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Estimation of residual stresses by inverse analysis based on experimental data from sample removal for “small punch” tests

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A B S T R A C T

“Small Punch” (SP) tests, at present frequently employed for mechanical characterizations of structural metals, particularly for diagnosis of plant components, are here considered in view of employment also for assessments of stresses. In the procedure proposed herein the standardised sample removal from an in-service component for SP tests is exploited as external action altering the residual stress state possibly present near to the surface in the location considered. Full-field measurements of consequent displacements in the surrounding surface are employed as input for inverse analysis based on the following features: computer simulations of the sample removal as for its consequences due to relaxation of the pre-existing stress state; “non-uniformity” of residual-stress dependence on depth described as layer-dependent with uniformity in each layer of a pre-defined set of layers; “discrepancy function” minimization with employment of the elasticity parameters provided by the subsequent SP test. The advantages of the novel method consist of no-more need of traditional usual “Hole Drilling” (HD) tests or other tests for residual-stress estimation. The SP experimental procedure proposed herein for estimations of both stress state and elastic-plastic material properties would imply reductions of damages, costs and times in structural diagnoses.

1. Introduction

Residual stresses are frequently present in metallic structural components as by-products of manufacturing processes and/or of welding, or as consequences of on-purpose treatments such as rolling or shot-peening. In other structures “locked-in” stresses may be consequences of phenomena in service (e.g.: dangerous stresses may be generated in concrete dams, during decades, by alkali-silica-reaction [1]; in pre-stressed concrete structures the ad hoc designed stresses are possibly reduced in time by creep [2]).

As for metal structures, particularly power-plant components, the assessment of residual stresses is the subject of a broad scientific literature (e.g. [3–5]) and of various national and international codes (e.g. [6]). Residual stresses in welds turn out to have been one of the causes of collapse in the Liberty ships (1943) [7] and in Alexander Kielland floating offshore platform (1968) [8].

Procedures based on strictly non-destructive tests, such as diffractions or ultrasonic emissions, are frequently adopted for stress estimation, but exhibit significant limitations as for informative results and estimates accuracy (see e.g. [9,3]). Also indentation tests, with methodological novelties and minimal damage generation, have been recently proposed [10–12].

At present, the most frequently employed and widely standardised method for the residual stress estimations in metallic structural components is the “Hole Drilling” (HD) method (see e.g. [13,14]). This method can be regarded as “quasi-non-destructive” and is considered in codes widely adopted by the international industrial community, e.g. in ASTM [6].

An equally popular and standardised procedure, and “quasi-non-destructive” as well, is the “Small Punch” (SP) experiment for the mechanical characterization of structural metals, see e.g. [15–17]. At present SP experiments are routinely performed for the assessment of elastic, plastic, creep and fracture properties of materials. Miniaturized specimens are obtained from a small amount of material preliminarily extracted superficially from the investigated structure by means of ad hoc instruments.

At present both HD and SP experiments are performed in structural diagnosis practice separately, each one with different experimental equipment and procedures, but complementary to structural diagnosis purposes. Clearly, SP tests cannot provide information on stresses; HD experiments do it, but only if elastic

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moduli (and sometimes plastic parameters as well) are known, e.g. from SP tests as usual in present practice.

In this article a novel method is proposed and computationally investigated for estimation of residual stresses by exploiting the above preliminary operative stage of the SP experimental procedure. As a consequence, HD tests might be avoided in several engineering situations with obvious advantages in terms of less damages and less costs. The novel procedure is called herein "pre-SP" for brevity. As for damages, both SP tests and HD tests are considered "quasi-non-destructive", strictly "non-destructive" being the traditional ultrasonic and diffraction tests.

Section 2 contains a description of the novel experimental procedure ("preSP"), which is related to the presently recurrent SP method, but it is centred on here proposed additional measurements of the displacements due to the relaxation of the residual stress state caused by sample removal for subsequent SP tests.

The proposed "inverse analysis" procedure based on "full-field" experimental data provided by Digital Image Correlation (DIC) instruments is outlined in Section 3. Section 4 is devoted to computational validation of the novel procedure by means of numerical exercises both with "uniformity" and "non-uniformity" of the stress state to identify, namely with diverse hypotheses on the depth-dependence of stresses. Computer simulations are employed in Section 4 for preliminary generations of "pseudo-experimental" results apt to assess by "direct analyses" the "sensitivities" of measurable quantities with respect to sought parameters. An inverse analysis procedure (or "back-analysis") by a deterministic approach is elaborated and numerically validated in Section 4. Uncertainties should here be attributed not only to DIC measurements, but also to the parameters governing the toroidal surface of the cavity. Probabilistic back-analyses by Kalman filter procedures are being employed in a subsequent study.

Conclusions are presented in Section 5 with comparative remarks on advantages and limitations of the proposed "quasi-non-destructive" method for both stress estimation and material characterization. The preliminary computational validation contained in this article might hopefully motivate consideration of the presented novelties by teams elaborating industrial codes and by industries producing ad hoc instrumental equipment.

2. On Small Punch (SP) sample removal as test on stresses ("preSP)

The removal of material from structural components for generation of miniaturized specimens to be employed in SP testing is described in a broad literature and, with details of particular present interest, in [17] by the European Committee for Standardization – Comité Europeen de Normalization (CEN). The guidance provided by CEN on technological issues concerning SP specimens sampling is there considered as preliminary formulation of a code of practice. This sampling procedure is outlined below, with quantifications according to present practice, in view of its exploitation proposed herein for residual stress assessment.

The dimensions of specimens to be employed later for SP tests (Fig. 1a) are: diameter $d = 8$ mm, thickness $h = 0.5$ mm. A set of 4 such miniature specimens is extracted from a material sample as shown in Fig. 1b. A typical sample removed from the structural component under diagnostic investigation is represented schematically in Fig. 1: the elliptical border of the generated cavity exhibits diameters $L = 33$ mm and $l = 27$ mm (Fig. 1b); the maximal depth amounts to $D = 4$ mm in the profile shown in Fig. 1c. The sample removal is performed by an hemispherical scoop cutter visualized in Fig. 2, and described by the following citation from [17]: "a sample is removed by spinning the cutter about its axis of symmetry while slowly advancing it about perpendicular axis to feed the cutter into the base material. During this feed the cutter is rotated; the (e.g. 25 mm-radius) cutter shell follows the path that the leading edge of the cutter has cleared for it through the material."

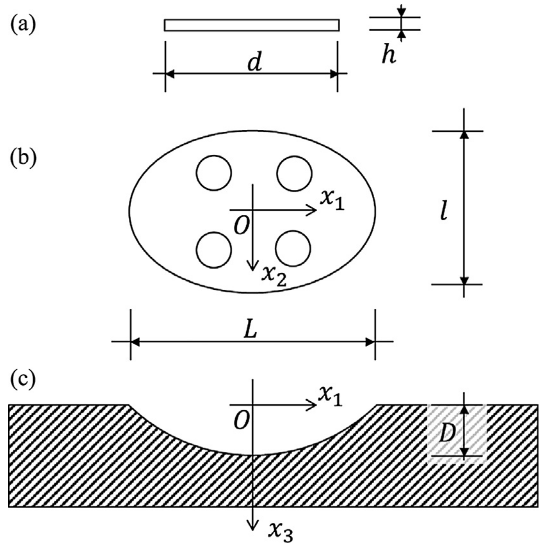

Fig. 1. (a) A circular miniature specimen for Small Punch (SP) tests; (b) a typical removed sample with visualization of SP specimens to be extracted; (c) a cross section of the sample cavity. Visualized in (b) and (c) are the lengths l, L and D, which govern the geometry of sample and cavity according to Eq. (1).

The surface of the created cavity turns out to be toroidal, represented by the following equations related to Fig. 1 as for the main symbols and resulting from the mathematical developments presented in Appendix:

$$\left(\sqrt{x_1^2+\left[x_3+\left(\frac{L^2}{8D}-\frac{D}{2}\right)\right]^2}-\frac{L^2-l^2}{8D}\right)^2+x_2^2=\left(\frac{l^2}{8D}+\frac{D}{2}\right)^2 \tag{1a}$$

$$L=2\sqrt{2D(s+r)-D^2}, \quad l=2\sqrt{D(2r-D)} \tag{1b}$$

The symbols in Eqs. (1) and in Figs. 1 and 2 have the following meanings. x_1 and x_2 are Cartesian coordinates on the plane tangential to the local surface (of the considered structural component) before excavation, as shown in Fig. 1b; x_3 is the coordinate orthogonal to that surface assumed as plane ($x_3 = 0$); r is the radius of the excavating half-sphere, as specified in Fig. 2; D denotes the maximum depth of the generated cavity, as shown in Fig. 1c; in the reference plane $x_2 = 0$, s represents the radius of the circumferential guide provided by the cutter shown in Fig. 2a.

Eqs. (1b) concern the typical lengths visualized in Fig. 1c and express them as consequent to the above geometrical quantities. The centre C of the toroid turns out to be the point with the following coordinates C $(0, 0, s + r - D)$.

According to Eqs. (1), the geometry of the cavity toroidal surface is governed by the lengths R, r and D. The values assumed here are, in mm: $R = 11.3$, $r = 25$, $D = 4$.

In practical applications it might be useful to select the geometry of the cavity (namely depth D and border diameters L and l) a priori for each category of structural components to test. The consequent test parameters r and s (namely rotating blade radius and revolution axis location) are defined by Eq. (A.6) in the Appendix as parameters to be adopted in the cutting instruments.

Clearly, the removal of the above sample gives rise to a change in the stress field possibly pre-existing in the structural component near the generated cavity: specifically, three components of the