## Registration Fees

| | Early (Until 10 Nov 2013 | Normal (Until 15 Jan 2014) | Late (Until 10 March 2014) | On Conference |
|---|---|---|---|---|
| Students | €320 | €340 | €360 | €560 |
| Participants from Developing Countries | €360 | €390 | €400 | |
| Participants from all over the World except Developing Countries | €430 | €475 | €500 | |

Include:

- ✓ Conference Proceedings (published in AIP -American Institute of Physics- Conference Proceedings)
- ✓ On line publication of the AIP Conference Proceedings of ICCMSE 2014
- ✓ Welcome Drink & Coffee Breaks
- ✓ Excursion
- ✓ Conference Dinner & Breakfast plus one meal (Lunch/Dinner) per day (only for the participants who have booked room in the via the Organizing Committee - Secretary of the Conference)


Contact: Yoann JOLIFF
University of Toulon
ISITV
MAPIEM (EA 4323)
83957 La Garde, France

☎ (+33) 04 94 14 29 74
✉ yoann.joliff@univ-tln.fr


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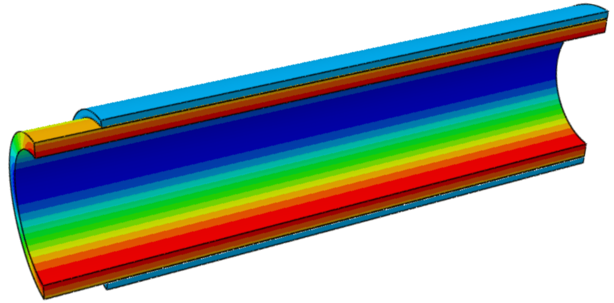
# ICCMSE 2014

10TH INTERNATIONAL CONFERENCE OF COMPUTATIONAL METHODS IN SCIENCES AND ENGINEERING

### Symposium

## Computational Methods Dedicated to Pipeline Design and Safety



**04-07 April 2014, Metropolitan Hotel, Athens, Greece**

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ICCMSE

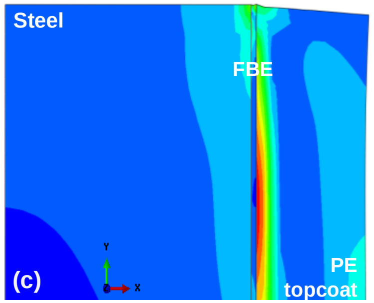
# ICCMSE 2014

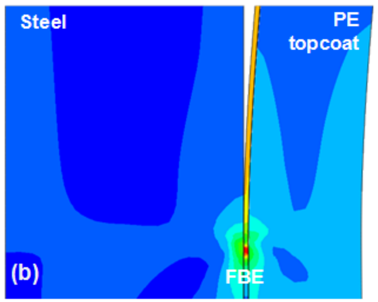
10TH INTERNATIONAL CONFERENCE OF COMPUTATIONAL METHODS IN SCIENCES AND ENGINEERING

The aim of ICCMSE 2014 is to bring together computational scientists and engineers from several disciplines in order to share methods, methologies and ideas and to attract original research papers of very high quality.

A special session is proposed about the **Computational Methods Dedicated to Pipeline Design and Safety**

Pipelines are used worldwide for the transportation of oil or gas and must be protected against extreme conditions (high pressure, corrosion, temperature …) over long periods of time to avoid any production failure. The aims of this symposium are to exchange around the numerical studies used in pipeline engineering to improve it and/or understand phenomena observed all long the pipeline life. Multidisciplinary approaches such as mechanical, thermal, electrical and/or moisture studies will be welcome.

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## Topics

All the topics where the numerical methods have been used can be described in this symposium, as example:

- ✓ Pipeline materials: steel, concrete, organic polymer coating …
- ✓ Pipeline engineering: manufactured, welding, reparation …
- ✓ Pipeline damages: fatigue, crack, ageing …

## Important Dates

- ✓ Submission of extended abstracts: **February 28, 2014**
- ✓ Notification of acceptance: **March 10, 2014**
- ✓ Submission of the source files of camera ready extended abstracts to American Institute of Physics (AIP Conference Proceedings): **May 15, 2014 - Final Date**
- ✓ Submission of full papers for consideration for publication in the journals: **April 15, 2014 - September 30, 2014**

## Accommodation

The possibilities of accommodation will be proposed in the Metropolitan Hotel with special prices.

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# Digital image correlation utilization in pipeline oriented residual stress estimation

Tomasz Brynk[a,1], Dariusz Mezyk[b], Dominik Kukla[c]

[a] *Warsaw University of Technology, Faculty of Materials Science and Engineering, Woloska 141, 02-507 Warsaw, Poland*
[b]*Institute of Power Engineering - Research Institute, Mory 8, 01-330 Warsaw, Poland*
[c]*Institute of Fundamental Technological Research, Pawinskiego 5b, 02-106 Warsaw, Poland*

**Abstract.** The aim of the paper is to present an idea of the utilization of Digital Image Correlation (DIC) method for industrial pipelines residual stress oriented investigation. For this purpose results of tests performed in laboratory and industrial conditions are presented. Obtained results showed that DIC method gives reliable near drilled hole strain/displacement distribution maps which may be used for accurate residual stress calculations.

**Keywords:** Digital Image Correlation (DIC), residual stress, Mathar's method
**PACS:** 62.20.-x, 81.05.Bx

## INTRODUCTION

The residual stress measurements are very important from the point of view of the maintenance and conservation of pipelines utilized in the energetic industry. One of commonly applied technique for the residual stress estimation is Mathar's method. This technique is based on strain measurements near a drilled hole. The idea of the method is related to the stress relaxation caused by drilled hole. The linked strain is measured by means of a rosette consisting of three strain gauges. On the condition that geometry of rosette is known, it is possible to calculate residual stress. The method is standardized and widely used, however it is sensitive to systematic errors induced by not concentric hole drilling and the quality of rosette mounting.

Full-field optical strain determination methods may be applied instead of three point measurements performed in the case of traditional rosettes. While using these methods it is possible to obtain more data, which may be utilized for residual stress calculations and may increase the accuracy of those calculations.

The most popular optical methods are based on laser interferometry (mainly Electronic Speckle Pattern Interferometry - ESPI) or speckle pattern tracing by means of digital camera (Digital Image Correlation - DIC [1]). The first group of methods allow to accurate strain measurement near the drilled holes, however the practical industrial application of them may be limited due to complicated set-up and vibrations sensitivity. DIC method is less accurate, however its set-up simplicity make it a better candidate for an industrial application. DIC method utilizes digital images of the sample surface registered before (reference image) and after applying the load (deformed images). The observed surface should posses the characteristic speckle pattern usually obtained by black and white paint spraying. Calculations algorithm traces the positions of a few pixel wide rectangular subareas of the area of interest (which is characterized by a unique distribution of gray level intensities) by minimization of an appropriate correlation function. After finishing the procedure for all selected subsets, displacement maps on the observed surface are obtained. When interpolation function for the description of gray level distribution inside subsets are applied, the achieved displacement measurement accuracy is better than one pixel, namely 0.01 pixel according to the commercially available DIC software producer.

DIC method which utilizes only one camera allows to planar displacement measurement on flat surface oriented perpendicularly to the camera. The drawback of one camera system, besides the limitation of the method to flat

[1] E-mail: tbrynk@inmat.pw.edu.pl

surfaces, is its sensitivity to out of plane displacement which may affect the measurement results. Above mentioned problems may be omitted by using two cameras system (3D DIC), however additional procedure of the calibration of cameras positions is required. For the calibration it is necessary to register a few images of calibration grid oriented with different angles to the cameras. Calibration grid consists of regular dots array (with specially 3 marked dots) which enables unequivocal determination of grid position by triangulation method. Basing on the set of images of calibration grid it is possible to calculate not only camera orientation but also lens distortion, which increases measurement accuracy.

## RESULTS AND DISCUSSION

Keeping in mind industrial applications oriented to residual stress determination as in the question, special approach should be undertaken to enable accurate calibration of 3D DIC system. Expected displacement near the drilled hole of 1.5 mm diameter is at the range of 1/1000th of millimeter, therefore the observed surface should be limited to a few square millimeter area. It follows to the calibration procedure made using small calibration grids printed on glass surface. Thus, for a convenient calibration of DIC system there were designed special grip which allows to rotate the grid in three orthogonal axes without its movement out of the area of observation. The grip was equipped with an illumination required for transparent glass calibration grids.

The aim of presented experiments was to deliver strain/displacement fields by means of 3D DIC system near the drilled hole, which may be utilized for the determination of the residual stresses in the industrial pipelines. First two experiments were devoted to the laboratory testing with known stress or strain. In the first one tensile sample was loaded in a servo-hydraulic universal testing stand while second one utilized set-up for 4 point bending of metal sheet. Both kinds of tests were accompanied with strain measurements with 3 elements rosettes for the results comparison. Last presented test was carried on in the industrial conditions.

In the case of tensile sample 100 MPa stress was applied and after loading a hole of 1.5 mm diameter was drilled through its thickness. The residual stresses were calculated with standardized procedure in the case of strain gauge rosette and the use of DIC measurements and inverse method (rosette was placed at the opposite site to the surface of DIC measurements). In the latter case displacement field maps were used as the input data to the iterative algorithm to find the best set of parameters of the following analytical equations describing displacement fields near the hole if stresses are present [2]:

$$u_k(r_k,\theta_k)=\frac{(1+\nu)a^2}{Er_k}\left\{\left(\frac{\sigma_x+\sigma_y}{2}\right)\cos\theta_k+\left(\frac{\sigma_x-\sigma_y}{2}\right)\left[\left(1-\frac{a^2}{r_k^2}\right)\cos 3\theta_k+\kappa\cos\theta_k\right]+\tau_{xy}\left[\left(1-\frac{a^2}{r_k^2}\right)\sin 3\theta_k+\kappa\sin\theta_k\right]\right\} \quad (1)$$

$$u_k(r_k,\theta_k)=\frac{(1+\nu)a^2}{Er_k}\left\{\left(\frac{\sigma_x+\sigma_y}{2}\right)\sin\theta_k+\left(\frac{\sigma_x-\sigma_y}{2}\right)\left[\left(1-\frac{a^2}{r_k^2}\right)\sin 3\theta_k-\kappa\sin\theta_k\right]-\tau_{xy}\left[\left(1-\frac{a^2}{r_k^2}\right)\cos 3\theta_k-\kappa\cos\theta_k\right]\right\} \quad (2)$$

where $\kappa = 3-4\nu$ and $E$ –Young's modulus, $\nu$- Poisson's ratio, $a$ – hole diameter, $\sigma_x,\sigma_y,\tau_{xy}$- components of stress tensor and $r_k,\theta_k$ - polar coordinates of point *k*.

Additionally, rigid body translation and rotation and the position of the hole center were taken into account during parameters fitting procedure. The iterative procedure was stopped when the difference between DIC measurement and the model was lower than specified value determined by the error function. The results of the fitting procedure gave very similar values of $\sigma_x$, $\sigma_y$ (see **TABLE 1**).

**TABLE 1** Results of residual stress calculations.

| Method | $\sigma_x$[MPa] | $\sigma_y$[MPa] | $\tau_{xy}$[MPa] |
|---|---|---|---|
| Mathar's | -42 | 103 | -14 |
| DIC based | -56 | 103 | - |

The maps delivered from 3D DIC measurements and the model with optimized parameters presented in **FIGURE 1** show qualitative and qualitative similarities.

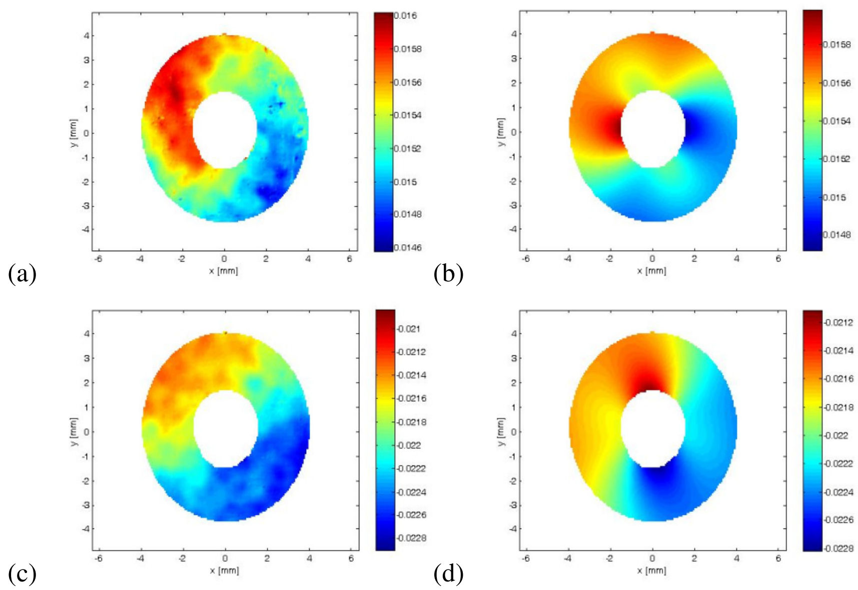


**FIGURE 1.** Results of DIC displacement measurements [mm] and the model after parameters fitting: (a) DIC horizontal. (b) model horizontal. (c) DIC vertical. (d) model vertical.

In the case of measurements planned to perform in the industrial conditions (for example for pipeline monitoring) there is obvious requirement for blind hole drilling. For such hole geometry it is unavailable direct analytical solutions, however it is possible to determine calibration coefficients for analytical models using Finite Elements Methods [3]. Here, only the practical aspects of 3D DIC measurements will be addressed.

Exemplary results of strain distribution for carbon steel plate with drilled blind hole (1.5 mm diameter and 1.5 mm depth) loaded in 4-point bending mode are presented in **FIGURE 2.**

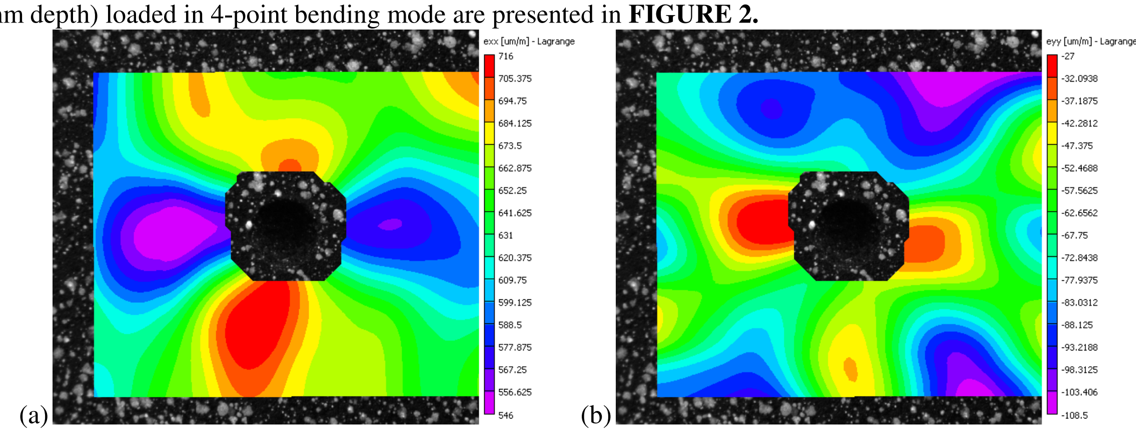



**FIGURE 2.** Strain map near blind hole resulting from bending of the plate. (a) $\varepsilon_{xx}$. (b) $\varepsilon_{yy}$.

The obtained results of $\varepsilon_{xx}$ strain tensor component were with good accordance to the tensometer readings (600 μm/m) and there is observed the influence of the hole to the strain distribution. The results gave the evidence of adequate accuracy of DIC for measurements in questions.

The final presented test was made on the real pipeline fragment made of P91 steel with unknown residual stresses. In **FIGURE 3** there is presented the measurement set-up. During test, the hole was drilled between registering initial and deformed images. Similarly to second experiment DIC method allowed to determine reliable strain tensor components distributions (see, **FIGURE 4**), however the amount of obtained data was limited (the areas without color maps) due to the disturbance of speckle pattern by chips produced during drilling.

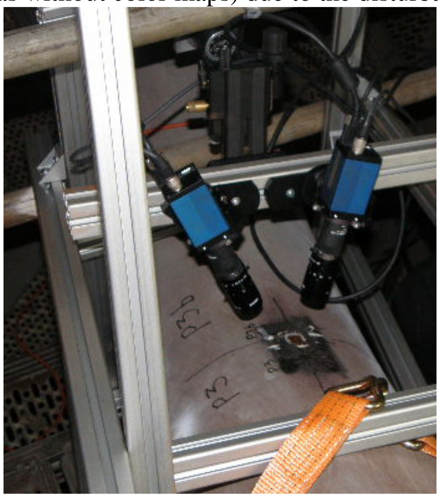
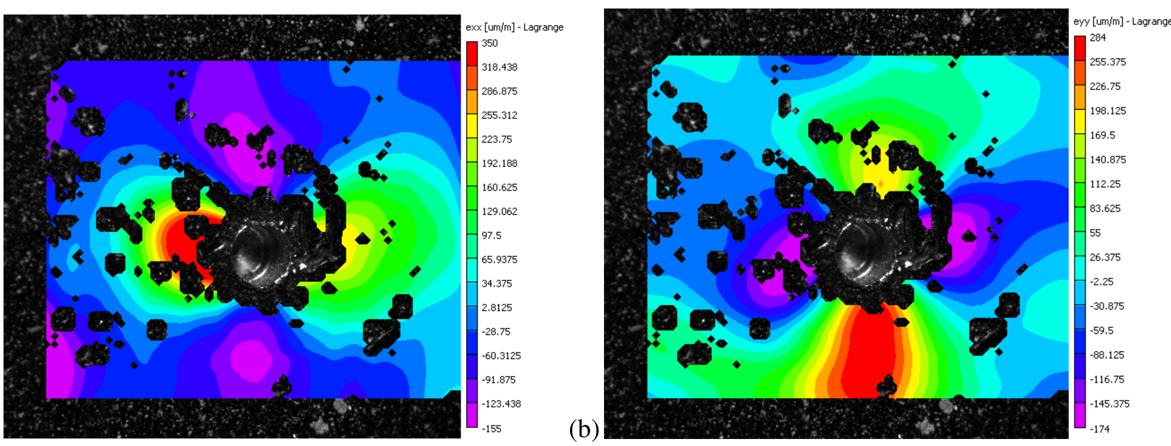


**FIGURE 3.** The experimental set-up for DIC measurement in the industrial conditions.




(a) (b)

**FIGURE 4.** Strain maps near the blind hole drilled in the industrial pipeline. (a) $\varepsilon_{xx}$. (b) $\varepsilon_{yy}$.

## CONCLUSIONS

Concluding, 3D DIC method is a promising tool for the improvement of the quality of residual stresses estimation for pipelines. The achieved measurements accuracy allowed to calculate residual stresses in the case of through hole. Tests with bended samples and pipeline showed possibility of near shallow hole strain heterogeneity determination, however the disturbing effect of falling chips revealed in industrial environment has to be limited.

## ACKNOWLEDGMENTS

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