Structural Fatigue Analysis based on Rainflow-counting methodology

using Resensys Wireless Strain Gauge SenSpot^{TM}

Fatigue is described as the weakening of a material as a result of cyclic loading. This process causes localized structural damage and the growth of progressive cracks. When a fatigue crack has started, each loading cycle will further develop the crack a slight amount. This can result in striations on some parts of the fracture surface. In some cases, the crack can extend past a critical size and dimension. When the "stress intensity factor" of the crack surpasses the "fracture toughness" of the material, quick propagation occurs and often results in complete fracture of the structure.

It has been estimated that 90% of the structure failure is due to Fatigue. Fatigue failure can occur due to varying load with respect to time. The fatigue life of the component which is subjected to constant varying load can easily be calculated; however, when the varying load is random it is difficult to estimate the fatigue life. There are several methodologies suggested to convert the random load spectrum to simpler cycles and one such approach is cycle counting. In the cycles counting methodology, the same cycles are grouped together and Miner's rule is used to calculate the damage and fatigue life.[1]

There are a number of methods for the cycle counting, i.e. 1) Level crossing cycle counting, 2) Peak counting method, 3) Simple-range counting method, 4) Rainflow counting method, 5) Range-pair counting method, 6) Two-parametric fatigue characteristics. Rainflow counting method is widely practiced across the industry to convert the fatigue load spectrum to simpler cycle. This method is the most accurate and also it gives the average value.

Rainflow Counting methodology (RFC) is based on the Stress-Strain response which is a memory characteristic of material for the various amplitude loading. The path of the stress-strain curve is influenced by the residual state of stress due to prior strain history under variable cycle loading conditions.

A key objective is that for practical design the time history must be reduced to a manageable format still retaining the characteristics of the loading, and the stress history must be broken down into individual stress ranges with an associated number of stress cycles. This implies that accurate, precise, high frequency/ sensitivity and sometimes long term collection of data is critical to closely understand the stresses experienced by a material.[2]

A key reason that a clear understanding of the fatigue experienced by a material is important is that the fracture member may be a part of a more complex and bigger structure, such as bridge or offshore structure and its fracture could cause a severe incident with people involved. Crack propagation is a key concern in both design and analysis in many fields of engineering, especially in civil engineering where safety is one of the superior importance factors. What makes crack propagation even more problematic

[1] https://www.researchgate.net/publication/320837837_Modified_Rainflow_Counting_Algorithm_for_Fatigue_Life_Calculation

[2] http://homes.civil.aau.dk/lda/Advanced%20Structural%20Engineering/Stress%20range%20histories%20and%20Rain%20Flowcounting.pdf

that it is very hard to be clearly detected and measured. Hence, fatigue analysis usually uses implicit statistical and predictive tools in bridge safety studies. The applicable, measurable and monitorable quantity in fatigue analysis (using rainflow as an example of a widely-used methodology) is strain. The ability to measure high rate strain is important because sudden strain changes can trigger the need for high rate data collection and transmission, Resensys Wireless Strain SenSpot^{TM} sensors are well-suited for this application because the triggering threshold is adjustable from 16μStrain to 512μStrain and the sampling interval can be changed from 25ms to 200ms. These gauges are thus able to record the waveform of a sudden strain change, allowing data collected by these sensors (in particular, precise high-strain events data) to be suitable for accurate fatigue analysis such as that achieved using the rainflow-counting algorithm.

In addition to the above-mentioned high rate data transmission, and adjustable triggering threshold and sampling interval, Resensys Wireless Strain Gauge SenSpot^{TM} sensors measurement responses and collected data are well-suited for bridge and other structure fatigue analysis due to their accurate, reliable, and repeatable results, without need for calibration in the field. Resensys sensors also exhibit ultra-low power usage and are quick and easy to install. This allows for both short and long term use, whereby short-term uses can be easily repeated multiple times without the need for battery replacement or charging and/or authorities can keep the sensors on their structures permanently for long-term use (bridge structure health monitoring). After installation, SenSpot™ does not need battery replacement or any other maintenance during its entire service life.

In addition to the ease-of-use benefit described above, Resensys' wireless design is quick and easy to install because there is no additional wiring required. This reduces installation cost and time, making Resensys solutions a cost-effective way for owners to get the quality data they need for fatigue analysis.

Resensys Wireless Strain Gauge SenSpot™ sensors are small in size and lightweight. They can be used in concrete, steel and composite materials, and in a variety of environments such as under wet, humid and extreme weather conditions (-40°C to +65°C or -40°F to +150°F). The product is corrosion resistant and can withstand salty environments.

A typical installation to collect and monitor data for Fatigue analysis comprises the following components:

- Wireless Strain Gauge SenSpot™which are attached to the elements requiring monitoring. The number of sensors required per structure is usually dependent upon the design, existing cracks on members and fatigue analysis needs.
- SeniMax^{TM}: gateway/ data logger, which collects SenSpot^{TM} data at the site and sends it to a remote server (one unit can cover as many as 100 SenSpot^{TM} sensors).
- Repeater: may be used to extend the range of the SenSpot^{TM} sensors.
- SenScope^{TM}: software for data analysis and visualization.

Resensys Wireless Strain Gauge SenSpot™ sensor installed on the bridge for fatigue analysis using the rainflow methodology

Resensys SenSpot™ sensors are easily placed/ installed on critical elements (girders, gusset plates, bearings, floorbeams, interior/exterior stringer, dead load consideration members, steel pier bent or truss members/connections) as determined by inspection (e.g. existing cracks on members), finite element modeling, previous fatigue analysis or authority's/client's suggestion especially after observation of big cracks on members. The sensors are mounted with adhesive or flange mounted depending on the application. A SeniMax™ data acquisition unit is conveniently mounted nearby (within 1.0Km (0.62miles) free space of the SenSpot™ sensors) and a SenScope™ module is installed on the client's/authority's laptop or PC.

A complete Resensys Structural Health Monitoring (SHM) system includes software and hardware components for (1) the reliable collection of SenSpot™ data, (2) aggregation of the data, (3) the addition of timestamps, (4) communication of encrypted data to a remote server, and finally, (5) an interface for data visualization and detection of structural issues. Figure below shows a picture of a practical Resensys Structural Health Monitoring (SHM) system, which can be used for bridge or other fatigue analysis based on rainflow methodology.

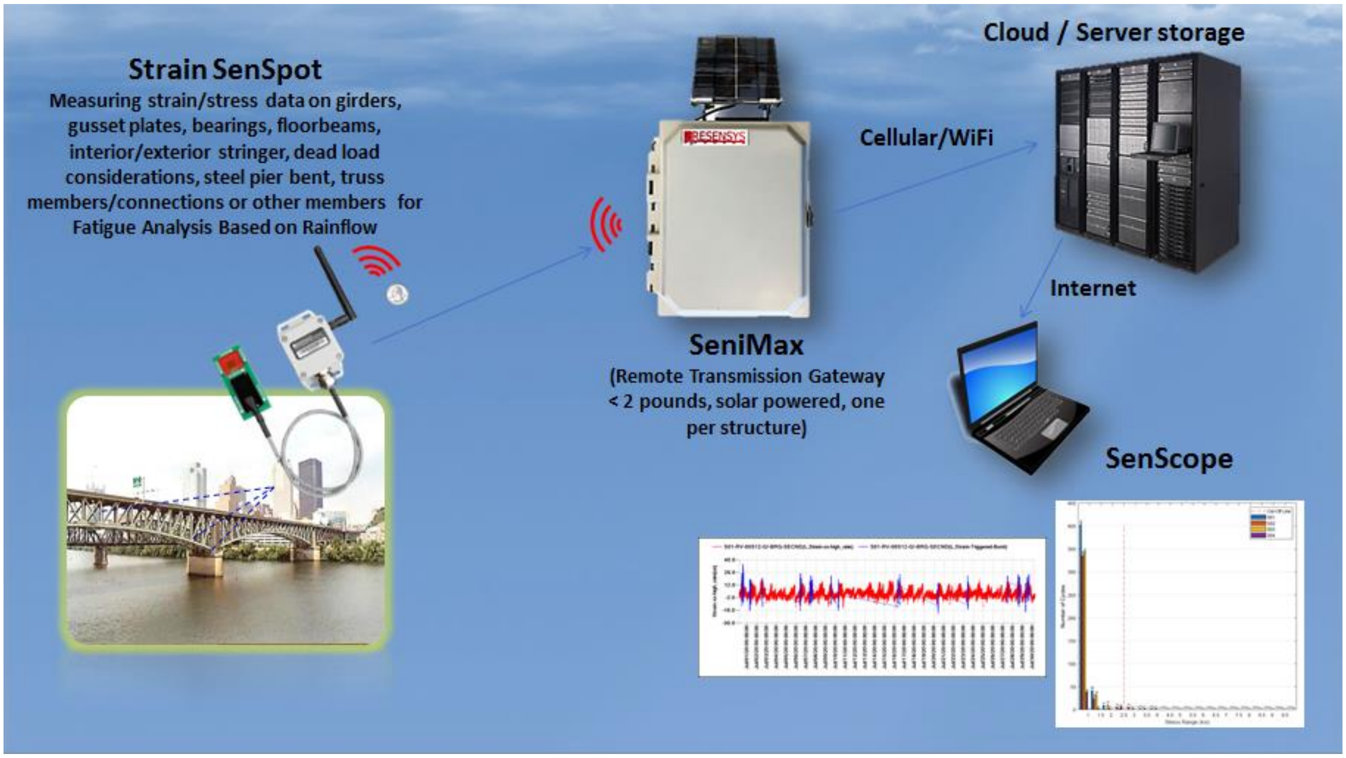
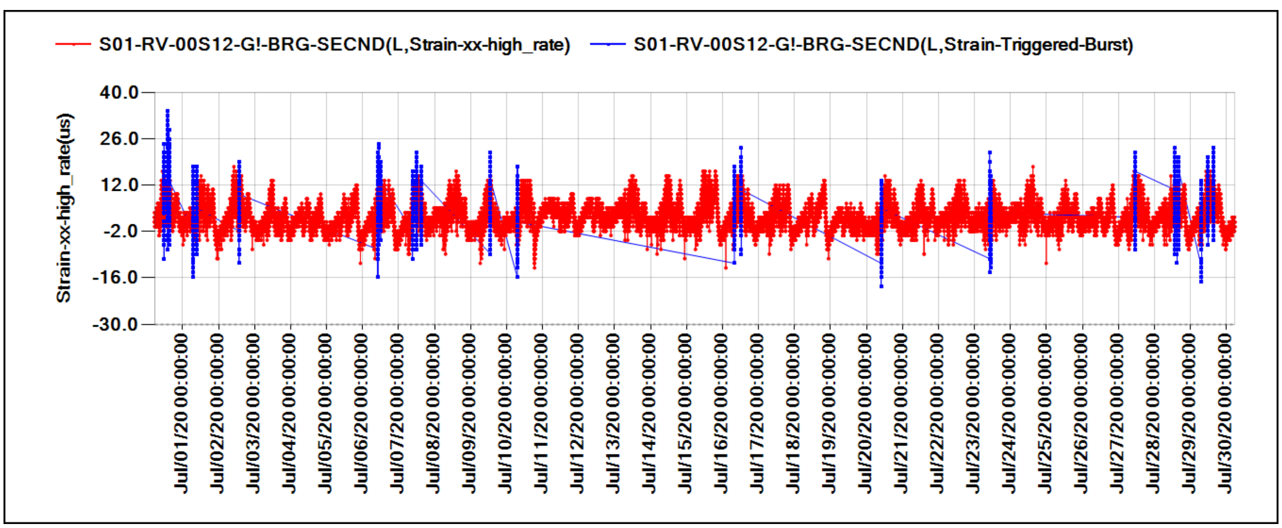


Illustration of Resensys SHM based on SenSpot™ sensors for bridge fatigue analysis using the rainflow methodology

Technical Note regarding strain gauge data as applied to fatigue analysis per AASHTO LRFD Bridge Design Specifications:

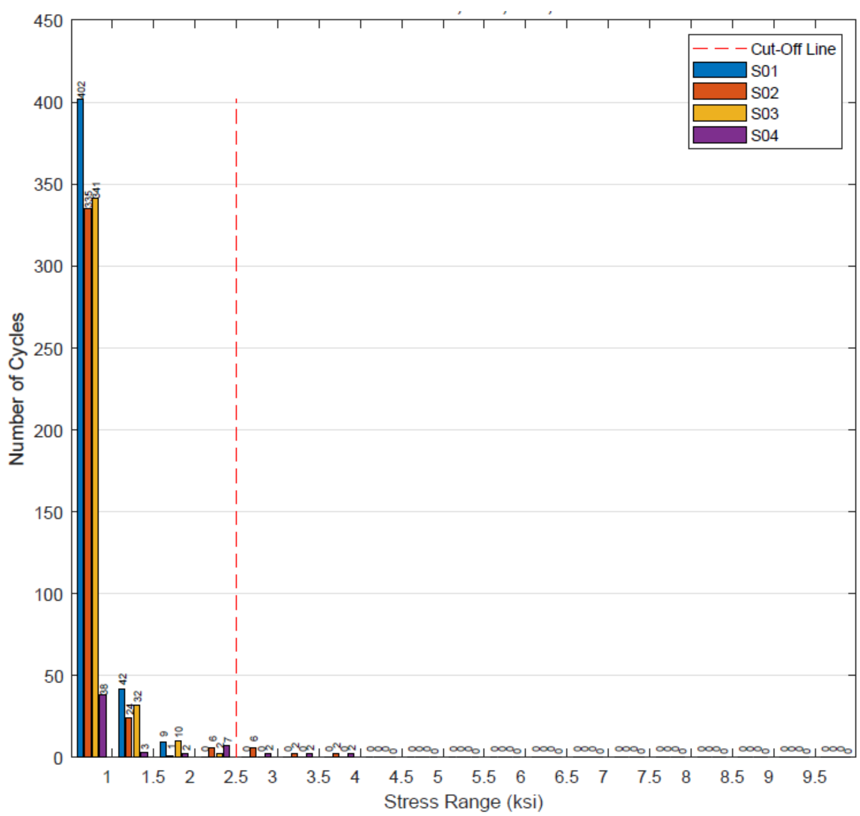
High-strain events would be detected by the Strain-Triggered-Burst technology of the Wireless Strain Gauge SenSpot™ sensors. This technology collects 40 samples per second. High-strain events corresponding data (Strain-Triggered-Burst) can be combined with all strain data (see graph below).



Strain (Red) and Strain-Triggered-Burst (high-strain events) (Blue) measurements of an installed Wireless Strain Gauge SenSpot™on a bridge

The sample data provided above is an example of strain gauge data that would allow fatigue analysis to be performed in accordance with AASHTO LRFD Bridge Design Specifications. This analysis is based on bridge operation start year; modulus of elasticity of steel used in bridge construction (E); category details of each strain gauge corresponding member position (A, B, C, D or E); and supposes that strain (stress) history measured has been repeated since the start of bridge operations and will remain unchanged into the future, i.e. traffic experienced during monitoring period is representative of the bridge's operational loads in the past as well as into the future. The rainflow counting technique is used in the analysis of fatigue data.

This data can be displayed as a frequency distribution as shown in the histogram image below, where the frequency distributions of stress-range detections at each strain gauges reported. Additional insights obtained from analysis of the strain measurements collected include effective stress range, cycles per day, and the number of times the stress range exceeded Constant Amplitude Fatigue Limit (CAFL).



Frequency distribution of stress-range detections at each [Wireless Strain Gauge SenSpot™]sensor (Histogram)

Technical Specifications:

	Wireless Strain Gauge SenSpot™ sensor
Size (Dimension)	76.2mm (3”) x 33.4mm (1.3”) x10mm (0.4”)
Weight	147g (5.2 oz.)
Mounting	- Self-adhesive, no drilling is required (e.g. steel) -Flange-mount, drilling is required (e.g. concrete)
Accuracy (Resolution)	2μStrain
Operating temperature	-40°Cto +65°C (-40 °F to +150°F)
Lifetime	Minimum expected life without battery replacement is 3 years (Ultra-low-power)
Installation Time	1-2 minutes
Complementary sensing	Temperature, battery voltage
Communication range	1.0km(0.62mile)free space
Power source	Replaceable lithium ion battery
Wireless communication	No wiring needed for deploying the system- IEEE 802.15.4
High rate data transmission triggered by sudden strain changes	- A balance between power consumption and performance. - Perfect for recording the waveform of a sudden strain change. - The triggering threshold is adjustable from 16μStrain to 512μStrain; the sampling interval can be changed from 25ms to 200ms.