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A HYBRID ESPI TECHNIQUE FOR RESIDUAL STRESS ANALYSIS IN DUCTS

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Abstract. *This work presents a hybrid experimental theoretical technique for residual stresses analysis in ducts. It was used a special Electronic Speckle Pattern Interferometry (ESPI) combined with a small indentation setup for acquiring radial displacement. Data collected is fitted under the Airy stress functions method for the determination of displacements and strain components. Radial displacement data is fitted in order to extract Airy stress function coefficients in a short combination designed specifically to pipe stress analysis. This technique is of great utility as an auxiliary approach to actual field data compilation.*

Keywords: hybrid technique, Airy Stress Function, radial interferometer.

1. INTRODUCTION

This paper presents a simple technique to simulate the displacement (strain and the stress field) (Cavaco, 2011) present in pipelines (Freire et al, 2009). Such analysis is of vital importance when dealing with areas subjected to ground movements (Freitas et al, 2009). The stress field depends on several conditions and this work will focus on bending stress due to ground-pipe interaction. A first work was recently introduced (Fontana, 2015) where the author develops and evaluates a bending stress measurement procedure applied to pipes using instrumented indentation in a minimally invasive way. This paper expands the technique adding the *Airy Stress Analysis* to fit the radial displacement data. The measurement system uses a laser interferometer characterized by radial in-plane sensitivity (Albertazzi et al, 2008) to measure radial displacement data in response to a controlled indented print. The indentation is well correlated to the stress state of the material.

This hybrid technique uses displacement information collected from a predefined mesh around the indentation. Stress functions coefficients are determined from the experimental data and displacement information is fitted to extract stress function coefficients.

2. THE APROACH

The stress field on a pipeline cross-section can be described as a combination of loads: (a) internal pressure (b) axial load (bending moment due to soil-pipe interaction) and (c) pipeline manufacturing residual stresses. The latter load is hard to determine and usually masks other components of stresses.

This work uses the old (and sometimes reliable) *Airy Stress Analysis* for modeling the bending moment due to soil-pipe interaction. And it seeks a different procedure for measuring the stress acting on a pipeline cross-section. This procedure uses a combination of radial interferometry, indentation and *Airy Stress* components.

2.1 Indentation and Radial Interferometry

Using a new concept of interferometer (Albertazzi et al 2008), *the radial interferometer*, it is possible to measure the radial in-plane displacement field in the region of interest (Figure 1). Instead of releasing the stress field to quantify residual stresses (hole-drilling technique), new stresses are introduced through the indentation producing a local plastic deformation. The radial displacement field around the indentation print is measured and fitted to an appropriate mathematic model and the stress state is modeled around the indented surface.

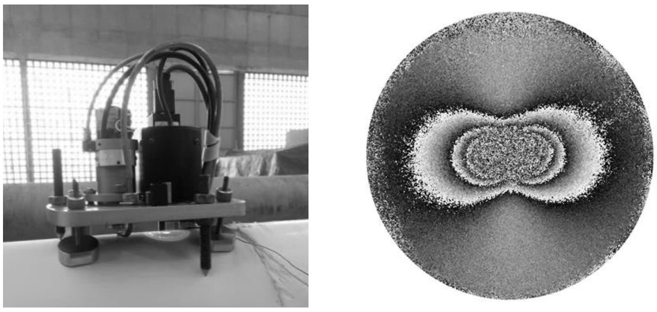


Figure 1: (Albertazzi et al , 2008) Radial interferometer positioned in a 219 mm diameter pipe.

2.2 Airy Stress Analysis

An elementary approach to obtain solutions of the bi-harmonic equation uses polynomial functions of various degrees with their coefficients adjusted so that Eq. (1) is satisfied. A brief discussion of this procedure follows:

$$\nabla^4 \Phi = 0 \tag{1}$$

A polynomial of the second degree Eq. (2) satisfies Eq. (1):

$$\Phi_2 = \frac{a_2}{2}x^2 + b_2xy + \frac{c_2}{2}y^2 \tag{2}$$

The associated stresses are:

$$\sigma_x = c_2 \ , \qquad \sigma_y = a_2 \ , \qquad \tau_{xy} = -b_2 \tag{3}$$

All three stress components are constant throughout the body. For a rectangular plate (Fig. 2), it is apparent that the foregoing may be adapted to represent simple tension ($c_2 \neq 0$), double tension ($c_2 \neq 0, a_2 \neq 0$), or pure shear ($b_2 \neq 0$). A polynomial of the third degree fulfills Eq. (1).

$$\Phi_3 = \frac{a_3}{6}x^3 + \frac{b_3}{2}x^2y + \frac{c_3}{2}xy^2 + \frac{d_3}{6}y^3 \tag{4}$$

It leads to the stresses:

$$\sigma_x = c_3x + d_3y + C_x, \qquad \sigma_y = a_3x + b_3y + C_y, \qquad \tau_{xy} = -b_3x - c_3y + C_{xy} \tag{5}$$

For $a_3 = b_3 = c_3 = 0$, these expressions reduce to

$$\sigma_x = d_3y, \ \ \sigma_y = \tau_{xy} = 0 \tag{6}$$

Representing the case of pure bending of the rectangular plate – that models the duct (Fig. 2b).

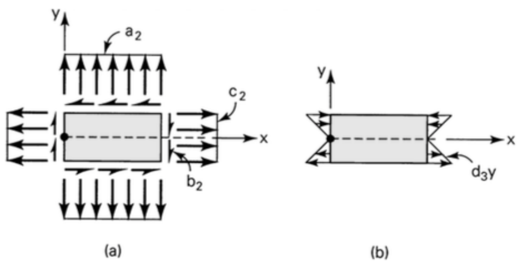


Figure 2 : Stress field of (a) Eq. (2) and (b) of Eq.(4).

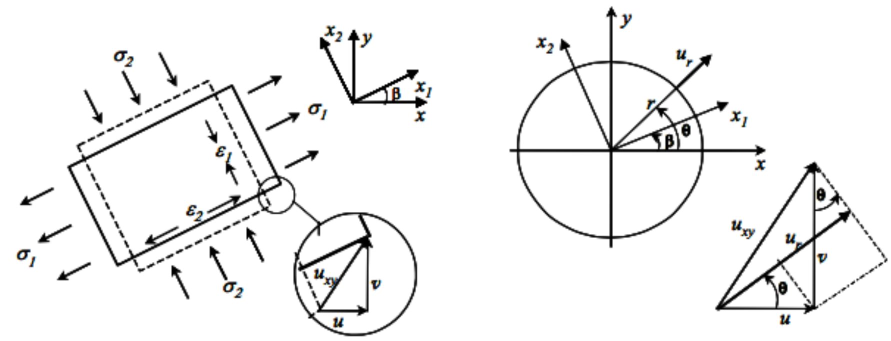


Figure 3: Stress/Strain element related to displacement in a point.

Using data from Fig.3, it is possible to show that:

$$u_r(r,\theta) = \frac{r}{E}(\cos^2\theta - \nu\sin^2\theta)\sigma_x + \frac{r}{E}(sen^2\theta - \nu\cos^2\theta)\sigma_y + \frac{r}{G}(sen\theta\cos\theta)\tau_{xy} + T_x\cos\theta + T_y sen\theta \tag{7}$$

With (7) and (8):

$$u_r(r,\theta) = u\cos\theta + v\sin\theta \tag{8}$$

One can find (9):

$$u_r = \frac{r^2}{2E}[cos^3\theta - (2+3\nu)sen^2\theta cos\theta]c_3 + \frac{r^2}{2E}[-(\nu)sen^3\theta + \mathrm{sen}\theta cos^2\theta]d_3 + \frac{r^2}{2E}[sen^3\theta - (2+3\nu)cos^2\theta sen\theta]b_3 + \frac{r^2}{2E}[-(\nu)cos^3\theta + \cos\theta sen^2\theta]a_3 + \frac{r}{E}[cos^2\theta - \nu sen^2\theta]c_2 + \frac{r}{E}[sen^2\theta - \nu cos^2\theta]a_2 + \frac{r}{G}[sen\theta cos\theta]b_2 \tag{9}$$

2.3 Application

In order to determine the solution for (9), one can solve an over deterministic system for the Airy's coefficient as:

$$u_{re} = u_r \tag{10}$$

$$u_{re} = u_r^{(3)} + u_r^{(2)} \tag{11}$$

$$\begin{bmatrix} {}^{(i)}\left(u_r^{(3)}(a_3,b_3,c_3,d_3) + u_r^{(3)}(a_2,b_2,c_{2,})\right) \\ {}^{(i+1)}\left(u_r^{(3)}(a_3,b_3,c_3,d_3) + u_r^{(3)}(a_2,b_2,c_{2,})\right) \\ . \\ . \\ . \\ . \\ . \\ . \\ {}^{(k)}\left(u_r^{(3)}(a_3,b_3,c_3,d_3) + u_r^{(3)}(a_2,b_2,c_{2,})\right) \end{bmatrix} \times \begin{bmatrix} b_2 \\ c_2 \\ d_2 \\ a_3 \\ b_3 \\ c_{3,} \\ d_3 \end{bmatrix} = \begin{bmatrix} {}^{(i)}u_{re} \\ {}^{(i+1)}u_{re} \\ . \\ . \\ . \\ . \\ . \\ . \\ {}^{(k)}u_{re} \end{bmatrix} \tag{15}$$

The linear system formed can be represented by:

$$A * C = u_{re} \tag{16}$$

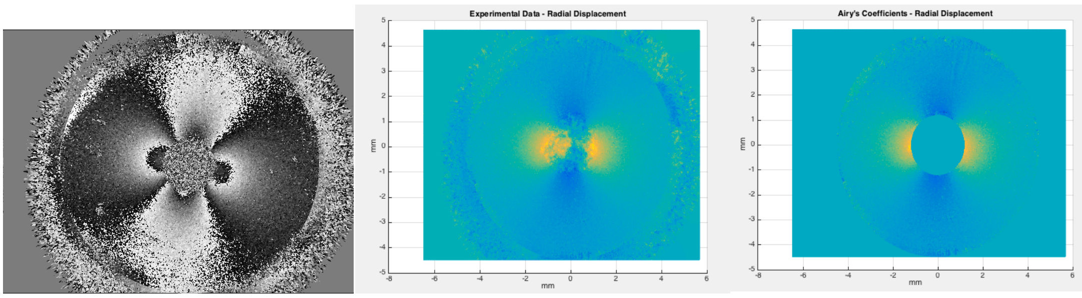
Where:

A - Constant matrix;
C - Coefficient matrix;
u_{re} - Independent vector with experimental data.

The least square solution can be found as

$$C = (A)^{-1} * u_{re} \tag{17}$$

Figure 4 shows raw and calculated data using coefficients from (9). A bidirectional state of stress is analyzed from a bended pipe according to Fig. 1. An approximately 45MPa and -20MPa is represented in Fig.4 (a).



(a) (b) (c)

Figure 4: Radial displacement output from experimental data. (a) Raw unwrapped displacement, (b) Raw preprocessed displacement (c) calculated (post-processed displacement).

Table 1- Airy's Coefficients

a2	b2	c2	a3	b3	c3	d3	Cte1	Cte2
-12e+006	1.30e+006	18.0	6.0e+009	4.30e+009	149e+006	6.0456e+009	0	0

Table 2 – Principal Stresses data from Fig. 5.

σ_1	42MPa
σ_2	-16MPa

Table 1 shows the Airy's coefficients determined from (9) using (15-17). Table 2 lists the approximately principal stresses. Some improvements still need to be done regarding to boundary conditions in order to take care of the sign of derivatives from stress and strain field calculated using displacement data.

3. CONCLUSION

An interesting approach was presented to evaluate data from a bended pipe. This situation models approximately the interaction between duct and ground movements. The experimental technique follows procedures based on indentation stress superposed to the surface of a pipe. A radial in-plane DSPI interferometer using diffractive optics is used to collect points of interest. An algorithm using Airy's stress function coefficients maps the radial displacement field close to the indentation. Results presenting less than 10% error are obtained for the principal stresses.

4. REFERENCES

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5. ACKNOWLEGEMENTS

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6. RESPONSIBILITY NOTICE

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