ANALYTICAL AND EXPERIMENTAL STUDIES ON SEVERAL ASPECTS OF CTOD DETERMINATION IN ELASTIC-PLASTIC AND CRACK GROWTH SITUATIONS

by

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CERTIFICATE

This is to certify that the thesis entitled "**Analytical and Experimental Studies on Several Aspects of CTOD Determination in Elastic-Plastic and Crack Growth Situations**" being submitted by **Sova Bhattacharya** to the Indian Institute of Technology, Delhi, India, for the award of the degree of Doctor of Philosophy in Applied Mechanics Department is a record of bonafide research work carried out by her under my supervision and guidance. The thesis work, in my opinion, has reached the standard fulfilling the requirements for the Doctor of Philosophy Degree. The research report and results presented in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

The present research is carried out with the purpose of improving upon the recommended method of CTOD determination by examining several controversial aspects. Attempts are made to obtain several models using both theoretical analysis and experimental data to address the following major aspects :

(a) CTOD evaluation in slow crack growth situations.

(b) R-curve generation and CTOD evaluation considering maximum crack size.

(c) Crack size estimation considering various crack front profiles in slow crack growth situation.

(d) Plastic rotational factor in blunt notch as well as sharp crack tip situation.

(e) Comparative analysis of CTOD estimation.

The first chapter is an introduction to fracture mechanics. It presents the limitations of the traditional design approaches. The need for fracture mechanics based engineering design is highlighted and some of the controversial aspects of EPFM parameters are discussed in short. The need for the present investigation has also been briefly outlined.

Chapter II on current literature survey gives an overview of the problem, present state of knowledge and objectives of the present work.

In chapter III the aspect of CTOD evaluation in slow crack growth situation has been dealt with. In ductile materials slow crack growth often follows crack initiation, and the R-curve analysis characterizes both the crack initiation and crack growth behaviour of a material. The existing standards determine the crack tip opening displacement (CTOD) from the total clip gauge output by separating it into elastic and plastic components. The present work outlines the need for further separation of the plastic part of CMOD into the displacements due to slow crack growth and true plastic yielding. While the CTOD values for the elastic and true plastic yielding parts may be inferred according to the present methods, a new and simplified approach is proposed to infer

crack growth CTOD from the corresponding displacement. Geometrical as well as analytical comparison between the CTOD values obtained by the standard method and the proposed method is made. The comparison reveals that the existing method overestimates the CTOD value as reported by others. However, as the crack growth continues, the difference in CTOD values is found to diminish.

Chapter IV discusses the aspect 'R-curve generation and CTOD evaluation using maximum crack size'. The standard methods of estimating the average size of slow crack growth region as described in BS 5762 and ASTM E1290 is cumbersome, painstaking, time consuming and depend on several factors e.g. section thickness, nature of cract front profile, number of measurements etc. Very often errors are introduced in determining the average crack size which in turn affect the determination of critical CTOD value.

Several merits associated with the use of maximum crack size is established. A theoretical relationship is established between the maximum crack size and average crack size assuming parabolic, semi-circular and elliptical nature of slow crack growth front profiles, which is supported by experimental data points. A new approach is proposed to make use of maximum crack size of parabolic crack front profile to generate R-curve which can be extended to yield critical CTOD values. The nonlinear regression analysis of CTOD - Δa_{max} (maximum crack size) R-curve yields critical CTOD value in agreement with the value that may be obtained by BS 5762. However, the linearly regressed CTOD, Δa_{max} points (linear R-curve) and extrapolated critical CTOD value are found to be highly conservative. Alternatively, the average crack size may be obtained theoretically using maximum crack size data to determine CTOD following BS 5762.

An analytical optimization of offset measurement number (N), for realistic crack growth sze estimation, for each crack front profiles as mentioned in Chapter IV is carried out considering two approaches, namely offset measurement and area consideration. The variation of average crack growth size (Δa_{av}) as well as the convergence of Δa_{av} as a function of measurement number (N) is studied. The difference in the Δa_{av} values obtained by the offset method and area method is also investigated. Experimental verification of crack growth front profiles as well as the change in the Δa_{av} value with N is carried out. Attempt is also made to study the effect of thickness and extent of maximum crack growth on the value of N. In general eight to ten measurement is found to be adequate to have a realistic determination of crack growth size in commonly used specimen thickness. This aspect is reported in Chapter V.

The location of plastic hinge point around which the rotation of the two halves take place is a highly controversial point. An unambiguous and reliable r_p value is very much essential for the determination of CTOD data. Although considerable research has been carried out in this direction, still the r_p factor is open to debate. Attempt is made to determine r_p value following a new method for two situations namely blunt notch with finite root radius and sharp crack tip situations. The r_p determination in blunt notch situation has been neglected although many engineering structures contain notch like defects in the form of functional hole, machine cut, weld toe etc. The r_p values are determined by both theoretical analysis as well as experimentation and reported in Chapter VI.

Theoretical estimation of r_p in both pseudo-elastic and elastic-plastic sitution is carried out through an analytical relationship among factors like plastic zone size, bend angle and opening of the notch tip. Estimation of plastic zone size is made in pseudo elastic and elastic-plastic situation using stress concentration factor and elastic as well as elastic-plastic stress distribution.

Using the theoretical expressions, values of r_p are found to increase from a small value of around 0.25 in elastic situation to around 0.54 in extensive plastic situation for blunt notch specimens.

The experimental r_p values are obtained from displacement measurement at several points using SEN bend specimens. The r_p values are found to be in the range of 0.26 - 0.28 and 0.50 - 0.56 respectively for elastic and elastic-plastic situation. Attempt is also made to investigate the 'r_p' values in slow crack growth situation where the hinge point is found to shift gradually away from the original notch tip.

In Chapter VII theoretical estimation of r_p is made in notched and deep cracked situation considering the bending moment approach. Several combinations of probable elastic stress distributions for situations in well below general yield are considered. Moreover, additional plastic stress distribution within the plastic zone is also considered in elastic - plastic loading around general yield.

The hinge axis around which the resultant bending moment for these stresses becomes zero is estimated. The 'r_p' is then related to the hinge axis through ligament length and width of the specimen. In case of notched bend geometry the rotational factor is found to be in the range of 0.26 - 0.35 for well below general yield regime, and in the range of 0.42 - 0.47 for around general yield situation. 'r_p' values are found to be constant at around 0.41 - 0.42 in elastic situation and vary between 0.42 - 0.47 in elastic - plastic situation for cracked specimen. Effects of other variables like initial crack size (a_o), load (P), elastic stress intensity range, state of stress etc. have also been investigated in deep cracked situation.

In the last Chapter a comparative analysis of CTOD estimation between BS 5762 and ASTM E1290 is presented. The major differences between the standards are outlined and the influence of these differences on crack initiation CTOD value is studied. The study is based on typical fatigue crack and slow crack growth front profile. A difference of upto 6 per cent in the CTOD values between the two standards irrespective of slow crack growth size is found in the present study. However, a marginal difference of only 2 per cent in the initiation CTOD value could be observed for the slow crack growth situation considered.

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