Geometrical identification of invisible defects in structural elements basing on digital image correlation data

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Abstract. The paper addresses an experimental-calculational technique intended to determine geometrical parameters of invisible crack-like defects in thin-wall structural elements. Object deformation response to low trial loading is used as baseline data for assessment. The response is recorded using the digital image correlation method. Further analysis consists in minimization of differences between experimental findings and serial model calculations. The description of the approach is carried out on the example of a test specimen in the form of cylindrical shell (tube section) with a non-through crack simulator on the inner surface. The expected displacement fields for different particular cases are calculated using the finite element method.

1. Introduction
One of the aims of non-destructive testing and evaluation (NDTE) of structural elements is early detection and geometrical identification of possible mechanical defects that cannot be observed directly [1–6]. In particular, local irregularity of surface deformation response to low (static force, vibration, thermal) trial impact may be a sign of a hidden anomaly. Conventional optical methods of experimental mechanics can detect this response as almost continuous displacement fields. This class includes a moiré fringe method, holographic interferometry, laser speckle photography, electronic (digital) speckle pattern interferometry, shearography, etc. [7–10]. These methods are widely used in NDTE [11, 12].

A rather new method, i.e. digital image correlation (DIC) is recently on a fast track in engineering practice [13]. The method involves use of a system of chaotic small size speckles on the object surface as a metrological basis for displacement measurements. The measurement procedure is based on establishing correlations between initial and deformed speckle patterns. A stereoscopic observation system detects fields of all three spatial components of the displacement vector on the object surface. The output information is a set of discrete grid functions. Strain tensor components are determined by numerical differentiation. DIC is already actively used by NDTE specialists due to its versatility, informativeness and comparative simplicity in practical application [14–17].

This paper demonstrates potentials of experimental-calculational procedure for geometrical identification of invisible defects on the example of study of thin-wall cylindrical shell. DIC was used to identify deformation response to its trial bending loading. Further calculation of defect size was based on minimization of difference between experimental findings and numerical solutions of a set of relevant model problems by finite element method (FEM).
2. Experiment set up and performance

An aluminium tube section with a massive edge back-up portion was used as a study object. A non-
through transverse cut was made on the inside surface in the tube center using a disk mill to mimic a
-crack-like defect. Figure 1 shows the cut parameters and the object size as a whole.

![Figure 1](image1)

**Figure 1.** Drawing (a) and appearance (b) of tube with crack-like defect on the inside surface.

The object was fixed rigidly in vertical state on a base plate, Figure 2 and Figure 3. A transverse
lever of an L length (960 mm) was joined to its upper console portion. There were two suspensions for
weights at both lever edges. Transfer of a weight of an M mass from one suspension to the other was
equivalent to application of a bending momentum \( \text{mom} = M g L \) where \( g \) is the acceleration of gravity,
to the specimen.
The bending loading as a trial mechanical impact is also most appropriate in study of actual tube elements of structures. Let defect detection is the result of a preliminary experimental series. However, its precise position within the discovered location area remains unknown. In other words, there is inevitably a sort of divergence in orientation of a previously unknown axis of symmetry of an invisible transverse crack-like defect and the directrix of axis of the trial bending. It follows then that angle $\alpha$ between these axes should be considered an additional parameter to be found, Figure 4.

**Figure 2.** Experimental setup.

The metrological speckle pattern on the specimen outer surface was made by small paint dispersion spraying. The test was conducted using a VIC-3D optical digital system (Correlated Solutions, Inc.). Figure 2 and Figure 3 show positions of two video cameras used in the system also. Figure 5 demonstrates typical polychromatic pictures reflecting fields of displacement components and strains calculated on their basis. (These pictures were obtained for $mom = 130 \, Nm$.)

**Figure 3.** Appearance of the setup.

**Figure 4.** Specimen orientation scheme.

**Figure 5.** Typical polychromatic pictures reflecting fields of displacement components and strains calculated on their basis. (These pictures were obtained for $mom = 130 \, Nm$.)
Figure 5. Results from DIC: (a) longitudinal displacements $U$, (b) transverse displacements $V$, (c) normal displacements $W$, (d) longitudinal strains $\varepsilon_x$ and (e) transverse strains $\varepsilon_y$.

3. Experimental data processing and results

Further interpretation of experimental findings is in fact solution of an inverse problem of experimental deformable solid mechanics [18]. For this purpose a preliminary database is created for model deformation responses of the object. Calculations are performed for multiple values of sought-for defect parameters from a given range. Numerical solution of this direct problem was carried out using FEM in ANSYS software. Elements of the deformation response database (DRDB) were represented by components of displacements and strains as determined in nodes of finite elements on the outer surface of the object at the defect location.

The general procedure of assessment of defect parameters involves selection of their values associated with minimum deviation of experimental values from corresponding DRDB data. Such approach requires two intermediate problems to be solved. First, both data sets should be reduced to a common coordinate system. Second, the values to be compared should be determined on a common spatial coordinate grid. The last requirement is satisfied through interpolation of values calculated by FEM in finite element nodes. Sum of squared differences, sum of modules of differences, maximum relative deviation and cross correlation may be used as criteria to assess closeness of aggregate responses for the entire set of points of the common grid. For the first three criteria the values themselves are compared, while for the cross correlation criterion $R$ similarity of geometrical shapes of aggregate responses is assessed. The $R$ criterion is somewhat preferable.

In our study the DRDB was created assuming variation in defect depth $h$ from 0.1 mm to 1.4 mm with a 0.1 mm increment and angle of orientation $\alpha$ from 0º to 10º with a 1º increment. The total computation time was quite small and it is not the critical factor in such tasks as a rule. Expanded analysis of experimental data was made using special Matlab software modules. The $R$ criterion was used to assess similarity of both (experimental and model) deformation responses. It should reach maximum in the sought-for point of the parameter space. It was noted that comparison of fields of transverse displacement $V$ provided the most accurate evaluation of defect parameters. Below are the results for predefined angle of defect orientation $\alpha = 5^\circ$. Figure 6 shows graphically simultaneous search for two estimated values of $h_o$ and $\alpha_o$. Additionally interpolation of values from the discrete database was made in the $R$-maximum region to have more precise results. The following values were therefore obtained: $h_o = 1.14$ mm (error 8%), $\alpha_o = 4.44^\circ$ (error 11%). (Percentages in parentheses show deviation from true values.) Figure 7 demonstrates experimental and model fields of displacement $V$, respectively, for predefined and calculated parameters of the defect.
Figure 6. Relationship between coefficient of cross-correlation and values of the defect parameters from the database.

Figure 7. (a) Experimental and (b) model fields of transverse displacements $V$ in the region above the defect.

4. Conclusion
The rather high precision of results in the demonstration experiment suggests this approach workable. Recording of deformation response to trial impact as digitalized fields of displacements is a necessary condition for reliable determination of defect parameters. Such study may be successfully performed with actual structural elements under practical in-service conditions.

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