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Crack growth analysis in welded and non-welded T-joints based on lock-in digital image correlation and thermoelastic stress analysis

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ABSTRACT

The method based on the digital image correlation (DIC) technique and thermoelastic stress analysis (TSA) is proposed to monitor the crack propagation process of T-joint specimens during the fatigue test. The lock-in amplifier is used to process DIC speckle pattern images while the specimen is dynamically loaded. The lock-in algorithm uses the fact that lock-in amplifier can be able to detect very small signal change within the measurement noise, which is often used in TSA. Using appropriate post-processing method, both the crack lengths and the stress intensity factors (SIF) can be evaluated in function of the number of fatigue cycles. The tests on non-welded T-joint specimens and welded T-joint specimens in two types of test rigs will be presented in the paper. All of the achieved results were validated by employing extended finite element method (XFEM) performed with ANSYS software.

1. Introduction

The use of full-field optical techniques has grown fast over the past several decades due to the progress in digital camera and infrared camera performance and increased computational power. The full-field nature enables the identifying of strain concentrations and damage more accurate. DIC and TSA have become the most popular of these optical measurement techniques. DIC is based on the correlation algorithm to track surface patterns and hence obtain the displacements and strains that occur during loading. Most of the application of DIC has been carried out on structures under static load. La Rosa et al. [1] used DIC to correct the thermoelastic curves in static tests. Recently several researchers explored the application of DIC in fatigue tests. Kirugulige et al. [2] combined the DIC technique with a rotating mirror-type high-speed digital camera for transient crack growth study. The dynamic crack growth behavior of a polymeric beam which was subjected to impact loading was researched using the developed methodology. Chao [3] used DIC to obtain the deformation fields around a crack tip from photographic films recorded by a high-speed camera. The SIF was also calculated using the in-plane displacements and strains. Giancarlo et al. [4] used DIC to obtain the SIF via experimental J-integral evaluations in a compact-tension specimen subjected to mode I loading conditions. The J-integral was computed over an arbitrary but elastic contour path enclosing the crack tip. Good agreement can be found between the calculated SIF and the analytical values obtained from ASTM equation. However, these applications are all based on the use of high-speed cameras which also bring difficulties: the DIC evaluation algorithm must be applied carefully to process the image sequences since many images are obtained. In addition, the cost of high-speed DIC cameras is quite high. Fruehmann et al. [5] used a lock-in amplifier in DIC to monitor crack growth process during fatigue tests without using expensive high-speed cameras. It is found that the low frame rate capability of standard digital cameras does not present an unsurmountable challenge in the application of DIC at high loading rates. TSA is based on the thermoelastic effect where a temperature change induced by cyclic loading can be directly related to the change in stresses [6]. An infrared detector is often used to obtain the surface temperature change, which has been proved to be a useful tool to evaluate the local effects such as damage. Farahani et al. [7]. studied the experimental determination of SIF using TSA for a compact tension specimen during a fatigue test. The stress field obtained with computational modelling and finite element method were used as a comparison. The results obtained with different techniques show a satisfied agreement. Yates et al. [8]. researched the crack paths under mixed mode loading using TSA. It is found that the direction of fatigue crack propagation may be governed more strongly by directionality of crack tip plasticity rather than by the magnitude of elastic stress field alone. Apart from DIC and TSA, synchrotron radiation X-ray computed microtomography (SR-μCT), a newly developed method for monitoring crack growth progress, has been applying to fatigue analysis on structures. Withers et al. [9]

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employed SR-μCT to study internal damage accumulation and evolution in structural materials. The method permits 3D imaging of damage accumulation and the time lapse imaging of damage evolution for environmental and mechanical loading and provides quantitative information about key fracture mechanics parameters.

In this paper, the crack growth mechanism of welded T-joints and non-welded T-joints in two types of test rigs is studied based on lock-in DIC technique and TSA. ANSYS software was used to design the test rig, decide the experimental load and validate results.

2. Theoretical background

2.1. DIC and lock-in amplifier

DIC is a kind of full-field optical technique which enables areal inspection of strains making them ideally suited for identifying strain concentrations and/or damage. In order to obtain whole displacement field and strain field, image comparison of the specimens coated with a random speckle pattern is needed. The speckle pattern of the undeformed specimen is compared with the images of deformed specimen. The pattern matching is based on obtaining a maximum correlation between subsets of the image in the deformed and undeformed states (see Fig. 1). The correlation function as shown in Eq. (1) is used for matching purpose. The displacement of the centre of pixel subset is returned when the best match is identified. The strain fields are obtained from the gradients of smoothed displacement fields using a numerical differentiation scheme:

$$C(u,v) = \frac{\sum_{i=1}^{m}\sum_{j=1}^{m}[f(x_i,y_i)-\bar{f}][g(x_i',y_i')-\bar{g}]}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{m}[f(x_i,y_i)-\bar{f}]^2}\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{m}[g(x_i',y_i')-\bar{g}]^2}} \tag{1}$$

where

$$x' = x + u_0 + \frac{\partial u}{\partial x}dx + \frac{\partial u}{\partial y}dy y' = y + v_0 + \frac{\partial v}{\partial x}dx + \frac{\partial v}{\partial y}dy \tag{2}$$

$\bar{f}$ is the mean intensity value of reference subset; $\bar{g}$ is the mean intensity value of deformed subset; m is the width of the subset in pixels; u_0 and v_0 are translations of the centre of the subset in the x and y directions.

Most of the application of DIC has been carried out on structures under static load. For fatigue tests, they are typically time-consuming and accordingly expensive. In order to elicit more information about the structural behaviour and enable more efficient testing approaches, a full-field technique such as DIC is highly desirable. Many researchers have successfully enabled DIC for dynamic tests. Wu [10] made the stroboscopic lighting synchronised to the loading. Risbet [11] directly synchronised the image trigger to the loading cycle. However, the set-up of these methods is very complex and relatively expensive. In addition, they do not provide any improvement in terms of strain or spatial resolution compared to the standard static approach. Since the capture frequency of DIC camera is very low compared to the load frequency, it is hard to reach the requirement of Shannon's sampling theorem [12] which requires the sampling frequency is greater than two times the maximum frequency contained in the measurement signal (the Nyquist or critical frequency).

In order to solve this problem, the lock-in amplifier is employed in this paper. The lock-in amplifier is established for obtaining the amplitude and phase of small sinusoidal signals embedded within a noisy signal [13–15]. The lock-in amplifier multiplies an input signal by a reference signal and integrates the result over a number of periods. This produces a DC level proportional to the amplitude of only that component of the input signal at the same frequency as the reference signal [16]. The lock-in amplifier is phase sensitive, hence a two-phase lock-in amplifier is applied that uses not only the reference signal but also its quadrature to output an X and a Y component from which the amplitude and phase angle between the input and reference signals can be obtained:

$$X = \frac{1}{N/2}\sum_{i=1}^{N} f(t_i)\sin(\omega t_i + \phi) \tag{3}$$

$$Y = \frac{1}{N/2}\sum_{i=1}^{N} f(t_i)\cos(\omega t_i + \phi) \tag{4}$$

$$A = \sqrt{X^2 + Y^2} \tag{5}$$

$$\phi = \tan^{-1}(Y/X) \tag{6}$$

where N is the number of samples, i is the sample number, $f(t_i)$ is the input signal as a function of time t, $\sin(\omega t_i + \phi)$ is the reference signal with frequency ω and phase ϕ, $\cos(\omega t_i + \phi)$ is the quadrature of the reference signal and A is the amplitude.

It is worth noting that the reference signal must have a mean of zero and an amplitude of 1 in order not to scale the results. This was done by generating a normalised reference signal according to:

$$r_{norm}(t_i) = \frac{r(t_i)-\bar{r}}{A_r} \tag{7}$$

where $r(t_i)$ is the reference signal, r_{norm} is the normalised reference signal, $\bar{r}$ is the mean of the reference signal and A_r is the amplitude of the reference signal obtained using Fast Fourier Transform (FFT). The quadrature was obtained as the imaginary part of a Hilbert transform of the normalised reference signal. Fig. 2 shows a typical flowchart of the procedure for lock-in DIC.

2.2. TSA

Thermoelastic stress analysis is a full-field stress measurement technique based on the thermoelastic effect. This effect states that any substance in nature experiences changes in its temperature when its volume is changed: compressive loads cause an increase in temperature while tensile load leads to a decrease in temperature. Hence, a cyclic change in temperature can be inferred if applying a cyclic load to the

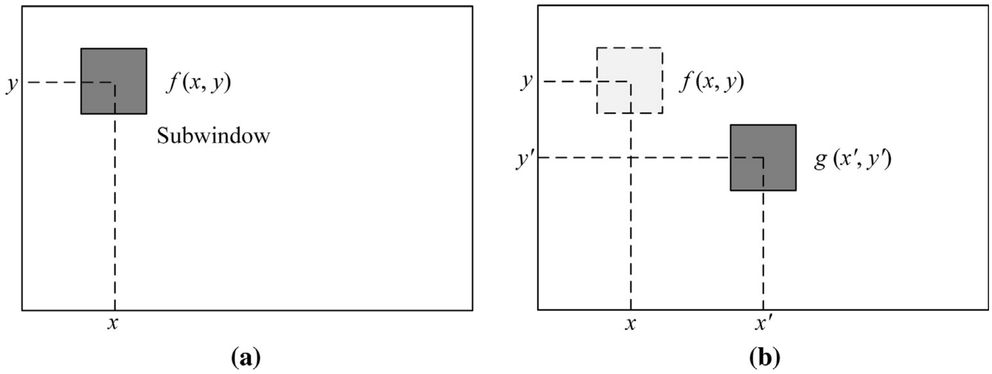

Fig. 1. Schematic of subset matching DIC. (a) Undeformed, (b) deformed.