The use of non-contact optical systems for determination of fracture mechanics parameters

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1. Introduction

A total picture of deformed elements can be seen by tracking changes of spatial component of the deformation [1], in respect, to determining the values of three mutually perpendicular deformation components and the angle between them after deformation. Coordinates of selected grid points change due to their displacement caused by increase of load.

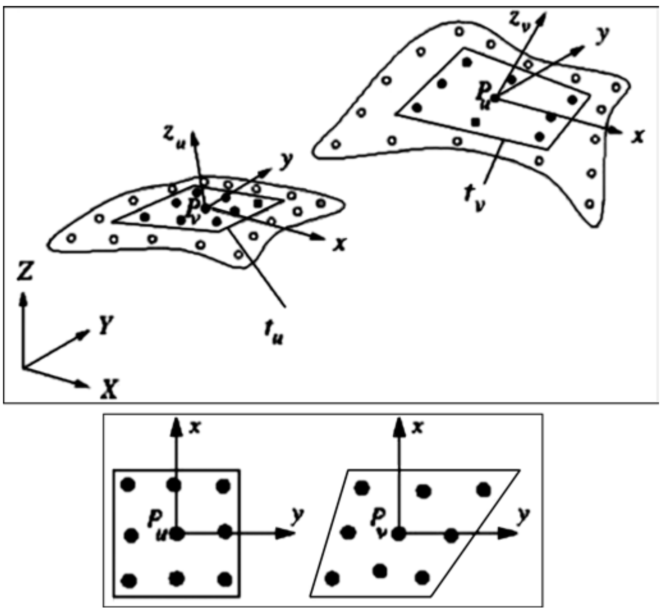

Figure 1. Image of coordinate of grating point in initial and deformed state of a structural element.

The observed segment of elements has an outlined grid in the coordinate system, and characteristic intersection points of grid are selected for tracking displacement. Figure 1 shows a segment of structural element with grid point in initial and deformed state.

2. Methods

Tracking of coordinates, allows the use of mathematical formulas for determining components of deformation or displacement. Measurements of displacement or deformation can be monitored with one camera - 2D technique or two cameras - stereometric method (Figure 2). Digital cameras continuously monitor components of the structure, for example, a critical section. It is necessary to adequately prepare the observed area before starting the test. When the structure is subjected to load, referent points start to displace, and the grid deforms. Pairs of digitalized images are entered in an ascribed timely fashion by the recording software, and based on differences in displacement of grid points; we can calculate the strain [1].

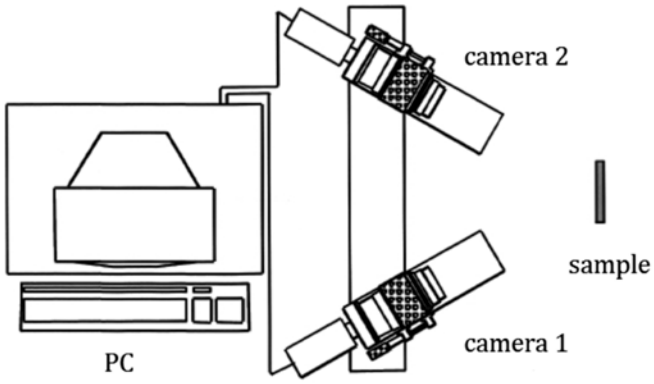

Figure 2. Scheme of the system for 3D digital image correlation - stereometric method.

The methods, focused on 2D analysis, are used for determining mechanical properties of specimens of simple geometric shape. More advanced 3D analysis can be used not only for specimens, but also for objects with complex geometric shapes. In tests, standard specimens, modified specimens, beams and duplicate cracked beams can be used to obtain detailed images of strain and displacements around the crack tip. Non-contact optical method can be used to determine the fracture mechanics parameters such as stress intensity factor K_I, its critical value K_{IC}, crack tip opening displacement - *CTOD*, crack tip opening angle - *CTOA*, the value of *J*-integral, extract parameters of a crack propagation law, obtained mechanical properties, analysis carried out on the basis of the deformation and displacement fields, etc. The results obtained by this method may be compared with the results of classical tests of specimens or the results of finite element method. Most commonly, all three methods are used at the same time in order to connect and verify the results.

The results of this method can be used for:

- Determining of the integrity of the structure and the machine part,
- The possibilities and limits of tested materials,
- Further material analysis.

The materials, on which it is possible to apply non-contact testing technique, can be divided into: metal materials, coatings, welds, composites, polymer materials, ceramic materials, organic materials, etc. Hereinafter, the results of some tests with explanations of the results and potential applications of contactless method are presented. Although this method has great advantages and decisive accuracy, it is necessary to check the results, because as each method, it is subject to the influence of errors.

3. The test results

3.1. Determining parameters of fracture mechanics I-beams under fatigue loading.

The experimental setup, which is shown in Figure 3, serve to determine the parameters K_I and K_{IC}, where test sample was an I-beam [3]. I-beam of steel S355J0, length of 1 m, is subjected to bending load. Shown in Figure 3 is single edge-crack and dimensions of the crack and beam.

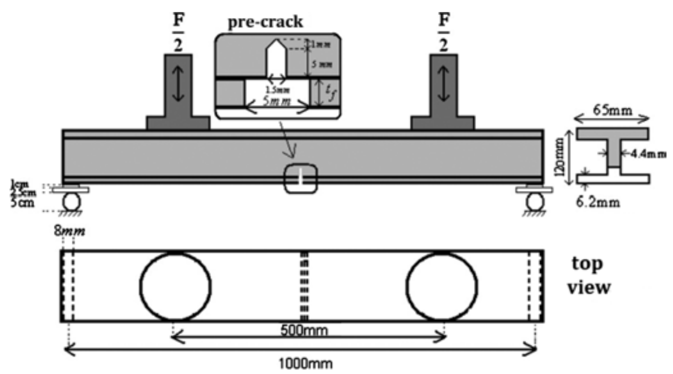

Figure 3. A schematic view of the cracked steel I-beam and dimensions.

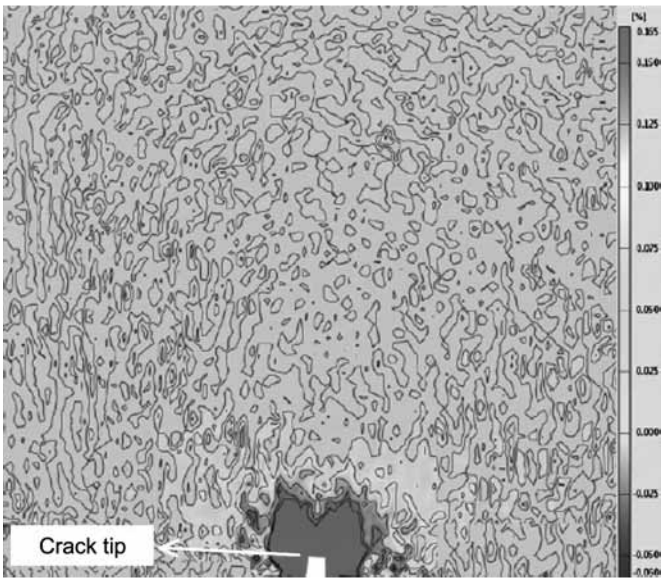

Figure 4. Strain distribution around the crack tip for a load of 16 kN and crack length of a = 12.2 mm.

The experiment consisted of two steps:

- First, a static test with a loading range of 0–16 kN was performed to measure the deformation field and plasticity zone around the crack tip.
- In the next step, in order to increase the crack length, the beam was loaded under fatigue loading range of 1–10 kN with a frequency of 8 Hz. Besides the fatigue loading, the specimen was statically loaded from 0 to 10 kN and then unloaded to 0 kN at the beginning of the test, and again after 24,000, 45,000, 62,800, 78,100, 101,000, 125,500 and 149,800 fatigue loading cycles.

After 149,800 fatigue loading cycles, the stiffness of the beam was decreased by 25% compared to original stiffness and the test was stopped. Figure 4 shows a result of the digital image correlation measurements for the static test which was performed before starting the fatigue cycling. Red region shows the elastic-plastic deformations. After the static load, beam was subjected to fatigue loading. The crack did not begin to propagate until 50,000 cycles. Its length then increased linearly until 149,800 cycles, after which the crack propagation rate became much larger. The reason that crack propagation did not begin immediately at the start of fatigue cycling may be the presence of the residual plastic zone around the crack tip caused by the previous static loading [3].

The average crack growth rate *da/dN* is related to $\Delta K = K_{max} - K_{min}$ by Paris Law [4]. At the end, it may be concluded that the crack growth rate increased after 149,800 cycles because the stress intensity factor growth rate became much larger after a = 50 mm [3]. The test was stopped at the 149,800 cycles, with a crack length of 74 mm, and the fracture toughness of the steel is K_{IC} = 131.6 MPa•m$^{1/2}$

Application possibilities: A 3D digital image correlation system was used to illustrate the stress evolution pattern around the crack tip of a cracked steel beam under an increasing external load.

3.2. The crack tip opening of weld (same materials in conjunction).

The tested joint was made of HT 50 pressure vessel steel, welded with filled wire (FCAW technique) [1]. The welded joint was produced partially with overmatched, and partially with undermatched weld metal. Test was performed with single-edge-notched specimen. The stereometric test method was applied. During the experiment, the load was tracked at 50 levels. Small load does not lead to crack opening, while opening is visible at intermediate level (22). At higher level (49), plastic deformation is dominant and followed by crack growth. In the vicinity of the crack tip, deformations are tracked at points A to F (Figure 5).

The results show crack tip opening displacement (*CTOD*) vs. load in a diagram form in these points for two characteristic cases: the crack develops from the undermatched weld metal into the overmatched weld metal (Figure 6a), and vice versa (Figure 6b).

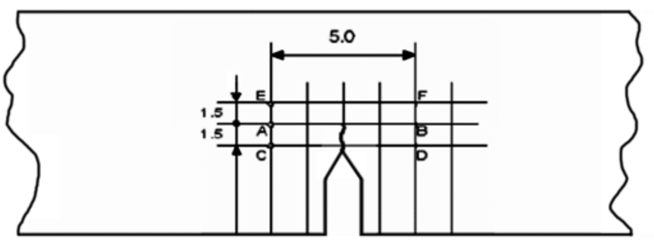

Figure 5. Typical grid points in stereometric test for determination of CTOD.

Application possibilities: It can be concluded that stereometric tests give much more data for analysis of deformation and crack development than standard fracture mechanics test [1], enabling constant tracking with data acquisition. Method is applicable for monitoring structures in service.

3.3. The crack tip opening of weld (different materials in conjunction).

The aim of the study was to observe the behavior of crack opening in two different welded materials, which have different mechanical properties [5]. The materials were HT780, which has a high yield stress and the SS400,

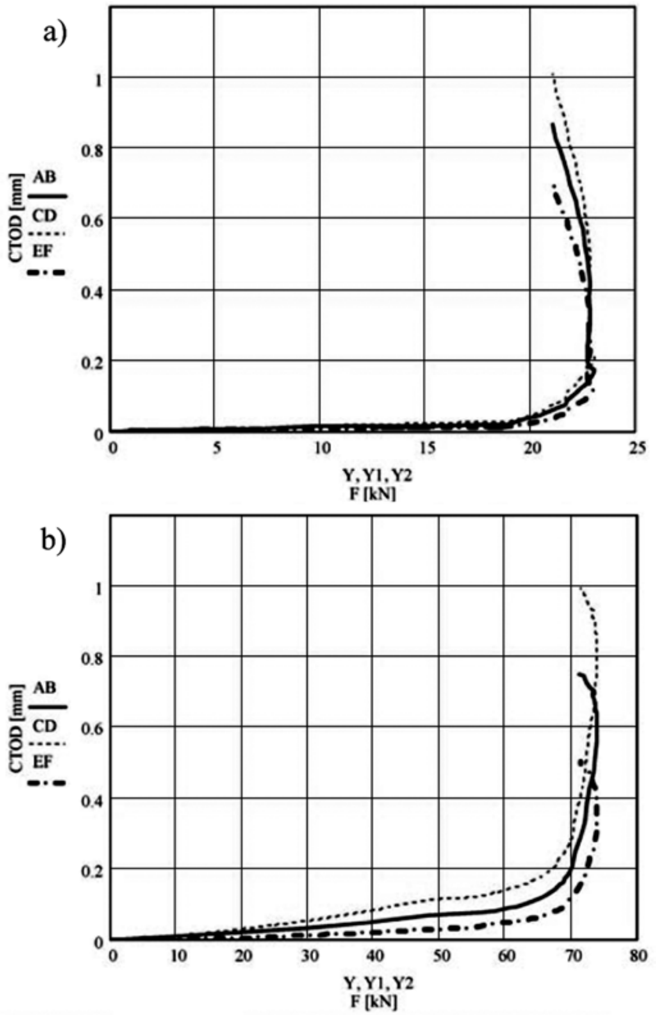

Figure 6. Crack opening displacement vs. loading in three planes around the crack tip: a) Crack growth from undermatched to overmatched weld metal, b) crack growth from overmatched to undermatched weld metal.

a softer material in conjunction. Welding was made by electron beam in two passes at same speeds. Then, the welded plate was cut into samples of smaller size. The welding is complex process during which complex physical, chemical and metallurgical reactions occur. Therefore, tests were performed on different places of the welded joint. Tested specimens were: Type 1 - cracks in the weld metal, Type 2 - the fusion zone closer to the softer metal, Type 3 - in the heat affected zone on the side of a softer metal and on pure materials. The experiment was performed with a single CCD camera. Samples for testing have the initial central crack. Tensile load was static. Parallel testing and parallel comparison with the results obtained by the finite element method (software MARC2001, MSC Software Corporation) were also performed. The comparative results are shown in Figure 7. Good match between the results of these two methods shows the credibility of the results.

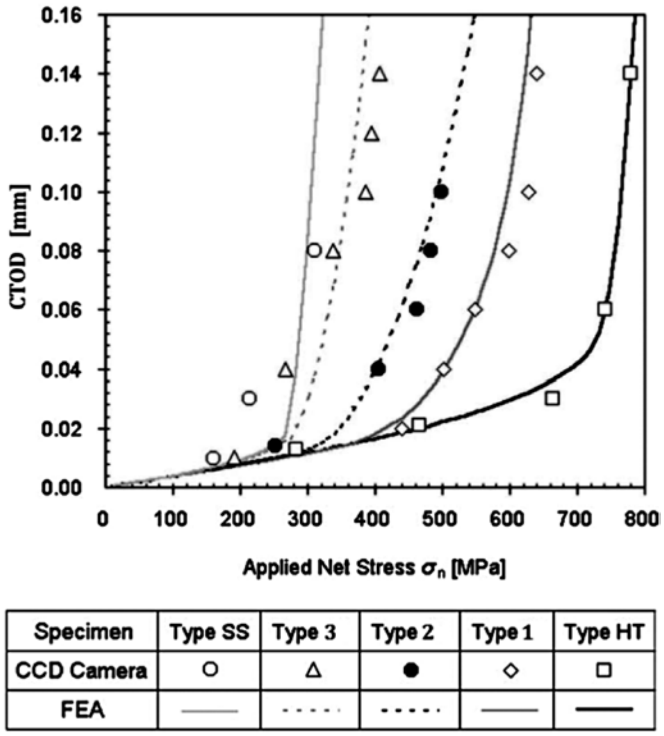

Figure 7. Relationship between CTOD and applied net stress. Comparison of DIC method and the applied finite element method.

Application possibilities: The CCD camera offers an alternative means of evaluating crack tip deformations once yield occurs. But, under small deformation, *CTOD* parameter is more difficult to evaluate.

4. Discussion

Standard tests must have a certain repeatability of results, i.e. experiment has to be done several times. With non-contact method this is not necessary; one test is sufficient for obtaining accurate results. Advantages of DIC method compared to conventional test methods include its ability to determine the parameters which influence the paths of crack propagation. Another advantage compared to the standard test methods are that the values of fracture mechanics parameters. Full-fields of displacement and strain can be obtained and used to illustrate stress state (as in steel I-beam). The use of non-contact methods is very appealing for brittle materials. They provide more precise and accurate value of displacement, deformation and mechanical properties than plastic materials.

However, there are certain disadvantages that may cause some errors in results. Under small dilatations (less than 0.04 mm), the *CTOD* is more difficult to evaluate, e.g., welded joint with two different materials. This is because for small *CTOD*s any error in evaluating the number of pixels between the crack faces can be quite significant relative to the *CTOD* magnitude [5]. Elastic mismatches can also occur and lead to discontinuities of displacement. Perhaps the biggest problem, noted above, are small deformations: crack openings much smaller than the pixel size, and even smaller than the wavelength of light, can be resolved by enabling the determine of the crack tip with a small uncertainty, and even the identification or the measurement of stress intensity factors. Uncertainty of the results is very small, after all.

5. Conclusion

Shown here are some examples of non-contact system application in order to determine the required characteristics of material. The variety of materials which have different areas of application and different loads in tests (static or dynamic) demonstrate the multifunctionality of this method. The digital correlation images can show: development of strain state, displacement and strain fields near crack tip, the mechanical properties of the material, etc. They can also be used to get a direct identification of fracture mechanics parameters (using I-DIC method), determine the parameters that influence the paths of crack growth and evaluate the deformation of crack. This is accomplished by analyzing a series of images recorded with one or two cameras.

It can be concluded that the application possibilities and aims for using non-contact technique are numerous, various and highly accurate.

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Calendar of international and national events

Calendarul manifestărilor ştiinţifice şi tehnice internaţionale şi naţionale

2014			
Jul. 7-11	12th International Conference on Quantitative InfraRed Thermography (QIRT 2014)	Bordeaux, France	http://www.ewshm2014.com
Jul. 13 - 18	67th IIW Annual Assembly and International Conference – “Advanced Technologies in Welding and Joining for Heavy, Automotive and Electronics Industries”	Seoul, Korea	http://www.iiw2014.com
Jul. 24-27	XVI International exhibition SVARKA / Welding - 2014	St. Petersburg, Russia	http://welding.lenexpo.ru/en/
Aug. 25-27	NDE/NDT for Highways and Bridges: Structural Materials Technology (SMT) 2014	Washington, DC, USA	http://www.asnt.org
Sept. 3-5	31st European Conference On Acoustic Emission Testing - EWGAE 2014	Dresden, Germany	http://www.ewgae.eu
Sept. 28 - Oct. 01	IIW International Congress - “Welding in the Arctic”	Vancouver, Canada	http://www.cwaevents.org
Sept. 29. - Oct. 3.	International Welding Engineering Fair	Brno, Poland	http://www.bvv.cz/en/welding
Nov. 5 - 7	Nordic Welding Expo 2014	Tampere, Finland	http://www.tampereenmessut.fi/tampereenmessut
Nov. 12-14	6th Inttnal Symposium NDT in Aerospace	Madrid, Spain	http://www.aero.upm.es/departamentos/aeroNDT2014/