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STRUCTURAL HEALTH MONITORING OF LEGACY WWII INFRASTRUCTURE WITHIN THE DEPARTMENT OF NATIONAL DEFENCE, A STAGE-WISE APPROACH

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Abstract: Structural Health Monitoring (SHM) programs have been widely adopted in structural engineering applications for knowledge, control, and emergency purposes. SHM programs aid in understanding the behaviour of structures, both globally and locally, and essentially provide the quantitative link between the design and actual performance of structures. The focus of this research is the long-term SHM of a 'temporary' World War II era timber Warren truss Air Force hangar located at a Canadian Forces Base (CFB) in St-Jean, Quebec. Hangar 1 is one of approximately 70 Warren truss structures still maintained by The Department of National Defence (DND). Originally designed as a temporary structure, this Warren truss warehouse has been subjected to environmental stresses, extreme material degradation, and extensive rehabilitation efforts. As a result, the structure exceeds serviceability and structural capacity limits leading to evacuations at snow accumulations of 100 mm, thus warranting an SHM system. This SHM endeavour will be achieved by implementing a robust monitoring plan, utilizing multiple instruments capable of determining the behaviours of selected Warren trusses within the overall structure. To achieve this objective, firstly, a scaled-down truss was created and tested within a laboratory environment at the Royal Military College of Canada (RMC). Critical monitoring locations were confirmed by multiple forms of monitoring and by means of numerical modelling. These preliminary results contribute to the current implementation of an optimal in-situ, remote, long-term SHM program in Hangar 1. This SHM program combined with predetermined serviceability and structural integrity limits will provide real-time alarms for evacuation purposes, an overall increase in occupant safety, and an insight into the behaviour of these complex, legacy structures.

1 INTRODUCTION

Hangar 1 at CFB St-Jean was constructed as one of the approximately 200 Warren truss Air Force hangars built during WWII as part of the Royal Canadian Air Force's contribution to the British Commonwealth Air Training Plan in 1942. The structure is a 34 m, double-span, parallel Warren truss structure consisting of eleven Douglas Fir timber trusses on each side. Additionally, a four cable post-tensioning system has been installed in the building (Muntz, 1946). Furthermore, a rehabilitation effort was made in 2014, resulting in the installation of intermediate columns to reduce deflections. This legacy truss structure has since been converted to a storage warehouse and is one of approximately 70 Warren truss structures still maintained by the Canadian Armed Forces (CAF). Subjected to environmental stresses, particularily snow loads, the truss structure may exceed serviceability and structural capacity thresholds. Subsequently, evacuations are conducted based on a snow accumulation of 100 mm, neglecting the effects of snow drift, snow pack, and snow-water equivalency, thus warranting a research-based investigation to include a sustainable SHM program. The SHM program for this study includes various forms of monitoring for comparison and redundancy purposes, including conventional instrumentation techniques, terrestrial laser scanning (LiDAR) scanning, the use of fiber optics, and the implementation of an automatic total station (ATS). Currently, Hangar 1, and four other truss structures subjected to the same evacuations, house numerous units that are vital in meeting the day-to-day operational requirements of CFB St-Jean. As such, these buildings are utilized extensively and evacuations significantly disrupt the operational capabilities of CFB St-Jean. The overall aim of this project is to determine an optimal SHM method that can be applied on similar legacy truss structures within the DND.

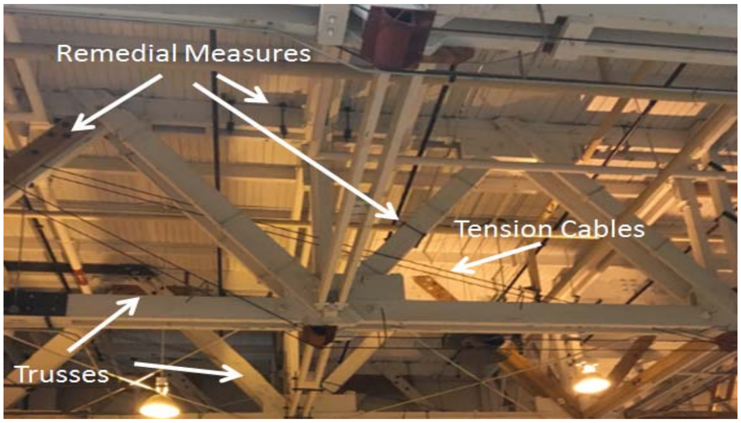

Figure 1: Hangar 1, CFB St-Jean

1.1 Timber Warren Trusses

Truss systems are utilized because of their significant span length capabilities and are designed to transfer loads to support systems. Thus, they are used extensively in large-span bridges and buildings where column supports affect the buildings usage, as is the case for Air Force hangars. Often referred to as an equilateral truss, the Warren truss is composed of panel lengths and vertical struts of equal length, connected with diagonal members thereby creating a sequence of pin-connected, equilateral triangles. As shown in Figure 2 the trusses in Hangar 1 are comprised of 3 main elements: top and bottom parallel chords, vertical struts and, diagonal web members.

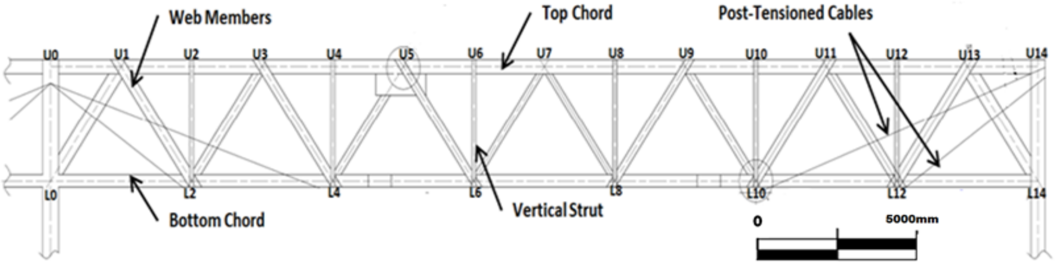

Figure 2: Truss Nomenclature (Modified from AXOR Experts-Conseils, 2014)

The truss is designed such that the chords are subjected to combined axial and bending loads and the latter two components are subjected only to axial forces. Due to the symmetrical nature of Warren trusses, specific web members are also designed to strictly carry tension or compression forces in terms of long term loading. Furthermore, based on this load path expectation, the web members increase in size from the center panel to the supports. The expected general structural response of a double-span, parallel Warren truss subjected to permanent or semi-permanent loading in the form of uniformly distributed loads or uniformly distributed point loads is shown in Figure 3, where red and blue indicate compression and tension forces, respectively (CSi, 2016).

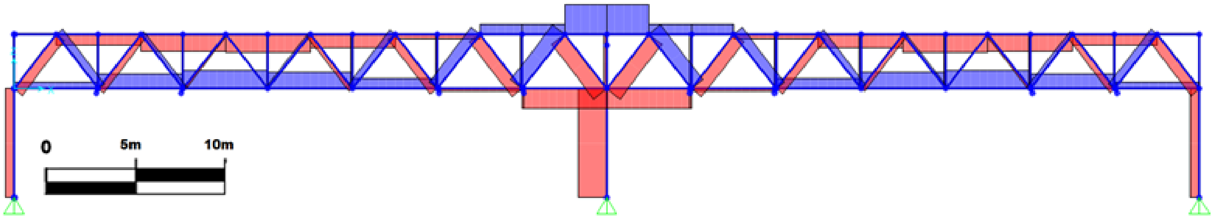

Figure 3: Axial response of a Warren truss subjected to a UDL

Finally, the importance of load duration on timber structures must be discussed as timber is capable of carrying much higher loads in the short term vice the long term. This is reflected in (CSA 086, 2014) as a load duration safety factor of 0.65 is utilized for long-term loading conditions. Long-term loading is outlined as dead loads, superimposed dead loads, and potentially snow loads at the designers discretion. Thus, these loading factors have been incorporated within this study. The load duration is of particular importance in this research due to the age of these legacy structures.

1.2 Structural Health Monitoring

SHM programs have been widely adopted in structural engineering applications for knowledge, control, and emergency purposes. SHM programs aid in understanding the behaviour of structures, both globally and locally, and essentially provide the quantitative link between the design and performance of structures.

A robust SHM program is capable of performing all three forms of monitoring:

1. Knowledge monitoring – Assess the structure and determine the structural behaviour;
2. Control Monitoring – Periodic testing; and,
3. Emergency monitoring – Provide an early warning system.

To satisfy the above mentioned monitoring forms, the SHM program must be capable of providing data remotely, continuosuly, and in the long-term. Furthermore, in terms of emergency monitoring, the SHM program must incorporate an alarm system that is capable of communicating with building occupants for evacuation purposes; thus, the SHM program must be contingent upon real-time data. Lastly, the amount of hardware must be limited in order to minimize distruptions in the day-to-day operations within Hangar 1. With the minimum SHM criteria finalized, the measurands required to meet these robust requriments were determined. These measurands were determined to be deflections, structural behaviour (stress/strain), in-situ properties, and environmental conditions.

2 PREVIOUS RESEARCH

An extensive amount of research has been conducted on CAF Warren trusses. Furthermore, extensive rehabilitation efforts have been made across many CFBs. Significant investigations were conducted to determine the behaviour of legacy Warren truss structure joints (Foo, 1993; Foo and Akhras, 1996). A knowledge-based computer system was developed to improve the inspection and maintenance process that is required for all CAF Warren truss structures (Akhras and Foo, 1993). Additionally, the failure characteristics of these Warren trusses were investigated by (Foo and Seckin, 1988). This cited research significantly improved the understanding of these legacy structures and aided in the development of the Construction Engineering Technical Order (CETO C-98) for 34m DND Warren truss structures; a core document published by DND and one that has been used as a guideline for this research project (CETO, 2015).

Particularily, SHM programs have been implemented on DND Warren trusses (Marjerrison et al. 2008; Morin and Akhras, 2013; and Locklin et al., 2017). Conventional electric strain gauges, fiber optic sensors, and vibration and wave-propagation based sensors were all considered within this cited research. High data volumes and environmental condition effects reduced the effectiveness of these previous SHM endeavours. Accordingly, the implementation of a more robust and redundant SHM system will lead to the determination of an optimized SHM method that can be applied to all DND truss structures, nationwide. Furthermore, the incorporation of environmental monitoring instruments will provide data necessary for a detailed numerical model to better understand the true behaviour of these legacy structures.

3 EXPERIMENTAL PROCEDURE AND METHODOLOGY

3.1 Laboratory Specimen

A ¼ scale truss structure was designed, constructed, monitored, and tested in the RMC Civil Engineering structures laboratory. The truss was constructed with 2"x4"s and bolted connections. This scaled down truss was tested under several loading scenarios within a laboratory environment. The primary purpose of the laboratory experiments was to analyze the specimen's behaviour to determine an optimal SHM plan prior to the implementation of a SHM program in Hangar 1. Furthermore, lessons learned during the laboratory experiments aided in the development of an optimized monitoring procedure; thus, employing a stage-wise approach. Objectives during this experimental procedure included:

1. Understand selected instrumentation capabilities and limitations;
2. Determine critical monitoring locations on Warren trusses;
3. Correlate structural behaviours under certain loading scenarios;
4. Compare various forms of monitoring techniques; and,
5. Determine optimal real-time, alarm system.

Throughout the experimental procedure, particular emphasis was placed on the effects of the intermediate columns on the structural behaviour of the truss. Predominantly, the placement of intermediate columns that replicated the in-situ truss and the correlating load reversals and bending reversals were studied. The laboratory set-up is demonstrated below in Figure 4.

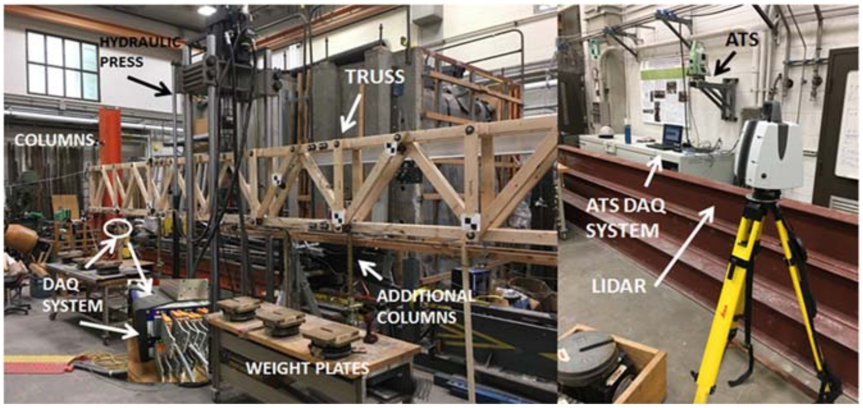

Figure 4: Laboratory set-up, Structures Lab, Royal Military College of Canada

3.2 Instrumentation

Multiple forms of instrumentation were utilized with a view to determine the best form of monitoring as well as to have redundant systems for comparison purposes. The following instruments were utilized throughout the experimental procedure and will be employed throughout the SHM project. The instruments are outlined in Table 1 in terms of the above mentioned SHM criteria. The locations of these instruments are detailed in Figure 5 and 6.

Table 1: Experimental Instrumentation

Instrument/DAQ/Software	Main Objective
Displacement Monitoring	

Automatic Total Station (ATS) Leica TM50 - 12 Targets, 2 Control Points DAQ: GeoMoS Monitor and Analyser	Monitor the 3 modes deflections of the Warren Truss, utilizing precision targets mounted on selected locations to monitor serviceability limits
Terrestrial Laser Scanner (LiDAR) Leica ScanStation P40/P30 -12 Paper Targets, 4 Control Points DAQ : Cyclone 9.1	Monitor the 3 modes deflections along the entire Warren truss to monitor serviceability limits
Linear Variable Differential Transducer (LVDT) - 3 LDS – 50 DAQ: QUANTUMX & Catman®AP	Monitor the vertical deflections of the Warren truss at selected locations to monitor serviceability limits
Structural Behaviour	
Electric Strain Gauges (ESG) 24 Gauges -KFG-5-120-C1-11 DAQ: QUANTUMX & Catman®AP	Measure strain at selected locations on the Warren truss to monitor the structural capacity and loadings on selected members
Fibre Optic Sensors (FOS) Luna ODiSI-B - 4Members	Measure strain along the truss to monitor structural capacity and loadings on selected members
In-Situ Properties	
Moisture Meter* - Delmhorst Navigator *Pro*	Measure the in-situ moisture content of the wood
Environmental Conditions	
Wind Monitors* - 2-YOUNG Model 05103V DAQ: QUANTUMX & Catman®AP	Monitor the wind conditions/loading on the structure
Temperature/Humidity Sensors - 2 – HTM2500LF Sensors DAQ: QUANTUMX & Catman®AP	Measure the environmental conditions within the structure and correlate instrument response
Snow Scale* - TBD	Determine snow loads and correlate loading effects with structural behavior for evacuation purposes

*Not utilized during experimental procedure

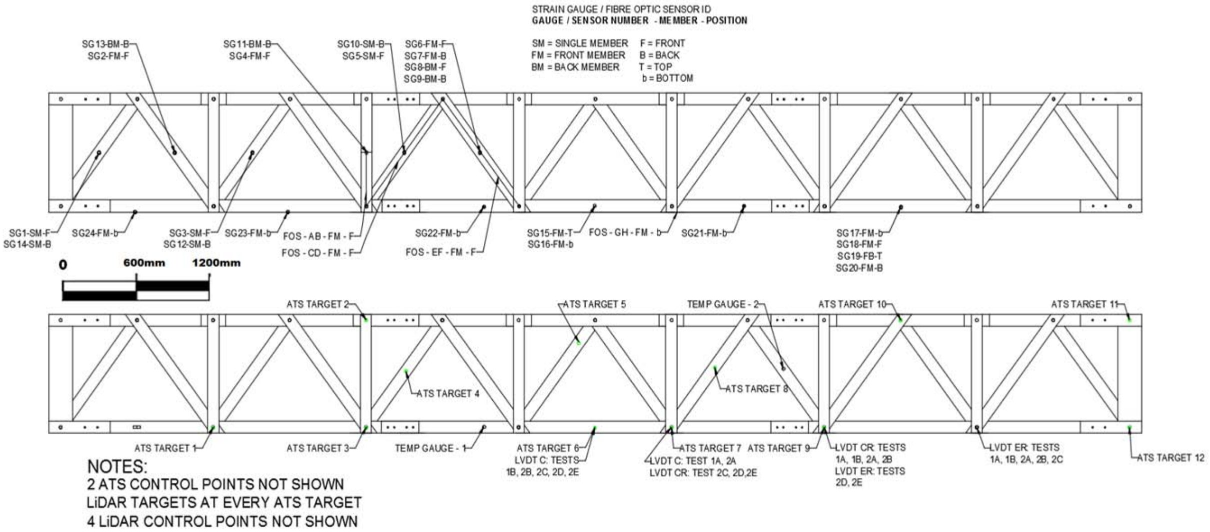

Figure 5: Laboratory Instrument Locations

QUANTUM X, a state-of-the-art data acquisition system (DAQ), was used throughout the experimental procedure. The software employed for the monitoring procedure was Catman®AP and was compatible with all monitoring instruments except the ATS, LiDAR, and Distributed Fibre Optic Sensors (FOS), as these have internal data storing capabilities. Additionally, the latter three instruments required specific software.

3.3 Testing Scenarios

Two point load tests (PLT) and five distributed point load tests (DPLT) were conducted throughout the experimental procedure, as shown in Figure 6. 3 kN and 5 kN PLTs were conducted using a hydraulic press at the center of the truss. DPLTs were conducted using weight plates that were manually placed at each vertical strut along the truss, thus accurately representing the in-situ loading conditions in Hangar 1. The total loading on each vertical strut was 0.70 kN, representing a total load of 4.2 kN. In order to replicate the in-situ truss, intermediate columns were installed and tested under the same loading conditions. Loading was introduced within the system incrementally, depending on the testing scenario. The instruments utilizing Catman®AP collected data continuously at a frequency of 1 Hz. The ATS collected data at each load increment. Finally, the LiDAR and FOS data was collected at the point of max loading for each testing scenario.

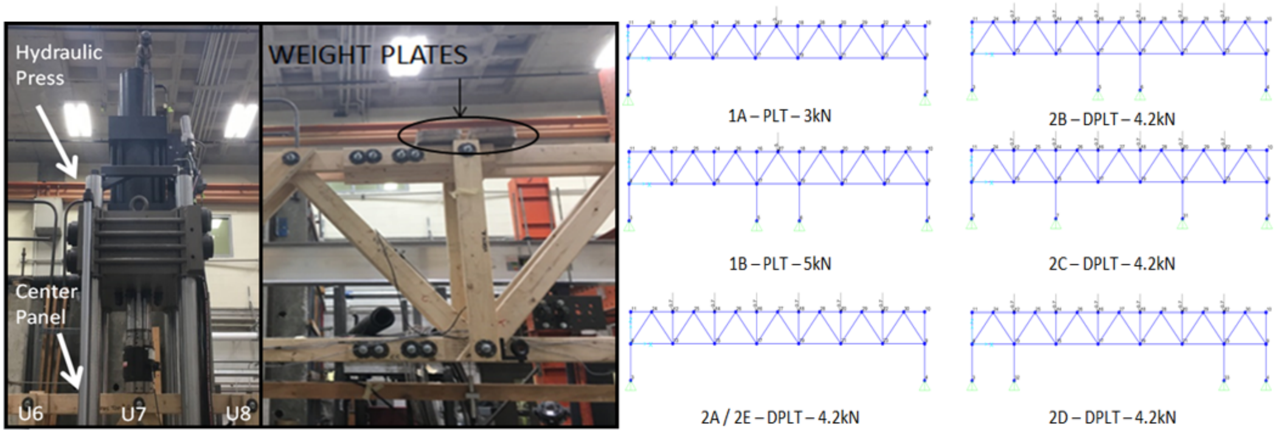

Figure 6: Laboratory testing scenarios

4 RESULTS

4.1 General Behaviour

Data was successfully analyzed to determine common structural behaviour trends resulting from the addition of the intermediate columns. Furthermore, the data provided insight on the accuracy of the SHM instruments. It was determined that results were significantly more consistent at higher loads than at smaller loads. Moreover, it was determined during experimental testing that the PLTs did not provide as reliable data as the DPLTs. Firstly, the PLTs did not reflect the in-situ loading conditions. Secondly, significant cracking occurred in members close to the hydraulic press.

4.2 Selected Laboratory Results

The selected results discussed below are focused on Test 2A (i.e. No intermediate columns) and Test 2B (i.e. Intermediate columns in the same locations as Hangar 1) in order to understand the effects of the additional intermediate columns that represent the true in-situ conditions.

The displacement data from the ATS, Linear Variable Differential Transducers (LVDTs), and LiDAR are compared in Figure 7. The displacement values were taken as the maximum displacements monitored by each respective instrument throughout the five tests. The location of maximum displacement for each respective test is also shown in Figure 7.

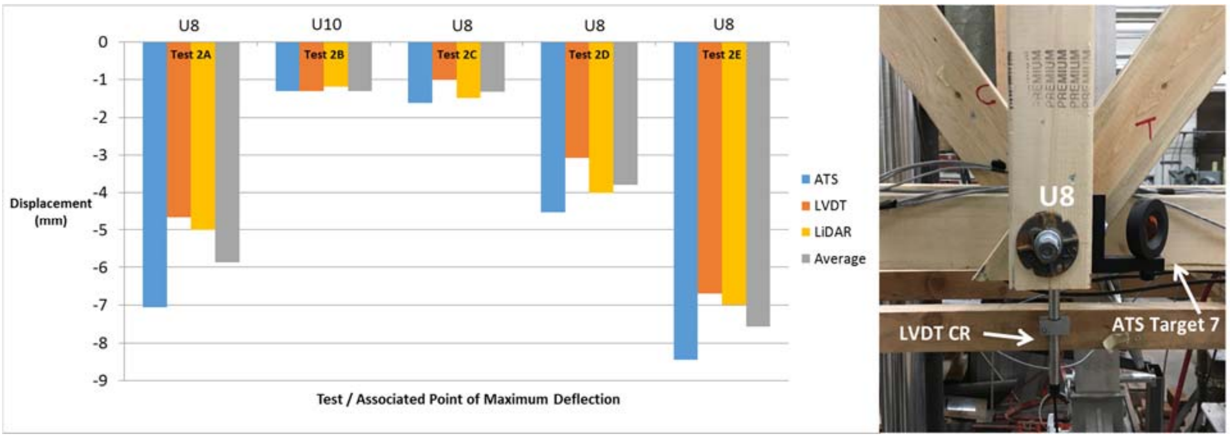

Figure 7: Maximum Displacement Values

As expected, the additional columns greatly improved the serviceability of the truss. In particular, the addition of intermediate columns in Test 2B resulted in nearly an 80% reduction in maximum displacement as the unsupported span is reduced to only three panels. Lastly, removing the intermediate columns in Test 2E details the creeping effects of loaded timber as maximum displacement increased from Test 2A and 2E. As the truss was loaded throughout the testing regime, permanent deformation and a reduction in overall strength of the truss occurred. It is shown that all deflection instruments successfully captured the displacement of the truss, thus validating the instruments for use during the in-situ SHM project. Furthermore, they provided a degree of data redundancy, of which is crucial for emergency monitoring.

The positive effects of intermediate columns are demonstrated in an increased serviceability, however, both serviceability and structural behaviour must be considered. The electric strain gauge (ESG) results, focus on the changes in structural behaviour between Test 2A and Test 2B. Particularly, the graphs presented in Figure 8 and Figure 9 focus on the local members that are most affected by the intermediate columns.

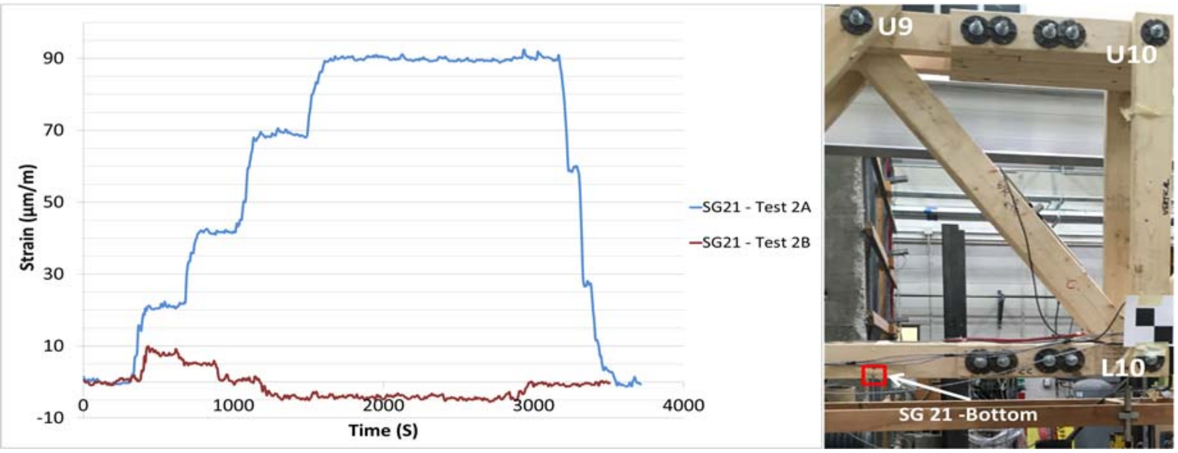

Figure 8: Strain Gauge 21 demonstrating bending reversals in the bottom chord between Test 2A and Test 2B

SG 21 is located on the underside of the bottom chord located between the intermediate supports and orientated parallel to grain. Gauges placed on the top or bottom of the truss chords successfully captured the extreme bending strain of these members. As the gauge is placed on the underside of the member, tension values in this location indicate sagging (positive bending moment) and compression values indicate hogging (negative bending moment). Figure 8 demonstrates the significant effect of the intermediate columns on the bending moments in the bottom chord. Despite a noteworthy reduction in the bending stress it is evident that bending reversal did occur in the bottom chord between Test 2A and Test 2B. The installation of intermediate columns in Test 2B caused the bottom chord at this location to switch from a positive to a negative bending moment.

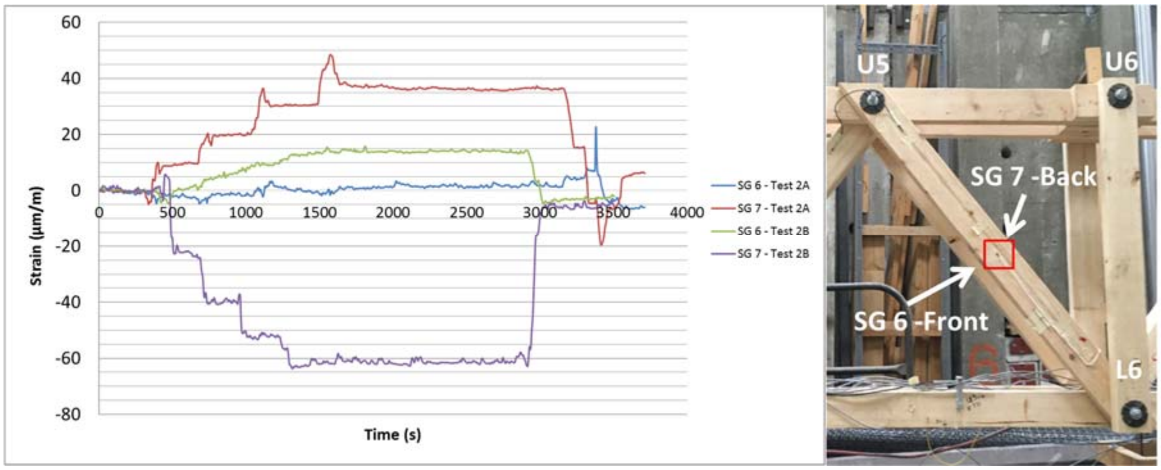

Figure 9: Strain Gauges 6 and 7 demonstrating load reversal in a web member between Test 2A and Test 2B

Data collected from SG 6 and SG 7 during Test 2A and Test 2B is displayed in Figure 9. Orientated parallel to grain and respectively located on the front side and back side of a tension web member, SG 6 and SG 7 indicate two noteworthy behaviours. Firstly, the addition of intermediate columns caused an axial load reversal in the web member. Secondly, during Test 2B this web member underwent bending as demonstrated by the compression values in the SG 7 and tension values in SG 6. This is important to highlight, as web members are not designed as bending members.

FOSs were successfully employed to capture the internal mechanisms along the entire member and thus data was not restricted to localized, discrete points as provided by the ESGs. This provision of distributed data is solely a capability of the selected distributed optical sensing technique, the Luna ODiSI-B (Optical Distributed Sensor Interrogator). In comparison to other commercially available optical strain sensing technologies, the ODiSI-B provides a superior spatial resolution of 0.65 mm (Forbes et al. 2018). Accordingly, the ODiSI-B solution was selected to investigate the strain distribution and potential inhomogeneities across truss members. In anticipation of an inconsistent response, two adhesives were tested: 1) Loctite acrylic adhesive and 2) five minute epoxy resin. Two variations in the protective layering along the optical fiber were also tested in consideration of protecting the FOS from localized failure: 1) optical fiber stripped to the buffer layer (900 um approximate outer diameter) and 2) optical fiber stripped to the protective polyimide protective coating (250 um approximate outer diameter). Figure 10 demonstrates the effects in distributed strain data due to the installment of intermediate columns. The FOS data from Test 2A and 2B clearly demonstrates load reversals in the vertical strut as represented by fibre lengths AB. The vertical strut of a Warren truss is designed to serve as a compression member; however, the additional column causes this member to act in tension.

A comparison between the measured FOS strain data on the wooden truss members and that from previous experiments investigating steel supporting members (Forbes et al., 2017, Vlachopoulos et al., 2018) determined the truss measurements to be much less consistent. Axially loaded members are expected to have uniform strain distribution; however the strain data indicates a high level of localized noise. It is hypothesized that this high noise level is a result of inconsistent bonding between the wood face and the fibre due to the inhomogeneity of wood. Thus, warranting further bonding development and testing for FOS installations on wood.

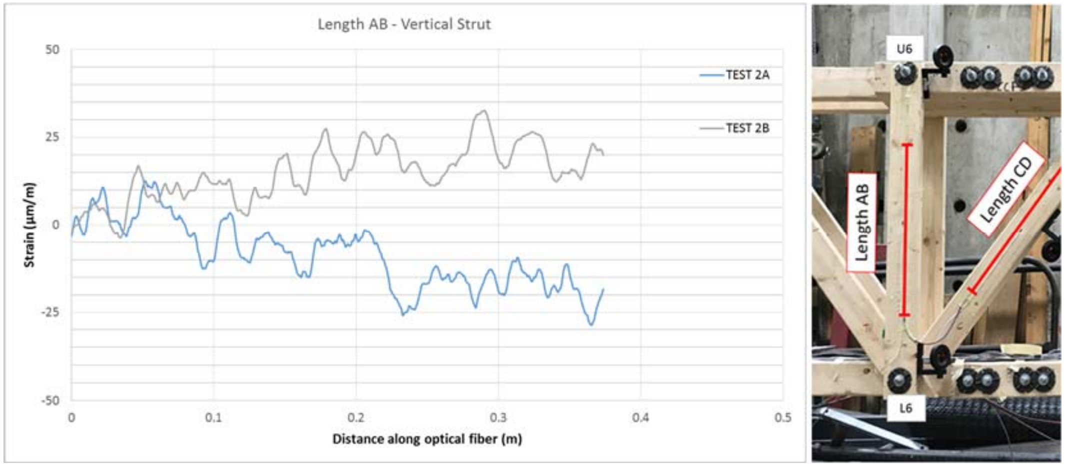

Figure 10: FOS data demonstrating load reversal in a vertical strut

5 NUMERICAL MODELLING

SAP2000® (CSi, 2016) was utilized to produce a numerical model of the truss located in Hangar 1. The analysis was performed to better understand the expected behaviour of Warren trusses, particularly with the addition of the post-tensioning cable system. In addition, the general effects on the structural behaviour of the truss due to the addition of the intermediate columns were determined. The model was produced with member sizing and material specifications characterizing the in-situ properties of the Warren truss in Hangar 1. The maximum tension or compression loads were determined for each member and compared to the member's axial resistance using (CSA, 2015) to determine axial safety factors. Numerical modelling determined that the addition of intermediate columns caused load reversals in fourteen members. Further numerical modelling will be conducted on the effects of combined axial and bending on truss members. Overall, numerical modelling aided in the selection of members for an optimized in-situ SHM program

6 DISCUSSION

Laboratory testing and data redundancy determined that all monitoring instruments provided reliable, accurate data. However, the ATS, ESGs, and LVDTs were more effective in providing real-time, continuous data. Most notably in their respective software's efficiency in communicating with the user to provide real-time, emergency monitoring. Furthermore, the large data files and non-autonomous nature associated with FOSs and LiDAR restrict their capabilities for remote monitoring. Despite the ATS, ESGs and LVDTs being efficient emergency monitoring solutions, these discrete sensing technologies inherently lack the spatial resolution to efficiently monitor the behaviour of the entire Warren truss. Thus warranting the employment of FOSs and LiDAR as an inspection, control, and monitoring tool.

It was demonstrated by experimental data that the addition of intermediate columns greatly affects the global and local behaviour of a Warren truss. The ESGs and FOSs captured significant load reversal and bending reversal behaviour due to the intermediate columns. This behaviour was also validated during numerical modelling. Load and bending reversal effects will be investigated thoroughly during the long-term SHM project, particularly in members that were in tension for nearly 80 years and are now under compression loading. Preliminary observations indicate severe cracking and increased rehabilitation efforts on members that succumbed to this long-term load reversal.

ESGs and FOSs will primarily be installed in members that demonstrate load or bending reversals and members with low safety factors. Optimal ATS target and LVDT placement in Hangar 1 was determined based on locations of maximum deflection. The above mentioned locations were all determined and validated during experimental testing and numerical modelling. Lastly, lessons learned during the experimental testing and site limitations optimized the instrumentation design and procedure.

Despite limited usage during the laboratory experiments, the in-situ and environmental condition monitoring instruments will be used extensively during the field monitoring. In particular, the wind monitor and snow scale will provide data capable of correlating external loading to the overall structural behaviour.

7 CONCLUSION

A monitoring plan was optimized by means of laboratory testing and numerical modelling for the long-term, SHM of a legacy WWII Warren truss structure located at CFB St-Jean. Future research will be conducted in further optimizing the SHM program to perform continuously and remotely; ultimately producing one that provides a real-time, alarm system for evacuation purposes while also explicitly determining the behaviour of such complex structural systems.

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