QUANTIFYING THE EFFECTS OF PLASTICITY ON CRACK STRESS FIELDS

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ABSTRACT

The presence of plastic zones at the tip and along the flanks of cracks has been recognized for a long time; however there has been controversy about their influence on crack propagation because of the difficulty in quantifying their impact on the stress/strain fields around the crack. In the last decade, there have been substantial advances in full-field measurement techniques which have allowed strains around a propagating crack to be monitored. An overview of three such techniques is provided and illustrated through their use in both fundamental studies and applications in the aerospace industry. Post-processing algorithms have been developed to compute stress intensity factors from displacement data obtained from digital image correlation using the surface texture of the material around the crack tip which offers the potential to monitor behavior in engineering components. A similar approach has been taken with thermoelastic stress analysis; however in recent experiments the phase difference between the applied load cycle and local temperature changes has been used to quantitatively identify the size and shape of the plastic zone at the crack tip. This novel approach has been used to study the interaction of the crack tip with the plastic zone during overload events. Photoelasticity has been used for sometime to evaluate stress intensity factors however in recent work it has been used to qualitatively examine the mechanisms associated with plasticity-induced shielding of crack tips; and to develop a new model that allows the associated forces to be characterized quantitatively. Together, these techniques from experimental mechanics allow a deeper understanding to be obtained of crack propagation mechanisms in complex applications such as the fracture of wing-skin panels and fatigue failure from cold-worked holes.

KEY WORDS: plasticity, crack propagation, digital image correlation, thermoelastic stress analysis, photoelasticity.

1. INTRODUCTION

Experimental mechanics has been deployed for many years in the study of fracture and fatigue phenomena. Photoelasticity was used more than seventy-five years ago to study the stresses around a crack [1]. About fifty years ago it was being utilized to study dislocations [2, 3] and to determine crack tip stress intensity factors [4, 5]. In this early work, photoelastic fringe orders were determined at single points on the apogee of fringe loops, this was later extended to acquiring data along a selected line, usually perpendicular to the crack path [6] and subsequently to the multi-point over-deterministic method (MPODM) [7] in which a set of stress field equations, typically either Westergaard's [8] or of the Muskhelishvili type [9], is fitted to a large array of experimental data points. Other techniques of experimental mechanics have been developed along similar paths including reflection photoelasticity [10], moiré interferometry [11], holographic interferometry [12] and thermoelasticity [13]. Sanford [14] and more recently Patterson and Olden [15] have provided reviews of the use of optical methods of strain analysis for determining stress intensity factors.

In the 1990s thermoelastic stress analysis became a viable technique for quantitative monitoring of the elastic stress field around the tips of fatigue cracks as a consequence of the development of staring array cameras [16]. In parallel, digital image correlation began to be used for the analysis of cracks [17]. Digital image correlation differs from the thermoelasticity or photoelasticity in that the primary data obtained are displacement fields to which a Muskhelishvili-type description can be fitted [18, 19]. Thermoelastic stress analysis and digital image correlation can be used on any material with only a small level of surface preparation making them attractive options for investigating the structural integrity of engineering components [20-23].

Since they are founded in linear elastic fracture mechanics, all of the techniques described above for determining the stress intensity factors involve the evaluation of the elastic stress, strains or displacements around a crack tip. With the exception of thermoelastic stress analysis, all the measurement techniques are valid for the assessment of plastic deformations but this has received very little attention although there were some very early investigations [24]. Perhaps, as a consequence the influence of the plastic zone around the crack tip and along the flanks on fatigue behavior, sometimes known as 'plasticity-induced closure', is poorly understood [25]. Plasticity-induced closure is one of a number of crack closure mechanisms; and crack closure remains controversial because there are some fundamental aspects that not completely understood [26]. The purpose of this paper is to illustrate how the techniques of experimental fracture mechanics can be extended to provide information on the influence of the plastic zone in both fundamental studies and more application-orientated work.

2. PHOTOELASTICITY

Photoelasticity is based on the temporary birefringence of transparent materials subject to strain which, when viewed in polarized light causes them to generate fringe patterns that are proportional to the difference in the induced principal strains. The effect is integrated along the light path and so James et al. [27] used thin polycarbonate specimens to obtain the stress intensity factor during cyclic fatigue loading using the MPODM approach. They observed that in the presence of plasticity along the crack flank, the stress intensity factor in the unloaded portion of the fatigue cycle was elevated compared to the nominal value. They demonstrated that the elevated values arose due to the presence of residual stresses around the crack tip when the fatigue load had been removed. Subsequently, they modeled contact of the fracture surface during the fatigue cycle and estimated the magnitude of the flank contact load as a function of the fatigue cycle [28]. This work has been substantially extended by Christopher et al. [25] who considered the effect of the plastic zone around the crack on the surrounding elastic stress field. This involved considering the shape of the plastic field, its origins and its cyclic variation during fatigue loading which led Christopher et al. [29] to define a new set of stress intensity factors: K_F which characterizes the stress field driving the crack and in the absence of closure is equal to the conventional mode I stress intensity actor K_I; K_S which characterizes the interfacial shear stress established between the elastic and plastic zones along the crack flank as a consequence of compatibility of displacements; and K_R which characterises the direct stress retarding the crack growth parallel to the plane of the crack. This model was verified for a number of simple cases using photoelastic data from saw-cuts in brittle and ductile materials as well as from a fatigue crack. In recent work this model [30] has been used to examine the mechanism by which overloads affect the fatigue crack behaviour, in particular K_F increased by about 20%, K_S by 100% and K_R was unchanged by a 120% overload for a single cycle.

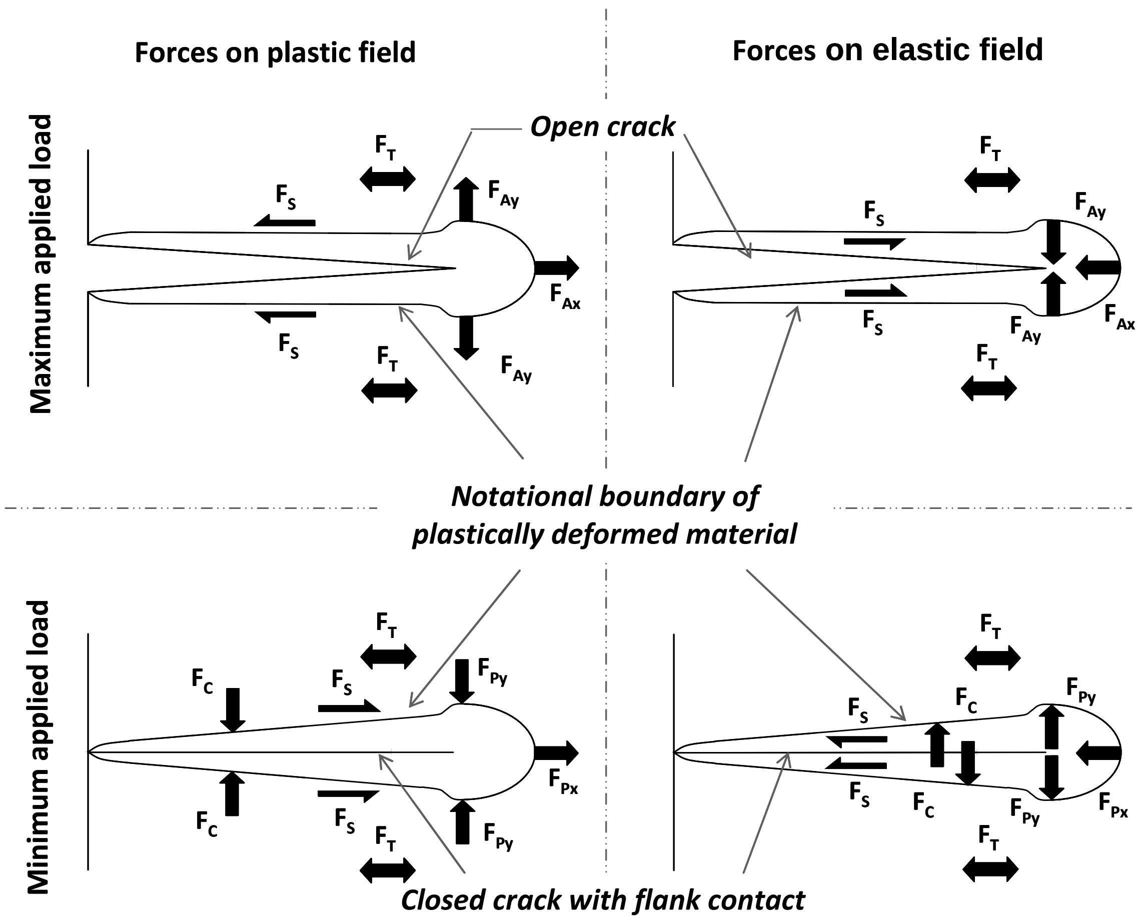

Figure 1. Schematic illustrating forces acting at the interface between the crack plastic zone and the surrounding elastic material for the maximum applied load (top) and the minimum applied load (bottom) during a fatigue cycle with the forces acting on the plastic zone shown (left) and the equal and opposite forces acting on the elastic field (right) (from [25])

3. THERMOELASTICITY

In thermoelastic stress analysis a very sensitive infra-red detector is used to monitor the change in the surface temperature of a component with applied load. In adiabatic, cyclic loading the amplitude of the surface temperature at a point is directly proportional to the amplitude of the sum of the principal stresses at the same point. The potential of thermoelastic stress analysis to provide data on the influence of the plastic zone around the crack was recognized early in the development of the technique [31]; however only recently has a comprehensive demonstration been provided [23] of the equivalence of thermoelastic data to that obtained from compliance analysis based on strain gauge measurements [32]. Unfortunately, since thermoelastic stress analysis provides the sum of the principal stresses it does not allow the evaluation of all of the stress intensity factors in the new model of Christopher et al. [25]; however an alternative feature of thermoelastic stress analysis has been utilized to investigate the effects of plasticity. In the thermoelastic effect, the induced strain and resultant temperature should be exactly out-of-phase (180°) with one another, so that a tensile strain causes a temperature drop and a compressive strain causes a temperature rise in adiabatic, elastic conditions. When plasticity is induced the resultant heat generation will cause a shift in the phase which can be detected by modern infrared cameras. Diaz at al. [33] have demonstrated that by employing a map of the phase differences between the applied load and surface temperatures it is possible to identify the plastic zone ahead of the crack, locate the crack tip and observe the extent of the crack flank contact. In recent work, Patki and Patterson [34] have shown that a quantitative measurement of the crack tip plastic zone can be obtained from such a phase map and correlated with fatigue crack behavior during overloads. They found that after an overload: the plastic zone size was larger, ΔK_I smaller and the growth rate slower and that these changes were proportional to the applied overloads; then as the crack tip emerged from the enlarged plastic zone: the plastic zone radius decreased, ΔK_I increased and the growth rate increased to values approximately equal to the pre-event values. They were able to correlate this behavior to Wheeler's model [35] for overloads.

4. DIGITAL IMAGE CORRELATION

In digital image correlation features on the surface of the component are tracked during the deformation and, or displacement of the component for small, overlapping facets within the image. In conventional analysis a speckle pattern is sprayed onto the object or component surface, however Lopez-Crespo et al. [36] have been able to obtain stress intensity factors using the metallic surface texture as the pattern. Work is in progress to exploit this capability to estimate the extent of the plastic zone and to compute the stress intensity factors defined by Christopher et al. [29]. However, in recent work, Du et al. [37] have demonstrated the use of digital image correlation on a large scale structures (approximately 5m × 1.5m) to track the development of the plastic zone size and the stress intensity factor for 10 minutes during a fracture test until just before complete rupture of the aircraft panel. They found that the structural assemblage of ribs, stringers and hole reinforcements in the panel acted as an energy sink allowing the skin to sustain very high levels of strain and correspondingly high values of the stress intensity factor that were substantially larger than the material fracture toughness.

5. DISCUSSION AND CONCLUSIONS

Three techniques of experimental mechanics have been highlighted, their basic principles outlined and recent progress in their application to quantifying the effects of plasticity on crack stress fields described. In general, optical methods of stress and strain measurement have been used for measuring elastic stress or strain fields. This is probably because not many applications demand information on plastic strains and because it is easier to interpret data when the material is homogeneous, isotropic and elastic. The later is certainly true for photoelastic and thermoelastic stress analysis. In addition, the field of structural integrity and structural prognosis is built upon linear elastic fracture mechanics with substantial less attention paid to elastic-plastic fracture mechanics.

Photoelasticity has provided substantial insights into the interaction of the plastic zone around a crack and the surrounding elastic stress field. However, transmission photoelasticity requires a transparent material which limits its applicability and interest, while reflection photoelasticity offers substantially less resolution, especially close to the crack. However, the insights obtained from transmission photoelasticity are helping to drive the development of thermoelastic stress analysis and digital image correlation in these areas. This is significant because both of these techniques offer the prospect of routine use in service applications either independently or in tandem [38]. These new developments include the concept of: (a) assessing the extent of plasticity in terms of size and shape of the plastic zone along the crack flank and around the crack tip; (b) measuring stress, strains or displacements in the surrounding elastic field where the data can be interpreted with confidence; (c) using the measured data to evaluate or characterize the forces acting at the interface between the elastic and plastic zones; and from which (d) the forces on the crack tip can be deduced. The growth of the crack is not a static or pseudo-static process so measurements have to be made throughout the load cycle if an accurate picture of the effects of the plasticity on the crack stress field is to be formed and its consequence understood in terms of the structural prognosis. Some work remains to be done but most of the pieces of this jigsaw are now in place.

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