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Finite element analysis of a center crack specimen warm pre-stressed under different modes of loading

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Abstract

Load bearing capacity of cracked specimens can be improved following pre-loading procedures like warm pre-stressing (WPS). In this paper, the effects of modes I and II pre-loading on fracture load of a central angled crack specimen are studied by finite element analysis. The specimen is reloaded either in mode I or in mode II. To predict the fracture load of cracked specimen after pre-loading, the maximum tensile stress (MTS) and maximum shear stress (MSS) criteria are used. It is shown that mode II fracture load is independent of pre-loading but the mode I fracture load is highly improved after warm pre-stressing. The mode mixity of the specimen is also changed when the pre-loading and reloading modes are not identical. An increase in the fracture load of the specimen following pre-loading may be due to change of failure mode as predicted by finite element analysis in this work.

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Keywords: Crack; Warm pre-stressing; Finite element analysis; Mode I; Mode II

1. Introduction

The loading history can affect the fracture properties of cracked structures significantly. Such effects may be observed after different processes. Proof testing, and warm pre-stressing are examples of loading history which often associated with an improvement in the load bearing capacity of cracked specimens [1–3]. If a cracked specimen is pre-loaded beyond its yielding point in a temperature higher than its service temperature, plastic deformation occurs near the crack tip. This procedure is called warm pre-stressing (WPS) and generally leads to an increase in the apparent fracture toughness of the cracked specimen.

Improvements in the apparent fracture toughness of warm pre-stressed specimens are suggested to be on account of different factors [4]:

- A compressive residual stress field in front of crack because of non-uniform plastic deformation.
- A decrease in the stress singularity following crack tip blunting.
- Material work hardening in front of crack.
- A change in the mechanism of crack growth from brittle fracture to ductile rupture.

In the WPS procedure, the cracked specimen experiences mechanical loading in two different stages: first in the pre-loading stage and then in the reloading stage. During each stage, the cracked specimen can be subjected to either pure tension (mode I) or pure shear (mode II) loading conditions. It is expected that the loading mode affects at least three of the mechanisms mentioned above. Each loading mode produces a different stress field and results in a different residual stress field. There is also a higher probability of ductile rupture when the shear load is dominant [5]. Besides, the significance of crack tip blunting decreases as the contribution of shear load increases [6].

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Nomenclature

a	semi-crack length
r, θ	crack tip coordinates
r_c	characteristic distance
J	J integral
J_{cr}	J integral upon fracture
K_I	mode I stress intensity factor
K_{II}	mode II stress intensity factor
M^p	mixity parameter
P	far field applied load
P_f	far field fracture load in as-received specimen
P_{imp}	percent improvement in far field fracture load
$(P_f)_{WPS}$	far field fracture load after warm pre-stressing
$R_{\tau\sigma}$	ratio of maximum shear stress to maximum tensile stress
W	semi-width of specimen
β	crack angle relative to vertical direction
λ	ratio of horizontal load to vertical load
σ_c	critical tensile stress
σ_{max}	maximum tensile stress along a circle of radius r_c around the crack tip
$\sigma_{r\theta}$	shear stress
$\sigma_{\theta\theta}$	tangential stress
τ_c	critical shear stress
τ_{max}	maximum shear stress along a circle of radius r_c around the crack tip

Although extensive amount of research work has been conducted for mode I cracks, effects of mode II loading have rarely been investigated in the warm pre-stressing procedure [7]. Meanwhile, there are many practical conditions where the cracked component experiences different modes of deformation in the pre-loading and reloading stages. Previous investigations have provided a very good understanding of crack behavior after warm pre-stressing but only for mode I cracks. However, mode II pre-loading or reloading does not necessarily result in the same behavior as that of a mode I crack. Thus, in this research the finite element method is employed to study the effects of loading mode in the pre-loading and reloading stages on a central angled crack specimen.

In this paper, an overview of WPS is given first. Then the fracture criteria employed to predict the fracture load in the warm pre-stressed specimens are described. The change in the probability of ductile rupture following the WPS procedure is investigated in the next part. It is finally explored that how warm pre-stressing affects the fracture load when pre-loading and reloading are in different modes of loading.

2. Overview of WPS

WPS is usually applied to structures made of ferritic steels which show enough fracture toughness transition with temperature [1]. There are different cycles for warm pre-stressing a structure. In all these cycles, the structure is pre-loaded in the upper shelf zone and then is used in the lower shelf zone. Between the loading, cooling and fracture stages, partial or full unloading can also take place. Among these cycles, the most frequently used one is LUCF cycle in which L stands for loading, U for unloading, C for cooling and F for fracture. Fig. 1 illustrates schematically the LUCF cycle. In this figure, as-received (AR) fracture parameters are referred to the values of fracture parameters in a virgin specimen without any warm pre-stressing. As

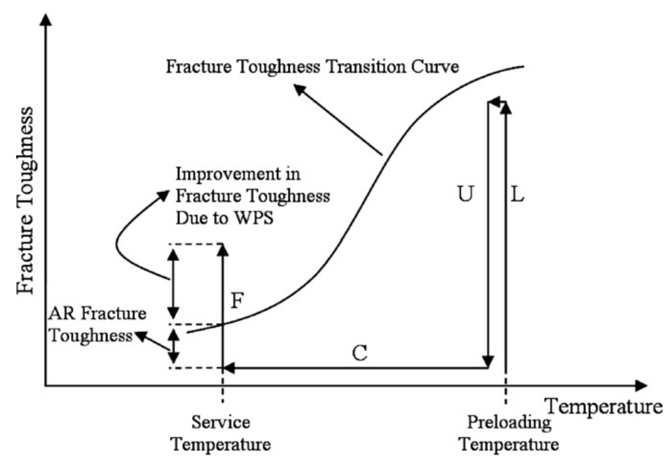

Fig. 1. Schematic representation of LUCF cycle.

shown in Fig. 1, the warm pre-stressed specimen can carry more load compared to the as-received specimen. The observed improvements in the apparent fracture toughness due to warm pre-stressing have been reported for example in [7] based on many experimental investigations conducted in this field.

One of the first published papers on the effects of pre-loading was appeared in 1963 by Brothers and Yukawa [8]. Since then, extensive theoretical, experimental and especially in the recent years numerical studies have been carried out in this field. The aim of theoretical studies was in general to find appropriate relations for predicting the fracture toughness of warm pre-stressed specimens. Chell et al. [9], Curry [2], Smith and Garwood [10] and Pokrovsky et al. [11] suggested well known theoretical models for warm pre-stressing. Meanwhile, the effects from different factors in warm pre-stressing were also examined through experimental investigations. Temperature [12], pre-loading level [13], pre-loading cycles [3,14], geometry of specimen [11], aging [15], etc. are examples of such factors.