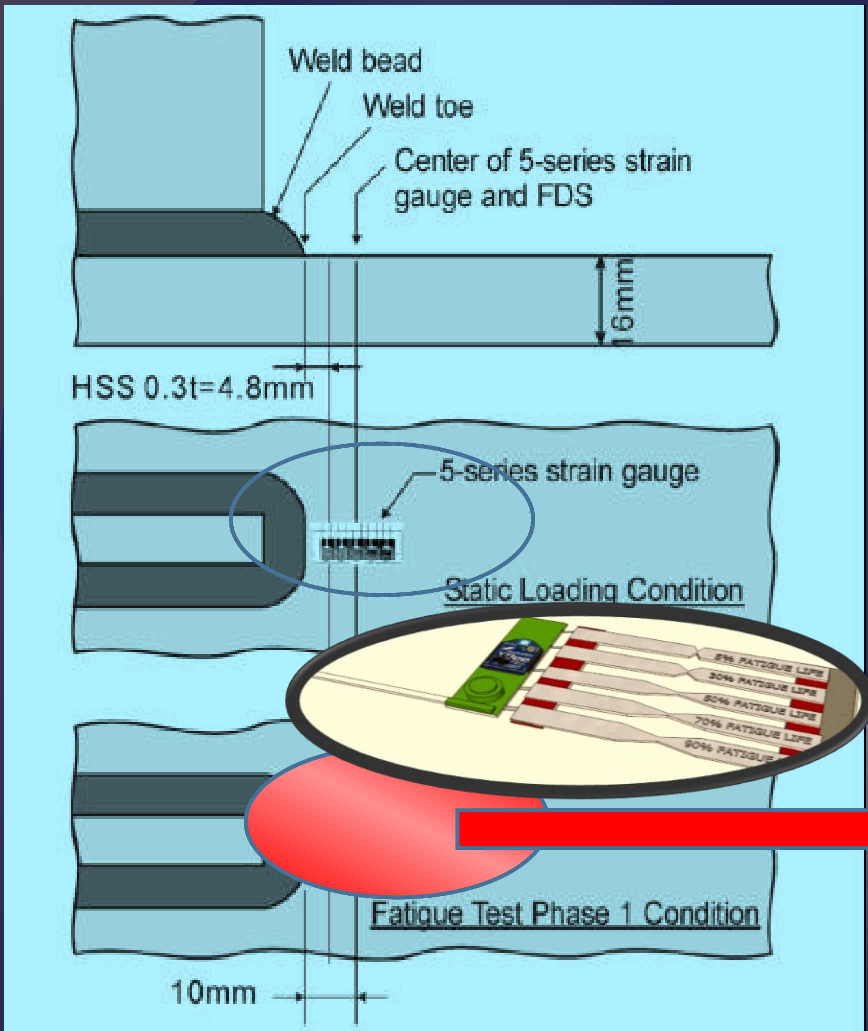


Fig.2.8 Location of strain gauge and FDS stuck near weld.

Fatigue sensitive regions, locations under high loads, predetermined and formerly known-experienced spots on the structures and mechanical components such as Welded, Riveted, Bolted and Hole Type Connections etc..

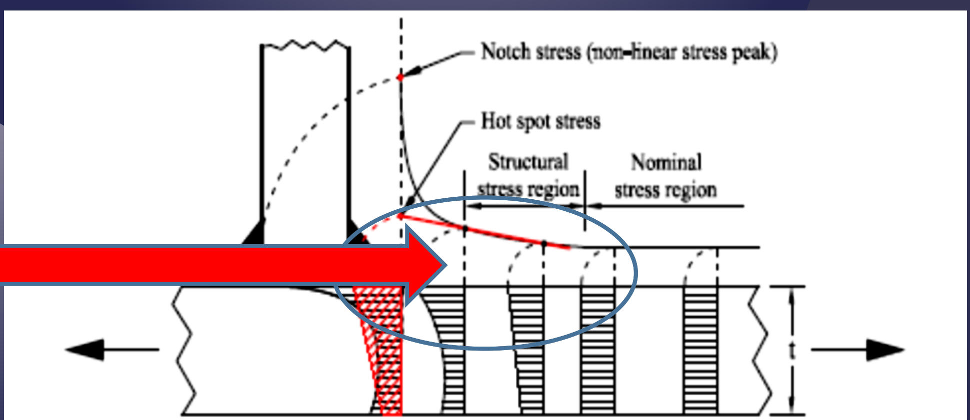
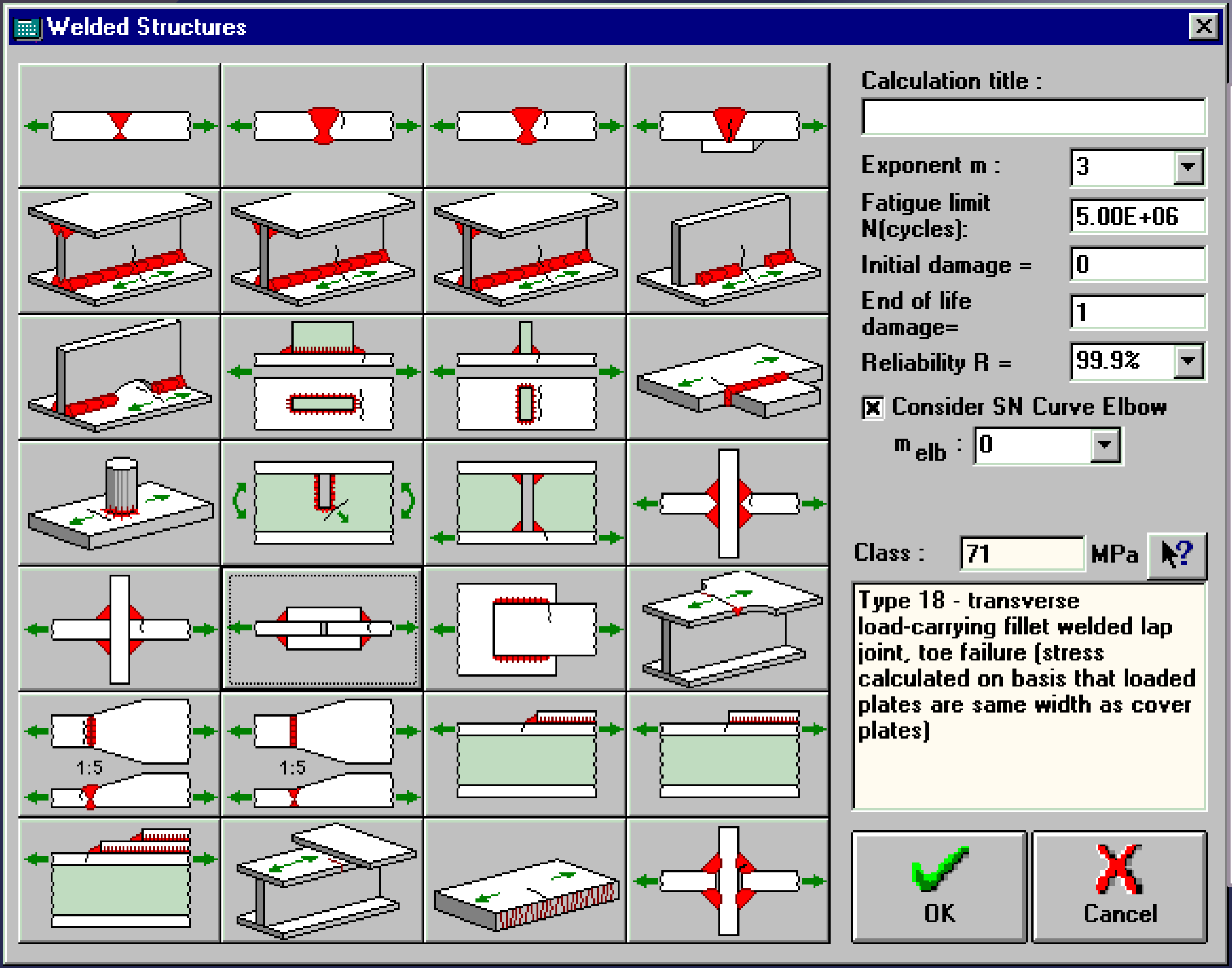


Figure 2-1 Stress distribution through plate thickness and along the surface close to the weld [5].

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (TANKER-SHIP APPLICATIONS-WELDED JOINTS)



Fatigue sensitive regions, locations under high loads, predetermined and formerly known-experienced spots on the structures and mechanical components such as Welded, Riveted, Bolted and Hole Type Connections etc..

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (TANKER-SHIP APPLICATIONS)

Fig. A5 View of Hopper After Erection, Looking Aft

(a) (b)

Fatigue sensitive regions, locations under high loads, predetermined and formerly known-experienced spots on the structures and mechanical components such as Riveted, Bolted and Hole Type Connections etc..

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (TANKER-SHIP APPLICATIONS)

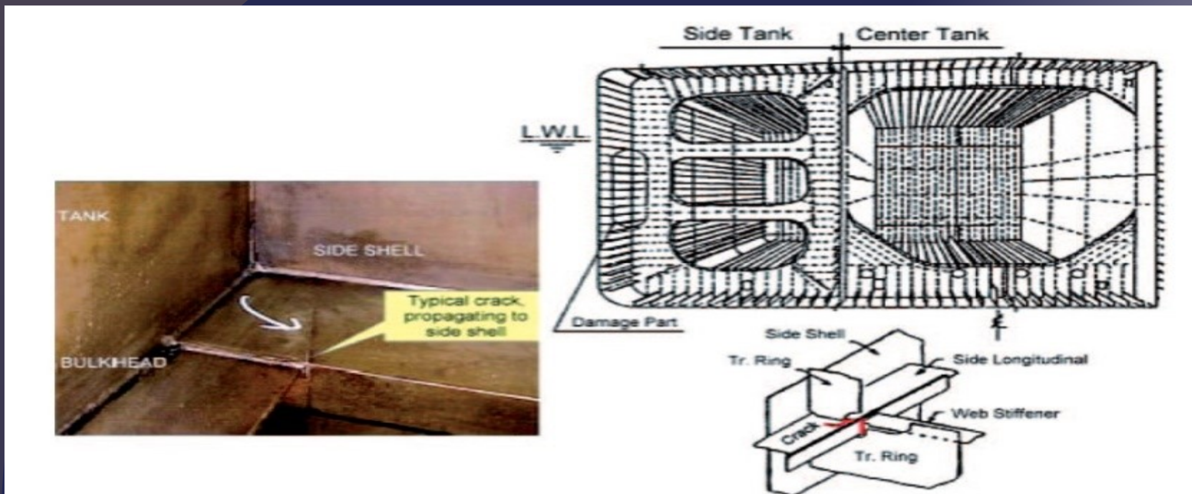


Fig. 1. Example of fatigue cracks in tankers [3]

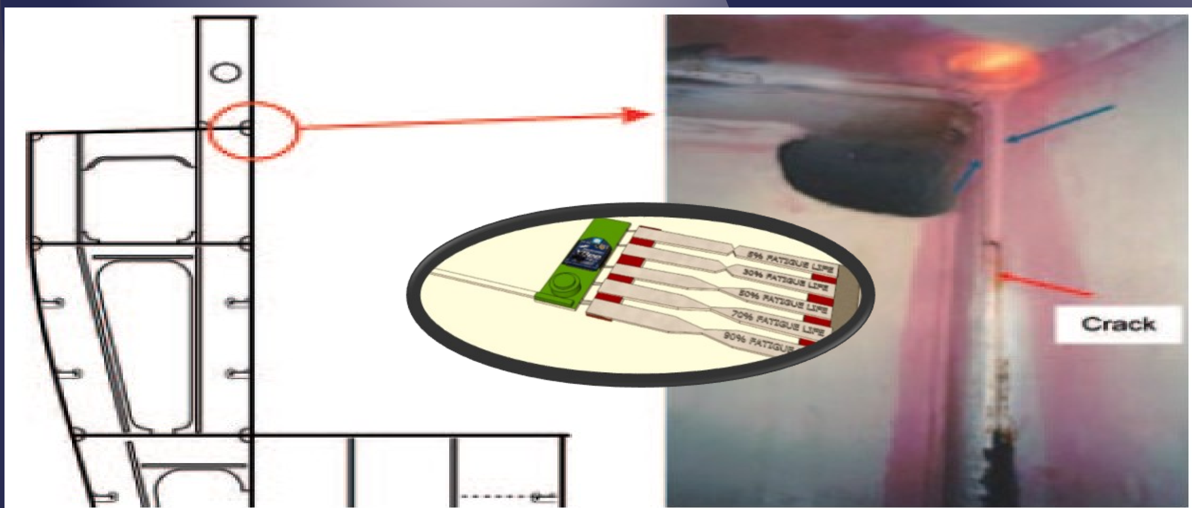
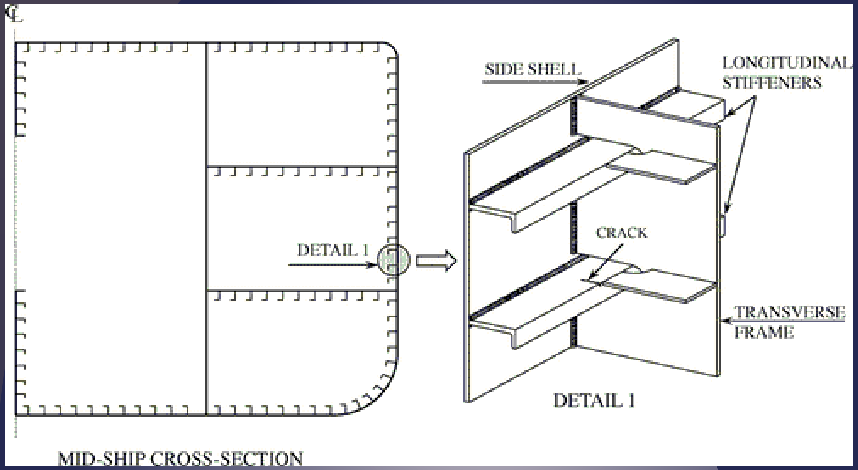


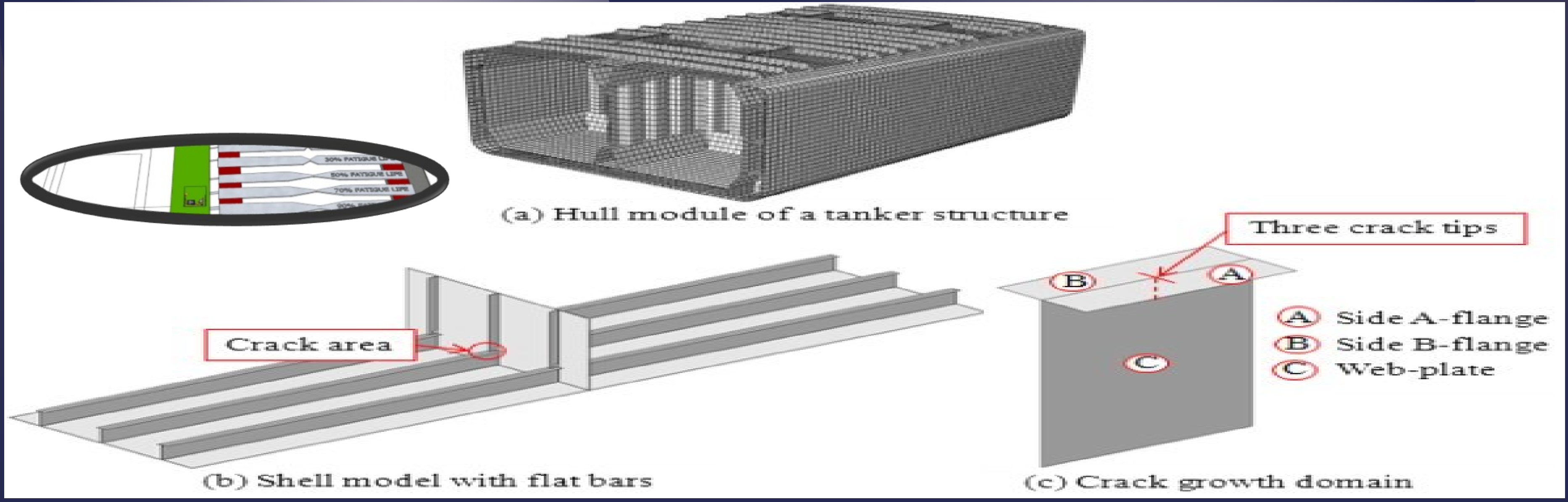
Fig. 3. Example of fatigue crack in welded joint of ship structure detail of a containership [3]

Fatigue sensitive regions, locations under high loads, predetermined and formerly known-experienced spots on the structures and mechanical components such as Riveted, Bolted and Hole Type Connections etc..

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor
(TANKER-SHIP APPLICATIONS)



Identify all the Fatigue Critical HOT SPOTS in STRUCTURES for the applications of Smart fatigue damage sensors in order to monitor the RESIDUAL FATIGUE STRENGTH



Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network

(WIRELESS FATIGUE DAMAGE SENSOR NETWORK FOR INTELLIGENT STRUCTURAL HEALTH MONITORING, MAINTENANCE AND DESIGN)

PRELIMINARY DESIGN

The overall scantling arrangement and Midship Section were developed and analyzed using ABS SafeHull and separate coarse meshed finite element

Nine Critical Details Addressed

The main objective in analyzing critical structural details was to identify and implement any potentially large structural changes prior to turnover of the design to

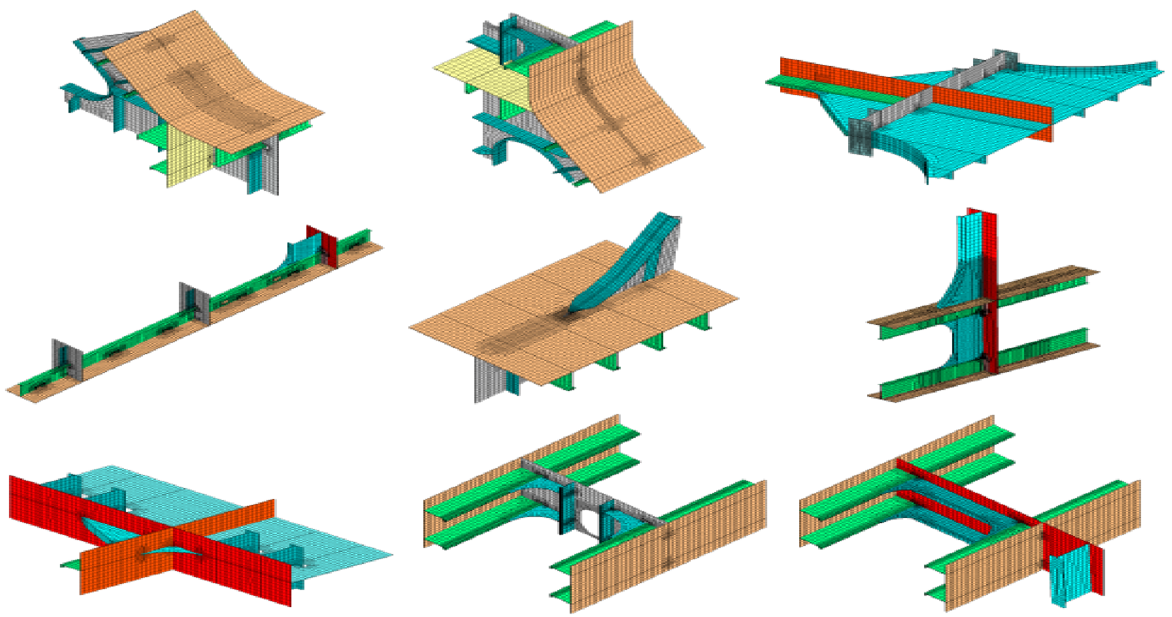


Fig. 5 Nine Local Details in Preliminary Analysis (Top row, l to r: Lower Hopper, Upper Hopper, Stringer at Centerline Bulkhead; Middle Row, l to r: Bottom Longitudinal, Transverse Web Frame at Tank Top, Double Bottom at Transverse Bulkhead; Bottom Row, l to r: Horizontal Stringer at Transverse Bulkhead, Inner and Outer Shell at Transverse Bulkhead, Inner and Outer Shell at Web Frame)

Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network

STRUCTURAL FATIGUE DAMAGE MONITORING, MAINTENANCE AND DESIGN in different components of TANKER-SHIP SYSTEMS (body frames or fatigue specific-sensitive elements) during normal service.

Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network (INTRODUCTION)

- **A Novel Smart RFID Fatigue Damage Sensor aiming to the prediction of fatigue residual strength of critical mechanical and structural components for Structural Health Monitoring has been DEVELOPED and PATENTED** (Patent N0. US 8,746,077 B2)**.**
- **The proposed smart sensor system is designed for early detection and estimation of the structural health cumulative fatigue damage level and wirelessly transferring the information using an active or passive RFID integrated system.**
- **The developed RFID fatigue sensor system has a specially designed geometry with multiple parallel oriented unidirectional, bidirectional or multi directional breakable C, 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.**

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network (INTRODUCTION)

- Whenever a particular beam of the sensor exceed the engineered number of fatigue cycles, the beam fails and sensor electronics detect that failure and transmit this information wirelessly.

- Having multiple beams that are designed to fail after precise number of fatigue cycles enables the health state of the structural member to be monitored. It gives ample warning about the health of the component so that necessary corrective measures can be taken.

- The sensor is quite lightweight with only several grams of weight and small in size slightly bigger than a credit card.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network (INTRODUCTION)

- Fatigue plays a critical role for design of structures or critical mechanical systems under cyclic dynamic loads. Several fatigue design methodology are used for fatigue design of mechanical components or structures. All these techniques are relied on STOCHASTIC MEDHODOLOGIES.

- Any failure in one of the structural members of the system causes catastrophic failure with serious consequences costing lives and property.

- Health status of structural members which undergo cyclic stress need to be monitored continuously and fatigued parts need to be replaced well before the failure limit is reached. Railway Systems, Aircrafts, Helicopters, Wind Turbines, Mega Cranes, Highway Bridges and Marine Vessels are especially considered as systems vulnerable to this sort of fatigue damage accumulation.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network (INTRODUCTION)

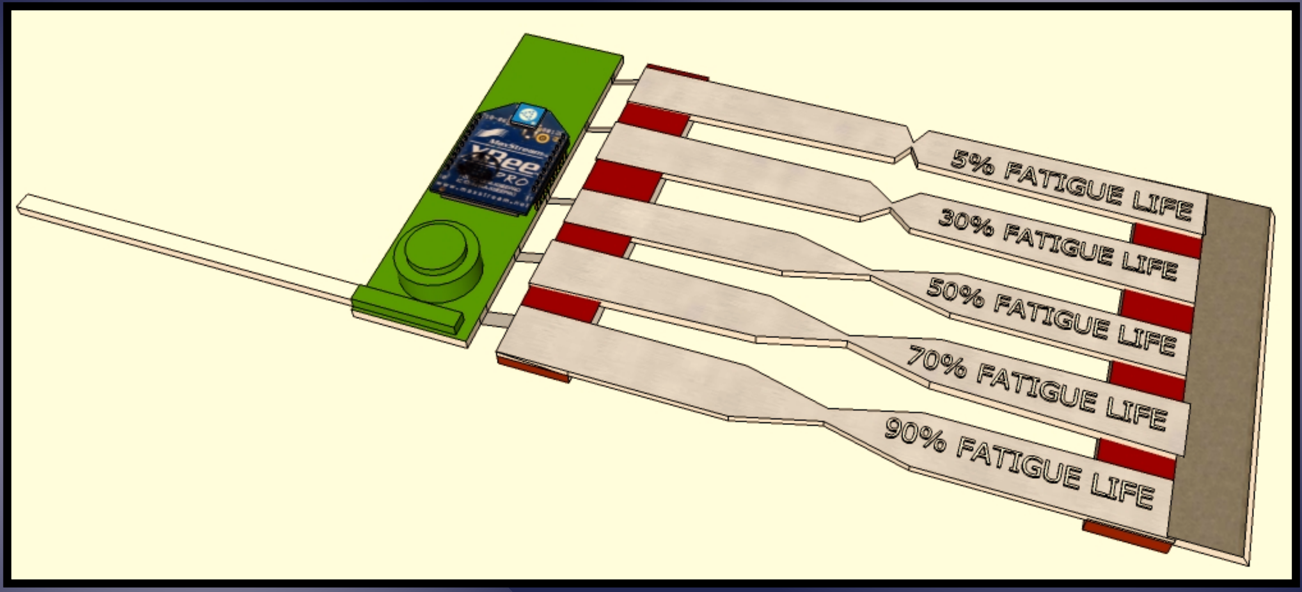
- **It is foreseen that the proposed RFID-IoT Smart Fatigue Sensor will revolutionize the concept of fatigue design and also will revolutionize the fatigue inspection and maintenance management methodologies by using the RFID-IoT Smart Fatigue Sensor Network Data.**

- **Since the distributed fatigue sensor network system periodically or continuously is 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 complex and large engineering structures or mechanic systems.**

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network (INTRODUCTION)

- The Figure shows the RFID FATIGUE DAMAGE SENSOR with 5 sacrificial beams members with fatigue life ranging from 10 % to 90 %.
- The 5-10% 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 5-10 % 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.

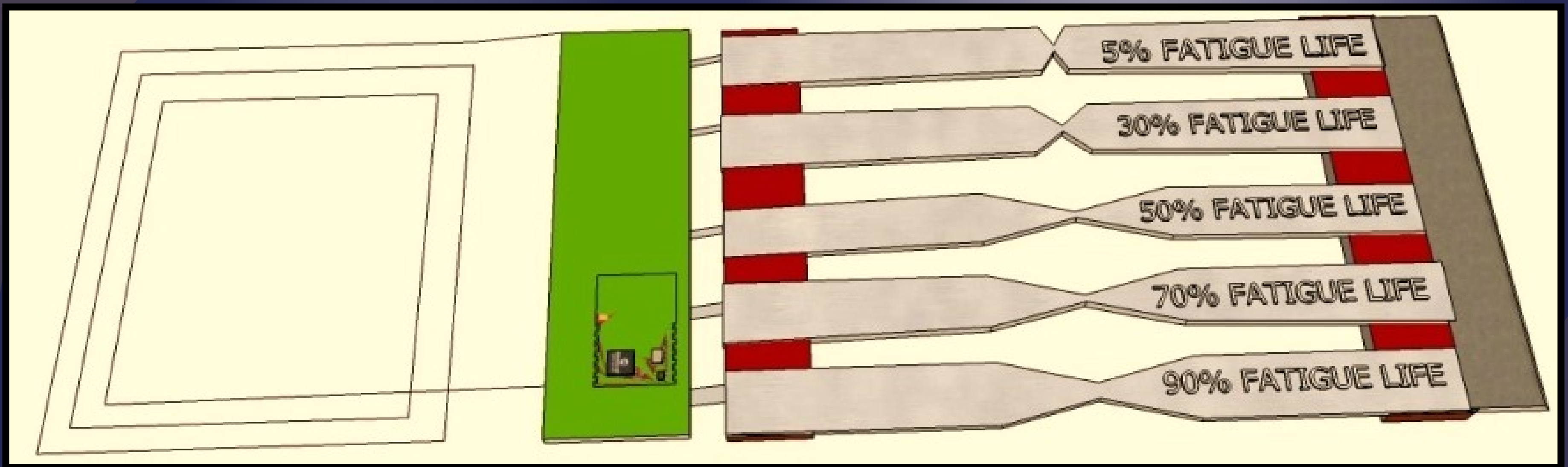
A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (ACTIVE SENSOR MODEL)



FATIGUE SENSOR (PATENT N0. US 8,746,077 B2)

There are two versions of the fatigue sensor, one with a battery version and another one which works with RF power. The one with the battery uses Zigbee 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.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (PASSIVE SENSOR MODEL)



Fatigue Sensor (Patent N0. US 8,746,077 B2)

The sensor with no battery is shown in figure. 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.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network (AS A NEW TYPE FATIGUE DAMAGE SENSING NDT MODEL)

- Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor is a novel smart methodology of Non-Destructive-Inspection (NDI) in order to monitor the structural integrity.
- Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor will be used for intelligent inspection, maintenance and maintainability. E.g. studies are predicting a maintenance cost reduction by up to 75% on Service Bulletin (SB) level and a clear increasing of the aircraft availability [1].
- Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor will be used to develop new methods and concepts for fatigue structural design, which can reduce the weight of structure for metal and composite structures up to 15% on component level [1].

- [1] Assler, H., Telgkamp, J. , "Design of aircraft structures under consideration of NDT", WCNDT-World Conference of Non-Destructive Testing, October 2004, Montreal, Canada

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network (APPLICATIONS TO STRUCTURES)

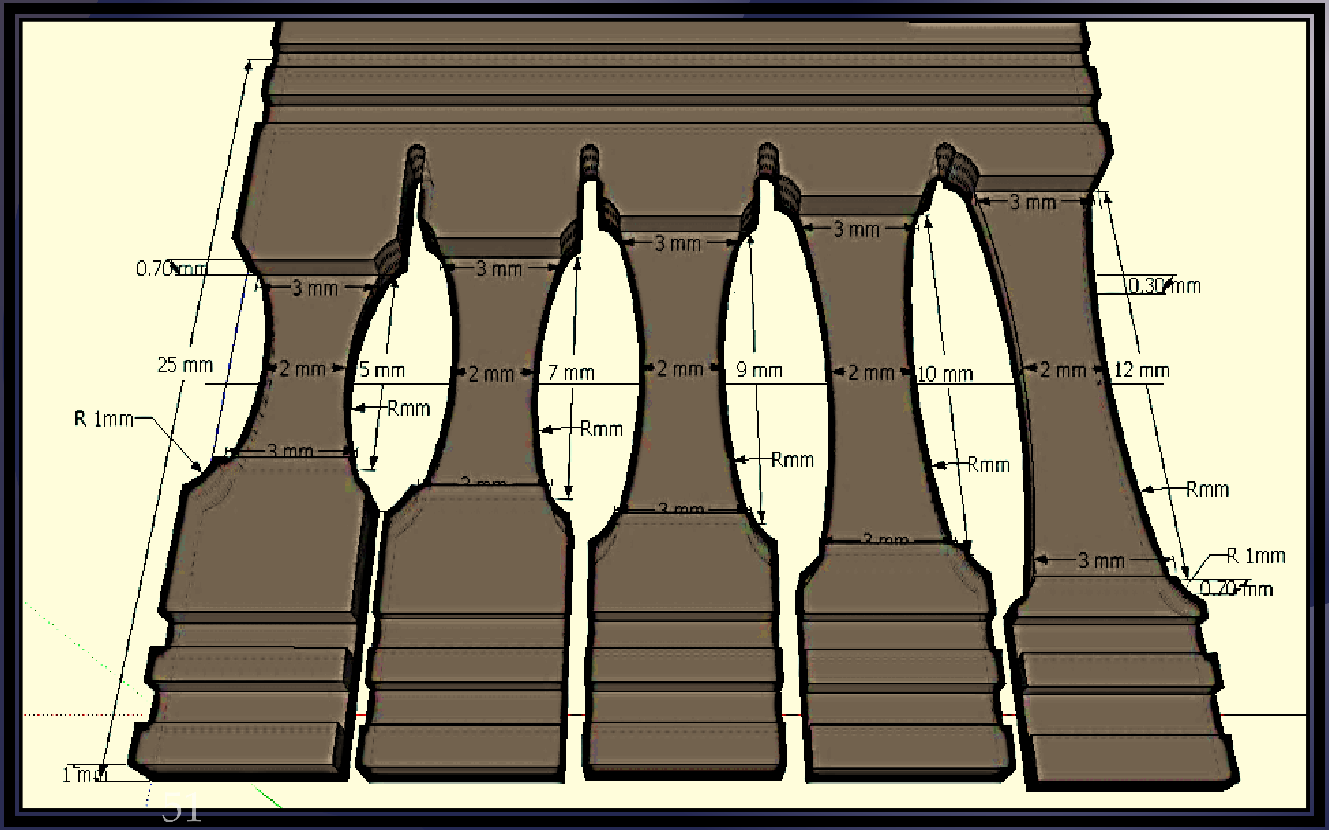
The fatigue sensor is designed to be attached to the surface by a special super bond very similar to strain gage attachments.

The 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 (Fatigue Life Cycles %10 N, %25 N, %50 N, % 75 N, %90 N)

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (APPLICATIONS TO STRUCTURES)

- Identify all the Fatigue Critical HOT SPOTS in STRUCTURES for the applications of Smart fatigue damage sensors in order to monitor the RESIDUAL FATIGUE STRENGTH or Fatigue Lifetime. Specific and Fatigue sensitive regions, locations under high loads, predetermined and formerly known-experienced spots on the structures and mechanical components such as Riveted, Bolted and Hole Type Connections etc..
- Determine of maximum critical STRESSES in all the Fatigue Critical HOT SPOTS in STRUCTURES(Bolted and Welded Joints) by using FEA numerical model of the structure for the applications of smart fatigue damage sensors in order to monitor the RESIDUAL FATIGUE STRENGTH or Fatigue Lifetime Monitoring.
- Development of Fatigue Model or Models of the selected FATIGUE SENSITIVE HOT SPOTS and Virtual FEA-Numerical Modeling and Analysis of the whole structure.
- Determine also the multi axial stresses acting locations and Find the principle stresses and directions for the applications of the sensors.

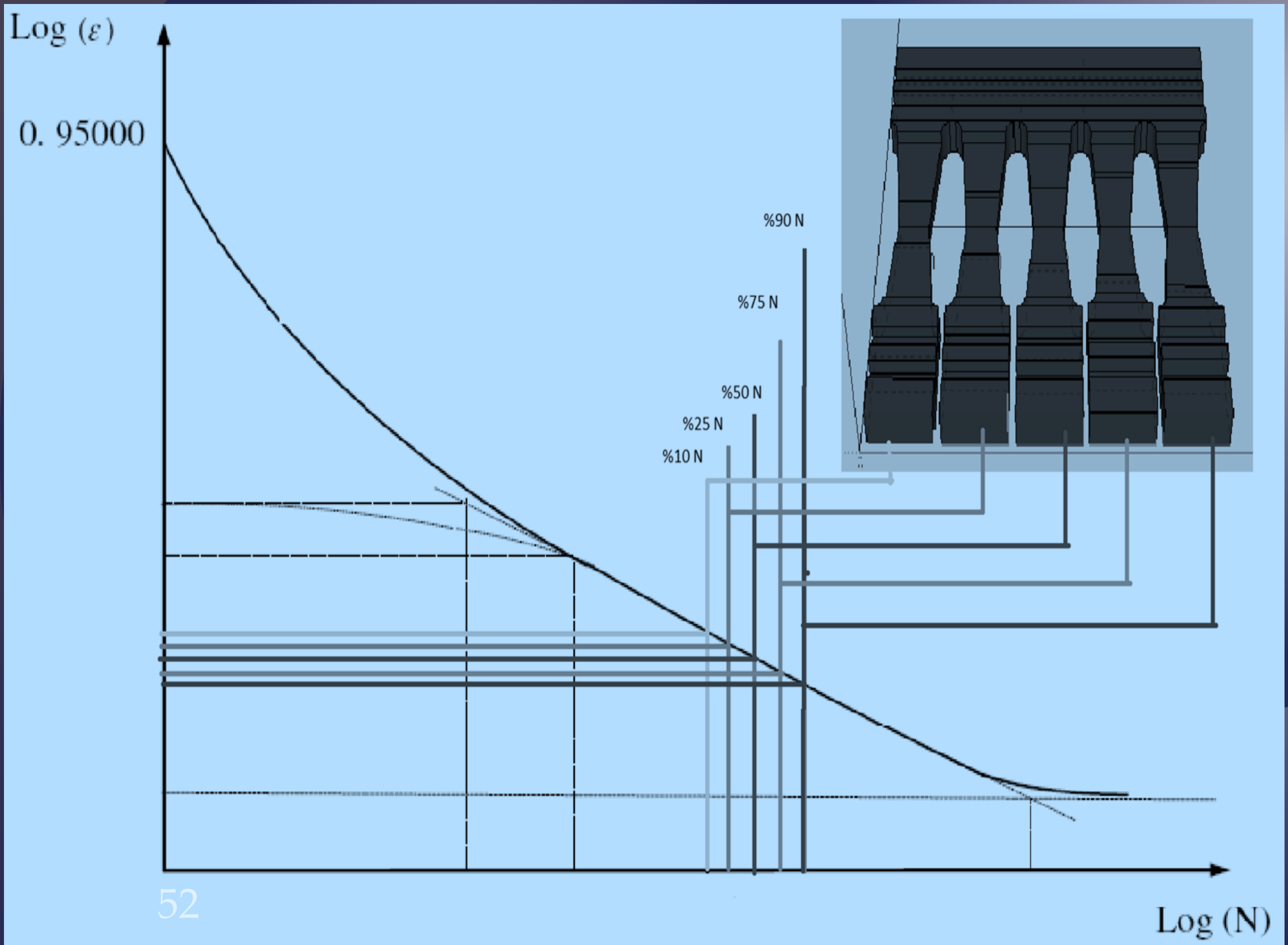
A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (DIMENSIONS)



Fatigue Sensing System with(BEAM (A), BEAM (B), BEAM (C), BEAM (D), BEAM (E), (%10 N), (%25 N), (%50 N), (%75 N) and (%90 N) Radius(R) Notch Mini (mm) Beams.

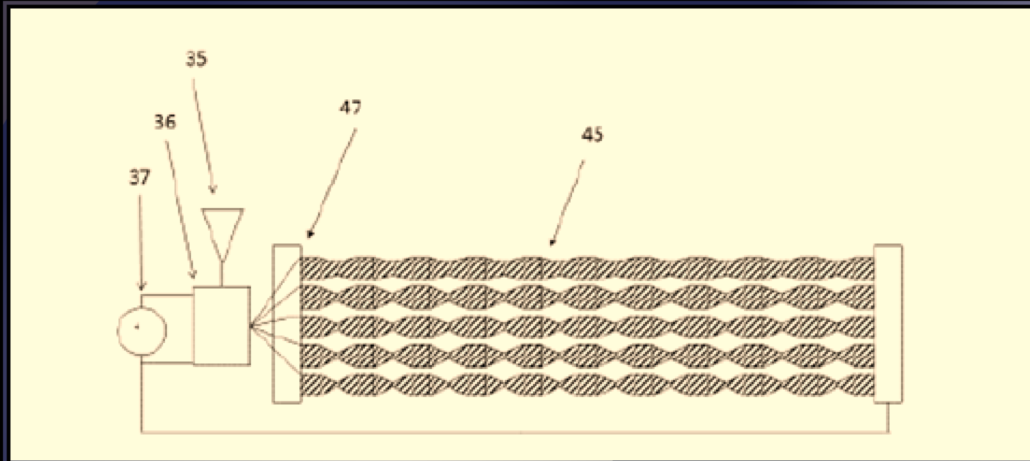
The fatigue sensor has five parallel mini beams with different fatigue lifetimes %10 N, %25 N, %50 N, % 75 N, %90 N-Total Lifetimes.

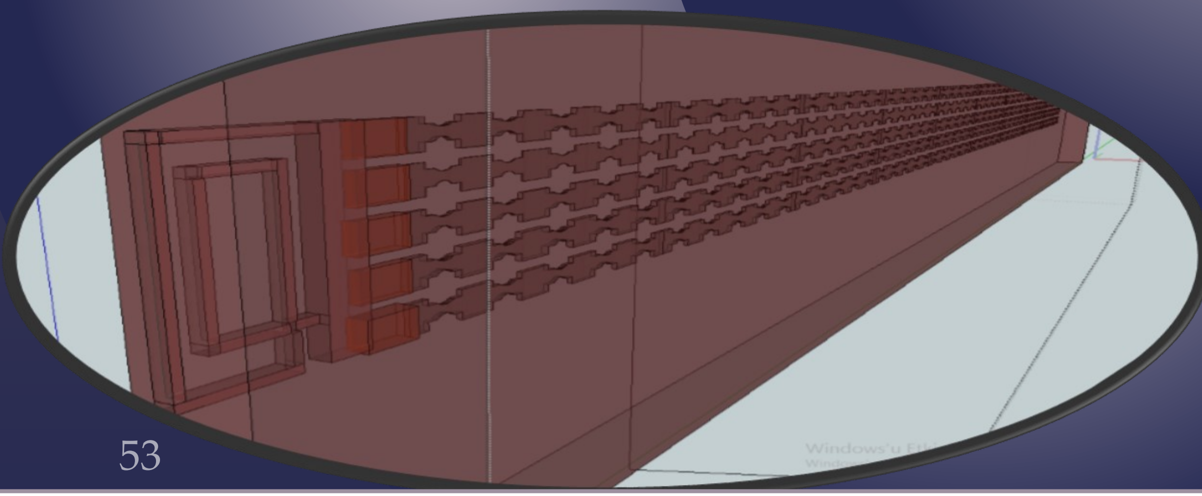
A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (STRAIN BASED FATIGUE DESIGN)



The FATIGUE DAMAGE SENSOR mini beams are designed according to STRAIN BASED FATIGUE DESIGN APPROACH.
The fatigue sensor with parallel mini beams having different fatigue lifetimes %10 N, %25 N, %50 N, % 75 N, %90 N-Total Lifetimes.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (SHIP APPLICATIONS)

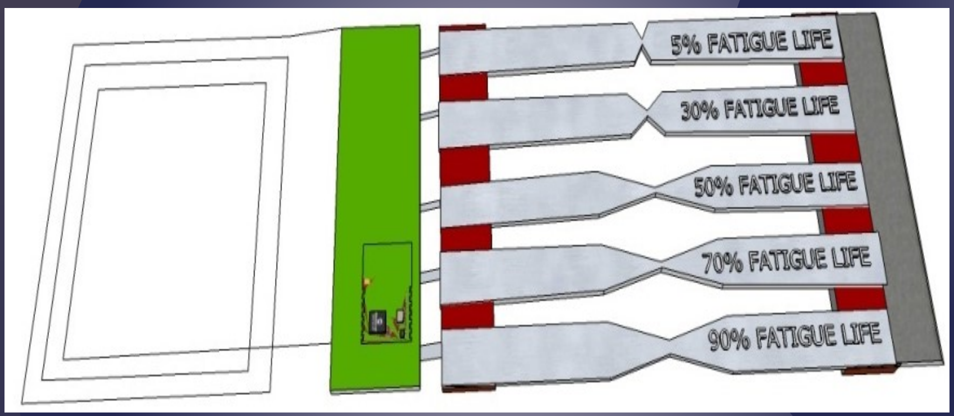


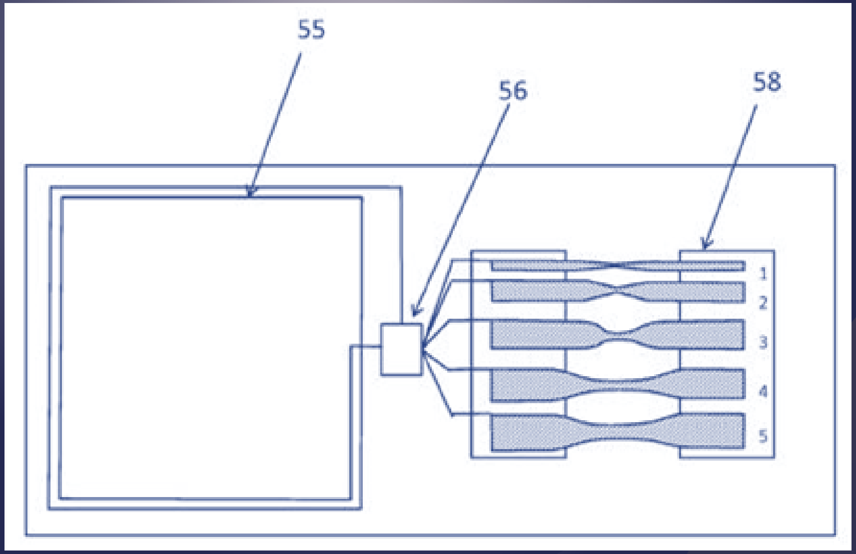


LONG SERIAL STRUCTURAL FATIGUE DAMAGE SENSOR

LONG SERIAL STRUCTURAL FATIGUE DAMAGE SENSOR AND APPLICATIONS FOR MONITORING, MAINTENANCE AND DESIGN in different components of TANKER-SHIP SYSTEMS (welded, riveted, bolted and other fatigue specific-sensitive elements) during normal service.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (PASSIVE SENSOR MODEL)

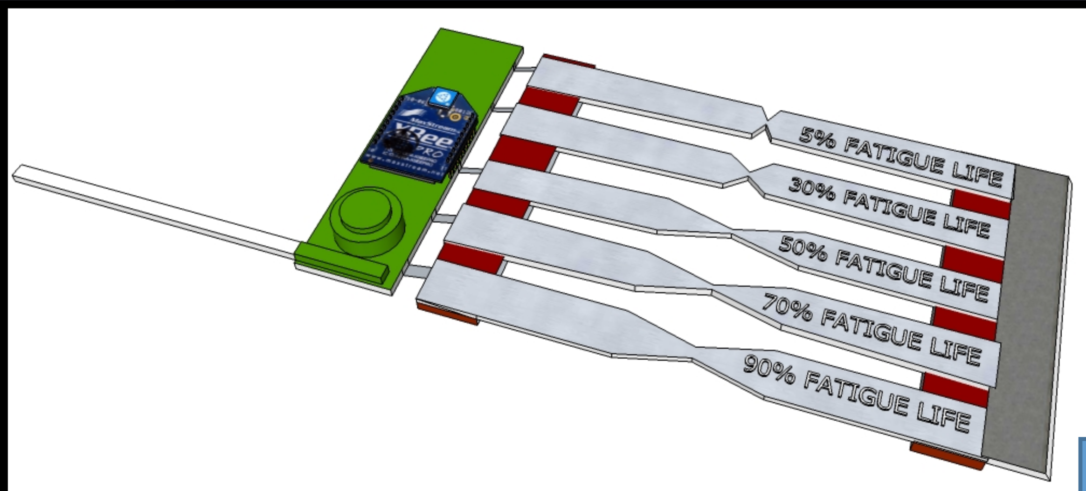




Fatigue Sensor (Patent N0. US 8,746,077 B2)

The sensor with no battery is shown in figure. 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.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (ELECTRONIC UNIT)



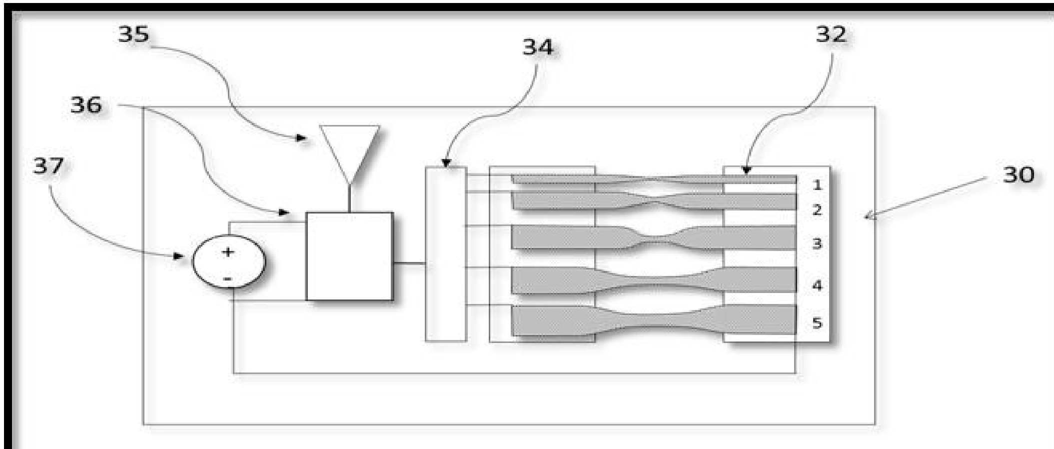
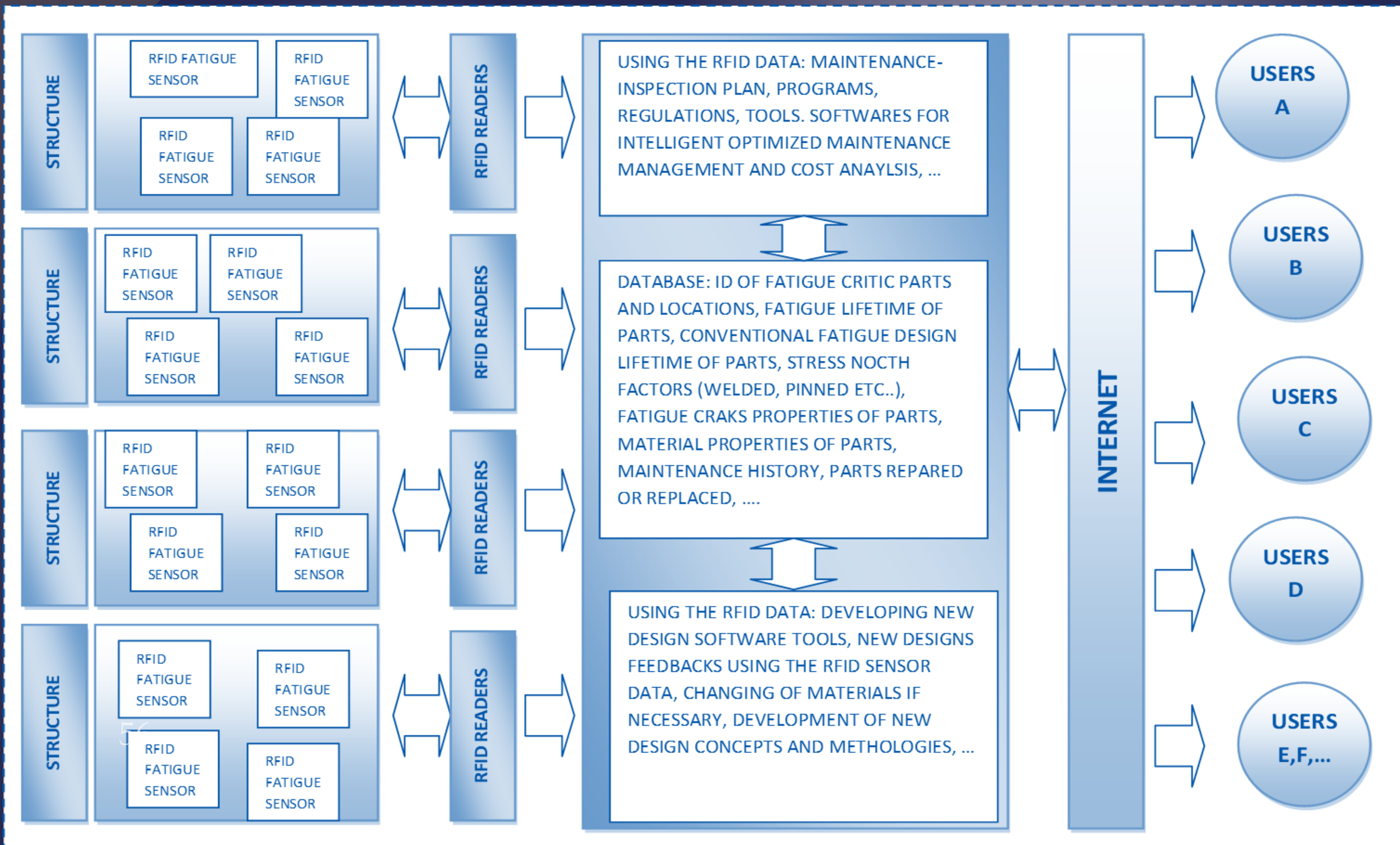


FIG 2.

The FATIGUE DAMAGE SENSOR mini beams are designed according to STRAIN BASED FATIGUE DESIGN APPROACH.
The smart fatigue sensor with parallel mini beams having different fatigue lifetimes %5-10 N, %25 N, %50 N, % 75 N, %80-90 N-Total Lifetimes.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (IoT SYSTEM MODEL)



A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (DISTRIBUTEDSENSOR NETWORK DATABASE)

DATABASE:

The RFID Fatigue Sensor System collects;

The operational lifetime history of each fatigue critical component or location, the fatigue properties of the critical part, the type of fatigue cracks, the maintenance history, the 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 parts repaired or replaced, the parts expected service lifetime, the parts crack lengths and many more useful information of structures.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (TANKER-SHIP APPLICATIONS)

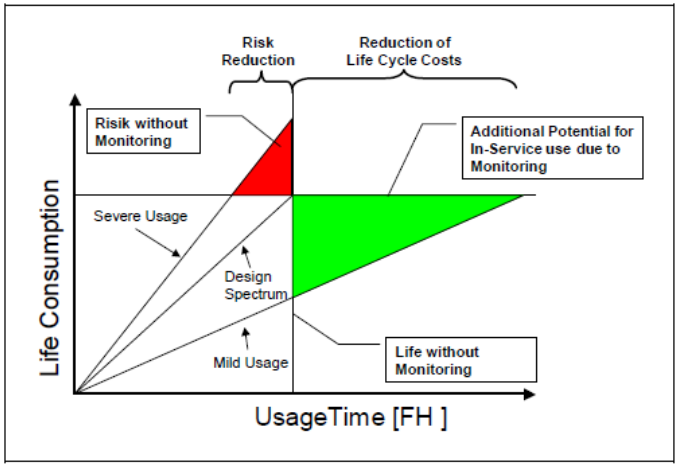
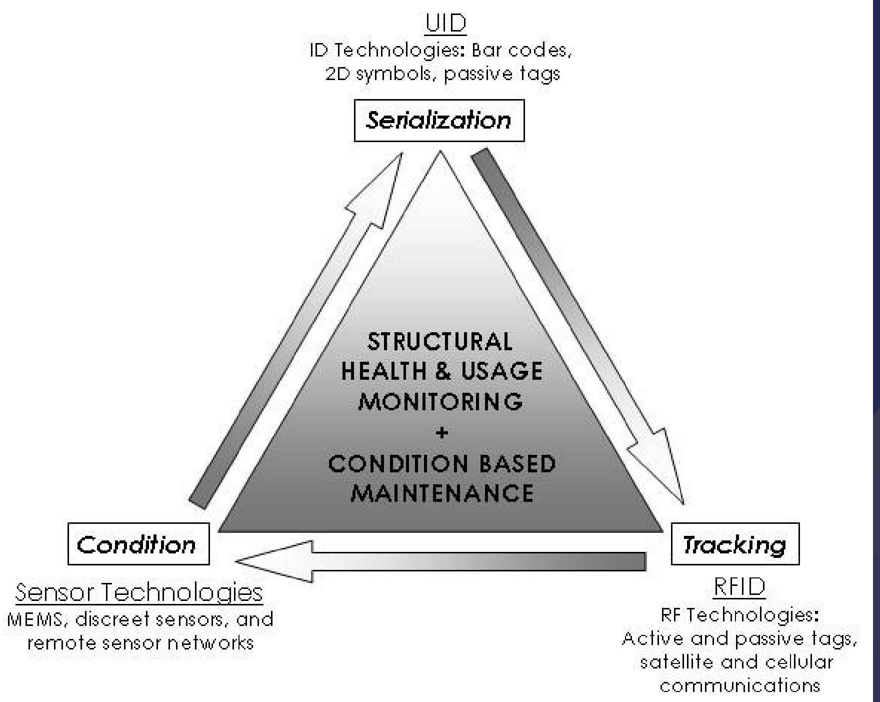


Figure 2: Benefit of Structural Health Monitoring



The Main Elements of the Smart Fatigue Damage Sensor for Structural Health Monitoring-SHM (INTELLIGENT CONDITION BASED MAINTENANCE MODEL)

The Smart RFID Fatigue Sensor System for SHM

- **Condition Detection with Sensors**
- **Tracking RF Technologies**
- **ID Technologies**

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (INTELLIGENT CONDITION BASED MAINTENANCE MODEL)

CONVENTIONAL STRAIN GAGE USED FATIGUE DESIGN AND SCHEDULED-PLANNED BASED MAINTENANCE OF STRUCTURES

PERIODICAL SCHEDULED-PLANNED BASED INSPECTION-CHECK DURING NOT IN SERVICE. FOR FATIGUE INSPECTION OF STRUCTURES, CRACKS SHOULD BE VISIBLE OR DETECTABLE CHECKING FOR ANY REPAIR OR MAINTENANCE CASES.

FATIGUE INSPECTION OF STRUCTURES WITH CONVENTIONAL STRAIN GAGE BASED DESIGN, FATIGUE CRACKS SHOULD BE VISIBLE OR DETECTABLE. HEALTH STATE OF STRUCTURES IS NOT KNOWN. A FULL SCALE FATIGUE TESTING OF STRUCTURE REQUIRED TO IDENTFY THE CRITICAL AREAS AND FATIGUE LIFETIME OF CRITICAL PARTS.

CONVENTIONAL STRAIN GAGE BASED INSPECTION-MAINTENANCE RELIES ON PERIODICAL SCHEDULED-PLANNED INFORMATION OR INSPECTION. CHECKING HEALTH STATE OF STRUCTURES IS MEASURED BY VISIBLE OR DETECTABLE SIGNS OR INSPECTIONS AND ALSO PROJECTED LIFETIME INFORMATION

RFID FATIGUE SENSOR AND PREDICTIVE-CONDITION BASED STRUCTURAL HEALTH MONITORING AND PREVENTIVE MAINTENANCE OF STRUCTURES

RFID FATIGUE SENSOR BASED CONDITION MONITORING OF STRUCTURAL HEALTH STATE. CONTINUEOUS OR PERIODIC CHECK OF STRUCTURES DURING OPERATION (IN SERVICE) FOR ANY REPAIR OR MAINTENANCE CASES DO MIANTENANCE BASED ON SENSOR DATA WHICH SHOWS THE HEALTH STATE OF STRUCTURE.

CUMULATIVE FATIGUE DAMAGE INDEX OF RFID FATIGUE SENSORS IS MIMICKING STRUCTURAL HEALTH STATE (CUMULATIVE FATIGUE DAMAGE INDEX) OF STRUCTURES. % 90 USAGE OF LIFETIME OF STRUCTURES OR TOTAL CUMULATIVE FATIGUE DAMAGE INDEX REACHES TO 0.9. PARTS CAN BE REPAIRED OR REPLACED.

RFID FATIGUE SENSOR BASED CONDITION MONITORING SHM SYSTEM RELIES ON THE SENSOR DATA.WHEN THE RFID SENSOR LIFETIME REACHES TO % 90 CYCLES OR TOTAL CUMULATIVE FATIGUE DAMAGE INDEX REACHES TO 0.9. THE STRUCTURAL PARTS CAN BE REPLACED OR REPAIRED. INCREASES RELIABILITY AND REDUCES MAINTENANCE COSTS

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (INTELLIGENT CONDITION BASED MAINTENANCE MODEL)

SOFTWARE FOR INTELLIGENT MAINTENANCE MANAGEMENT FOR STRUCTURAL FATIGUE HEALTH MONITORING OF A UNIT AND A FLEET

- 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 RFID Fatigue Sensor based Intelligent Predictive-Condition Based Maintenance Model is very efficient and effective strategic system since it increases service life and reliability and reduces maintenance and operations expenses.
- The proposed RFID Sensor Based Structural Health Monitoring and Maintenance Strategy are based on the periodic or real-time sensor information to optimize maintenance resources.

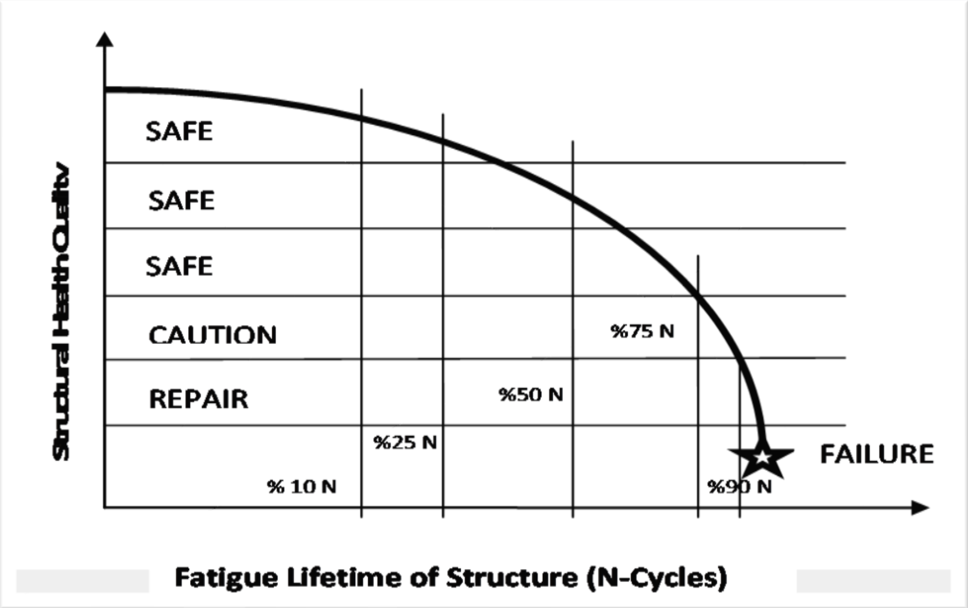
A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (INTELLIGENT CONDITION BASED MAINTENANCE AND LIFECYCLE MANAGEMENT MODEL)

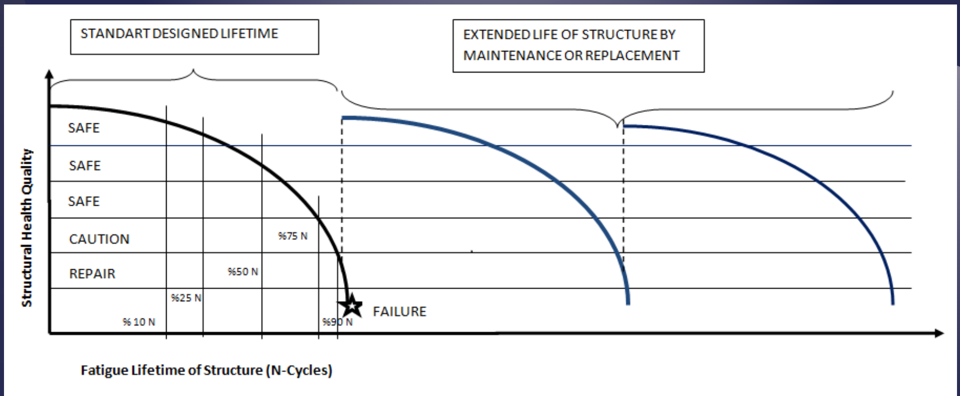
- Do maintenance based on the state of the structure as need arises
- Increases availability
- Reduces maintenance costs
- Increases reliability

THE LIST OF RFID CHIPS STORED STRUCTURAL FATIGUE MANAGEMENT INFORMATION OF EACH FATIGUE CRITICAL PART OF RAIL STRUCTURES

- a) The operational history of each critical component
- b) The maintenance or fatigue maintenance history of each component
- c) The information related to the configuration of the AICRAFT PARTS in which the component is installed
- d) The date the component manufactured
- e) The name of the supplier of the component
- f) The serial number of the component
- g) The part number of the component.
- g) The part expected scheduled repair time
- h) The part material properties
- i) The part redesigns needs and design modification or revision
- k) The part connection properties (rivet, welded etc...)
- l) The part repaired or replaced
- m) The part expected service lifetime
- n) The part ....

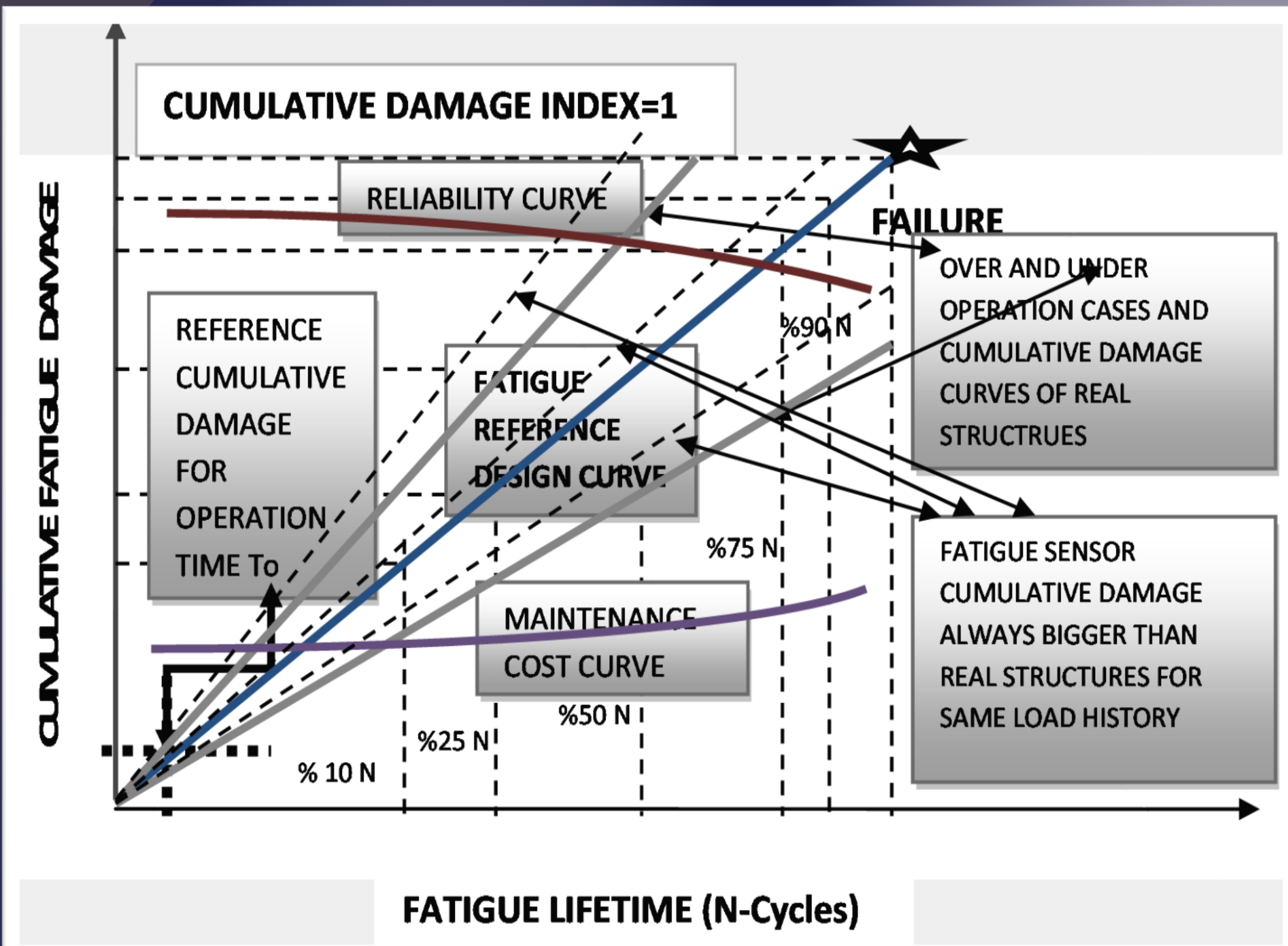
A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (HEALTH QUALITY AND LIFE EXTENSION)





- 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 RFID Fatigue Sensor based Intelligent Predictive-Condition Based Maintenance Model is very efficient and effective strategic system since it increases service life and reliability and reduces maintenance and operations expenses.

A Novel Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor (CUMULATIVE DAMAGE MODEL)



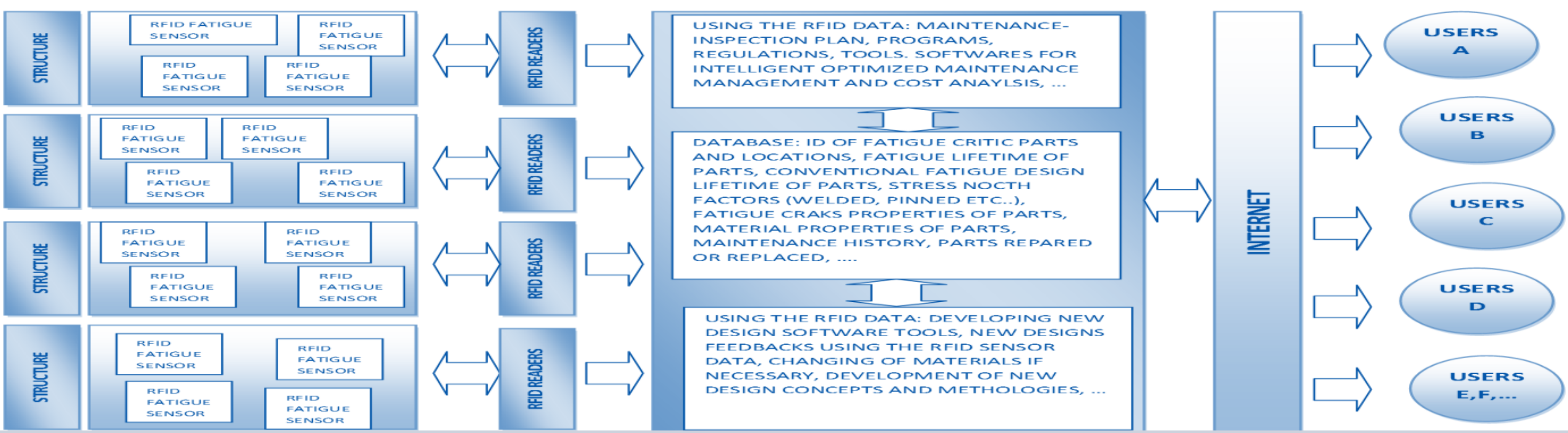
The proposed RFID Sensor Based Structural Health Monitoring and Maintenance Strategy are based on the periodic or real-time sensor information to optimize maintenance resources., INCREASES RELIABILITY, AVALIBILITY, SAFETY, AND EXTENT THE SERVICE LIFE OF STRUCTURES

Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network

(WIRELESS FATIGUE DAMAGE SENSOR NETWORK FOR INTELLIGENT STRUCTURAL HEALTH MONITORING, MAINTENANCE AND DESIGN)

INTELLIGENT DESIGN SOFTWARE BY USING THE RFID FATIGUE DAMAGE SENSOR DATA FOR FATIGUE STRUCTURAL HEALTH MONITORING

The structural fatigue health conditions of critical parts of structures are given according to the RFID Fatigue Sensor Network data. These data also provide a lot of information for new fatigue design improvements and also new design concepts. For this reason, the sensor data could affect the fatigue design regulations and methodologies since it is representing an extended periodic or real lifetime fatigue data for a unit and fleet of structures with SHM system.



Wireless Enabled SHM-RFID-IoT Smart Fatigue Damage Sensor Network