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Review on Fatigue Crack Growth Behaviour and Damage Mechanics in Steel

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Abstract:

Ductile fracture occurs due to micro-void nucleation, growth and finally coalescence into micro-cracks. In the present work, a continuum damage mechanics model is applied to three dimensional, static, large deformation, elasto-plastic, finite element analysis of ductile fracture in steel in tension test. A logarithmic strain measure which allows the use of large incremental displacement is employed. The stress is updated in material frame to make it objective. Since tension test is mostly carried out under displacement controlled loading, an arc length method, in conjunction with Newton-Rapshon scheme, is used to accelerate the convergence. A critical value of damage variable is used as an indicator for failure. Load displacement curve up to the failure and deformed configuration at the failure are presented. Localized necking is observed to start when the load reaches the maximum value in the load displacement curve after which the load falls. Also it is observed that the damage reaches critical value first at the centre of the specimen. Thus, the failure initiates at the centre and then grows radially outward towards the free surface.

Keywords — **Steel, Fatigue, Crack, Damage mechanics, Ductile.**

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I. INTRODUCTION

Damage represents, in mechanical sense, surface discontinuities in the form of micro cracks or volume discontinuities in the form of micro voids in a solid material considered as continuous at a larger scale. The description of a material behaviour of a damaged material involves an additional internal variable, called the damage variable, which quantifies the intensity of damage. If it is assumed that the micro voids are scattered in an isotropic way, then this variable can be assumed as a scalar quantity which is denoted by D.

Ductile fracture is defined as nucleation, growth and finally coalescence of micro voids to form a micro crack. In order to model the void growth phenomenon in continuum mechanics, the idea of Continuum Damage Mechanics (CDM) is very helpful. The basis of CDM rests on the theory of continuum thermodynamics. In CDM, the material behaviour is represented by a plastic potential which includes the damage as an internal variable. The plastic flow rules and the damage growth law are derived from the plastic potential.

Mc Clintok and Rice and Tracey developed a model considering a single void in a continuum. Their models assumed a pre-existed finite size void in a continuum and hence did not consider the void nucleation phenomena. Based on Berg's theory of dilatational plasticity, Gurson proposed a plastic potential taking into account both the void nucleation and growth. A critical value of void volume fraction is normally used as criteria for micro-crack initiation in the Berg-Gurson model. Based on continuum thermodynamics, Lemaitre proposed a continuum damage mechanics model for elasto-plastic case. Another continuum damage mechanics model is due to Rousselier which incorporates the damage implicity through current density. Dhar obtained a damage growth law by using the Lemaitre's continuum damage mechanics model together with the experimental results of Le Roy et. al.

Tvergaard and Needleman performed two dimensional tensile test simulation of round bar to numerically simulate necking and failure. The crack was reported to start from the center of the neck and was shown to propagate radially outwards forming a cup cone fracture. Besson et. al. modeled the crack growth in round bars and plain strain specimens and studied the formation of cup cone fracture using various two dimensional axisymmetric finite elements. Some other researchers viz. Tang et. al., Komori have carried out two dimensional studies on tensile test on steel using commercial finite element codes and have reported similar observations. A three dimensional, static, large deformation, elastic-plastic, finite element code is developed for this purpose. An element failure model based on the critical damage is used for the crack growth simulation. Therefore, for convergence, the unbalanced force vector needs to be made small in an absolute sense and not in comparison to any known external force. This slows down the convergence. To accelerate the rate of convergence, the arc length method of Batoz and Dhatt, originally proposed for proportional loading, is suitably modified for the non-proportional loading and used in conjunction with the modified Newton-Raphson method. In this approach, the unknown nodal reactions at the nodes, at which the displacement is specified, are expressed as a linear combination of a set of known nodal forces. The unknown coefficients in the linear combination are found from the condition that the axial component of incremental displacement vector at the displacement specified nodes has a specified value. Mechanical systems are generally subjected to loads of variable amplitude including random loading. Recognizing the practical importance of the fatigue crack growth under random loading many models [1-5] have been proposed. Also extensive analyses on the suitability of the available models for the prediction of crack growth under random loading have been carried out by ASTM Task Group E24.06.01. Determinations of the crack response under random loading conditions are available for mode I loading where as the response under mixed mode stress field is very few. One of the main difficulties in the evaluating the fatigue crack growth in mechanical components under spectrum loading is associated with the interaction or sequence effects by extreme over load peaks. Though such types of over loads are rare in practical applications, but their effect is very much significant. This over loads in spectrum loading mostly causes retardation or acceleration in the crack growth rate. Several models are available to predict the crack growth behavior under random loading, but their applications in the mixed mode loading condition is very few [6-8]. As is well known that fatigue crack growth behaviors under random loading are quite different from those observed under steady loads of constant amplitude, because the crack growth rate is strongly affected by the load history, especially by the proceeding over load, which produces crack retardation. It is impractical to determine experimentally crack growth curves and hence the life for all loading histories. They are normally calculated using any crack growth model.

II. CRACK CLOSURE METHOD

Several models proposed so far for the prediction of crack growth under spectrum loading for mode I crack growth, the models based on crack closure concept can physically well account for load interaction effects, and may lead to a simpler prediction procedure. The main problem in crack closure concept is the prediction or estimation of crack opening stress accurately. Several models available for the estimation of closure stress are based on opening mode

(Mode I). The empirical models presented by Mageed & Pandey are based on mixed mode constant amplitude experimental results. Hence it will fail to take the random loading effect. The study of crack closure under a mixed mode and random loading and its correlation with the opening mode is rarely available in the literature.The available basic approach for the estimation of closure stress under spectrum loading for mode I crack is extended for mixed mode case and presented here.

III. PAGE STYLE

Generally, the opening and closing of a crack is progressive during the loading portion and the unloading portion of the load cycle, respectively. Therefore, opening and closing of different points on the crack surface occurs at different load levels and some portion of the crack surface may keep opening or closing in all of the cycle depending upon the magnitude of peaks of the random loading cycles. Hence when the loading history is highly uneven, large peaks raises the crack opening stress and delay the crack growth. Hence sequence of the applied cycle plays an important role in the crack growth under random loading. When the sequence effect becomes important, the loading history must be defined in such a way that the real order of the loading cycles can be reproduced. Under these conditions, cycle by cycle simulation of crack growth is most widely accepted procedure for its study.

IV. CONCLUSIONS

A continuum damage mechanics model has been applied for numerical simulation of ductile fracture in steel. Fracture has been shown to initiate at the centre of the specimen and is found to be consistent with the observation reported in literature. It is believed that the damage growth law can be used for simulating failure in other materials and different geometries like pre-necked specimens. Also it is believed that it can be used for simulating failure in complex loading conditions. The model provides estimates that are very similar to the expected mean values for the material and random process studied and available in literature. History length has marked effect on the fatigue life and a decisive element in making a test or simulation of a crack growth process under random loading. The too short history and their repetition produces non-conservatives result and provide longer lives than produced by longer history. Extreme narrow band processes produce shorter life than wide band processes. Maximum peak value for the random load history produces a strong sequence effect.

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