# Finite Element Method (FEM) Model Verification and Validation for Bridges, Buildings and other Structures

## with Resensys Wireless SenSpot™ Sensors Measurements

The **Finite Element Method (FEM)** is the most widely used method for solving problems of engineering and mathematical models. The FEM is a particular numerical method for solving partial differential equations in two or three space variables (i.e., some boundary value problems). To solve a problem, the FEM subdivides a large system into smaller, simpler parts that are called finite elements. This is achieved by a particular space discretization in the space dimensions, which is implemented by the construction of a mesh of the object: the numerical domain for the solution, which has a finite number of points. The finite element method formulation of a boundary value problem finally results in a system of algebraic equations. The method approximates the unknown function over the domain. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. The FEM then uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function.[1]

Verification and Validation (V&V) is an enabling methodology for the development of computational models that can be used to make engineering predictions with quantified confidence. **Validation** in finite element methods (FEM) is the process to check whether the simulation results reflect real world results. In other words, validation is the process of defining the grade to which a model is a precise representation of the real world from the perspective of the projected uses of the model. **Verification** is the process by which we check that the finite element analysis (FEA) was conducted properly. In other words, verification is the process of defining that a model implementation correctly represents the developer's conceptual description of the model and its solution. Verification and Validation are processes that cumulate evidence of a finite element model's correctness and accuracy for a specific scenario. [2] [3]

Once the finite element model is created, the solution process is initiated, which in itself involves solving large number of linear equations, introducing numerical errors at each step. While most of the errors can be neglected, there are errors due to approximations that can lead to FEA malpractices. Hence, it is always better to verify the models and validate FEA results against experimental tests. This requires a finite element solution to provide proper data against which to run experimental validations.[4]

It is essential for engineers to verify the precision of the FEA models and also validate the outcomes against experimental tests, in order to guarantee a final model without an error. Moreover, verification and

[1] Daryl L. Logan (2011). A first course in the finite element method. Cengage Learning.

[2] https://www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/11356/Verifying-Your-Finite-Element-Analysis-Results.aspx

[3] Zong, Z., Lin, X., & Niu, J. (2015). Finite element model validation of bridge based on structural health monitoring—Part I: Response surface-based finite element model updating. Journal of traffic and transportation engineering (english edition), 2(4), 258-278.

[4] https://www.hitechfea.com/fea-knowledgebase/why-verification-and-validation-should-be-a-part-of-fea-studies.html

validation processes are currently required by authorities and industry to reduce time, cost, and risk associated with full-scale testing of bridge structures or any kind of structure.

To find out importance of verification and validation in FEM, it should be mentioned that FEM analysis is approximate, and it is not robust. So, possible errors in modeling, input data and boundary conditions can lead to very big errors in the results. Unfortunately, these errors can be relatively very small and difficult to identify, but they have significant and considerable effect on structure operation and service life.

For instance, using the inappropriate reference temperature for thermal strain in a structural model may simply affect the stresses by a few percent. This error will not be large enough to be noticed when comparing FEA (finite element analysis) results to a hand calculation. However, the error may be more than large enough to change some significant factors/parameters of structure/bridge such as fatigue life. These types of errors are hard to find unless someone is reviewing the analysis very carefully.

Errors are inevitable in finite element models. Also, more errors can be occurred in the complex models. FEM models validation and verification is a critical process to put in place to find these errors before they result in any damage.

This illustrates the huge effect of verification and validation of FEM model to reach convergence, and its importance in calibrating the model to a valid and effective experimental test.

The applicable, measurable and monitorable quantities in finite element method (FEM) verification and validation are strain, tilt, displacement, vibration and ambient temperature.

Resensys Wireless SenSpot™ sensors measurement responses and collected data (with the capability of high rate data transmission, and adjustable triggering threshold and sampling interval), are well-suited for bridge and other structure FEM verification and validation due to their accurate, reliable, and repeatable results, without need for calibration in the field. Resensys SenScope™ software has the capability of data visualization and data analysis (e.g. statistical analysis). So, precise and detailed data that provided by efficient Resenys devices can help clients to calibrate their FEM models very carefully and accurately to reduce possible errors in their models.

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 intra-test charging if users wish to use the products for their own experimental tests. After validation, these same sensors can also be left on the structure 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 flexibility and accuracy benefits 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 FEM verification and validation.

Resensys Wireless SenSpot™ sensors are able to monitor structural quantities such as tilt, displacement, strain, vibration and ambient temperature in concrete, steel and composite materials under wet, humid and extreme weather conditions (-40°C to +65°C or -40°F to +150°F). The products are corrosion resistant and can withstand salty environments. They are small in size and lightweight.

A Resensys Finite Element Method (FEM) Verification and Validation for Bridges, Buildings and other Structures solution comprises the following components:

- SenSpot™ sensors (for strain, tilt, displacement and vibration): which are attached to a bridge/structure and its members. The required number of sensors per structure depends on design and on FEM model verification and validation needs).
- SeniMax™: gateway/ data logger, which collects SenSpot™ data at the site and sends it to a remote server (one unit can cover as many as 100 SenSpot™ sensors).
- Repeater: may be used to extend the range of the SenSpot™ sensors.
- SenScope™: software for data analysis and visualization.

Resensys **Wireless Strain SenSpot™ sensor** in girder for FEM model verification and validation


Resensys **Wireless Tilt SenSpot™ sensor** on bridge bearings to verify and validate FEM models

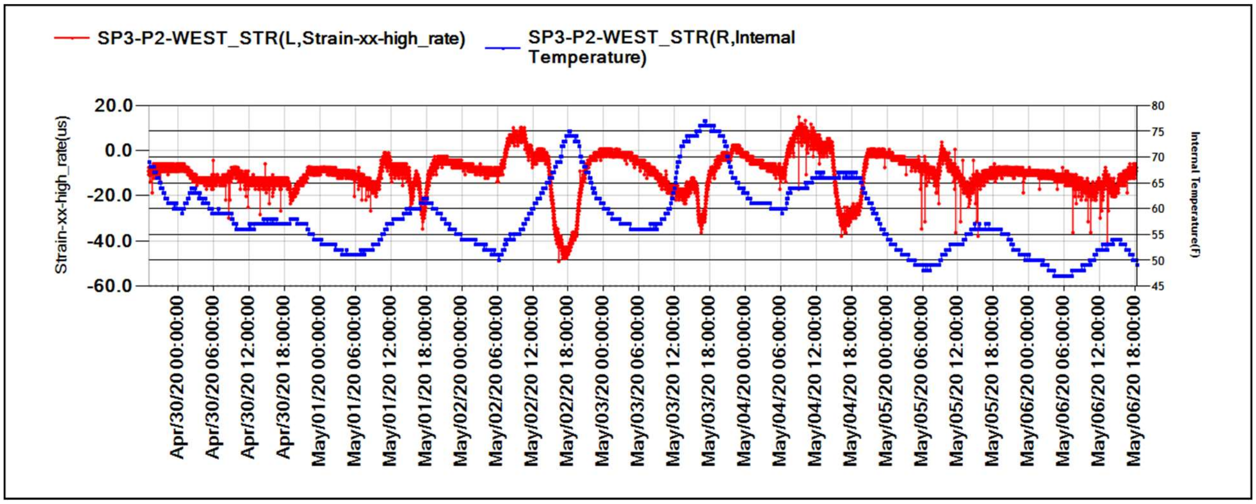
Resensys **Wireless Vibration/Acceleration SenSpot™ sensor** on a abutment for FEM model verification and validation


Resensys **Wireless Displacement SenSpot™ sensor** on bridge expansion joint to verify and validate FEM models

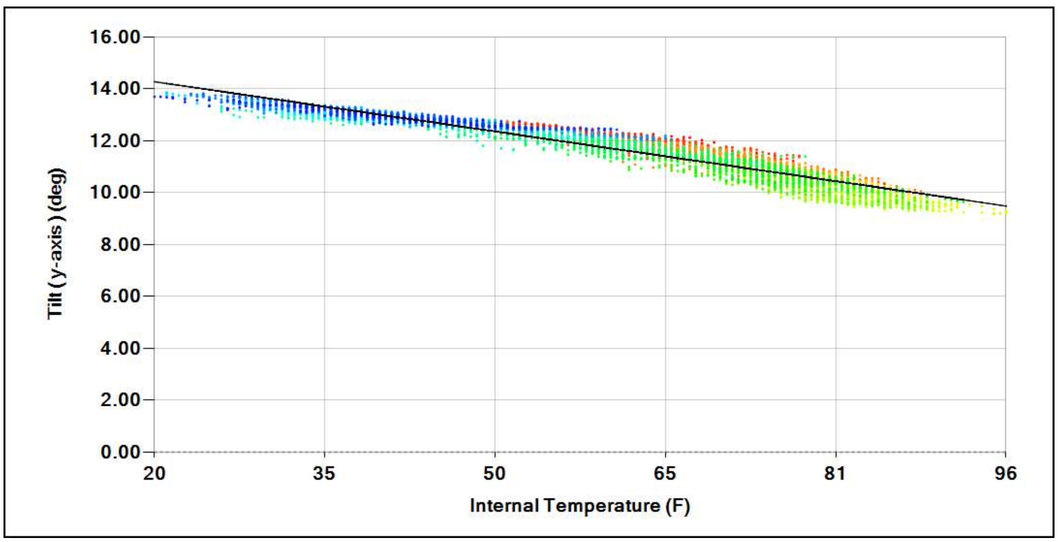
Resensys Wireless SenSpot™ sensors are easily placed/ installed on critical elements (girders, gusset plates, bearings, floorbeams, interior/exterior stringer, dead load consideration members, steel pier bent or truss members/connections) as determined by authority's/client's suggestion based on their current or previous finite element modeling that they implement for their own experimental tests. Since they are wireless, no additional wiring is required, and 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 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 SHM system, which can be used for bridge FEM model verification and validation.


Illustration of Resensys SHM based on SenSpot™ sensors for finite element method (FEM) model verification and validation




A sample for measured strain and temperature of an installed [Wireless Strain SenSpotTM sensor] on a bridge for finite element method (FEM) models verification and validation (Resensys [SenScope™] software has the capability of data analysis and visualization).




<<Linear Equation Trend Line: Tilt = 15.5104 - 0.0629*Internal Temperature>>

A sample of linear regression model between tilt (bearing rotation) and temperature for a bridge bearing in a specific time period that produced by Resensy [Wireless Tilt SenSpotTM sensor] to verify and validate FEM model (Resensys [SenScope™] software has the capability of data analysis and visualization).

**Technical Specifications:**

| | Wireless Strain SenSpot™ sensor | Wireless Tilt SenSpot™ sensor | Wireless Displacement SenSpot™ sensor | Wireless Vibration/Acceleration SenSpot™ sensor |
|---|---|---|---|---|
| **Size (Dimension)** | 76.2mm (3") x 33.4mm (1.3") x10mm (0.4") | -Transmitter Dimension: 79.6mm(3.13")x74.6mm(2.94") x 52mm(2.05")<br>-AssemblyDimension:120.8mm (4.76") x 96.6mm (3.8")x149.9mm (5.9") | Model 2": 176mm [6.9"],<br>Model 3": 201mm[7.9"],<br>Model 4": 227mm[8.9"],<br>Model 6": 277mm[10.9"] | 50mm (1.96") x 50mm (1.96") x 34mm (1.34") |
| **Weight** | 147g (5.2 oz.) | 180 g (6.3 oz.) | 245 g (8.6 oz.) | About 120grams (4.2 oz.) |
| **Mounting** | - Self-adhesive, no drilling is required (e.g. steel)<br><br>-Flange-mount, drilling is required (e.g. concrete) | Flange-mount or adhesive tape | self-adhesive or flange-mount | - Self-adhesive, no drilling is required (e.g. steel)<br><br>-Flange-mount, drilling is required (e.g. concrete) |
| **Accuracy (Resolution)** | 2µStrain | -Narrow Range HRT: ≤0.0003º(5.2µrad)<br>-Regular tilt : 0.1º | 0.1mm (4mil) | 4 ug ("g" is the acceleration of gravity) |
| **Measurement Range** | - | -Operating range:<br>• Narrow Range High Resolution Tilt : ± 0.5º(with respect to vertical position)<br>• Regular tilt: all directions<br><br>-Linear range:<br>• Narrow Range HRT: ±1º<br>• Mid-Range HRT: ±10º<br><br>-Repeatability:<br>• Narrow Range HRT: ≤0.001º (17.5µrad)<br>• Regular Tilt:1º<br><br>-Time constant: ≤1sec(High resolution tilt) | 25mm (1"),<br>50mm (2"),<br>75mm (3"),<br>100mm (4"),<br>150mm (6"),<br>300mm (12") | ±2g ("g" is the acceleration of gravity) |
| **Operating temperature** | -40°Cto +65°C (-40 °F to +150°F) | -40°C to +65°C(-40°Fto +150°F) | -40°C to+65°C(-40°F to +150°F) | -40°C to +65°C (-40 °F to +150°F) |
| **Lifetime** | minimum expected life without battery replacement is 3 years (Ultra-low-power) | battery life of 10 years (Ultra-low-power) | battery life of 10 years (Ultra-low-power) | battery life of 10 years (Ultra-low-power) |
| **Installation Time** | 1-2 minutes | 1-2 minutes | 1-2 minutes | 1-2 minutes |
| **Complementary sensing** | temperature, battery voltage, etc. | temperature, battery voltage, etc. | temperature, battery voltage, etc. | temperature, battery voltage, etc. |
| **Communication range** | 1.0km(0.62mile)free space | 1.0km(0.62mile)free space | 1.0km(0.62mile)free space | 1.0km(0.62mile)free space |
| **Power source** | Replaceable lithium-ion battery | Replaceable lithium ion battery | Replaceable lithium-ion battery | Replaceable lithium ion battery |
| **Wireless communication** | no wiring needed for deploying the system-IEEE 802.15.4 | no wiring is required for data collection- IEEE 802.15.4 | no wiring needed for deploying the system-IEEE 802.15.4 | no wiring needed for deploying the system-IEEE 802.15.4 |