MONITORING CRACK PROPAGATION USING DIGITAL IMAGE CORRELATION AND COD TECHNIQUES

Ozelo, R. R. M., renanozelo@fem.unicamp.br
Sollero, P., sollero@fem.unicamp.br
Sato, M., sato@ fem.unicamp.br
Barros, R.S.V., raventurini@fem.unicamp.br
Faculdade de Engenharia Mecânica – FEM – UNICAMP
Departamento de Mecânica Computacional – DMC
Rua Mendeleyev, 200, Campinas, SP, Caixa Postal 6122, CEP 13083-860, Brasil

Abstract. *This paper presents a methodology that combines the COD and Digital Image Correlation (DIC) techniques to monitor crack propagation tests. The displacement field in a specimen can be determined applying the DIC in the images of analysis area in undeformed and deformed stages. The COD can be obtained through the results provided by the application of the Digital Image Correlation at the crack center and can be used to estimate the crack length. This methodology was applied to the fatigue analysis of thin cracked plates made of 2024-T3 aluminum alloy under cyclic loading in mode-I.*

Keywords*: Digital Image Correlation, Crack Opening Displacement, Fatigue, Crack Propagation.*

1. INTRODUCTION

Fatigue analyses are important in engineering to estimate fatigue life and ensure the safe use of a structural component during its application. The fatigue phenomenon can be treated using fracture mechanics concepts. An important parameter from this research area is the crack opening displacement (COD). As usual, it is applied the Clip-gauge or Crack-gauge to determine this parameter. However, these types of technology require the devices fixed on the surface of specimen. This feature can influence the test results.

The Digital Image Correlation (DIC) is a versatile technique and, in the last years, has been applied in different engineering applications. In many fracture problems DIC was used to the analysis and provading satisfactory results. A recent work applying DIC in a fracture problem can be found in Vanlanduit *et al.* (2008).

In this work, a methodology using the DIC to determine the COD is applied. This parameter is used to estimate the crack length and stress intensity factor. The results obtained in this work are in good agreement with those found in the literature.

2. CRACK OPENING DISPLACEMENT

Wells (1963) introduced the crack opening displacement concept for low fracture toughness materials (Broek, 1986). This concept employs the crack opening displacement as the parameter governing crack length.

The COD can be expressed as a function of crack length (a). This relation can be defined as:

$$COD = \frac{4\sigma}{E}\sqrt{a^2 - x^2}\ , \tag{1}$$

where σ corresponds to the tension applied on specimen, x is the position on the crack and E is the Young's modulus of the material. Evaluating at crack center ($x = 0$) where the COD has the maximum value, Eq. (1) is reduced to:

$$COD_{\max} = \frac{4\sigma}{E}a\ . \tag{2}$$

Eq. (1) and (2) were developed for pure mode-I (see Fig. 1). Then, the application of the methodology described subsequently, is applicable only for mode-I crack propagation.

Additionally, in studies of crack tip plasticity, the parameter COD is indirectly related to the stress intensity factor (K) considering the Eq. (3). This approach was developed by Irwin to characterize the plastic zone size in cracked bodies (Meguid, 1989). In Eq. (3), K_I denotes the stress intensity factor for mode-I and σ_y is the tensile yield strength.

$$K_I = \left[\frac{\pi \sigma^2 a}{1 - \frac{1}{2}\left(\sigma/\sigma_y\right)} \right]^{\frac{1}{2}} \tag{3}$$

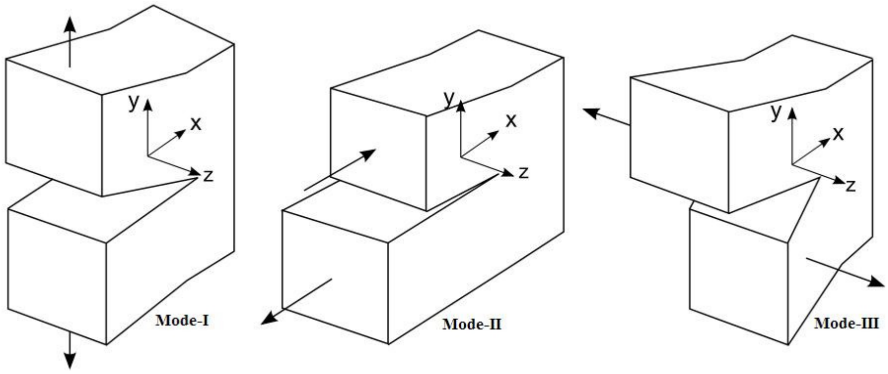

Figure 1. Crack opening modes.

3. DIGITAL IMAGE CORRELATION TECHNIQUE

Sutton *et al.* (1983) proposed the digital image correlation (DIC) as an optical (noncontact) technique that could be applied in experimental test to estimate the displacement field in a deformed specimen. In 2002, Wan used DIC to measure the COD in a specimen of FRP-concrete (Wan *et al.*, 2002).

The determination of the displacement field is obtained through the correlation between two images of the specimen, the reference image that correspond the undeformed specimen and the target image that correspond the deformed specimen.

The correlation is made in a specific area around each control point, as shown in Fig. 2. The control points create a grid in the surface of the specimen where the displacements will be determined. Each area around these points are the functions that will use in correlation.

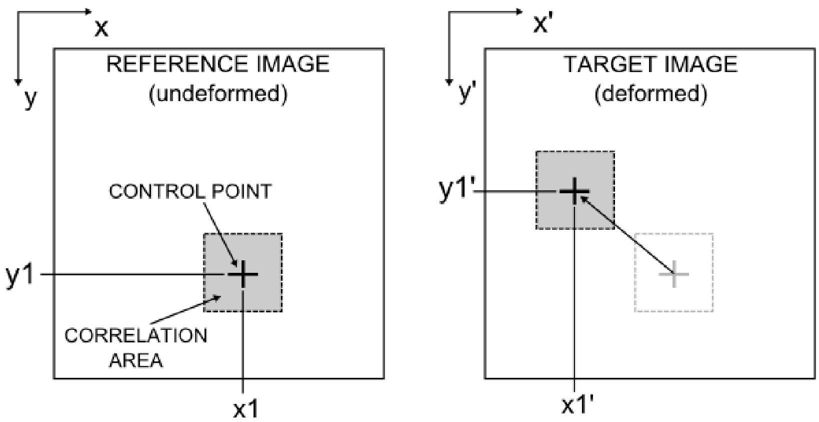

Figure 2. Correlation area around the control point and displacement of the control point.

The function that corresponding to the correlation area in reference image can be represented by $I_0(x, y)$, while $I_n(x', y')$ corresponds to the function of the correlation area in the target image. Assuming then:

$$I_0(x, y) = I_n(x+u, y+v), \tag{4}$$

where u and v are the displacements in the directions x and y, respectively.

The displacements u and v are determined from the position where a correlation coefficient exhibits its maximum value. This parameter might be calculated through the cross-correlation of the functions $I_0(x, y)$ and $I_n(x', y')$. A commonly expression of the normalized cross-correlation function is:

$$C(u,v) = \frac{\sum_{x,y} I_0(x,y) I_n(x+u, y+v)}{\left[\sum_{x,y} I_0(x,y)^2 \sum_{x,y} I_n(x+u, y+v)^2\right]^{\frac{1}{2}}} . \tag{5}$$

Many articles describe methods to solve the Eq. (5). Vendroux *et al.* (1994) show an implementation to solve it in their work.

4. MONITORING CRACK PROPAGATION

The methodology applied for monitoring crack propagation in this work, uses the DIC technique to obtain the experimental value of the COD, so that, the crack length can be estimated. The DIC, as described previously, is able to determine the displacement in specific points (control points) on the surface of the specimen. Then, if these points are located at positions above and below the crack center (see Fig. 3), the difference between the vertical displacements of upper (v_u) and lower (v_l) points can be used to evaluate the experimental COD. Then, the expression for the experimental COD is defined as,

$$COD_{xp} = \bar{v}_u - \bar{v}_l . \tag{6}$$

The rigid displacements are automatically removed, using the Eq. (6) to calculate the experimental COD, because they occur both $\bar{v}_u$ and $\bar{v}_l$.

Manipulating the Eq. (2) is possible to relate the crack length with the maximum value of the COD:

$$a_{xp} = \frac{E}{4\sigma} COD_{xp} , \tag{7}$$

therefore, the crack length can be monitored by the evaluation of the maximum experimental COD during the tests. From the Eq. (3), the experimental stress intensity factor is calculated,

$$K_{I_{xp}} = \left[\frac{\pi\sigma^2 a_{xp}}{1 - \frac{1}{2}\left(\sigma/\sigma_y\right)}\right]^{\frac{1}{2}} . \tag{8}$$

The crack center must be determined manually in this work. Hence, as illustrated in Fig. 3, it was employed more than one control point above and below the crack to obtain the average displacements ($\bar{v}_u$, $\bar{v}_l$) of these points, in order to decrease errors related to the manual procedure.

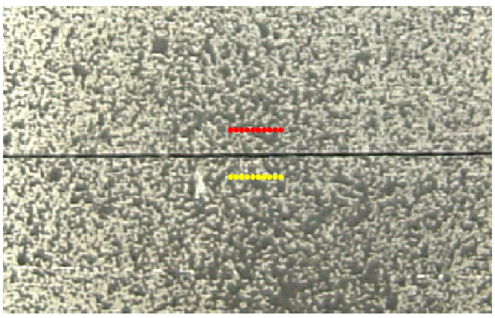

Figure 3. Control points positioned to determine the COD.

5. EXPERIMENTAL TESTS

The experimental tests were made to characterize the fatigue parameters of a 2024-T3 aluminum alloy under a cyclic loading. A hydraulic actuator was used to create the cyclic loading, as showed in Fig. 4, and the specimens tested used were three thin plates with a horizontal notch at the center of the geometry. These plates need a special treatment of the surface to obtain a better speckle pattern for the images that would be analyzed by DIC. Tab. 1 presents the properties of the 2024-T3 aluminum alloy.

The cyclic loading used had a maximum load of 24 kN, a minimum load of 2 kN and a frequency of 8 Hz. The lengths of the initial notch with the pre-cracks in the tested plates (a_0) were between 24 and 30 mm. The tests were carried on until the crack length reached a value of approximately 70 mm.

The images were captured using a digital camera with resolution of 2522x1944 pixels, as showed in Fig. 4. On average, 40 images were captured for each plate. The pixel dimension changes for each plate tested, then it is necessary the calibration of the pixel dimension (see Fig. 5). The calibration is made using a reference, in this case a graduated ruler, to determine how many pixels are in a unit of length.

Table 1. Properties of 2024-T3 aluminum alloy (Matweb, 2009).

Modulus of Elasticity (GPa)	73.1
Poisson Ratio	0.33
Tensile Yield Strength (MPa)	345

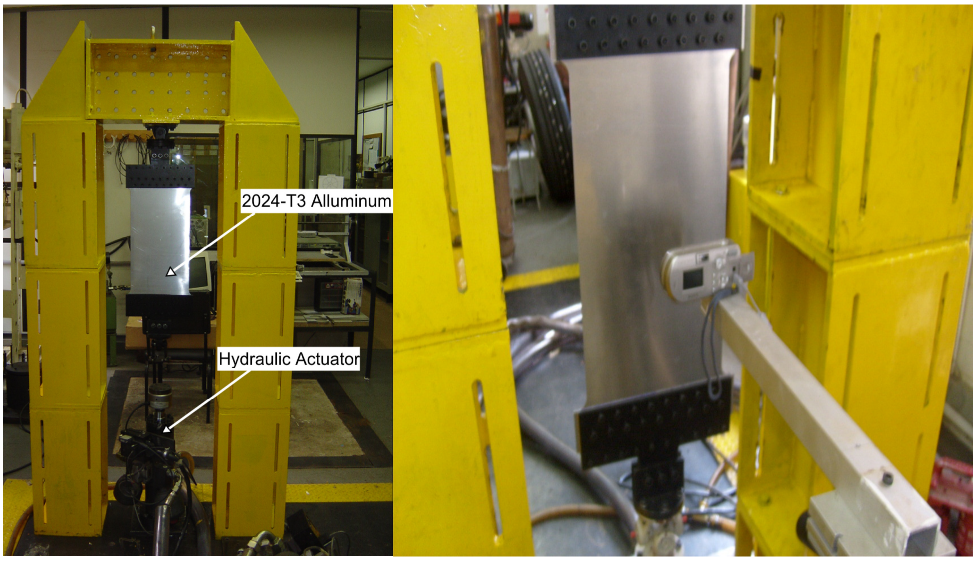

Figure 4. Set-up experimental.

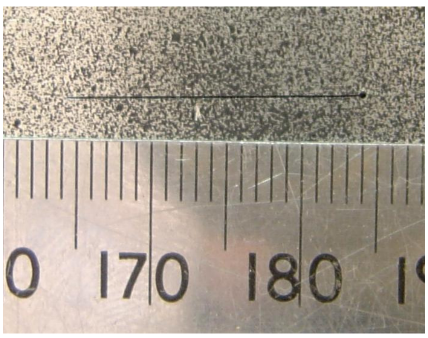

Figure 5. Calibration of the pixel dimension.

6. EXPERIMENTAL RESULTS

6.1. Curves of crack length by the numbers of cycles

Monitoring the crack propagation, using the DIC and COD techniques, as described before, is possible to obtain the values of crack length and number of cycles, during the tests. These data allow plotting the curves below (Fig. 6).

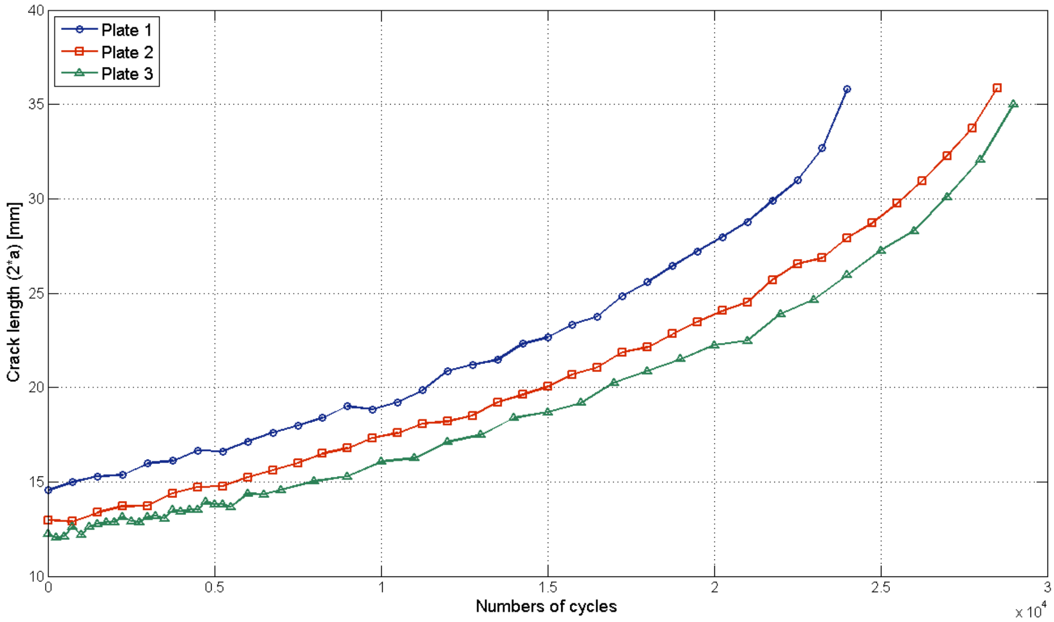

Figure 6. Curves of crack length by number of cycles to the three plates tested.

Sabelkin *et al.* (2006) made fatigue tests in thin plates made of aluminum 2024-T3 alloy using Clip-gauge, and obtained curves of crack length by number of cycles. Considering the setup differences and load conditions, a comparison between the results obtained in the present work with those from their work, reveals that they are reasonably close. Additionally, the fatigue life curve behaviors of each plate tested in this work are similar, showing good repeatability in the tests.

6.2. Determination of the Paris Law constants

Interpolating each curve of Fig. 6 with polynomials, we can obtain an approximated value of derivative da/dn at each experimental point. Monitoring crack propagation, using Eq. (8), the stress intensity factors can be determined, and the results of curves $\Delta K_I \times da/dn$ obtained. ΔK_I is denoted as,

$$\Delta K_I = K_I^{\max} - K_I^{\min}, \tag{9}$$

where $K_I^{\max}$ correspond to the stress intensify factor to the maximum load and $K_I^{\max}$ the stress intensify factor to the minimum load.

In Fig. 7 we observe a linear behavior of fatigue life curves. This feature is due to the second stage of crack propagation, where the Paris Law is valid. The Paris Law is expressed by (Paris *et al.*, 1960),

$$\frac{da}{dn} = C(\Delta K)^m, \tag{10}$$

where C and m are empirical constants.

The Paris Law can be used to estimate the fatigue life of a cracked body. Then, in the context of a fatigue analyses, it is important to know the value of the constants C and m.

Approximating the experimental results with a linear fitting, we can determine the Paris Law constants. The constants values calculated, considering all plates and for each plate, are shown in Tab. 2.

Table 2. Constants values of Paris Law.

	C	m
All plates	2.1772×10^{-9}	4.1678
Plate 1	3.0479×10^{-12}	6.3271
Plate 2	3.5465×10^{-8}	3.2153
Plate 3	2.1657×10^{-9}	4.1799

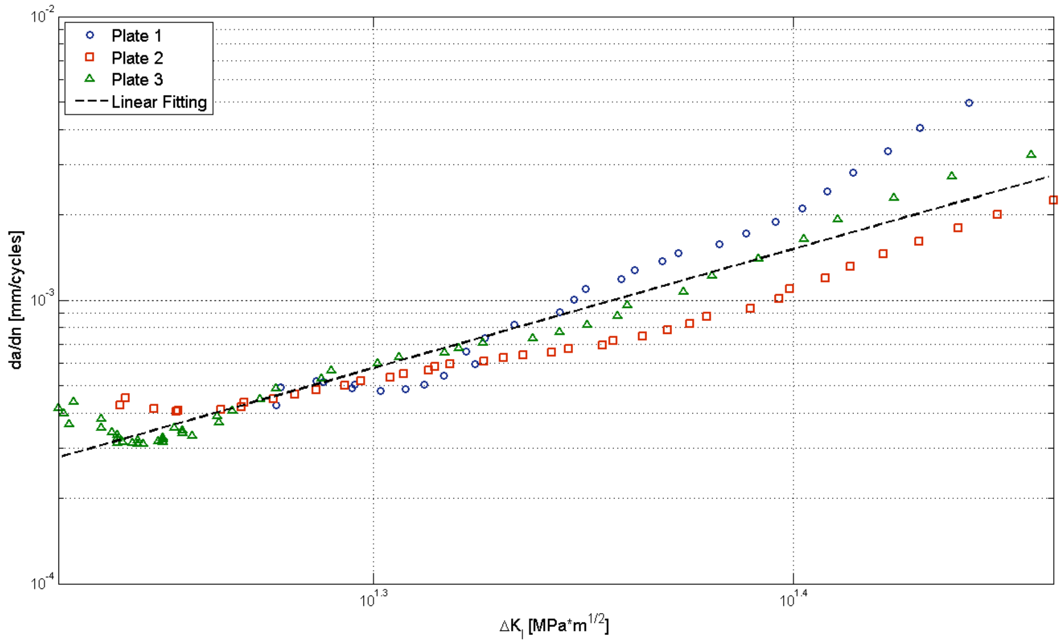

Figure 7. Curves $\Delta K_I \times da/dn$ of three plates tested.

The results obtained for the constants are close to those found in the literature (Sabelkin *et al.*, 2006), except the Plate 1, which presents a discrepancy. Comparing the results with Sabelkin's, Plate 2 presents the best results.

7. CONCLUSIONS

The methodology presented in this paper, using DIC and COD, was robust and efficient. By the application of this methodology, it was possible to determine important fracture parameters. The results are in good agreement with those found in the literature and present good repeatability and consistency. Additionally, DIC is a noncontact technique; therefore, the only special specimen preparation required, is a surface treatment to obtain a better speckle pattern.

8. ACKNOWLEDGEMENTS

The authors would like to acknowledge the FAPESP (The State of São Paulo Research Foundation) for the financial support for this work.

9. REFERENCES

Vanlanduit, S., Vanherzeele, J., Longo, R. and Guillaume, P., 2008, "A digital image correlation method for fatigue test experiments", Optics and Lasers in Engineering.
Wells, A.A., 1963, "Application of fracture mechanics at and beyond general yield", British Welding Res. Ass. Rept.
Broek, D., 1986, "Elementary engineering fracture mechanics", Klumer Academic.
Meguid, S.A., 1989, "Engineering Fracture Mechanics", Elsevier Applied, pp. 171-175.
Sutton, M.A., Wolters, W.J., Peters, W.H., Ranson, W.F. and McNeill, S.R., 1983, "Determination of displacements using an improved digital correlation method", Butterworth & Co, Vol. 1, pp. 133-139.
Wan, B., Petrou, M.F., Harries, K.A., Sutton, M.A. and Yang, B., 2002, "Experimental investigation of bond between FRP and concrete", QuakeWrap.
Vendroux, G., Knauss, W.G., 1994, "Deformation measurements at the sub-micron size scale: II. Refinements in the algorithm for digital image correlation", SM Report.

Matweb, 25 April 2009, Online materials information resource, < http://www.matweb.com/ >.

Sabelkin, V., Mall, S. and Avram, J.B., 2006, " Fatigue crack growth analysis of stiffened cracked panel repaired with bonded composite patch", Engineering Fracture Mechanics, pp. 1553–1567.

Paris, P. and Erdogan, F., 1960, "A critical analysis of crack propagation laws", Journal of Basic Engineering Failure Analysis, 85, pp. 528-534.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.