Health monitoring of buried pipelines using brillouin scattering FOS

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ABSTRACT: Large-size buried pipelines have been proven to be an effective method to transporting oil and gas from remote regions to urban regions. As the exploration of oil and gas in Alberta been extended further into the Artic and sub-Artic regions of the Canadian North, the buried pipelines must undergo extreme harsh environment conditions. Consequently, under this complex and severe loading condition the buckling or overstressing of buried pipelines has become a concern. However, for the thousands of kilometer long line pipes, conventional strain gauges or point fibre optic sensors (FOS) are not suitable for continuously monitoring the pipe behavior under complex and severe environment in long-term. Therefore, a continuously distributed sensor, Brillouin scattering fibre-optic sensor (BSFOS), is noticed. Both laboratory tests and field tests were conducted to verify the feasibility of BSFOS system. An integrated monitoring system including the BSFOS system and numerical models for health monitoring of buried pipelines is in progress

1 INTRODUCTION

1.1 *The energy pipelines in Alberta*

Alberta energy industry plays a very important role not only for Canadian economy but also for North American energy supply. Over 80% of oil and natural gas production in Canada is coming from Alberta and over 100,000 km of large transmission pipeline, of which over 85% are in Alberta (Cheng, 2004). As the demand for these resources increases, pipeline construction pushes further into the Arctic and sub-Arctic regions of the Canadian North. Consequently, these buried pipelines suffer much harsh and unpredictable environmental condition, such as freeze and thaw, differential settlement, soil movement, and permafrost. Furthermore, to improve the efficiency of the transportation, higher strength materials, larger size pipes and higher operation pressure are used. These severe and unpredictable conditions introduce complex loading on the pipes and increase the risk of pipeline failure, especially, local buckling failure as shown in Figure 1. The local buckling failure and sequential pipe fracture not only cause enormous cost loss but also lead to high risk due to the leakage of these resources.

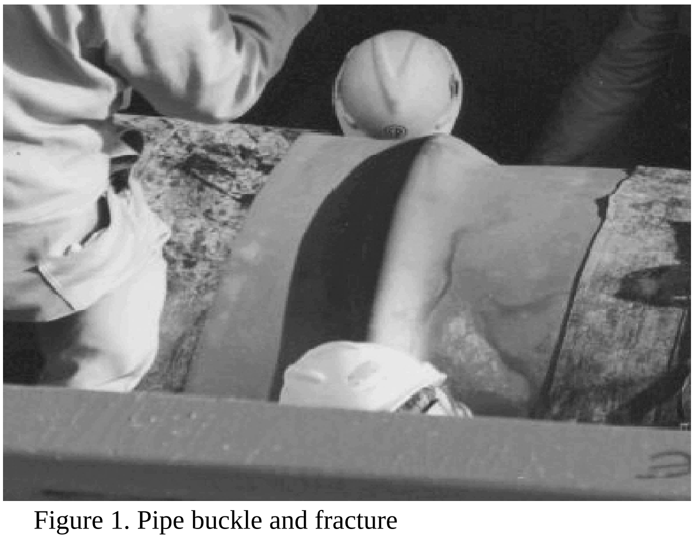

Figure 1. Pipe buckle and fracture

1.2 *The importance of SHM for buried pipelines*

For the thousands of kilometer buried pipelines in remote Canadian North, it is very difficult to detect their damage. In the past, to prevent the buried pipe from buckling failure, engineers need to inspect the pipeline in the field periodically and decide the stress relief schedule through excavation, as shown in Figure 2. The whole inspection procedure is mainly based on engineer's judgment, which is a variant, and the excavation process is quite expensive. In addition, this procedure has no active warning system for possible failures between inspections. Therefore, how to develop a technology to reliably monitor the health of buried pipeline and to reduce the risk is very important for the energy industry. The structural health monitoring (SHM) system has become a promising and effective technology to provide real time monitoring and warning possibilities.

Figure 2. The excavation of the buried pipeline

In order to monitor thousands of kilometer pipelines in remote areas, an indiscriminate distributed sensor system is essential for the SHM system. The Brillouin scattering fiber-optic sensor (BSFOS) system is identified as a potential technology for this application. This research project is designed to investigate the feasibility of using the BSFOS system in the SHM of buried pipes. Both field and laboratory full-scale pipe tests were used in the program. Numerical models will be developed and embodied into the integrated SHM system to promote the reliability of the system.

2 SHM SYSTEM FOR BURIED PIPELINES

An integrated SHM system for buried pipelines using BSFOS consists Brillouin-based data acquisition system, a centered control computer and server, database system (DBS), terminal computers, a diagnostic and discriminate program for collected data, and communication equipment, as shown in Figure 3. The calibrated behavioral signatures of buried pipelines should be identified before they are employed by the diagnostic program, and these calibrated signatures can be found not only from the observations in field and laboratory tests, but also from the Finite Element Analyses (FEA).

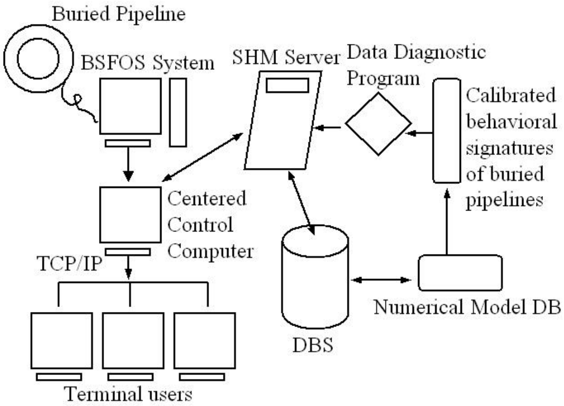

Figure 3. The scheme of SHM system using BSFOS

The BSFOS system has some unique features for pipelines, such as distributed measurements along optical fibers that provide average measurements in a continuous manner with a specific resolution. The SHM system employing BSFOS system must be able to correctly discriminate the varied responses of buried pipelines through the interpretation of collected data by using diagnostic program or damage detection models. Therefore, FEA technology used to perform parametric simulations and case studies is imperative.

The first phase of developing the monitoring system for buried pipelines using BSFOS was presented in this paper; that is application of BSFOS system, the evaluation of BSFOS system through field and laboratory tests, and establishment of numerical models.

3 BRILLOUIN SCATTERING FIBER-OPTIC SENSNOR (BSFOS) SYSTEM

3.1 *The advantage of BSFOS for monitoring buried pipelines*

Fiber optic sensor technology has been progressing rapidly in the last decade, but this technology is difficult to be applied in monitoring of pipelines, especially buried pipelines. The reason is that even though the normally used fiber-optic sensors (FOSs), such as Fabry-Pero and FBG FOS, can continuously monitor structural responses under severe environment, they can only provide very limited data in few specific locations. Hence, these discrete measurements can not sufficiently reveal the real behavior of buried pipelines, in which the location and severity of failures are unknown and unpredictable. The BSFOS system on the other hand is an excellent candidate for monitoring the buried pipelines due to its unique ability of measuring distributed strains along the pipelines.

3.2 *BSFOS*

The concept of using Brillouin scattering for fiber-optic sensing was first proposed by Horiguchi et al., (1989). However, not until the improvement of the spatial resolution of the BSFOS by Bao et al. (1993), the BSFOS system has become a viable technology for continuous structural health monitoring of large civil engineering infrastructures (Zeng et al., 2002; Zou et al., 2004).

The BSFOS is based on the Brillouin loss technology whereby two counter-propagating laser beams, a pulse and a cw, exchange energy through an induced acoustic field. The Brillouin scattering is simulated in backward direction, and by measuring the depleted cw beam and scanning the beat frequency of two lasers, a Brillouin loss spectrum centered at the Brillouin frequency V_B is obtained, as shown in Figure 4. In addition, The Brillouin frequency V_B has a linear dependence with temperature and strain as follows (Horiguchi et al., 1989; Kurashina et al., 1990):

$$V_B\,(T_o, \varepsilon) = C_\varepsilon\,(\varepsilon - \varepsilon_o) + V_{B\,0}\,(T_o, \varepsilon_o) \qquad (1)$$

$$V_B\,(T, \varepsilon_o) = C_T\,(T - T_o) + V_{B\,0}\,(T_o, \varepsilon_o) \qquad (2)$$

where C_ε = the strain coefficient; C_T = the temperature coefficient; and ε_o and T_o = the strain and temperature corresponding to a reference Brillouin frequency $V_{B\,0.}$

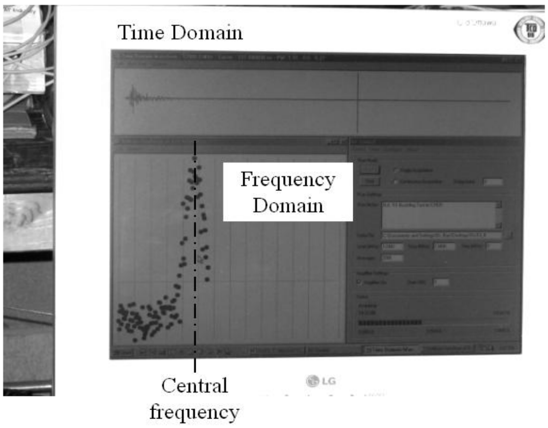

Figure 4. Data acquisition of BSFOS system

3.3 *Pre-processing of BSFOS system*

The length of optical fiber, including leading fiber, glued sensing fiber, and designed losing fiber must be exactly measured before data collection. Since the condition that processing speed of laser beams is constant and the processing distance is known, the processing time of the laser beams, respective to the location where data is acquired, can be obtained by calculation. This timing information was then input into the control computer of the data acquisition system.

In addition, trial scanning should be performance on the data acquisition system in order to obtain the preliminary range of frequencies for monitored structure, and to reduce the data collecting time.

3.4 *Data processing of BSFOS system*

The measured data collected from BSFOS system is the Brillouin-loss power spectra, not strain, so data processing was different from that in the conventional data acquisition system. In addition, the signals are in frequency domain to increase the effect of data processing, but they can be simultaneously observed in time domain shown in Figure 4. The steps of data processing were describe as follows.

First, based on the built in pre-processing, acquisition system automatically detects the Brillouin frequency spectrum at each assigned measured location.

Second, for the each measured location, through scanning different frequency, whose interval is about 5 MHz, the Brillouin spectrum shown in Figure 4 is established based on these different frequencies. The frequency corresponding to the maximum Brillouin loss is the central frequency, also called Brillouin frequency.

The previous step is repeated for all assigned measured locations, whose spacing is about 50mm, along the optical fibre. The shifted frequencies respective to these measured locations are then obtained.

Next, the data acquisition system converts the signals in frequency domain into spatial/time domain in order to easily observe the measurements along the optical fiber.

The procedure of the data acquisition is repeated in each following loading stages.

After a test was completed, the measured data of BSFOS is stored with frequency and corresponding time in a text file. These data were analyzed and synthesized, and then the actually central frequencies are obtained for the distributed, measured locations.

The distributed, averaged strains along the optical fiber are computed on every loading stage, based on the equations (1) and (2).

4 TWO PILOT TEST PROGRAMS

4.1 *Field excavation program*

A Brillouin scattering fiber-optic sensor (BSFOS) system was installed on a buried pipeline in the west of Edmonton, Alberta. The dimension of the steel pipeline is 27.5 m in length, 914.4 mm in diameter, and 13.2 mm in thickness; the specific minimum yielding stress (SMYS) is 70 ksi for the pipe material.

A total of one hundred meter BSFOS was mounted on five transversal directions and two longitudinal directions of this line pipe, as shown in Figure 5. The BSFOS system recorded the distributed strains every 50 mm along the optical fiber.

Three excavation procedures were designed in this test program, and in every procedure there are two steps, excavation and backfill. The internal pressure up to 50% of SMYS is used in the pipe. The BSFOS system was used to provide continuous, real time monitoring, with sampling rate of one strain reading per second, during the excavation. In addition, excavation tests were conducted in both summer and winter. Figure 6 shows one of the test results acquired from BSFOS system. The numbering on horizontal coordinate of the Figure 6 represents the different loading stages, including excavation, backfill and referenced stages. The strain values on vertical coordinate are total strains. These results showed the distributed strains of this buried pipeline at a specific position, in every loading stage. They contained the strains generated during the installation of BSFOS, the initial strains before load applied, and the strains measured during the test. The strains on top and bottom of the pipe are apparently different due to various stages of excavation.

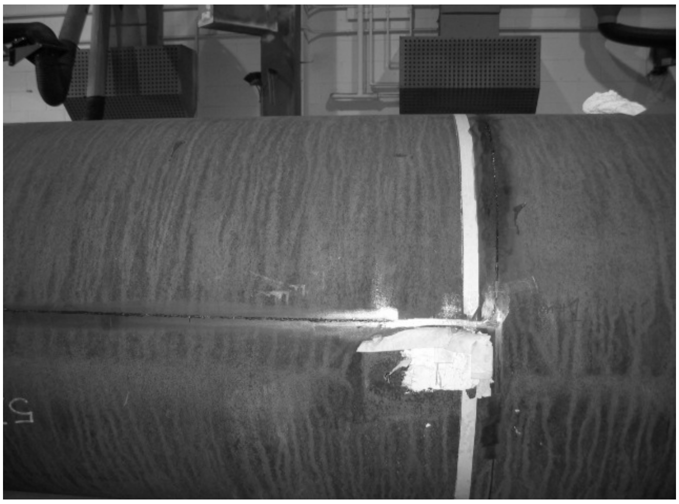

Figure 5. BSFOS installed on pipeline

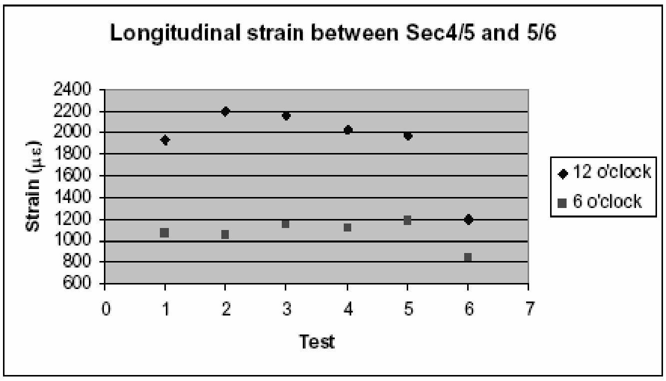

Figure 6. The stage strains collected from BSFOS

4.2 *Laboratory buckling test program*

The BSFOS system was also employed to monitor the behavioral signatures of pipe failure under combined bending, axial, and internal pressure loading conditions. In this test program, a total of 19 pipe specimens were tested to failure. The pipe specimens are either 762 mm or 914 mm in diameter, 552 MPa or 690 MPa in SMYS, and the outside diameter to thickness ratios range from 40 to 76. The internal pressures of 0% to 80% of SMYS are used in the tests.

A total of 20 meters BSFOS was installed on 10 longitudinal directions of a test pipe specimen to monitor the buckling or overstress of the large-size pipes under combined loading. Conventional strain gauges were used to validate the test data acquired from BSFOS system. Due to laboratory test schedule and availability of BSFOS system, so far, only one test using BSFOS was completed. Figure 7 shows the test setup, pipe under load, and local buckling of the specimen. The compressive and tensile strain distributions at the time of pipe buckling obtained form BSFOS are shown in Figure 8. From the figure, it is evident that the results acquired from BSFOS provide detailed strain distributions and distinct behavioral characteristics (or signatures) of a buckled pipe. The distributed strains captured not only the local buckling position but also the location of the girth weld. More significantly, these test results were recorded when there was no visible sign of buckling. In other words, the BSFOS can be used to detect pipe buckling and its location before significant wrinkling occurs in the pipe.

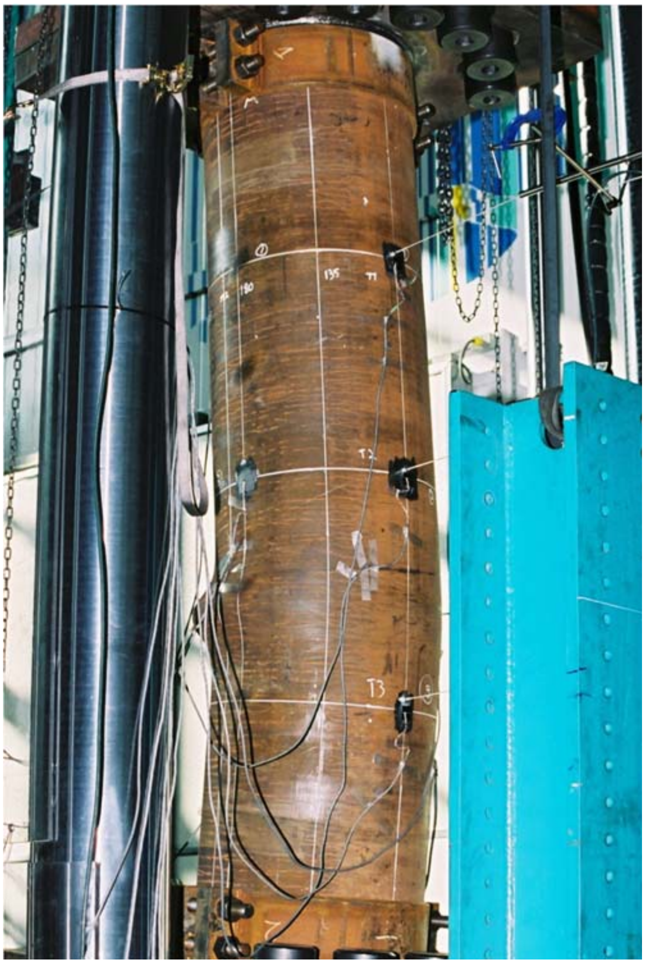

Figure 7. Test setup, test under load, and local buckling

5 DEVELOPEMNT OF THE FINITE ELEMENT MODEL

5.1 *Purpose of the finite element model*

In the past ten years, the non-linear, finite element analysis (FEA), numerical modeling technology has been well developed to simulate the behaviors of pipes at the University of Alberta (Dorey et al., 2001). Nevertheless, these numerical models were developed based on the test data acquired from conventional strain gauges and Demec gauges, and usually focused on the compressive strains in the vicinity of the local buckling. The numerical models require to be modified based on the distributed strains obtained from BSFOS system, in order to establish the characteristic strain distribution curves for local buckling of buried pipelines.

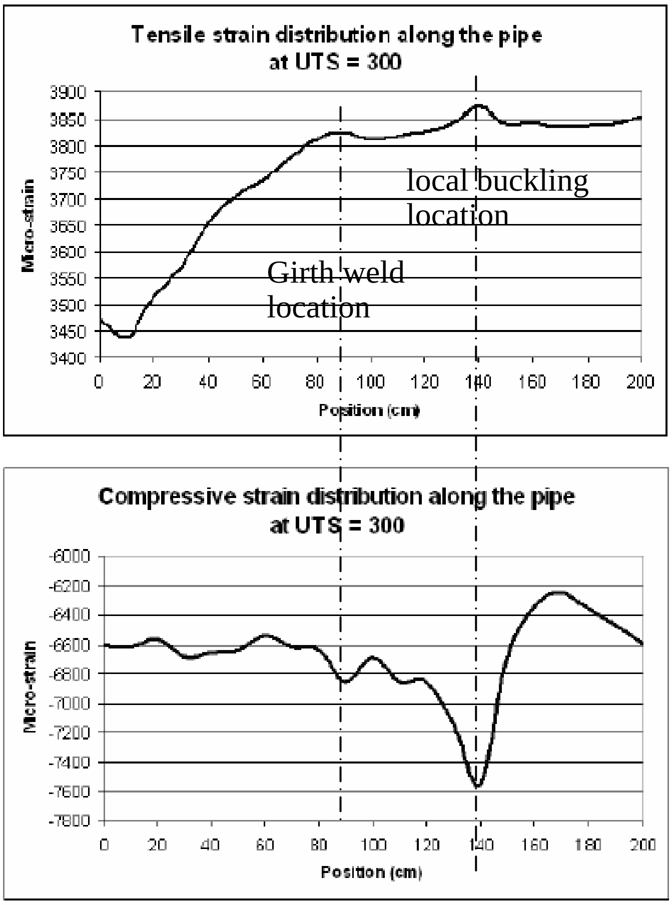

Figure 8. The distributed strains obtained from BSFOS

5.2 *Finite element model*

The numerical model was developed by using ABAOQUS/Standard Version 6.3 (Hibbitt, Karlsson, Sorenson, Inc., 2002). This software package is suitable to simulate large non-linear deformation, and able to apply varied loadings in the structure through multi-step loading procedure.

Shell element and a symmetric, half pipe was employed by this numerical model, and the plane of symmetry along the length of the specimen is shown in Figure 9. Since both the loading conditions and pipe section are symmetric, using symmetric, half geometry as a simulated model increases the efficiency of the FEA. In addition, because the test specimen was combined with two segments of pipes by girth weld, the different plate thickness and residual stress at the girth weld location were considered in the model, as shown in Figure 9.

The residual stresses were generated by heating the weld elements in the model to a prescribed temperature, where 300°C was used, and then cooling the elements back to the initial temperature. Therefore, there will be no net thermal stresses in any of the elements before loading was applied.

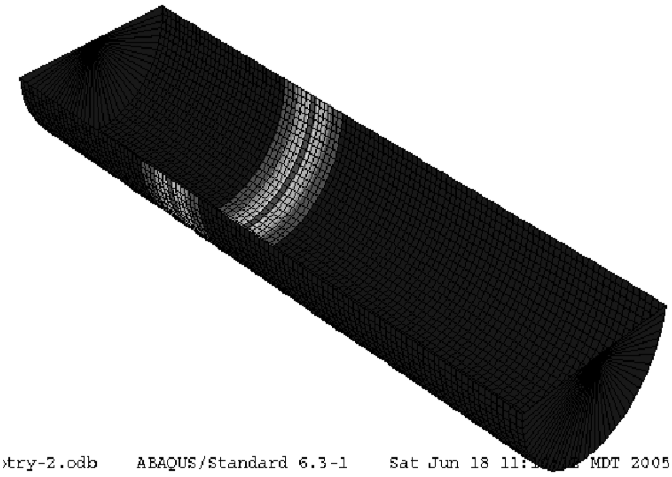

Figure 9. Finite element model

5.3 *A case study of FEA*

A fundamental concept for SHM is that monitor a structural performance is based on a structural behavioral signature change rather than exact magnitude. Herein a case study was used to interpret the application of FEA technology in studying the behavioral characteristics of pipes when local buckle occurs. In this example, a focus was placed on the behavioral pattern on tension side of the pipe, which normally was ignored by engineers when study the responses of pipe buckling.

First, based on the test conditions, a reliable numerical model was established by varying test parameters, such as initial imperfection and welding situations, and the responses obtained from the simulated model were compared with the results from the test, as shown in Figure 10. After the model was developed and verified, a series of simulations was conducted to evaluate the possibility of using the behavioral characteristics as a monitoring signature. In Figure 11, a developing scenario of the anomaly on the tension side of the pipe is agreed with forming of the initial local buckling on the compression side. The peak moment didn't occur until loading step 12.

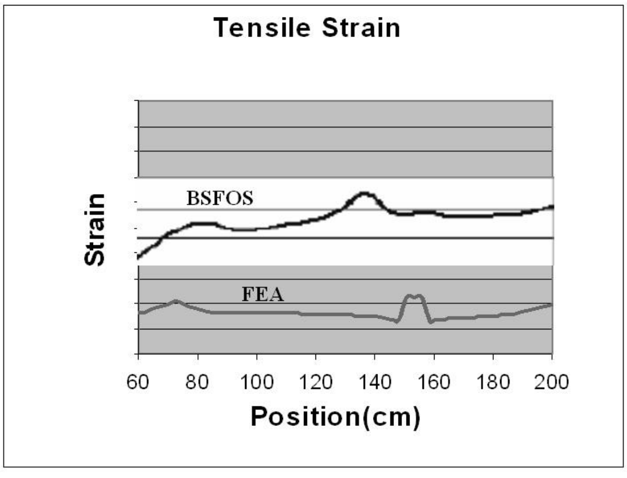

Figure 10. Comparison of strains from BSFOS and FEA

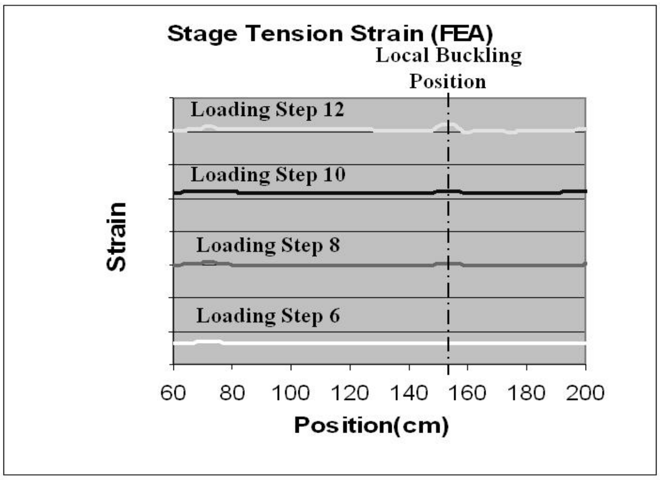

Figure 11. Stage behavioral responses of the pipe simulated by FEA

6 CONCLUSION

Due to the high risk of the buried energy pipelines in the Canadian north, an active warning system is necessary. The SHM system using BSFOS was found to be a viable technology to meet these challenges. The advantages of BSOFS include continuous distributed sensors for strains and temperatures, low cost optical fibres, plus all the other FOS advantages, such as durability, absolute strains, electric and magnetic immunities, etc.

Both field tests and laboratory tests were conducted to verify the feasibility of using BSFOS system in SHM of buried pipes. Both field excavation tests and laboratory buckling tests have proven the BSFOS system can provide viable behavioral signatures for large diameter buried pipelines. Numerical models using the FEA method have been developed to evaluate the characteristic signatures obtained from the BSFOS system. Good agreement was found between the results from the BSFOS system and the numerical models.

However, more test data from the BSFOS system are necessary to calibrate against the behavioral signatures from the numerical model. The more behavioral signatures a system can monitor, the more reliable the SHM system will be.

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