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Automated non-destructive integrity assessment of metal structures

Gabriella Bolzon*

Department of Civil and Environmental Engineering, Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy

Abstract

Offshore windmills and pipeline networks are examples of strategic infrastructures used for the production of clean energy and for the storage and long-distance transportation of hydrocarbons, hydrogen and water. The relevant structural elements are mainly made of welded portions of steel pipes, which often interact with aggressive fluids and hostile environments. Material aging is thus accelerated and localized damage processes are promoted, harming the design safety factors. The structural health of such components can be monitored in operation, throughout their lifetime, by non-destructive testing performed by portable devices. The equipment at present available on the market permits to develop fully automated testing campaigns, overcoming the difficulties associated to large extension and difficult accessibility. The data collected on site can be transferred through virtual networks, to be evaluated and processed in order to permit the quantitative evaluations required by the optimization and the planning of repair and retrofit operations. This contribution discusses the potential offered by the current practice and illustrates the methodological adaptations that produce effective diagnostic tools in the outlined context.

Keywords: steel structures; diagnostic analysis; non-destructive testing; automation.

1. Introduction

Offshore windmills and pipeline networks are examples of strategic infrastructures used for the production of clean energy and for the storage and long-distance transportation of hydrocarbons, hydrogen and water; see e.g. Sherif et al. (2005), Pirani and Yafimava (2016), Haesen et al. (2018). The relevant structural elements are mainly made of welded portions of steel pipes, often interacting with aggressive fluids and hostile environments. Material aging is thus

* Corresponding author. Tel.: +39-02 2399 4319; fax: +39-02 2399 4330.
E-mail address: gabriella.bolzon@polimi.it

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accelerated and localized degradation processes are promoted, harming the design safety factors (Bolzon et al., 2011; Zhu and Li, 2018). Critical situations may arise in correspondence of welds and of other connections, as documented by Farzadi (2016) and by Lacalle et al. (2011), and local failures may be also induced by accidents and fires. The consequent partial replacement of the damaged elements makes inhomogeneous the distribution of the material properties.

The structural health of such exercised components can be monitored in operation, throughout the entire lifetime, by non-destructive testing performed by portable devices. In this context, the evolution of the material properties can be followed by hardness tests, which can be performed directly on operated parts, with no need of extracting and machining any specimens, in fast, economical and non-destructive manner (Broitman, 2016).

On metals, hardness tests produce the permanent deformation of small material portions. The imprint geometry can be visualized by optical microscopes. The corresponding 3D mapping can be returned in digital form and this information can be exploited to diagnostic purposes.

Portable devices and a proper definition of the testing procedures allow the survey campaigns to be performed in a completely automated way, while the data collected on site can be transferred through virtual networks to be further processed as briefly illustrated in this contribution.

2. Diagnostic analysis based on hardness test

The permanent deformation produced by hardness test on structural steels contains significant information about the mechanical characteristics of the metal. Nowadays, the residual imprint can be mapped by several portable devices and the geometry details can be returned in digital format; see e.g. Bolzon (2020). The data thus collected reflect the material status only indirectly, but quantitative evaluations can be obtained by combining the experimental work with the numerical simulation of the tests as shown by Bolzon et al. (2012).

The considered identification methodology is illustrated by the sketch in Fig. 1 in the common case of axisymmetric deformation produced by axisymmetric tips in isotropic solids. In particular, the graphs concern the sphero-conical Rockwell tip.

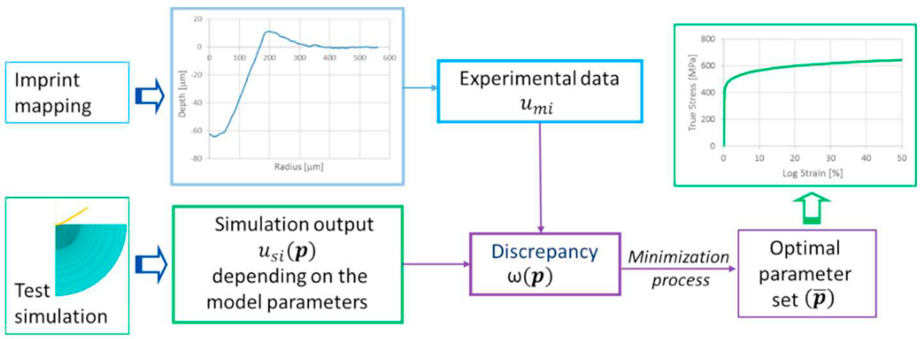

Fig. 1. The considered material identification procedure.

The main components of the considered procedure can be summarized as follows.

i. The experimental information collected from the performed harness test consists of the depths u_{mi} of the permanent deformation, measured at given distances from the imprint axis.

ii. The test simulation returns the residual depths u_{si}, which depend on the constitutive parameters (e.g., elastic limit, material strength) inserted in the model. The input values are collected by vector $\boldsymbol{p}$.

iii. The overall discrepancy between the data sets u_{mi} and u_{si}, for instance evaluated within least square context, defines the function $\omega(\boldsymbol{p})$.

iv. The actual properties of the investigated material are assumed to coincide with the entries of the parameter set $\overline{\boldsymbol{p}}$ that minimizes the discrepancy $\omega(\boldsymbol{p})$.

The optimum result $\overline{\boldsymbol{p}}$ is usually obtained by iterative computations, which may be quite time consuming when based on non-linear finite element methods. However, the simulations to be performed are quite repetitive. Therefore, traditional numerical approaches can be replaced by suitably trained analytical surrogates, which provide the optimal parameter set $\overline{\boldsymbol{p}}$ in almost real time (Bolzon and Talassi, 2012).

3. Automation issues

Full automation of the diagnostic analyses to be carried out on site is facilitated by the equipment maneuverability. Thus, durometers are here proposed as more flexible substitutes of the indenters employed by Bolzon et al. (2015). This choice eliminates the stiff, and therefore bulky, loading column that maintains control of the penetration depth in instrumented indentation. As a counterpart, the elastic modulus is hardly detectable by durometers. However, this property is not significantly affected by the damaging processes suffered by most metal structures and, therefore, remains practically unchanged over time.

Portability is further improved by reducing the overall dimensions and weight of the equipment, which can be obtained by lower applied loads. Meanwhile, Bolzon et al. (2018) showed that the representativeness of the results of indentation tests is not compromised by assuming 200 N maximum force instead of 2 kN load as in the previous work.

The load reduction affects the size of the imprint and the relevant geometry details as for instance shown by Fig. 2 and Fig. 3, which visualize the residual deformation left on pipeline steel by a sphero-conical Rockwell tip at 2 kN and 200 N force. The represented data were acquired with the same portable instrumentation (Alicona IF system).

Fig. 2 shows the regions that contain the most significant information in the two considered cases. The area of the square domain in Fig. 2(a) is 4 times larger than the one visualized by Fig. 2(b). Thus, the geometry of the smaller imprint, in Fig. 2(b), was mapped in one shot, in a few seconds' time, while image stitching and a few minutes' time were required to produce the image of the residual deformation shown in Fig. 2(a), for 2kN load. The difference becomes particularly significant when the work has to be repeated tens or hundreds of times.

The graphs in Fig. 3 show the mean profile and the confidence limits of the almost axis-symmetric geometries visualized by contour plots in Fig. 2. The diverse details returned by the same optical tool at the different scales are emphasized. In particular, the curves in Fig. 3(b) evidence the roughness of the indented surface, which was simply polished.

Some disturbances appear also in the lower part of the imprint. The noises are produced by peaks of reflected light, only partially removed by the post-processing of data illustrated by Bolzon (2021). In other situations, part of the geometry information may not be detected due to poor illumination. These limitations are expected when operating on-site, with ambient conditions changing over time, where the setup of the lighting system may not always be optimal.

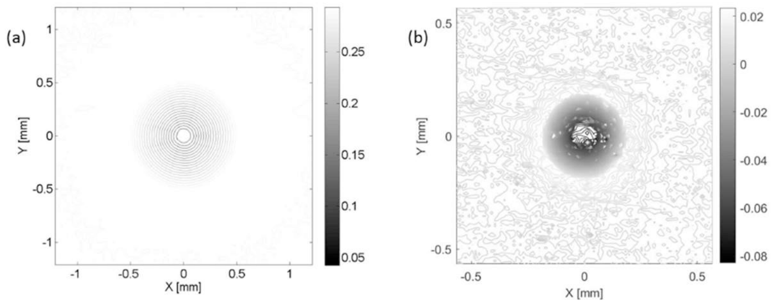

Fig. 2. Contour plot of the residual deformation produced on pipeline steel by hardness tests: (a) at 2 kN load, with the zero level placed on the bottom of the imprint; (b) at 200 N load, with the zero level coinciding with the mean position of the free surface.

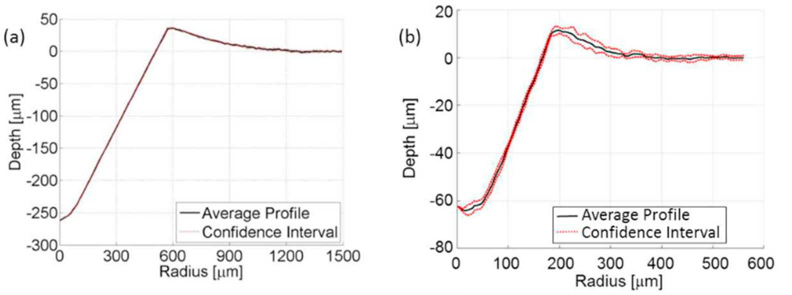

Fig. 3. Mean profile and confidence limits of the imprint produced on pipeline steel by hardness tests: (a) at 2 kN load; (b) at 200 N load. In both graphs, the zero level coincides with the mean position of the free surfaces.

4. Closing remarks

The equipment at present available on the market is potentially apt to perform fully automated non-destructive testing campaigns, overcoming the difficulties associated to the large extension and difficult accessibility of infrastructures devised for the production of clean energy and for the storage and long-distance transportation of hydrocarbons, hydrogen and water.

In this context, portable durometers and optical microscopes can be mounted on the arms of moving collaborative robots to perform hardness tests and visualize the residual imprint left on metal surfaces. The geometry data can be acquired in digital format, they can possibly be transferred through virtual networks and then stored to be used to diagnostic purposes. In this way, the information gathered on site can be exploited to assess the current state of the examined components, and to plan and optimize repair and retrofit operations.

Some disturbances associated with on-site operation have been highlighted in this work. However, most of the limitations can be overcome by proper training and by the post-processing of the data.

Acknowledgements

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