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Effects of notch sharpness and depth on brittle fractures in single-edge notched bend specimens

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ABSTRACT

Fracture mechanics-based defect assessment procedures assume flaws are infinitely sharp cracks. However, this results in large safety factors for non-sharp flaws because of the loss of the plastic constraint. Fracture toughness tests were performed on four types of single-edge notched bend steel specimens with different degrees of plastic constraint, caused by fatigue cracks and machined notches with different notch root radii as well as by deep and shallow notches. This paper examines the differences in the stress states of the fatigue cracks and machined notches and the ability of the Weibull stress approach to predict the occurrence of brittle fractures under high and low plastic constraints in a unified manner.

1. Introduction

The effects of plastic constraints on the occurrence of brittle fractures are of key interest with respect to fracture mechanics and structural integrity and have therefore been investigated extensively. Several promising methods have been proposed for taking into account the loss of plastic constraints. One such method is the Weibull stress approach [1–3]. This approach has also been used to study the effects of ductile tearing [4,5]. A few researchers have proposed fracture assessment procedures that take into account the effects of plastic constraints while making use of the Weibull stress. There also exist two engineering approaches that employ the Weibull stress for the constraint-based assessment of fractures: the FITNET (European Fitness-For-Service procedure [6,7]) and ISO 27306 [8]. Comprehensive overviews of these approaches, which consider the effects of plastic constraints on brittle fractures, have been published by Cicero et al. [9] and Minami et al. [10]. The authors also considered specimens with low plastic constraints caused by specimen geometries, such as single-edge notched bend (SENB) specimens with shallow notches as well as centre-notched tension specimens. The Weibull stress approach and the toughness-scaling model were effective in predicting brittle fractures in these specimens [11].

At present, the SENB test is used as a fracture toughness test for evaluating the fracture toughness of materials [12]. It has been reported [13,14] that the currently used defect assessment procedures such as BS 7910 [15] and R6 [16], which are based on fracture mechanics, usually assume the flaws to be infinitely sharp cracks [12]. While this assumption may be appropriate for fatigue cracks, it can be an overconservative assumption and result in a large safety factor for non-sharp flaws such as porosities or weld undercuts, because of the loss of plastic constraints. In addition, it is necessary to conduct fatigue tests prior to the fracture toughness test to introduce a fatigue crack; this can be expensive and time consuming. If

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Nomenclature

Abbreviations

COD	crack opening displacement
D-f	deep-notched SENB specimen with fatigue crack
D-n015	deep-notched SENB specimen with machined-notch (ρ = 0.15 mm)
D-n050	deep-notched SENB specimen with machined-notch (ρ = 0.50 mm)
D-n10	deep-notched SENB specimen with machined-notch (ρ = 1.0 mm)
FEA	finite element analysis
SD	standard deviation
SENB	single-edge notched bend
S-f	shallow-notched SENB specimen with fatigue crack
S-n015	shallow-notched SENB specimen with machined-notch (ρ = 0.15 mm)
TSM	toughness scaling model

Symbols

a_0	crack or notch length
β	scale parameter of J_c
$_vE_0$	energy absorbed at 0 °C
$_vE_T$	energy absorbed at test temperature (−30 °C for Material A or −50 °C for Material B)
ε_u	uniform elongation
F	cumulative probability
i	rank number
J_c	critical fracture toughness in terms of the J integral, as per BS 7448-1
m	Weibull parameter
n	total number of the specimens for each type
ρ	notch root radius
σ_{eq}	von Mises equivalent stress
σ_h	hydrostatic pressure
$\sigma_{\max}$	maximum principal stress
σ_t	ultimate tensile strength
σ_u	scale parameter of Weibull stress
σ_W	Weibull stress
σ_{Wc}	critical Weibull stress
$\sigma_{W\text{-}U}$	unit volume Weibull stress
$\sigma_{W\text{-}Uc}$	critical unit volume Weibull stress

the fracture toughness is determined using machine-notched specimens, there is no need for a fatigue test. A method for determining the crack tip opening displacement fracture toughness of materials from the toughness values of machine-notched SENB specimens using the Weibull stress approach has already been reported [13,14]; however, only deep-notched specimens were considered in this approach. There have been studies that have attempted to determine the probability of occurrence of brittle fractures from notches using the Weibull stress approach [17–19]. However, few studies have considered the effects of the constraints caused by both the crack length and the notch sharpness in a unified manner. Therefore, to be able to predict the occurrence of brittle fractures initiated from notches, it is important to consider the effects of the low plastic constraint conditions attributable not only to the crack length but also to shape of the crack/notch. At the same time, the effects of constraints caused by both the crack length and the notch sharpness should be evaluated in a unified manner. Although we already performed SENB tests with different crack length (Deep or Shallow) and different notch sharpness (fatigue crack or machined notch) and considered the effect of these on brittle fracture [20], only one type of material was used to conduct the research. In addition to that, only one notch root radius (ρ = 0.15 mm), which is relatively small, was used for the notched specimens. It is therefore important to consider a different material and a different notch sharpness for predicting brittle fracture in a unified manner not depending on differences in the length, shape and sharpness of the crack/notch, including notches of root radius of large size, say, 1.0 mm.

In this study, it has been investigated whether the Weibull stress approach can be used to predict the occurrence of brittle fractures in a unified manner by evaluating comprehensively the low plastic constraint conditions caused by both non-sharp notches (i.e., machined notches) with different notch radii and shallow cracks. Fracture toughness tests were performed on six types of SENB specimens possessing deep notches and shallow notches with different materials; the specimens had both a fatigue crack and a machined notch. Brittle fractures were found to occur at different toughness levels, depending of the specimen type, as the different specimens exhibited different levels of plastic constraint at the crack tip. Finite element analysis (FEA) and the Weibull stress values were used to determine the corrected fracture toughness for each specimen type.