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Smart Bridge: Autonomous Structural Integrity Monitor for Railroad Bridges

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ABSTRACT

This paper provides an introduction to Smart Bridge; a railroad bridge structural integrity monitoring system based on Continuous Fiber Optic Strain Sensing (CFOSS) technology. This design concept allows for the real time observation of how a bridge responds to dynamic loading and provides for autonomous reporting of abnormal structural conditions.

The CFOSS technology can monitor the entire bridge and observe changes in the behavure of its structural elements. The structure is constantly monitored, both when the structure is at static load and when the bridge is supporting the load of a train. When significant changes are observed they can be defined by location and the degree of deviation from normal.

A Smart Bridge provides automatic notification of sudden changes to the structure in real time. These changes may be an indication of bridge impact damage. It also provides a graphical map of the changes in structural behavure over time. In both circumstances the technology will identify the specific structural element that is degrading.

Smart Bridge is based on Continuous Fiber Optic Strain Sensing technology. This technology manifests in the form of a cable that is bonded along the entire length of the structural elements of the bridge. The cable senses strain in both the axial and transverse directions. Unlike conventional strain gauge elements that are bonded to a single location, CFOSS cables run continuously along the beam, plate or tendon. The technology is able to observe the changes in the concentration of strain along a structure and identify the origin of the change.

CFOSS technology is currently under development as part of the Smart Rail project. The underlying fiber optic strain sensing cable technology is in commercial use in the oil well and petrochemical pipeline industry.

The adoption of Smart Bridge provides enhanced operational safety because it monitors the structural integrity of the bridge continuously and provides automatic status annunciations. This monitoring is active during times when the bridge is in dead load and when it is supporting the load of a passing train. Smart Bridge also improves the working safety of bridge inspectors by providing a map of structural changes that may indicate hazardous conditions. The use of Smart Bridge improves the inspection process by identifying potential structural problems that may require visual confirmation. And it provides autonomous warnings when sudden changes in the bridge structural integrity are detected.

SMART BRIDGE DESCRIPTION

Smart Bridge is a technology that monitors the structural behavure of a railroad bridge and provides actionable information concerning the bridges structural integrity. The technology provides continuous monitoring of the bridge by detecting and recording changes in the way the individual structural members respond to cyclical loading caused by passing trains. Smart Bridge provided both a long-term record of bridge deterioration and also appropriate alarms of sudden changed in structural integrity.

In a physical context the technology includes a network of Continuous Fiber Optic Strain Sensing (CFOSS) cable bonded to the bridge's structural members and an electronics package located in a suitable cabinet on or near the bridge. See Figure 1

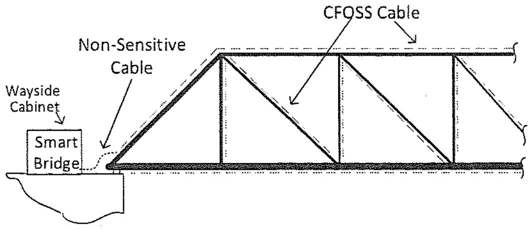

FIGURE 1: Smart Bridge Physical Components

FUNCTIONAL DESCRIPTION

Smart Bridge autonomously communicates information related to the bridge's structural integrity, when appropriate, to the bridge inspection personnel by means of text messages and data transfers. The Smart Bridge system, as shown in Figure 2, includes the following elements: 1-One or more Fiber Optic Strain Sensing cables that are bonded to the structural elements of the bridge; 2-An Interrogator that illuminates the FO cable and detects changes in the strain patterns in the sensor cable; 3-An analytical software function that stores, manipulates and aggregates the strain patterns; 4-An Artificial Intelligence function that extracts actionable information from the accumulated data; 5-A communications function that allows Smart Bridge to autonomously initiate notifications concerning bridge structural status.

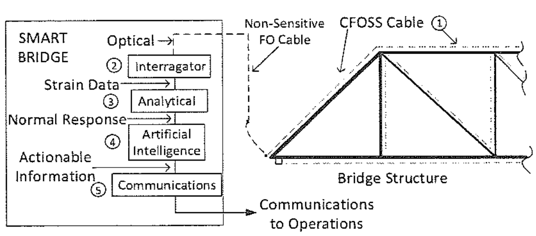

FIGURE 2: SMART BRIDGE FUNCTIONAL COMPONENTS

By extension, Smart Bridge can also provide a platform for bridge intrusion detection, impact detection and remote bridge assessment. The Interrogator can also support ancillary applications such as sensing the use of the bridge by non-railroad vehicles or people. The analytical software can also monitor impact sensors mounted on the bridge piers or pilings The communications function can also support various video feeds that may show the source of the intrusion or impact on the bridge.

BRIDGE SAFETY

Two truths: A bridge that is well maintained will last indefinitely. A bridge not maintained will eventually fail. Too much maintenance is wasteful and increases the possibility of construction accidents. Too little maintenance is an invitation to disaster. It is bridge inspection that defines the median path. Here too: unnecessary inspections are wasteful and is a threat to worker safety; while too little inspection is neglectful and prone to allowing small problems to become major repairs.

Bridge safety depends on careful and timely inspection by qualified professional Bridge Inspectors. This is a labor-intensive job that must not be rushed. As each bridge is unique, the inspection of each bridge is also unique. There is no standard map to guide looking for something out of the normal and that may or may-not be visible. In recent times owners have explored the use of emerging technology such as aerial drones and high-resolution laser mapping to improve inspection efficiency and safety. But even with these aids the inspection process still relies on the inspector's awareness and in the end it is his 'expert opinion' that the bridge is safe.

LIMITS OF CURRENT TECHNOLOGY

The current technology available for the monitoring of railroad bridge integrity uses an array of strain gauges attached to various key locations on the structure. In the most advanced incarnation, these discrete strain gauges are distributed along a continuous fiber optic cable. Typically, these discrete fiber optic strain gauges utilize a technology called Bragg Gradient (BG). Each of the BG strain sensors makes a single measurement at a single location. A bridge may require hundreds of discrete sensors.

Some of the limitation of BG based strain measurement technology are: First – Increasing the number of measurements, improves resolution of the data but also constricts the time available to secure coherent results from a moving loading source. Second – Even a large number of individual sensors does not guarantee that there will be a sensor on the structural member that is displaying deteriorating.

Each BG sensor requires an individual optical address and an individual measurement cycle. The required time to accumulate all of the measurements increases in proportion to the number of strain measurements. In order to get a coherent image of strain distribution, all strain measurements must be made under the same loading conditions. But trains are always in motion across the bridge. The constant change in live loading is fast enough to constrain the ability to get a coherent strain observation.

Limitations in sensor size can be compensated for by comparison of the observed bridge structural conditions to a dynamic computer model. A series of what-if comparisons can be run in the model to find a set of bridge degradations that correspond to the observed measurements. This approach may result in several alternative combinations of bridge element changes that may satisfy the observed strain measurements. The multiplicity of possible solutions may prove to be of little help to the bridge inspector.

BENEFITS OF CONTINUOUS STRAIN SENSING

The Smart Bridge concept is based on Continuous Fiber Optic Strain Sensing (CFOSS) technology. Using this technology, we can observe the distribution of strain across the entire bridge with a single pulse of laser light from the Interrogator. In as little as a millisecond, all of the strain observations on the bridge will be converted to a data file. It can make complete observations of the bridges structural responses to locomotives crossing the bridge as often as every inch of train movement.

Note, CFOSS is not measuring strain, rather, it is observing changes in the distribution of strain over time and as a train loads and unloads the bridge. The technology can record the response of each structural member of the bridge every time a train crosses the bridge. The technology compares the current set of strain observations to a "normal" set of strain observations. The normal set is an aggregation of previous observations with adaptations for various variations including: train speed, temperature, age of the previous observations and others.

The CFOSS cable is intended to be permanently bonded to the consequential structural members of the bridge. The cable can be installed as one continuous sensor over the entire bridge. Or it can be broken into sections and connected by non-strain sensing jumper cables when desirable as shown in Figure 3.

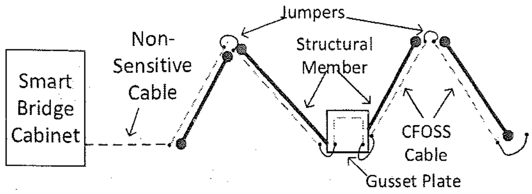

FIGURE 3: CFOSS CABLES AND JUMPERS

It can be installed as a single system or as two independent systems, each covering half of a symmetrically designed bridge and including two independent Interrogators. The dual system can improve overall system reliability and system sensitivity. The cable is suitable for installation as part of a new bridge construction project or installed on an existing structure. The details of the installation can be detailed by the bridge designer.

Figure 4 illustrates the benefit of continuous strain sensing. The CFOSS cable is shown as bonded to top of a "I" beam like structural member. The cable observes the strain profile along the entire member. Whether in compression or in tension, the strain at either end of the member is the same, as indicated by the level line. The strain increases in the vicinity of a non-homogeneous portion of the member. The cause of the non-homogeneous condition may be: rust, corrosion, buckling, etc.

The CFOSS cable is capable to responding to changes in local strain in all three directions. When the cable is distorted by structural strain in either the X or Y direction, there is a small but detectable change in the light that is reflected back to the source. This sensitivity provides a means to detect local bending or buckling of the underlying structural member. The degree of the change in the light pattern is proportional to the degree of change in the local structural strain. The CFOSS cable is also sensitive to longitudinal strain changes. As the underlying structural member is forced to elongate, the attached CFOSS cable will respond with changes in the light returned to the detector. Unlike strain sensing cable using BG technology, CFOSS will provide a representation of how the strain is distributed over the length of the cable. This quality permits the detection of local concentrations of strain that may represent a local weakening of the underlying structure. This weakening may be the result of rust, corrosion or other damage. This relative increase in strain is represented by the peak in the strain profile. The physical location of the strain anomaly can be derived using the time of flight of the light pulse in the fiber optic medium.

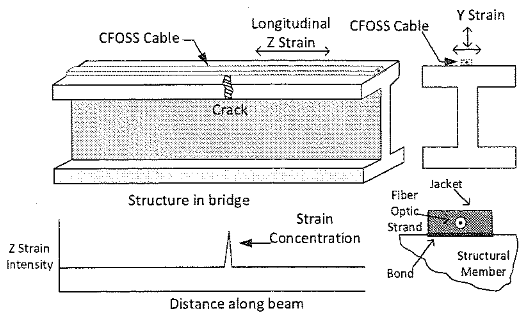

FIGURE 4: CFOSS CABLE BONDED TO A STRUCTURAL MEMBER

CFOSS TECHNOLOGY DEVELOPMENT

The technology underlying Smart Bridge is Continuous Fiber Optic Strain Sensing (CFOSS) cable. This is a fiber optic cable that is sensitive to changes in stress. When this cable is bonded to a structural member, it is able to sense the minute changes the strain applied to the structure. The CFOSS technology is currently being developed by AFL as part of the Smart Rail project. Smart Rail is a concept that permits the detection of rail degradation and train location using a CFOSS cable bonded to the rail web. The two applications differ in that the cable used for the Smart Rail application is sensitive to strain in the two transverse directions and the cable used for the Smart Bridge application is also sensitive to longitudinal strain.

FIBER CABLE AS A STRAIN SENSOR

All fiber optic applications, both communications and strain sensing, use the same basic core/ cladding structure of silica glass. The core/ cladding fiber is protected by a jacket or buffer layer that provides mechanical protection for the strand. See Figure 5 and Note 1. The core and the cladding are both glass, but each has a slightly different density. This change of density results in a difference in the speed of light in the core and in the cladding. (See Note 2) This, in turn, results in a reflective boundary between the core and the cladding. A light ray entering the core of the fiber is constantly reflected off the cladding boundary as it passes down the strand. The conduction of light in the core is extremely efficient as long as the angle of incidence of the light energy does not exceed the angle of reflection. As the light energy ricochets off the cladding boundary, every reflection causes a slight dispersal of light, some of which is reflected back to the source and is called backscatter. When the fiber is straight the backscatter is minimal.

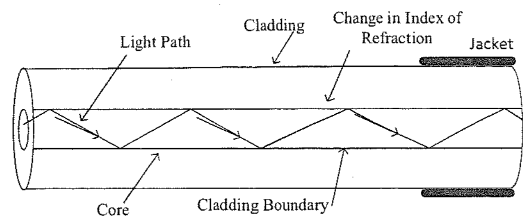

FIGURE 5: FIBER OPTIC STRAND WITH BACKSCATTER

When the fiber is bent, as depicted in Figure 6, the light beam strikes the cladding barrier more frequently, thus causing more reflected light to return as backscatter. The more the fiber is bent the greater intensity of the backscatter from the location of the bend. The degree of backscatter is directly related to the degree of fiber bending. This is a very simplistic explanation of a very complex phenomenon.

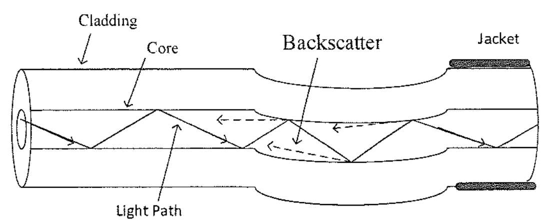

FIGURE 6: BENT FIBER OPTIC STRAND

The forgoing is intended to illustrate how mechanical movement (strain) can influence photons in an optical fiber. It represents only the seed of CFOSS technology. The final embodiment of CFOSS is far more complicated.

FROM STRAND TO CABLE

Most of the development work needed to adapt fiber optic technology to a real-world application is focused on the design of the cable or jacket. In the case of Smart Bridge, the jacket must: protect the fiber from all of the deleterious environmental effects, provide a means to securely bond the cable to the underlying structural member and conduct the effects of structural strain into the fiber. In all communications cables the strands of fiber are protected and isolated from the environment. When the fiber is being used for strain sensing the strand must be protected but not isolated.

USING THE FIBER

The CFOSS cable by itself is inert. It only produces data when it is Interrogated (2). This interrogation is done with a laser source and an optical detector. The detector provides a continuously varying data stream in the form of an electrical signal. This must be manipulated by the Analytical Functions (3) to format the stream of data into a series of file that contain information. The data files represent both past structural responses and current structural behavure. The differences between the past or normal structural responses and the current structural behavure is analyzed by the Artificial Intelligence (4) functions to discern when an abnormal condition exists. When the Artificial Intelligence function identifies a significant deviation from the normal structural behavure, it issues a notification by way of the Communications (5) functions.

Interrogator (2 in Figure 2)

The Interrogator is a electro-optical device that sends out a light pulse and observes the reflected light intensity and the time it took for the light pulse to return. It is a specialized version of the common OTDR (Optical Time Domain Reflectometer). The interrogator is connected to the CFOSS cable by means of a non-sensitive (ordinary) FO cable. Its primary function is to send a pulse of laser light into the near end of the CFOSS and to observe the pattern of reflected light. Whenever the fiber is bent or stretched, the Interrogator will see a minute change in the amount of reflected laser light (backscatter). By measuring the time of flight of the light pulse, the Interrogator can determine exactly where each deviation in reflected light intensity is located. A single pulse of light will in sequence travel through all of the CFOSS cable sections on the bridge. Operating at nearly the speed of light, the pulse will travel across every structural member of even the longest bridge in a fraction of a second. The Interrogator will provide, with each pulse, a file of data that describes the changing intensity of the light reflected laser light as a function of distance from the source.

Analytical Functions (3 in Figure 2)

The Analytical Function provides for the following: A - Storing of Data files; B – Adjusting the Data to compensate for known variables; C – Aggregating the Data into a "Normal" strain profile; D – Identifying changes in local strain conditions. E – Controlling the Interrogator functions; F- Identifying system faults.

The output of the Interrogator is a data file that represents the strain intensity pattern of all of the structural members of the bridge in relation to distance from the laser source. Every time a train crosses the bridge several scans are made, each with the train in a different location. This constant changing of the location of the live load on the bridge is beneficial because it allows examination of how the bridge responds to a dynamic load. The trains constant movement also demands thet the complete strain scan be done quickly enough to qualify as a single coherent scan.

This is an enormous amount of data, that by itself, has no meaning. It is only meaningful when it is compared to a "Normal" strain response. The Analytical function creates the "Normal" strain profile by aggregating many previous data files into the best fit profile. This "Normal profile is also constantly changing due to changes in the environment and to changes in the bridge structure. The Normal profile is the composite of previous profiles that are weighted by their age. These profiles must also he corrected to account for several variables including: the weight of the train; the speed of the train and the ambient temperature. In some cases the orientation of the sun on the bridge may cause structural imbalances that can be corrected prior to inclusion in the composition of the Normal profile. Over time, and in particular with the seasons, the Normal profile will change to reflect normal ageing. The changes that are of interest are the ones that are happening much faster than the Normal or changes that are slow but not consistent with the other changes in the bridge's distribution of strain.

These analytical functions are essentially the same as those now in development as part of the Smart Rail project.

Most bridges are designed to be symmetrical around the center-line of the roadbed. For each structural element on the right side of the bridge, there is a matching structural element on the left side of the bridge. For a new bridge, the strain profiles of the structural elements on the right side of the bridge should be identical for the left side. This design symmetry provides another way of detecting bridge structural degradation. Smart Bridge can compare the strain profiles of symmetrical bridge members. If the bridge has only a single track, the dynamic loading will be applied equally to each of the symmetrical members. If there is no degradation, the strain profiles will be very similar. If there is degradation, it is very unlikely to affect both symmetrical elements equally. If one of the paired structural members is damaged or seriously corroded, there will be a significant difference in strain distribution. This detection methodology can operate independently of the change over time function described above. This detection methodology will require a normalizing function to compensate for unequal solar heating.

Artificial Intelligence (4 in Figure 2)

The Analytical functions produce data that identifies the intensity and location of an anomalous strain profile. The Artificial Intelligence function discerns that anomalous changes are worthy of attention. The AI function is provided with a set of initial parameters for determining what changes will be identified as reportable. After the system is installed the AI function will continue to learn what changes are normal and what changes are beyond normal. The function will continue to define the limits that define actionable information.

The Smart Bridge system as delivered will have processes for performing the analytical functions. It will have a framework for the AI functions. But when AI is first connected to the bridge, there will be a period when on-the-job learning must take place. At first all anomalies will look new and will have the same importance. Over time the AI functions will discern what anomalies are a manifestation of normal bridge behavure and what may be indicative of structural degradation.

Communications (5 in Figure 2)

The foundational function of Smart Bridge is to provide the Bridge Inspector a real time, dynamic display of the strain concentrations in the monitored structural elements of the bridge. This information can be configured in several ways. The displays can include both static and dynamic bridge loading. The inspector can use these displays to inform his physical inspection. The displays can be extracted at the bridge site or they can be transmitted to the Bridge Inspection office.

Smart Bridge and specifically the AI function can also identify sudden or swiftly intensifying changes in strain. This situation may be the result of impacts on the pilings or piers by barges or trucks. These may exhibit qualities and circumstances that the AI programing identifies as appropriate for immediate communication to the bridge owner. This sort of information will be delivered by an autonomous communications processor. The medium for delivery to the bridge owner may be a proprietary network and/or it may be augmented by direct text messaging.

RAILROAD BRIDGE STRUCTURES

Railroad bridges come in a vast spectrum of variations and Smart Bridge can be adapted to all of them. These designs including: truss, girder, cable stay, steel trough and post tensioned pre-cast concrete. This paper limits its discussion to only two common varieties: truss bridges and plate-girder bridges. The other applications are left to the bridge design engineer.

EXAMPLE: I – 35 BRIDGE

Although this paper is focused on the application of Smart Bridge in the furtherance of the art of railroad operations, I will use the I-35 highway bridge as a basis for this example. That is because the collapse of that bridge is very well documented. The bridge spanned the Mississippi River in Minneapolis, MN and was opened in 1967. Figure 7 shows the truss bridge before its collapse in 2007. The primary cause of the collapse has been determined to be the failure of a gusset plate that was too thin for the application. The immediate cause was a deposit of building materials in a concentrated location on the bridge surface that exceeded previous loading.

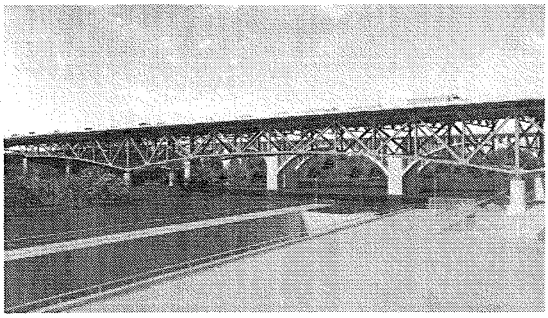

FIGURE 7: I-35 BRIDGE OVER THE MISSISSIPPI

The gusset plate had actually failed years before the bridge collapsed. Figure 8 shows the deficient gusset plate (U-10') during an inspection in 2003. Four years before the actual bridge failure, the doomed plate was exhibiting evidence of its deficiency. There is no clarity for why the inspector who took the photo in 2003 did recognize the deteriorating conditions. It may be that the warping, while visible in hindsight, was not severe enough to attract attention at the time.

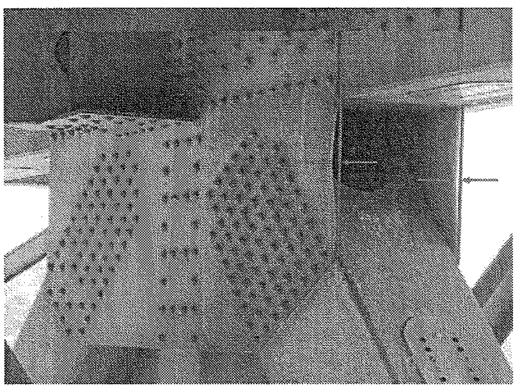

FIGURE 8: DAMAGED GUSSET PLATE "(U-10')"

Had Smart Rail technology been available and applied, it could have provided a notification that there were serious alterations of the strain patterns in the bridge's structural members. The CFOSS cable would have been bonded to the beams and trusses of the bridge. In particular it would have been bonded to the gusset plate as shown in Figure 9. Prior to the bridge collapse the strain in the plate would have been excessive (thin plate) but presumably stable. At some time before the collapse the plate was overloaded and warped. Smart Bridge would have observed and recorded the overload(s) and the warping of the plate on the right/ near side. The CFOSS cable on the left edge of the gusset plate would have been in tension. At the point of bridge collapse the plate ripped along a vertical line following the bolt holes nearest to the left edge. Smart Bridge would have recorded the catastrophic decrease on plate tension as the rip progressed.

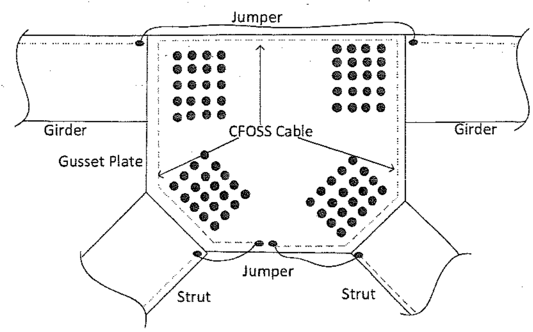

FIGURE 9: GUSSET PLATE AND STRUCTURAL MEMBERS WITH CFOSS CABLE

EXAMPLE: PLATE GIRDER BRIDGE

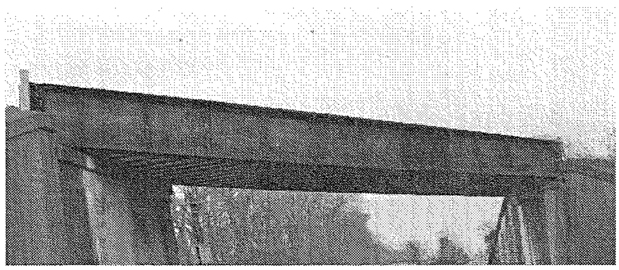

FIGURE 10: TYPICAL PLATE-GIRDER BRIDGE

The Plate-Girder bridge (a.k.a. Pony Plate-Girder) is a simple and common design and it comes in several variations. The bridge in Figure 10 is a trough design with the tracks between the girders. Another variation such as the Deck Plate-Girder has the girders closer together and the tracks on a roadbed above the girders. In the design above, the side girders are spanned by floor-beams. The weight of the train is borne by the floor-beams and transferred to the side girders. The girders use plates and stiffeners to keep the top and bottom plates parallel and the side girders perpendicular to the roadbed. In an unloaded state the top plate of each girder is in compression and the bottom plates will in tension. When loaded, the forces are in the same direction but increased and the girders will display a greater deviation from a rectangular norm. The cross-bracing is ignored for simplicity.

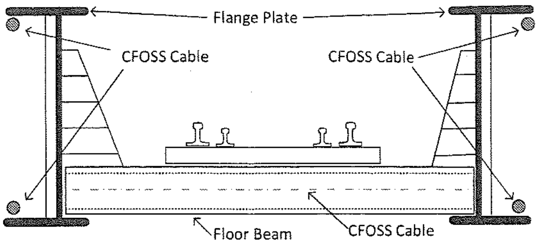

FIGURE 11: PLATE-GIRGER BRIDGE WITH CFOSS CABLE

The application of Smart Bridge to this structure could include bonding the CFOSS cable along the outer edge of the top and bottom girder flange plates. In this position the cables will be able to observe changes in the tension and compression of the girders. When the bridge structure is sound, the loading due to a passing train will increase the strain in the flanges but it will remain evenly distributed along the plates. In a similar way the CFOSS cables on each of the floor-beams will observe the beam strain increasing and decreasing while remaining evenly distributed. A change in the strain distribution is indicative of a change in the structural integrity of the bridge. The location of the change is indicative of the location of the structural deterioration. Buckling or other distortion of the girder plates will be detected and recorded.

In some situations, the bridge and its foundation may be subject to impact damage from trucks or barges. In this circumstance it may be appropriate to incorporate impact sensors on the bridge and foundation or piling. The impact sensor could be integrated into the Smart Bridge artificial intelligence functions. Upon sensing an impact Smart Bridge can initiate a notification message and follow up with a report on the bridge's structural integrity.

SUMMATION

The installation of Smart Bridge technology will make existing bridges safer. Not because the technology can remediate existing structural deficiencies, but because it provides a means of continuous monitoring of a bridge's structural integrity without an increase in bridge inspections. Smart Bridge does not diminish the importance of the work of experienced Bridge Inspectors and it makes their work: safer, more efficient and more effective.

Smart Bridge technology provides:

Continuous monitoring of the structural health of the bridge.

Autonomous reporting of impending structural degradation and sudden structural changes.

Reporting of changes in the bridge's structural health.

Identification of structural conditions that may require Bridge Inspector attention.

Warning to the Bridge Inspector of potentially hazardous conditions on the bridge.

Standardization and archival maintenance of inspection records.

Black Box function for forensic analysis of bridge damage or collapse.

REFERENCE DOCUMENTS:

1. "Bridge Health Monitoring with Fiber Optic Sensors"; Cleveland Electric Laboratories, 11/26/2008 (On line)

2. "Optical Fiber Sensors vs. Conventional Electric Strain Gauges for Infrastructure Monitoring Applications"; C. Barbosa, Fiber-Sensing, HBM. Inc. (On line)

3. "Smart Rail: Rail Break and Train Location using Fiber Optic Technology", F J Smith, Joint Rail Conference 2019, ASME (Available from ASME)

NOTES:

1 Core diameter: 9 Microns (nm) / Cladding diameter: 125 Microns (nm).

Operating window: 1,550 Nanometers Single mode.

2 The speed of light in a vacuum is 186,282 Miles per Second. A typical single mode fiber optic core of silica glass will have an Index of Refraction of 1.4475. This translates into a light speed of 128,692 Miles per Second. An appropriate cladding will have an Index of Refraction of 1.4444 or a speed of 128,968 Miles per Second. Light moves faster in the cladding than in the core but the reflective cladding boundary keeps the light rays in the core.

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