Diagnostic of Corrosion Based Thinning in Steam Pipelines by Means of Neubrescope High Precision Optical Fiber Sensing System

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ABSTRACT

The Structural Health Monitoring (SHM) of steam pipelines is of crucial importance in many industry systems. This is especially valid, due to safety reasons, in nuclear power plants. Inspections for corrosion-based pipeline thinning in such systems are enormously time consuming and expensive. The Ultrasonic Technology (UT) is considered today as a standard technique in this type of examinations.

In the paper, we present the new diagnostic method, exploiting the optical fiber technology within the Neubrescope SHM system. In the method, highly accurate, and of cm-order spatial resolution, strain measurements and numerical analysis are combined to monitor and detect the shape (both depth and size) of the corrosion-based changes in the pipe thickness. As the distributed optical fiber sensing can cover distance of kilometers and, furthermore, does not require a local power supply, it might become safe, economically efficient, and reliable key component of SHM system. The selected results of the experimental test, validating and confirming the high accuracy the presented SHM system, are also included in the paper.

INTRODUCTION

The steam pipelines system is an essential component in the generation of electricity in any power plant. Any failure within this system, may lead to serious operational problems. The primary cause of any pipelines related problems is thinning, what most commonly means a local corrosion at the inner surface of the pipe. Although its link to turbulence in steam flow is well known, it still has not been completely understood, and it cannot be predicted nor avoided at the design stage. Moreover, the process itself is very slow, as it takes usually up to 3 years per 1 mm. Thus, the corrosion-based thinning might lead to failure within 20-year period.

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The Ultrasonic Technology (UT) is considered today as the standard technique while inspecting the pipeline for corrosion-based thinning. The measurement process is twofold. First, an experienced engineer selects portions of the pipelines system to be sampled (commonly, including several thousands of portions for a plant), and then the actual measurement is performed (typically every three years). It also requires stopping steam supply to the selected pipe (typical working conditions involve temperatures varying between 250 and 300 °C). Moreover, the thermal insulation of the examined pipe must be removed. This makes UT based SHM systems extremely expensive. Even though there is no guarantee, due to the nature of the measurement process, that the pipeline system can be safely operated, as proved by recent fatal accident at Mihama Power Plant, Japan, which took five lives. The failure occurred in the portion of the pipe that was not qualified for examination. A thorough investigation revealed that there are 71,000 potentially dangerous and not checked portions of the pipelines in power plants in Japan. The checking process alone will consume more than 10 years, whilst most of the nuclear plants already is 30 years old.

Thus, a need for the new technique of SHM in steam pipelines is extremely vital. It should considerably reduce time required for inspections, reduce their costs, and improve their reliability. In this paper, the SHM system based on distributed optical fiber sensing is suggested and presented. Its core component is recently commercialized Neubrescope system, which provides highly accurate, with spatial resolution of cm-order, strain measurements in on-line mode. The accurate measurements should reveal any changes in the deformation pattern of the considered pipeline, allowing one to employ structural analysis in order to determine extent of the thinning. In the next Section, the fundamentals of the NeubreScope measurement technique are outlined.

HIGH PRECISION OPTICAL FIBER MEASURING SYSTEM

The key component of any SHM system is the sensor technology, which needs to provide reliable and accurate measurement results, ensuring the in-situ self-calibration, durability, high spatial resolution, information links among sensors, redundancy due to changes in sensor material etc. The Stimulated Brillouin Scattering (SBS) measuring technique addresses all of these issues, as it employs the single mode optical fiber, entirely avoids requirement of in-situ self-calibration, while achieving stable, reliable, and accurate results.

The Neubrescope fiber sensing system employs the pump pulse with leakage light (Fig. 1 a). The effect of leakage light was experimentally discovered by Bao et al [1]. The theoretical analysis of the phenomena, developed by Nishiguchi et al [2], and Kishida et al [3], demonstrated that the interactions of the amplitude modulated (AM) pump would stimulate phonon far more effectively than rectangle, single pulse.

In the Neubrescope, in contrast to other studies and applications, the quality of pump light is improved by having limited time duration of light leakage.

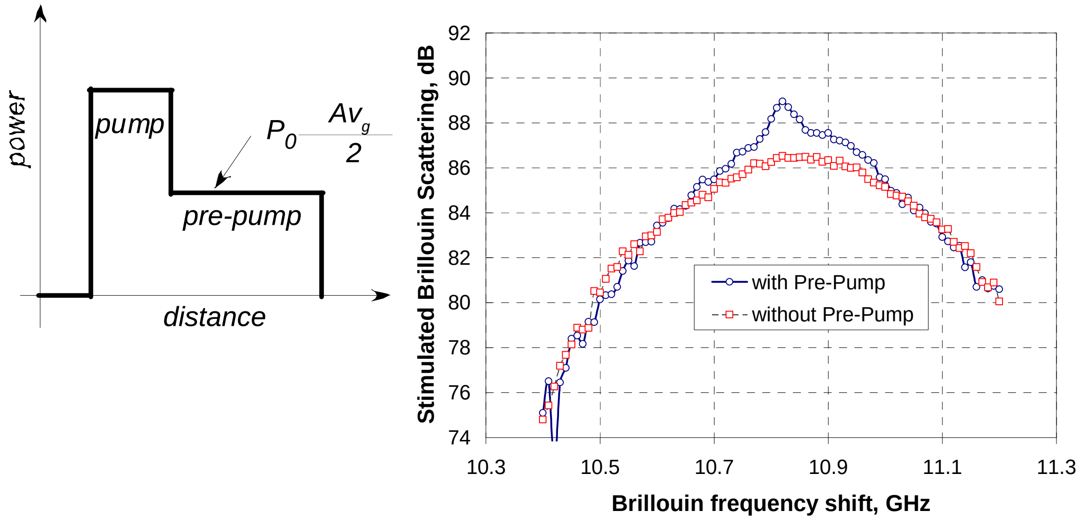

Figure 1. Pre-pump pulse (a – left); SBS spectrum comparison (b – right).

Fast response as well as a narrow frequency line width can be obtained at the same time. The former ensures the high spatial resolution (1 ns corresponds, approximately, to 10 cm), while the latter the high measurement (strain) precision. Comparison of (experimental) pump pulse distributions in Fig 1 (b), with and without the pre-pump (PPP), clearly shows that PPP-method has a narrow ‘hat’ and of about + 3 dB stronger signal. All that enables us to achieve ten times higher spatial resolution and strain measurement precision, that is, cm-order spatial resolution and strain accuracy as high as 25 $\mu\varepsilon$.

NUMERICAL ANALYSIS

The Neubrescope optical fiber sensing system provides a large amount (reaching in single set typically several thousands points) of highly accurate strain measurements. This data can be effectively used in numerical simulations, improving their reliability and helping to detect any undesirable changes in the deformation pattern of considered structure. In this process, the measured and calculated strains are used, only. It means that any numerical method capable of solving structural problem can be employed. Moreover, any available (including commercial) codes might be used, with arbitrary geometry and boundary conditions. In this paper, as the numerical method the Finite Element Method (FEM) is employed [4]. In the remaining of this Section, the mathematical background of the approach used in analysis is briefly discussed.

The data obtained by means of the Neubrescope measuring system contains a set of strain values, $\bar{\varepsilon}_f$, at points along the fiber. The spatial resolution, *d*, of the measurements, that is distance between measurement points, *i*, along the fiber path, is usually longer than the sampling rate. Thus, the strain at measurement point can be obtained using formula:

$$\bar{\varepsilon}_f = \frac{2n}{cD^2}\int_0^d A(t)\varepsilon_f \, ds \qquad (1)$$

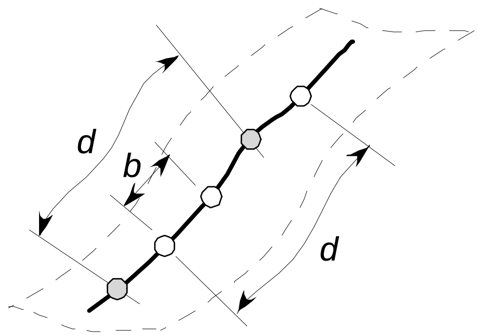

Figure 2. Moving average scheme.

where *c*, *n*, and *s* are the light speed in vacuum, the fiber index of refraction, and distance along the fiber, respectively. In Eq. (1) *A(t)* and *D* stand for the profile of pump pulse (expressed as a function of time, *t*) and its duration. The relationship between time and distance is easily calculated via:

$$t = \frac{d-s}{v_g} \tag{2}$$

with v_g denoting the light speed in optical fiber. In cases, where *A (t)* can be treated as rectangular shape, Eq. (1) can be simplified to:

$$\bar{\varepsilon}_f = \frac{1}{d}\int_0^d \varepsilon_f \, ds \tag{3}$$

In other words, the Neubrescope optical fiber sensing system provides a *moving average* of strain components along the optical fiber path (see Fig. 2). Assuming that the location of the optical fiber is known (what is the case after attaching it to the structure), at any measuring point, *i*, along the fiber the directional vector:

$$\mathbf{T}_i = \{k \quad l \quad m\}_i^T \tag{4}$$

can easily be calculated. Its components *m*, *k*, and *l* are the directional cosines, expressed in the global coordinate system. Collection of these vectors is required to transform strain tensors, $\boldsymbol{\varepsilon}$, obtained by means of numerical analysis in the same coordinate system, and usually expressed in the matrix form as:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix} \tag{5}$$

The transformation of strain tensor is straightforward, namely:

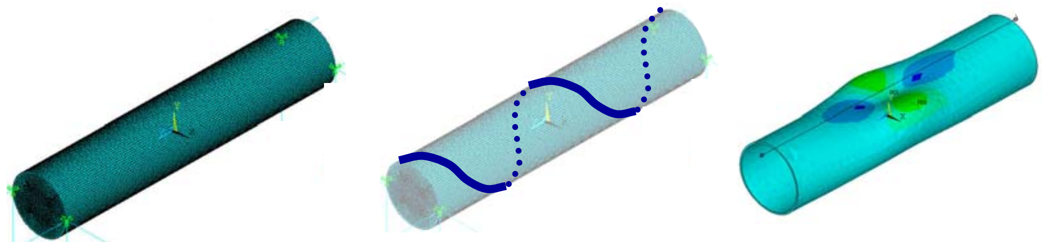

Figure 3. Stages of analysis employing optical fiber.

$$\mathbf{s} = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix} \begin{Bmatrix} k \\ l \\ m \end{Bmatrix} \tag{6}$$

and

$$\varepsilon_T = \mathbf{s} \circ \mathbf{T} = s_1 m + s_2 k + s_3 l \tag{7}$$

The minimization of the differences between measured, $\bar{\varepsilon}_f$ and calculated, $\bar{\varepsilon}_T$, strain values, leads to the solution of inverse problem, and estimation of the unknown shape and dimensions of the thinning area.

The SHM system contains, thus, three stages. First, numerical model is built, next measurements are carried out (while location of the fiber is transferred to the model), and finally, the inverse analysis performed (Fig. 3). The key factor in success of this process is the large amount of accurate measurement data. In the next Section, the experimental test of the thinning detection procedure is presented.

EXPERIMENTAL VALIDATION

The test was carried out on experimental stand comprising of the PMMA pipe (with water), water pump, and two steel plates, covering ends of the pipe. The pipe had the external diameter of 300 mm, length of 1,000 mm, and the wall thickness of 10 mm. The internal surface of the pipe contained thinned area, of approximate diameter 300 mm and depth up to 4.5 mm. For validation purposes, this area was scanned using UT technique (with grid size of 25 mm), providing a map of thinning. Result of this measurement is shown in Fig. 4, where the boundary of the area is denoted by a solid line.

In the experiment, four load cases were considered. Applied internal pressure was monitored at each load by a set of three strain gauges. The optical fiber was then attached to the external surface of the pipe. The location of the fiber, dimensions, and the thinning area are shown in Fig. 5. In the measurements, the spatial resolution of 20 cm was used. The obtained strain distribution along the fiber is given in Fig. 6, where, for reference, area of thinning is also marked.

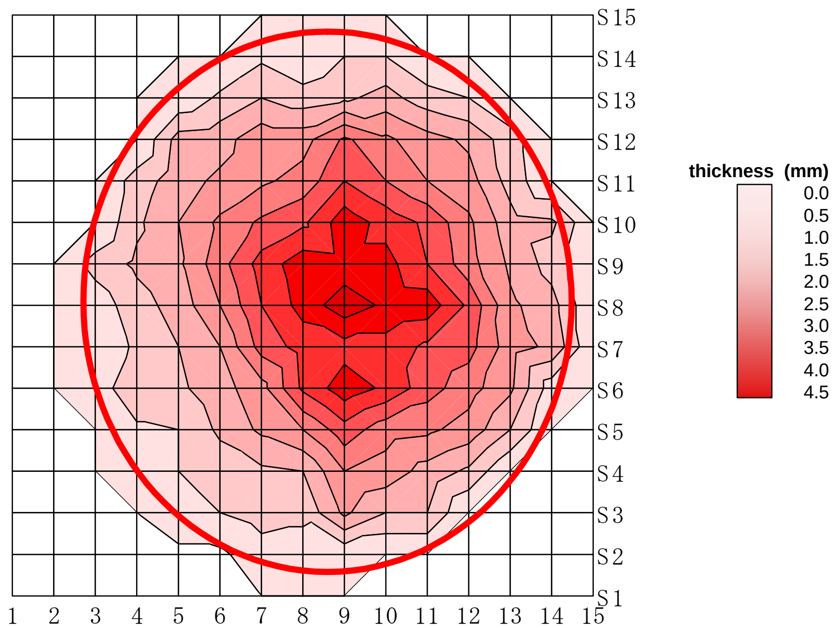

Figure 4. Thinning distribution (UT scan with grid size of 25 mm).

In FEM simulations, the unknown thinning area was parameterized by assuming its shape as ellipsoid. This brought a desired effect of reducing the number of unknowns. In the case under consideration, the unknown parameters were coordinates of its center, major and minor axes lengths, and depth.

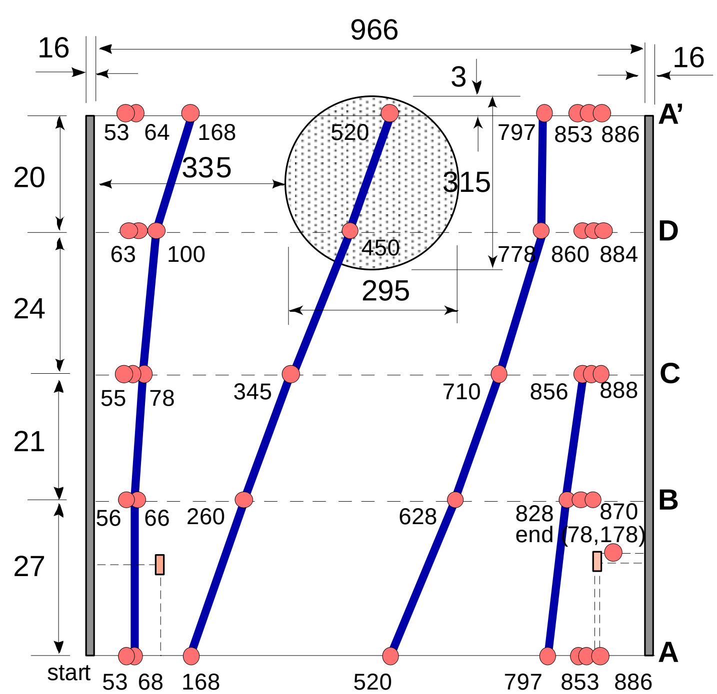

Figure 5. Location of fiber, dimensions, and the area of interest (unfolded surface view).

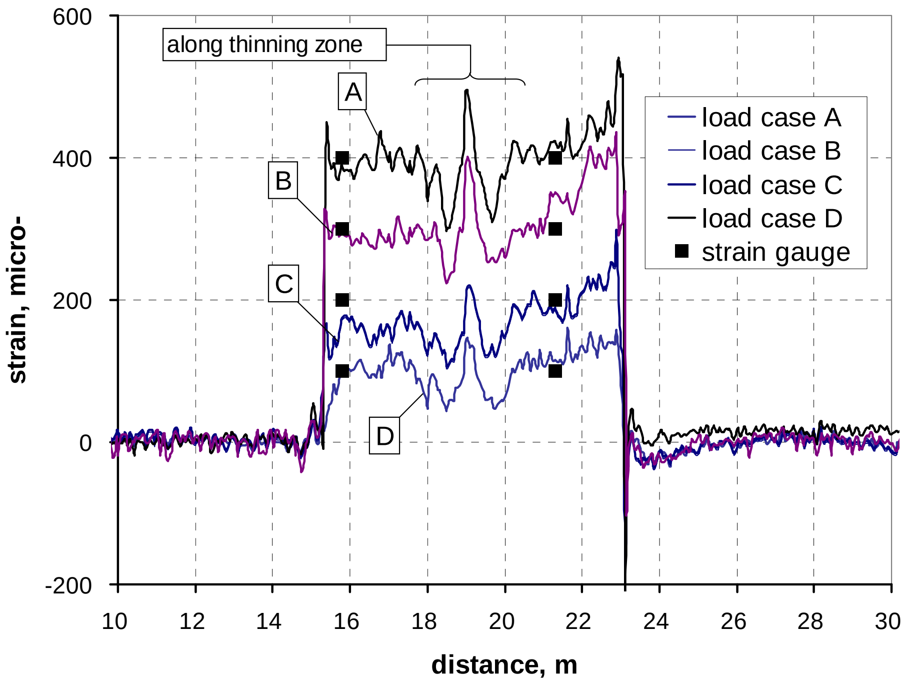

Figure 6. Measurements results (distance measured along the fiber).

The calculated thinning depth was as high as 4.7 mm (see Fig. 7), which lies within acceptable accuracy. Fig. 8 presents distribution of measured and calculated strains at selected points.

CONCLUSION

In the paper, the new diagnostic method, exploiting the optical fiber technology within the Neubrescope SHM system is presented. In the method, highly accurate, and of high spatial resolution, strain measurements and numerical analysis are combined in an attempt to monitor and detect the shape (both depth and size) of the changes in the pipe thickness. This ongoing research, requiring further improvements in both measuring and solution techniques, demonstrates the capabilities of proposed methodology and clearly shows that it has potential to become safe, economically efficient, and reliable component of monitoring systems.

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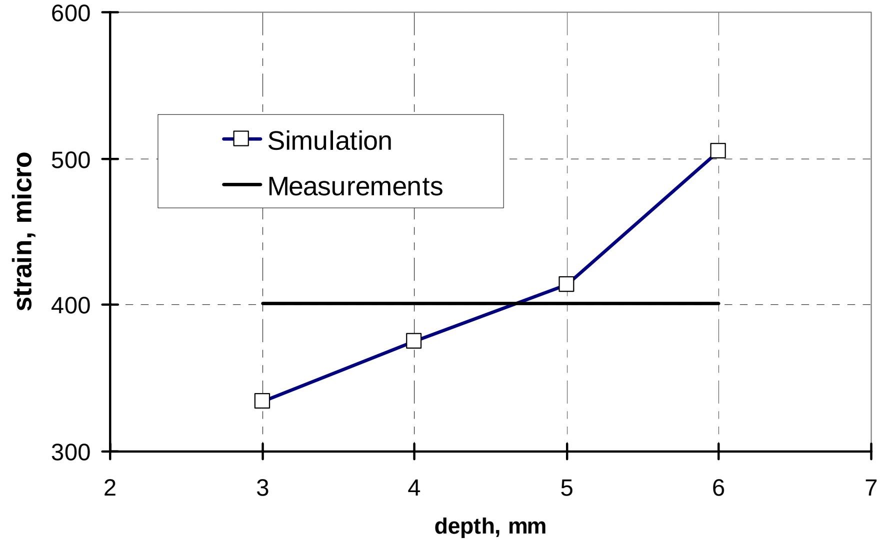

Figure 7. Comparison of calculated and measured values of peak strain.

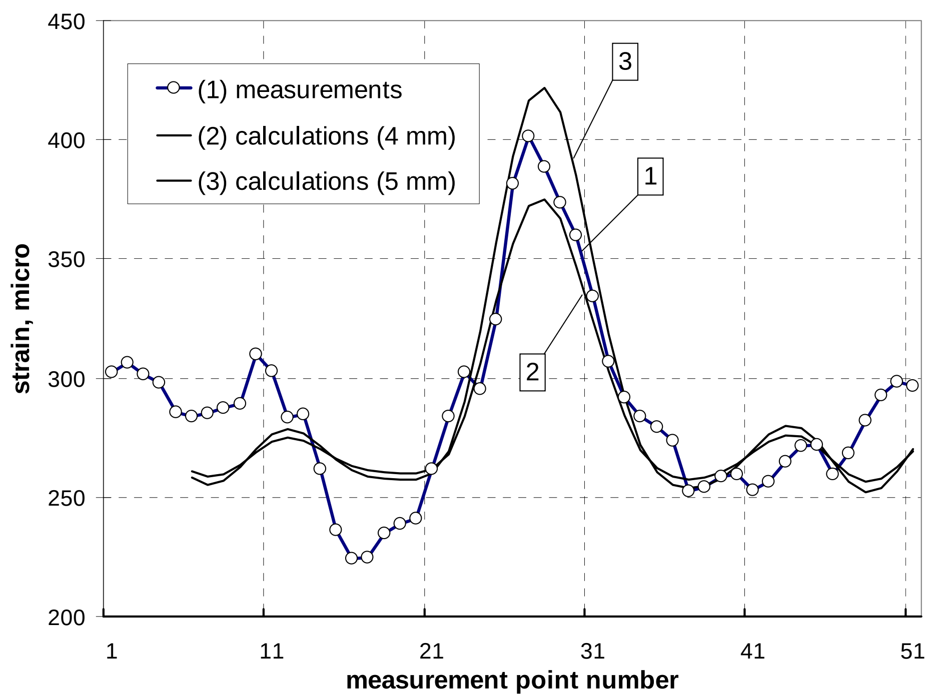

Figure 8. Comparison of experiment and numerical results.