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Study of alternatives and experimental validation for predictions of hole-edge fatigue crack growth in 42CrMo4 steel

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ABSTRACT

The objective of this work is to establish pertinent criteria allowing an optimal alternative to be chosen for calculating the inputs needed to make Run/Repair/Replace decisions and to program inspection plans for cracked wind turbine bearing rings. With this aim, the growth of a hole-edge through-crack was predicted analytically, simulated and measured in a 42CrMo4 steel plate subjected to mode-I cyclic loading. Different alternative procedures according to BS 7910:2013 fitness-for-service code were implemented. Unexpectedly, the numerical calculation of the local stresses in the uncracked body did not improve the estimations of the critical crack length and the number of cycles to failure performed following purely analytical alternatives. That alternative underestimated the critical crack length by 50%. Among the alternatives studied, the one based on numerically calibrated stress intensity factors and crack growth coefficients characterized at the corresponding stress ratios proved to be the most suitable one. Following that alternative, the fatigue life was found to be overestimated by 3.96% in the best scenario whereas the critical crack length was underestimated with an error less than 3%, determined using the Failure Assessment Diagram (FAD) as a failure criterion.

1. Introduction and motivation

Fatigue crack growth represents one of the predominant failure mechanisms in bearings used for pitch rotation of wind turbine blades (see Fig. 1a). In particular, the in-service cracking of the outer ring is a major issue, as it has been reported by many bearing manufacturers from the wind energy industry [1]. This ring displays holes at a regular distance for bolt tightening, grease fittings and other handling and maintenance operations, which act as stress concentrators giving rise to local concentrations of the nominal stresses. At a given point along the lifetime of the bearing, a crack may initiate at the edge of a hole where stresses reach maximum values. Firstly, the crack propagates as a surface crack, afterwards evolving to a through-crack that leads eventually to a catastrophic failure of the ring, as shown in Fig. 1b [1].

Such components are usually made of 42CrMo4 steel, which exhibits excellent hardenability properties allowing high hardness to be achieved on the raceway [3]. Regarding loading conditions, the critical location where the crack initiates is subjected to multiaxial variable amplitude stresses, generated by the tightening preload of the bolts and the wind and inertial loads transmitted from the blades through the rolling elements. Nevertheless, the variable component of the total stress tensor causing fatigue cracking is predominantly uniaxial in the hoop direction, what explains the mode-I growth observed in Fig. 1b [1].

In order to make Run/Repair/Replace decisions and to program inspection plans for cracked bearing rings, the following parameters must be considered: (1) critical crack length and (2) number of cycles to failure. These parameters can be calculated by a crack propagation analysis performed according to fitness-for-service procedures as those proposed in BS 7910:2013 [4–6]. In any case, lifetime predictions are performed by integrating crack growth law, taking the Stress Intensity Factor (SIF) range as an input, until the sudden failure is detected by evaluating the Failure Assessment Diagram (FAD) [7]. However, the BS 7910:2013 standard allows different alternatives for lifetime prediction to be applied, which differ in terms of prediction accuracy and invested assessment time. The computation of SIF ranges and FAD evaluation may be done analytically resorting to closed form formulas of different standardized geometries [7] or numerically, using Finite Element

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Nomenclature

Latin characters

a	crack length (mm)
da/dN	crack growth rate (mm/cycle)
E	Youngs modulus (GPa)
e	thickness of the component (mm)
f	crack opening function (–)
H	width of the component (mm)
K	stress intensity factor (MPa mm$^{1/2}$)
L	load (N)
M	geometric factor (–)
N	number of cycles (–)
P	applied axial force (N)
R	stress ratio (–)

Greek characters

ε	strain (–)
σ	strength, normal stress (MPa)

Subscripts and superscripts

$()_b$	bending
$()_c$	critical
$()_m$	membrane
$()^{loc}$	local
$()_{max}$	maximum
$()_r$	ratio
$()^{rem}$	remote
$()_{th}$	threshold
$()_u$	ultimate
$()_y$	yield

Abbreviations

CT	Compact Tension
FAD	Failure Assessment Diagram
FEA	Finite Element Analysis
SIF	Stress Intensity Factor

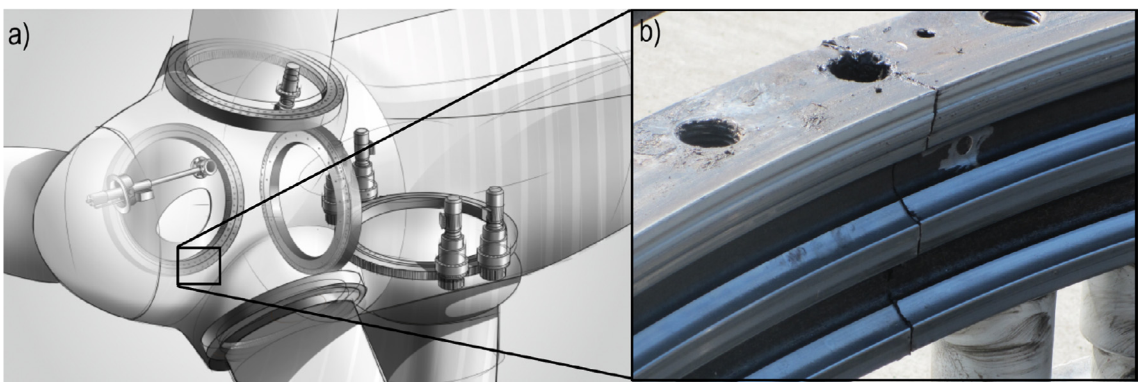

Fig. 1. (a) Schematic representation of a wind turbine and some internal components [2]. (b) A real blade bearing ring broken during operation (courtesy of RBB Engineering ©[1]).

Analysis (FEA) [8–10]. For computing the crack growth rate, a number of crack growth laws are available [11] either using crack growth coefficients taken from literature or characterized ad hoc.

Fatigue crack growth has drawn the attention of many researchers in the last decades [12–16] and has become a mature field of study. More specifically, extensive research has been conducted regarding crack growth near holes or circular notches [17–22]. However, a remarkable lack of comparative studies is noticed that quantify and justify discrepancies between the different predictions resulting for real cases based on aforementioned alternative procedures.

The objective of this work is to establish pertinent criteria allowing an optimal alternative to be chosen for calculating the inputs needed to make Run/Repair/Replace decisions and to program inspection plans for cracked wind turbine bearing rings. With this aim, the crack growth in the larger ligament of a drilled plate made of 42CrMo4 steel, subjected to mode-I cyclic loading (Fig. 2) is studied. Crack propagation is predicted according to the alternatives mentioned above and is also simulated jointly using the FRANC3D and ANSYS codes. An experimental campaign is conducted, in which real components are tested under three different load ranges and stress ratios. Finally, the experimental lifetime data are compared with the simulated and analytically derived results, providing useful guidance for practical design of wind turbine bearing rings.

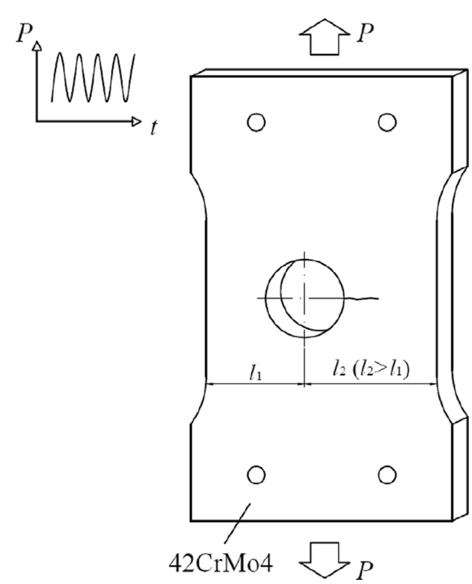

Fig. 2. Structural detail studied in this work.