International Journal of Fatigue 58 (2014) 12–19

Contents lists available at SciVerse ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

# Fatigue crack growth rates and paths in two planar specimens under mixed mode loading

I. Varfolomeev [a,*], M. Burdack [a], S. Moroz [a], D. Siegele [a], K. Kadau [b]

[a] Fraunhofer Institute for Mechanics of Materials IWM, Wöhlerstraße 11, 79111 Freiburg, Germany
[b] Siemens Energy, Inc., 5101 Westinghouse Blvd., Charlotte, NC 28273, USA

ARTICLE INFO

*Article history:*
Received 20 December 2012
Received in revised form 16 April 2013
Accepted 21 April 2013
Available online 6 June 2013

*Keywords:*
Mixed mode crack growth
Crack path
XFEM
SE(B)
SE(T)

ABSTRACT

This paper focuses on the evaluation of methods for estimating fatigue crack growth (FCG) under mixed mode I/II loading. The experimental part of the study consists of a series of fatigue crack growth tests on bend and tension specimens with geometries similar to the standard SE(B) and SE(T) ones. For the above specimen types, both Mode I and mixed mode FCG tests are first performed. To facilitate an accurate evaluation of the test results, finite element analyses of stress intensity factors for crack geometries following the experimentally measured crack trajectories are carried out. Additionally, the XFEM based algorithm available in the finite element code ABAQUS is explored with respect to its performance in estimating crack growth paths.

The subsequent test evaluation focuses on examining a correlation between FCG rates for mixed mode loading conditions with the Mode I baseline curve. The results suggest that, using Mode I experimental data, both conservative and non-conservative estimation of mixed mode fatigue crack growth is possible. In this context, recommendations of failure assessment procedures regarding the flaw re-characterisation and projection onto principal stress planes, as well as rules for the transferability of Mode I FCG curves to mixed mode conditions, are discussed.



## 1. Introduction

Cracks initiated in structural components subjected to multiaxial stress state, in welds, or flaws originated at manufacturing defects in forged or cast members, which are originally randomly oriented, can reveal some amount of mixed mode growth prior to become aligned with one of the principal stress planes. The assessment of such defects, including fatigue crack propagation stage, may follow rules established in fracture mechanics guidelines, e.g. [1–4]. The latter provide recommendations with respect to the alignment of mixed mode defects by their rotation or projection onto principal stress planes, the definition of an effective crack size [4] or an equivalent crack driving force [3,5], whereas subsequent calculation procedures essentially rely on material data derived from Mode I crack tests.

Comprehensive surveys of theoretical approaches, experimental techniques and examples of fatigue crack growth (FCG) evaluation under mixed mode conditions can be found elsewhere, e.g. [5–7]. In particular, numerous investigations have been devoted to establish criteria and solutions for determining the crack propagation angle in mixed mode, as well as to develop numerical techniques for simulating crack growth in complex structural components and stress fields [8–10]. Inherently or by definition, most of the calculation models for mixed mode cracks incorporate Mode I FCG curves along with an equivalent stress intensity factor as the crack driving force parameter. Validation of such a procedure requires experimental data for both Mode I and mixed mode loading conditions, whereas the respective tests are rather scarce, see e.g. [11,12].

In this paper, FCG tests are performed on bend and tension specimens subjected to Mode I and mixed mode I/II loading conditions. Based on the experimental results and finite element analyses of stress intensity factors for the respective specimen and crack geometries, FCG rates for mixed mode loading are compared to the Mode I baseline $da/dN - \Delta K_I$. The results show that, using Mode I experimental data along with a Mode I specimen analysis, both conservative and non-conservative estimates of mixed mode FCG rates are possible. To explore the performance of alternative analysis methods, the XFEM [10] algorithm implemented in ABAQUS [13] is applied for calculating crack growth paths.

## 2. Test description and experimental crack paths

The material considered in this study is high-performance rotor steel. The geometries of the test specimens are shown in Fig. 1. All

* Corresponding author. Tel.: +49 761 5142 210.
*E-mail address:* igor.varfolomeev@iwm.fraunhofer.de (I. Varfolomeev).

0142-1123/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijfatigue.2013.04.013

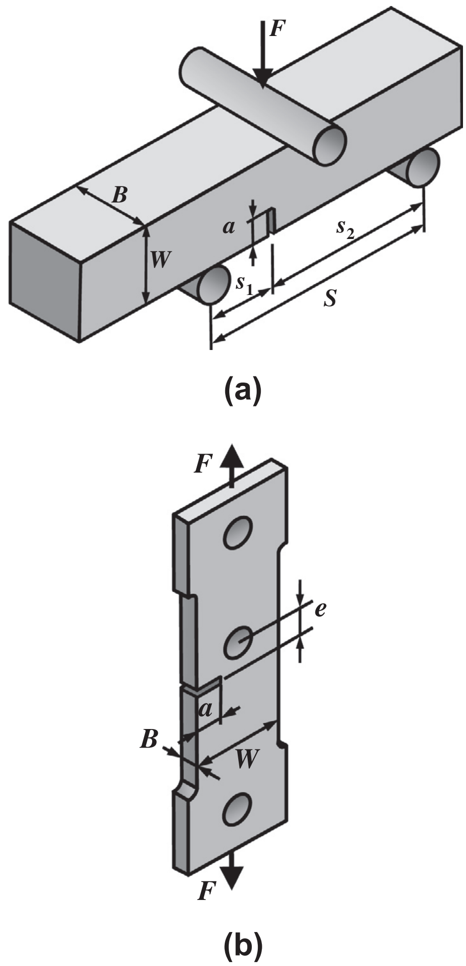


**Fig. 1.** Schematic of specimen geometries adopted in this study: (a) SE(B); (b) SE(T).

specimens are 240 mm long, with a test cross-section of $W \times B = 40 \times 20\ \text{mm}^2$ for SE(B) and $W \times B = 40 \times 10\ \text{mm}^2$ for SE(T) geometries. Altogether eight SE(B) and four SE(T) specimens were tested.

When preparing the specimens, an initial edge notch of 4 mm depth was first introduced by spark erosion. In all but four SE(B) specimens, the initial notch is located at the specimen centre, i.e. a distance of 120 mm from the specimen ends. In the remaining four SE(B) specimens, the initial notch is located 40 mm from the specimen centre. Fatigue pre-cracking up to the crack depth of about 6 mm was accomplished in all cases under pure Mode I cyclic loading.

To avoid load interaction effects and their influence on fatigue crack closure, all subsequent tests of SE(B) specimens were carried out at constant amplitude loading. With increasing FCG rates, the final phase of testing for some specimens and the whole testing for SEB2 were performed in a servo-hydraulic machine at a frequency of 5 Hz. In contrast, all SE(T) specimens were tested in a resonant testing machine at a frequency of about 110 Hz, at gradually decreasing load amplitude to attain moderate crack growth rates. Both fatigue pre-cracking and crack growth tests were performed at the load ratio of $R = 0.1$ and room temperature.

Both SE(B) and SE(T) specimens shown in Fig. 1 allow for testing at Mode I and mixed mode loading conditions. Three bend specimens referred to as SEB1, SEB2 and SEB3 were tested under pure Mode I loading with symmetrically positioned supporting rollers ($s_1 = s_2 = 80$ mm). Further three specimens denoted as SEB5, SEB6 and SEB7 were subjected to mixed mode loading by asymmetrically placing the lower rollers with the span values equal to $S = s_1 + s_2 = 160$ mm and $s_2/s_1 = 3$. Two additional specimens, SEB4 and SEB8, were tested following a two-stage procedure:

- At first, the specimen with a Mode I pre-crack of depth $a = 6$ mm was subjected to asymmetric loading at a span ratio of $s_2/s_1 = 3$. This resulted in a crack propagation direction inclined by on average 18° with respect to the initial pre-crack plane.
- In the second test stage corresponding to crack growth from about 12.5 to 27 mm, symmetrical loading with $s_1 = s_2 = 40$ mm was applied, thus forcing crack propagation towards the pre-crack plane.

Mixed mode loading for the SE(T) specimens was achieved by machining a hole of 10 mm diameter in the central part of the specimens after pre-cracking, similar to the approach described in Ref. [12]. The hole was centred with respect to the specimen width but shifted with respect to the original crack plane. The eccentricity parameter $e$, i.e. the distance from the hole centre to the pre-crack plane (Fig. 1), was equal to $e = 10$ mm for the specimens SET1 and SET2, and $e = 8$ mm for the specimen SET3, respectively. One further specimen without hole drilling, denoted as SET4, was tested under pure Mode I conditions. Geometrical parameters and loading conditions for the bend and tension specimens considered in this study are summarized in Tables 1 and 2, respectively. Note that, throughout the paper, the crack size $a$ represents the projection of the crack path on the initial pre-crack plane.

Fig. 2 shows crack growth trajectories in two bend specimens SEB5 and SEB4. Note different crack propagation behaviour for the former specimen tested at a fixed position of the supporting rollers, as compared to the SEB4 specimen for which a two-stage loading procedure was adopted. For the latter specimen, the initial phase of crack growth from about 6 to 12.5 mm depth is governed

**Table 1**
Geometrical parameters and test conditions for SE(B) specimens.

| Loading mode | Specimen, test phase | $a_{min} \ldots a_{max}$ (mm) | Frequency (Hz) | Span parameters (mm) | | | Upperload (kN) | Nominal tensile stress (MPa) |
|---|---|---|---|---|---|---|---|---|
| | | | | $S$ | $s_1$ | $s_2$ | | |
| I | SEB1 | 6…24 | 110 | 160 | 80 | 80 | 12 | 90 |
| | SEB2 | 6…24 | 5 | | | | 36 | 270 |
| | SEB3 | 6…10/10…27.5 | 110/5 | | | | 24 | 180 |
| I + II | SEB5 | 6…18.7/18.7…30.5 | 110/5 | 160 | 40 | 120 | 24 | 90 |
| | SEB6 | 6…12.1/12.1…26.5 | 110/5 | | | | 36 | 135 |
| | SEB7 | 6…26.2 | 5 | | | | 48 | 180 |
| I + II (2 stages) | SEB4/1 | 6…12.6 | 110 | 120 | 30 | 90 | 32 | 90 |
| | SEB4/2 | 12.6…23.5 | 110 | 80 | 40 | 40 | 36 | 135 |
| | SEB8/1 | 6…12.5 | 110 | 160 | 40 | 120 | 24 | 90 |
| | SEB8/2 | 12.5…26 | 110 | 80 | 40 | 40 | 24 | 90 |