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Effects of lateral load on warm prestressing in a center crack plate

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Abstract

The load bearing capacity of cracked components increases if an appropriate compressive residual stress field is created near the crack tip. Warm prestressing is a well-known technique for introducing such a residual stress field. In this paper, the finite element method is used to study the effect of the load applied parallel to the crack (or the lateral load) in warm prestressing of a cracked specimen. The specimen is a square plate containing a center crack and the lateral load is applied in the preloading stage. The numerical results suggest that the lateral load in the preloading stage can influence significantly the apparent fracture toughness after the warm prestressing. It is shown that the improvement in the apparent fracture toughness due to a compressive lateral load is more significant than the improvement due to a tensile lateral load.

Keywords: Finite element analysis; Warm prestressing; Elastic–plastic fracture mechanics; Mode I; Center crack plate

1. Introduction

Proof tests are commonly used to explore whether the engineering structures or components sustain the applied stresses under service loads. For example, to ensure the structural integrity of pressure vessels or boilers, the internal pressure is often increased to 25–50% more than the pressure corresponding to the service conditions [1]. If the proof test is conducted in a temperature higher than that of the working conditions and the material yield stress is considerably temperature-dependent, the procedure is called warm prestressing (WPS). Such a procedure often increases the fracture resistance of the structures containing cracks [2,3].

Although several different procedures can be used for warm prestressing, only one of the most frequently used procedures is studied in the present paper. In this method, the cracked component is first warmed to a temperature above the fracture transition temperature. The component is loaded and unloaded (preloading stage). The temperature is then reduced to that of the service conditions. Eventually, the component is reloaded to final fracture. Such a procedure is often called load–unload-cool-fracture (LUCF).

Two possible reasons suggested in the past for improvement in fracture toughness of cracked components after warm prestressing are "residual stresses" and "crack tip blunting". Due to high levels of stress concentration, a plastic zone develops around the crack tip in the preloading stage. When the specimen is unloaded, the initially sharp crack is blunted. Also unrecoverable plastic strains create a region of residual stresses in front of the crack tip. Either of the crack tip blunting and the compressive residual stress field near the crack tip can decrease the tensile stresses associated with reloading the specimen. Such a procedure eventually increases the load bearing capacity of structure or equivalently enhances the apparent fracture toughness of material. Using finite element analysis, Ayatollahi and Mostafavi have recently studied the roles of residual stresses and crack tip blunting in warm prestressing of cracked structures both for pure mode I [4,5] and for mode I–mode II conditions [6].

The level of improvement in the apparent fracture toughness in warm prestressing depends on the value of load applied (or the value of J-integral) in the preloading stage. A higher load (or J) in this stage causes a larger plastic zone and higher residual stresses upon unloading. However, if a very high load is applied in the preloading stage, the residual stresses near the crack tip can be tensile causing a decrease in the apparent fracture toughness of material [7]. On the other hand, if the load applied in the preloading stage is not large enough, warm prestressing exhibits only little effect on the apparent fracture toughness [2].

The effect of warm prestressing on the apparent fracture toughness has been studied in the past both experimentally (e.g. [8–17]) and theoretically (e.g. [18–22]). For experimental

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Nomenclature

a	semi-crack length
CCP	center crack plate
J	path-independent integral
J_c	J-integral at fracture load after warm prestressing
J_{pre}	J-integral in the preloading stage
K_{Ic}	fracture toughness (without warm prestressing)
LUCF	load–unload-cool-fracture
$R_{p,max}$	maximum plastic zone radius
S_x	the remote load applied parallel to the crack
S_y	the remote load applied normal to the crack line
S_{yc}	fracture load after warm prestressing
t	specimen thickness
$2W$	specimen width
x_0	critical distance in front of the crack tip

Greek letters

λ	lateral load factor
σ_{yy}	stress normal to the crack

studies, the warm prestressing procedure is often applied to standard crack specimens and the values of fracture toughness determined with and without warm prestressing are compared. A similar procedure can be simulated using finite element analysis and the effect of warm prestressing on fracture toughness can be studied using appropriate theoretical models available for cleavage fracture [17–23]. However, almost all of the experimental and theoretical studies in the past are confined only to crack specimens having high plastic constraint around the crack tip. Research studies conducted on the single edge notched bend (SENB) specimen [8–10,23], the four-point bend specimen [11] and the compact tension (CT) specimen [12] are to name a few. When the crack tip constraint is high, the stresses around the crack tip can be described by a single parameter like J [24,25]. Thus, the use of J alone is considered to be sufficient for the finite element simulation of warm prestressing [23] but only for high constraint specimens.

In the present research, the finite element method is used to simulate a warm prestressed center crack plate (CCP) specimen made of an alloy—steel. A residual stress-based model for warm pressing is used and the LUCF procedure is simulated for fixed values of J-integral in the preloading stage. It is intended to study whether a lateral load in the preloading stage affects the level of improvement in the apparent fracture toughness. The specimen is loaded biaxially with different ratios of lateral load to normal load. The effects of lateral load on the size of plastic zone, the residual stresses after unloading and the final fracture load after reloading are investigated.

2. Finite element simulation

The finite element code ABAQUS [26] was used for simulating the LUCF procedure. Fig. 1 shows the center crack plate specimen. The specimen is subjected to two perpendicular loads:

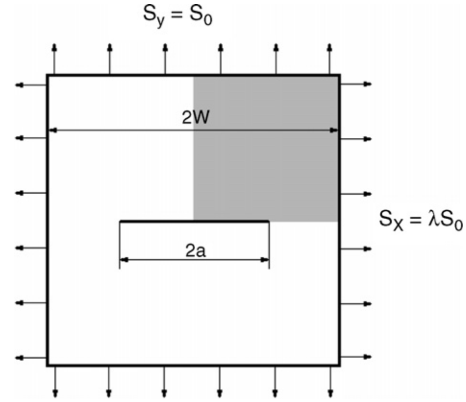

Fig. 1. The center crack plate (CCP) specimen.

one normal to the crack $S_y = S_0$ and one parallel to the crack $S_x = \lambda S_0$. The thickness t and the width $2W$ of specimen are 25 and 200 mm, respectively, and the crack length $2a$ is 100 mm. Eight-noded plane strain elements are used to simulate the specimen. Due to symmetry in geometry and loading conditions, only one quarter of the specimen is modeled (Fig. 2). The crack tip constraint is low when the lateral load S_x (or the lateral load factor λ) is negative [27]. By changing λ from negative to positive values a wide range of plastic constraint can be achieved.

The material was considered to be A533B alloy steel for which the stress–strain curves (see Fig. 3) and other material properties are available [23]. Similar to other materials commonly used for warm prestressing, this alloy steel displays a significant variation in yield stress with temperature. The material properties of A533B steel as described below have been taken from the results of an earlier experimental work by Fowler [23]. Fig. 3 shows the simplified stress–strain curves for A533B steel at 20 °C (room temperature) and −170 °C, for which the preloading and fracture stages in the LUCF procedure are simulated here. The average fracture toughness K_{Ic} for A533B steel at −170 °C is about 65.6 MPa $\sqrt{m}$ (or equivalently J_{Ic} = 18.91 MPa m). At both temperatures, the Young's modulus and Poisson's ratio remain almost the same and equivalent to 207 GPa and 0.3, respectively. The yield stress at 20 °C

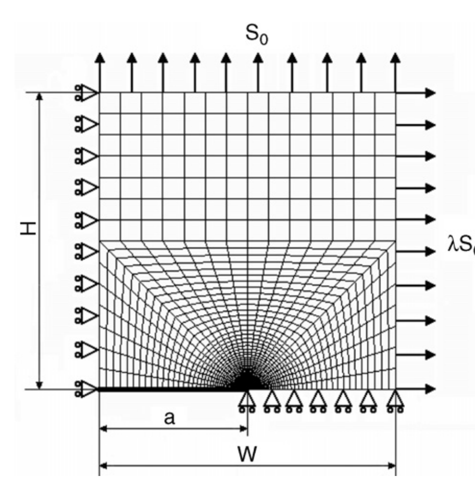

Fig. 2. Mesh pattern used for the finite element modeling.