Development of a Smart Timber Bridge Girder with Fiber Optic Sensors

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Summary

Past timber bridge evaluation and maintenance efforts in the USA have principally focused on the internal integrity of timber components using various non-destructive evaluation tools to supplement visual inspection data. This project is part of a comprehensive effort to develop smart structure concepts for improving the long-term performance, maintenance, and management of timber bridges. This comprehensive effort focuses on developing an integrated turnkey system to analyze, monitor, and report on the performance and condition of the most commonly constructed timber bridge type in the USA, the longitudinal glued-laminated girder with transverse glued-laminated bridge deck. This paper describes an initial project to develop techniques for integrating fiber optic sensors (FOS) within timber bridge glued-laminated beam components.

Keywords: Smart timber bridge, fiber optic sensor, FBG packaging, glued-laminated girder, health monitoring techniques.

1. Introduction

The always present deterioration of bridges has alerted bridge owners and managers to develop new techniques for constructing, repairing, rehabilitating, and monitoring bridges. In the case of timber bridges, service conditions have historically been determined with visual inspection techniques and maintenance decisions being based upon the information gathered. To improve this situation, the development of an innovative timber bridge structure with capabilities to monitor long-term performance parameters through the implementation of fiber optic gages was undertaken as part of the previously developed Five-Year Research Plan [1]. The initial work of this research plan consisted of development of techniques for embedding FBG sensors with and without physical attachment to glulam members for detecting structural and non-structural attributes. In addition to this, small scale glulam members were constructed in the laboratory and instrumented with commercially available FBG strain sensors and specially designed sensor packages. These specimens were tested at common bending levels varying loading rates and temperature conditions to assess the performance of the different FBG sensor packages.

2. Smart Timber Bridge Research Plan

The goal of this research plan is to develop smart timber bridge structures by using both existing and new forms of instrumentation types to measure the structural adequacy and the degree of deterioration of the bridge through the integration of health monitoring technologies, and bridge management approaches.

A smart structure would typically incorporate the use of structural materials, sensors, data reduction techniques and remote systems that allow for the monitoring of the structure. With these elements, the smart structure is able to monitor the in-situ behavior of the structure, to assess its performance under service loads, determine the current condition and detect damage/deterioration [2]. In this context, a conceptual smart timber bridge was developed with the purpose of improving the long-term performance, maintenance, and management of timber bridges. Four concepts were established to develop the smart timber bridge comprising of:

- Selection of the bridge structural materials.
- Identification of the measured performance metrics (attributes).
- Selection/development of the sensor types.
- Communication/processing and reporting.

Stress rated glued-laminated timber (glulam) members were selected as the material for the smart timber bridge due to the growth in usage. In contrast to the variable range of solid wood, glulam is an engineered, stress-rated product that provides distinct advantages over solid-sawn timber. To date, bridges constructed with glulam have received minimal attention from the bridge health monitoring community and there lacks of a body of data on the in situ behavior. In brief, the superstructure of the conceptual bridge composed of a series of transverse glulam deck panels supported on longitudinal glulam beams is the main focus of the smart timber bridge development.

By identifying the bridge-specific behaviors and deterioration modes, the assessment of the smart timber bridge condition would be conducted through the evaluation of the structural adequacy and decay. Structural adequacy of the bridge would be determined by measuring the flexural strains to evaluate the lateral load distribution, dynamic load allowance and cumulative fatigue for comparison to acceptable design levels. In addition, the decay/deterioration of the timber structure, specifically due to moisture, metal corrosion and ultraviolet light would be evaluated through the application of novel sensors [3].

The overall health condition of the smart timber bridge might be monitored using commercially available as well as new sensors incorporating Fiber Bragg Grating (FBG) technology. Besides being linear and absolute in response, electrical interrupt immune and readily multiplexed, these FBG sensors have the ability to be both embedded and/or surface mounted. In recent laboratory as well as field tests conducted by the Bridge Engineering Center at Iowa State University, FBG sensors demonstrated 99% accuracy when compared to foil strain sensors [4]. In addition, sensors to detect moisture content, ferric ions and degradation in wood lignin would be developed and implemented to detect the decay/deterioration of the glulam members.

As a part of the health monitoring technologies and bridge management approach, a communication/reporting system would be developed. This system would consist of a data acquisition system with developed data processing techniques and software applications to interpret and report the results of the data obtained during monitoring activities. The behavior of the superstructure would be summarized integrating all the responses related to the attributes of the smart timber bridge and be addressed to the bridge owner in a clear report. With this information, the owner could program routine maintenance and/or rehabilitation of the bridge. Also, this system would serve as an immediate alert to early damage or a catastrophic event (e.g., wood decay, collision, etc).

3. Development of the Sensor Packages

The first of part of this research focused on the development of new packages that would protect the FBG sensors embedded within the glulam.

3.1 Structural Packages

Structural packages were developed to protect the fragile bare FBG strain sensor during handling and installation while also providing mechanical connectivity between the FBG sensor and the glued-laminated specimen. The structural FBG sensor package conceptually consists of a backing material and a bare FBG strain sensor bonded together. The resulting system could be either attached to an exposed wood surface or embedded between the laminates of glulam members to measure the response of the member to external forces. In this work, five new backing material configurations were developed using either stainless steel shims or aluminum mesh sheets shaped as shown in Figure 1 (a). The dimensions of the structural packages were developed to resist the horizontal shear stresses and to allow for the redistribution of localized strain irregularities between the package and the wood laminates. The embedding technique consisted of surface preparation, followed by the application of a structural adhesive to bond the backing material to the wood laminate. After curing for a minimum of 24 hours, the bare FBG sensor was applied to the backing material using a similar structural adhesive and cured for an additional 24 hours.

(a) Backing materials (b) FBG strain sensor (c) Instrumented internal wood laminates

Figure 1. Structural Packages: Materials and Installation

In addition to the bare FBG strain sensors, one commercially available surface mounted FBG strain sensor bonded to a C-FRP package was evaluated (Figure 1 (b)). The FBG structural packages as bonded to the internal laminates are shown in Figure 1 (c). Nine small scale three-ply glued-laminated specimens were instrumented with eighteen FBG sensor packages consisting of combination of six package designs and three structural adhesives.

3.2 Non-Structural Packages

The non-structural FBG sensor package conceptually consists of a backing material and an adhesive or adhesive tape that protects and isolates the FBG sensor from load induced behaviors. In that sense, no physical attachment between the FBG sensor and wood laminate was allowed. Ten non-structural packages were prepared with a combination of stainless steel shims and aluminum foil as backing materials which were bonded with two different types of adhesives and two adhesive tapes. The process of installing the FBG non-structural packages consisted of the wood preparation by routing a recess area, to house the FBG sensor, isolation materials, and leads, and the application of the non-structural FBG package on an external wood surface (see Figure 2). In all cases, the packages were cured for a minimum of 24 hours. Five small scale three-ply glued-laminated specimens were instrumented with ten FBG strain sensors isolated with non-structural packages.

(a) FBG sensor in a recess area and applied adhesive tape.

(b) Installed backing material

Figure 2. Non Structural Package: Materials and Installation

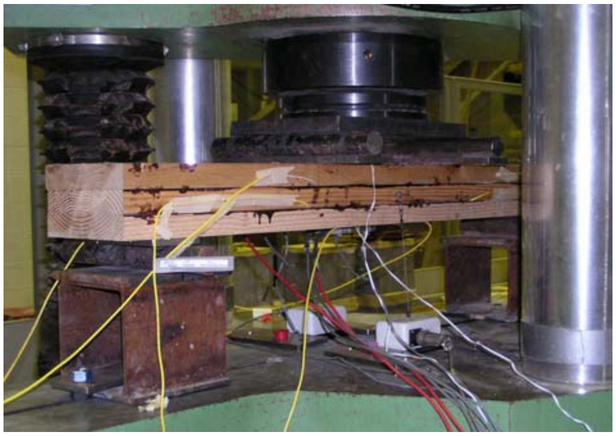
3.3 FBG Sensors during Beam Manufacturing

The three-ply glued-laminated specimens were assembled with a constant pressure of 0.689 MPa (100 psi) between laminates sustained throughout the curing period at room temperature. After completing the assembly process, twelve of the eighteen internal FBG sensors with structural packages were operative. The fragility of the gages and the robustness of the specimens made retrievals of the embedded gages impossible, so the cause of the failure could not be determined. Possible causes of the failure were attributed to the transition between the FBG sensor package and leads and/or differential displacements between glued laminates during assembling and stressing process. As for the non-structural packages, all ten FBG sensors were functioning.

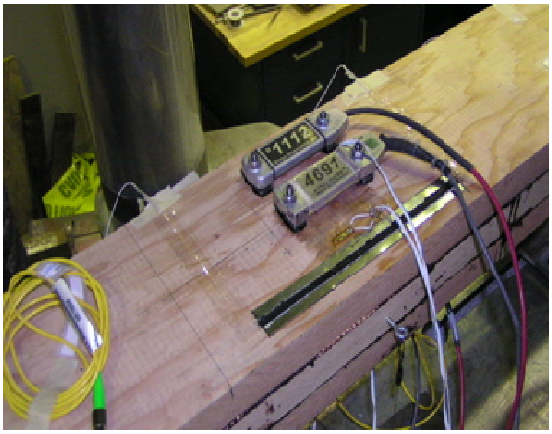
4. Testing Program

All specimens were tested in bending under third-point loading with a total load of 11 KN (2500 lbs) (Figure 3(a)). The tests were adapted from the ASTM 198 05a provisions [5]. Various loading rates and temperature variations were applied to investigate the behavior of the sensor packages. To test the compressive and tensile response of each sensor, the load was applied to each bending surface. Additional external sensors beyond those developed in this work were installed to provide comparative sensor performance data.

In the structural package specimens, external structural FBG sensor packages, strain transducers and electrical resistance strain gages (foil strain gages) were installed for strain comparison (Figure 3(b)). Thermocouples were installed to record temperature variations during long duration tests. In the non-structural package specimens, external strain transducers were installed.



(a) Test fixture



(b) Instrumented external glulam specimens

Figure 3. Test Setup: Small Scale Glulam Specimen with Structural Package

4.1 Structural Package Specimens' Tests

4.1.1 Bending Test

The basic bending test was performed to establish the response of the FBG sensor packages to flexural loading in the elastic range. The FBG strains were compared to theoretical values and to the data gathered from the foil strain gages and strain transducers. Upper and lower bound theoretical flexural strains were estimated from conventional beam theory by applying the modulus of elasticity values (E) contained in AASHTO Specifications [6].

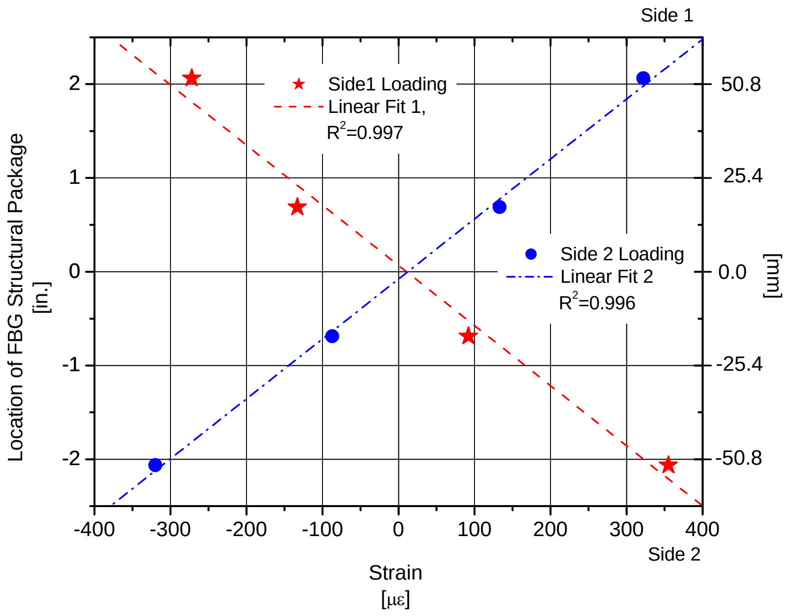


Figure 4. Bending Test – Structural FBG Sensor Packages' Results: Strain levels vs. Linear Regression Model

All FBG sensors immediately responded to loading and unloading with a nearly linear elastic strain response. In Figure 4, a typical plot of the external and internal FBG strains for an applied load of 11 KN (2500 lbs) for both Side 1 and 2 loadings compared to a linear regression model are shown. In all cases, the compressive and tensile flexural strains were dissimilar. The differences were attributed to anatomical wood factors in the vicinity of the FBG sensor packages. In Specimen 1, material properties varied significantly due to the included knots and slope of grain near the sensors; this is evident by the consistent difference of 50 με between the Side 1 and 2 loadings. When comparing to the theoretical upper bound strains (with E = 10 GPa (1500 ksi)), all external and internal FBG strains were lower. With respect to the theoretical lower bound strains (with E = 14 GPa (2000 ksi)), the FBG strains differed by up to 40%. In Figure 5, the external FBG sensors, foil strain gages and strain transducers readings were plotted to evaluate their performance. Comparing the external FBG strain values with the average strain determined as the arithmetic mean of all external sensor readings, both strain values differed by up to 11%. Specimen 1 differed by up to17%.

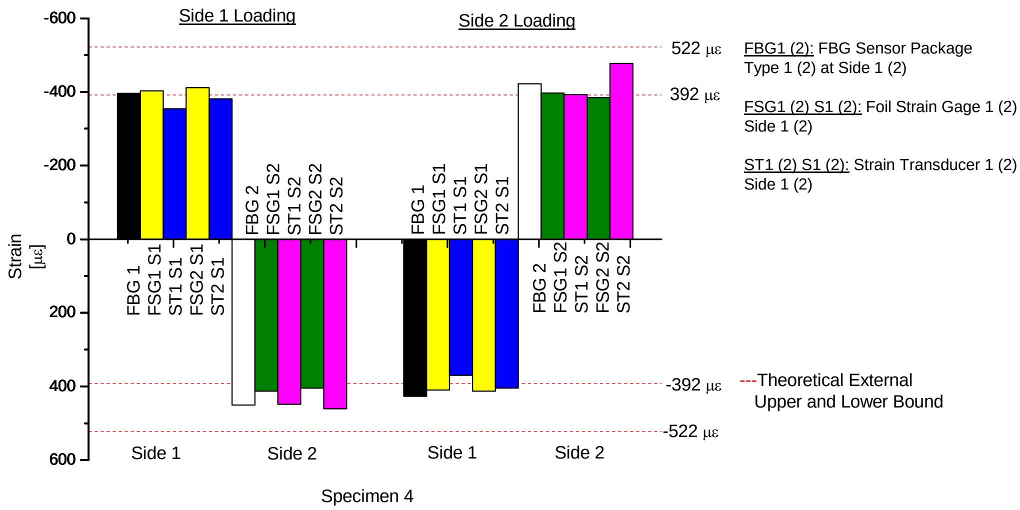


Figure 5. Strain Comparisons for the Bending Test Results

4.1.2 Sustained Loading Test

The objective of this test was to evaluate the elastic and viscoelastic behavior of the structural FBG packages under a 24-hour sustained loading and uncontrolled ambient laboratory temperature. The effectiveness of the FBG sensors was evaluated by comparing both basic bending and sustained loading results in the short term. Both tests' results differed by up to 8%. In Specimen 1, Side 2 Loading, a noticeable reduction in strains was observed attributed to the wood surface irregularities at the sensor packages' regions (i.e., knot, spiral grain). Throughout the 24 hour test, the external and internal FBG strains visibly varied with the temperature fluctuations (up to +/-2 °C (+/-4 °F)) (e.g., Figure 6). When assessing the wood and package materials' thermal properties, only the FBG sensors are significantly affected by temperature variations. A linear regression model was fit to the strain and temperature data to investigate the strain-temperature relationship. The resulting R^2 coefficients varied from minimal to 0.96. The higher values may indicate the higher influence of the temperature fluctuations in the strain variations. The minimal values may indicate the predominant effect of the time-dependant load over the temperature variations. The presence of residual strains at the end of the loading revealed that creep deformation, due to the combined effect of load and temperature effect, had occurred in all packages. For each sensor, the strain recovery was evaluated by calculating the rate of recovery as the strain difference per unit time. The rate of recovery was determined for the strain data collected for a minimum of 15 min. The positive rate of recovery values indicated that the FBG packages' response would decrease to zero strain. In the case of Specimen 1, Side 2 Loading, the FBG sensors had higher residual strains which may indicate changes in the internal make up of this specimen.

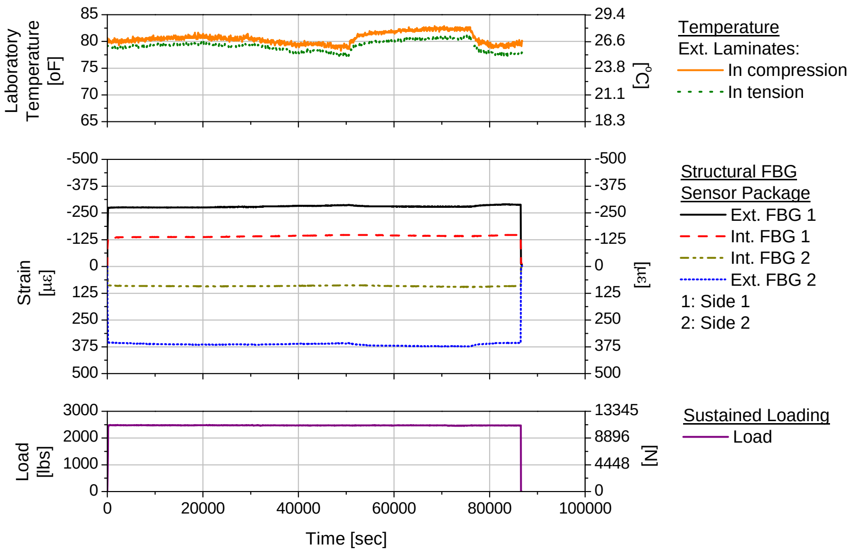


Figure 6. Sustained Loading Test – FBG Strains, Load and Temperature vs. Time

In the short term, all structural FBG sensor packages had comparable strain performance to the basic bending test results. After 24 hours, the strain levels were influenced by both time-dependant loading and ambient temperature fluctuations. After unloading, the residual strains of two internal and four external structural FBG sensor packages were found to decrease to zero strain over a period of an hour.

4.1.3 Fast Loading Test

The main objective of these tests was to evaluate the viscoelastic behavior of the FBG structural packages when applying a load 11 KN (2500 lbs) with fast loading rate followed by stabilized loading and unloading. During testing, constant laboratory temperatures were observed for which temperature effects were neglected. All specimens were tested under loading rates of 11 KN/min (2500 lbs/min), 22 KN/min (5000 lbs/min) and 667 KN/min (150,000 lbs/min). The latter test was performed twice per specimen to verify the reproducibility of the strain data. No major differences between 11- and 22-KN/min fast test results were observed. At the fastest rate, both peak strains were up to 2% higher than the average strain determined from the stabilized strain data. In the 667 KN-lbs/min fast test, the increments in load and strains were at least 30% larger than the average values (see Figure 7). After 5 seconds, the strain levels and load were stable. With the exception of Specimen 1, the average strains were on the same order as the basic bending test results, indicating that the FBG sensor packages had consistent flexural stiffness after fast loadings. The residual strains were minimal in most cases showing a tendency to decrease over a period of approximately 15 minutes.

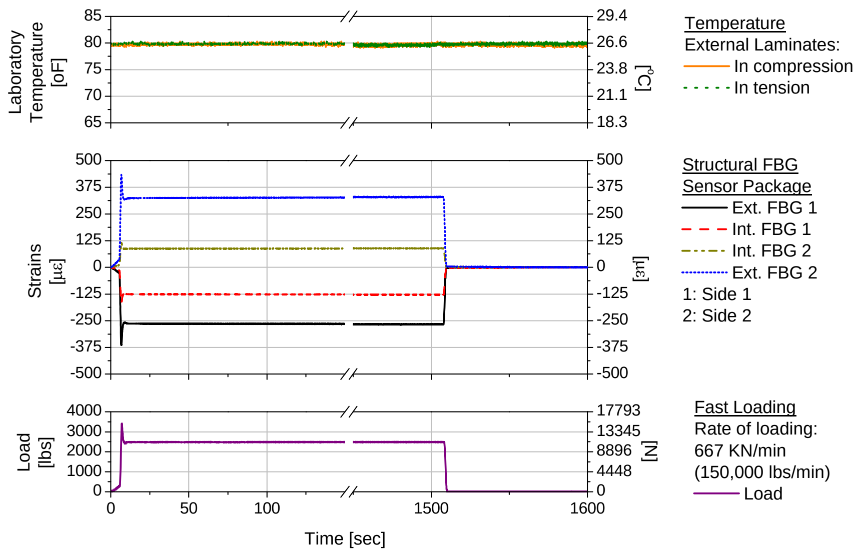


Figure 7. Fast Loading Test – 667 KN/min fast loading results

4.1.4 Pseudo Cyclic Loading Test

This test was conducted with the purpose of examining the behavior of the structural packages for phase lag during loading and after removing the applied load. Two pseudo cyclic tests consisting of 10 cycles with rates of loading and unloading of +/-22 KN/min (+/-5000 lbs/min) and +/-6 KN/min (+/-1250 lbs/min) were applied on each specimen's side. In all tests, the dispersion of the peak strains was minimal (i.e., below 3 με), demonstrating that the strain phase lag was negligible. When comparing both tests, the peak strains differed by up to 10 με; relatively high peak strains were obtained in the test with fast loading (i.e., +/-22 KN/min). Higher strains were associated to the higher rate of loading. In addition, the residual strains were also assessed and in all cases, the strain recovery was impending demonstrating that the FBG packages have a viscoelastic response.

4.1.5 Heat and Sustained Loading Test

The specimens were subjected to a combined heat and sustained loading for 24 hours to evaluate the viscoelastic behavior of the FBG packages due to both effects during and after loading. The specimens were confined in a heat box in which the temperatures were increased from ambient laboratory current conditions to approximately 49°C (120 °F). As observed in Figure 8, the external FBG strains varied in phase with the temperature fluctuations. Internally, the FBG packages lagged behind the external temperature changes. In the absence of the internal thermocouples, the internal FBG strains were not evaluated for temperature correlation. A linear regression analysis was completed to assess the relationship between external strain and temperature. The quality of the linear model was determined through the associated R^2 coefficients. These coefficients varied from 0.25 to 0.97, indicating that strain data were impacted by the temperature fluctuations and creep. After loading, the residual strains were above 80 με. After testing, each package was visually examined to detect any physical deterioration. In Specimen 1, elevated temperatures above 66°C (150°F) were accidentally applied. In this specimen, one package delaminated. In general, the FBG sensor packages had a viscoelastic behavior; reduction of higher strain levels after unloading and returning the specimen to ambient temperatures confirmed the creep recovery.

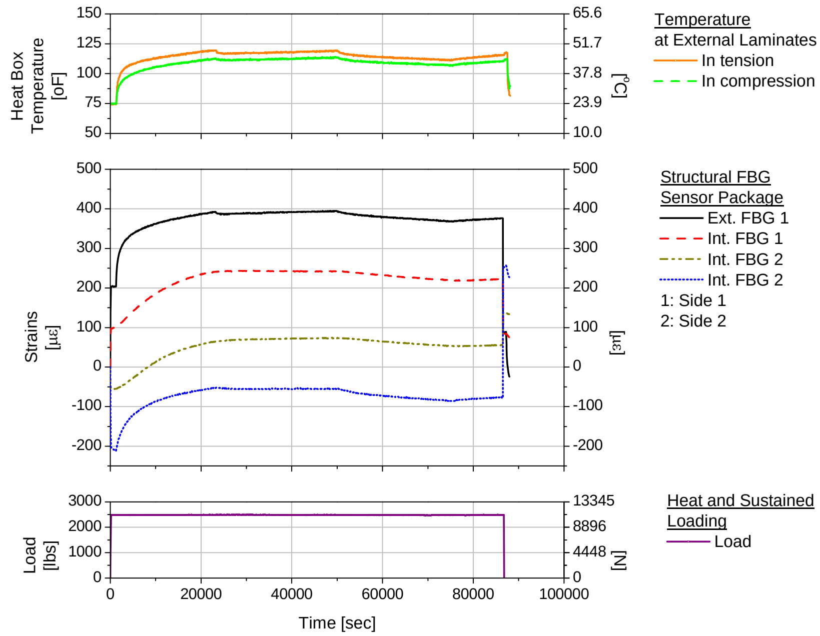


Figure 8. Temperature and Sustained Loading Tests

4.1.6 Cold and Sustained Loading Test

The effect of cold temperatures and sustained loading were assessed to determine the viscoelastic behavior of the structural packages. The specimens were placed in a cold box for reducing the temperature to around -18°C (0°F). However, after enclosing the specimen, the temperatures were uncontrollably lower during the first three hours and steadily stabilized later. The tensile bending surface was cooled to temperatures near -18 C (0°F), while the compressive bending surface was subjected to temperatures that initially were lower than -46°C (-50°F) and increased to approximately 10°C (50°F). Difficulties of generating a constant cold flow were due to the dry ice instable conditions and its distribution inside the cold box. As a result, the initial flexural stiffness and physical properties of the specimens and/or structural packages may have varied. As observed in Figure 9, strain lags with respect to the cold temperature fluctuations were observed in all external and internal FBG packages. The lag was associated to the inherent insulation and thermal properties of dry wood members.

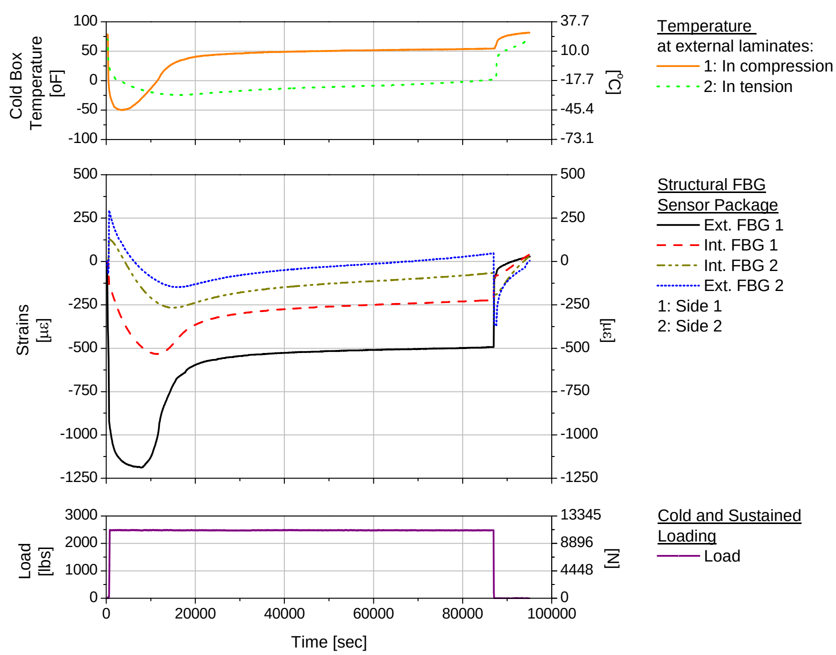


Figure 9. Temperature and Sustained Loading Tests

4.2 Non-Structural Packages' Test

One bending test was performed in five specimens instrumented with non-structural FBG sensors to investigate the embedding techniques by obtaining no strain in the FBG sensors. During loading and maintaining a constant load of 11 KN (2500 lbs), the FBG sensors registered strains that were consistently less than 10 $\mu\varepsilon$. Only one sensor had strain levels equivalent to the structural internal FBG sensor packages denoting an error in the non-structural package application. The source of error was attributed to the package adhesive that may have bled in the recess area and partially attached the sensor to the recess area. Among five non-structural package types, four had negligible strain levels demonstrating the effectiveness of installation techniques.

5. Discussion and Conclusions

In general, the installation techniques for FBG sensors with and without physical attachment to the wood laminates using structural and non-structural packages were satisfactory. The developed embedding techniques were proven to be adequate at the laboratory level; however, the application of these techniques must be developed at the manufacturing level before being implemented at widespread scale.

Regarding the laboratory testing over the short term loading, the structural FBG sensor packages demonstrated to perform within the tolerances of theoretical values (beam theory) and the foils strain gages and strain transducers' response. Note that all small specimens were subjected to the same bending tests, while varying the duration of the load, rates of loading, cyclic loadings and ambient temperatures. In the short term bending tests, strain levels in all packages were consistent and in the order of the basic bending test results. During and after loading, strain levels were influenced by both creep and temperature fluctuations in a lower or higher degree depending on the duration of the applied load and the imposed temperatures. In all tests, after unloading, the presences of residual strains and the imminent strain recovery over time demonstrated the viscoelastic behavior of the structural FBG sensor packages inherent of the constituent packages materials and specimens.

With the exception of one package, the developed non-structural FBG sensor packages and embedding techniques were proven to isolate the FBG sensor from strain response. Only one bending test was conducted to verify the no strain in the FBG sensors; however, these techniques are required to be tested under different loading conditions to demonstrate that the non-structural response would be registered by the FBG sensors.

6. Acknowledgements

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7. References

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