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Extended FEM analysis of fatigue crack growth in Ti-6Al-4V orthopaedic plates

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Abstract

The extended finite element method (xFEM) was used to analyse fatigue crack growth in orthopaedic locking compression plates (LCP), made of Titanium alloy, Ti-6Al-4V, loaded in four-point bending. The optimal geometry was defined previously in respect to the remaining life of LCP used for patients with different body weights (BW - 60, 90 and 120 Kg). The plate with optimal geometry is analysed in more details here to assess the effect of BW and get better insight into fatigue crack growth path.

Keywords: Fatigue Crack Growth; Locking Compression Plates; Extended Finite Element Method; Ti-6Al-4V

1. Introduction

Failure due to fatigue crack growth is well known phenomenon, typically associated with initial cracks at the stress concentration regions like thickness change and reduced cross-section. Some of typical failures are shown in Fig. 1.

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Figure 1. Typical failures of LCP caused by fatigue, [1],

Having in mind the seriousness of in-service failure of orthopaedic plates, it is necessary to analyse their structural integrity and life from all possible aspects, [2]. Numerical simulations are widely used for simulating different behaviour of various implants under static or dynamic loading, such as hips and dental implants, [3-8], typically by using the Finite Element Method (FEM) and its extended version for fatigue crack growth, xFEM, [9-16]. Experimental investigations directly on implants are typically performed by using optical strain measurement systems to assess stress-strain state under static loading, [17-19].

This analysis uses xFEM to simulate fatigue crack growth under four-point bending in LCPs with different designs, having cracks initiated in the stress concentration area. Material parameters for Ti-6Al-4V are expe–rimentally determined to enable numerical evaluation of remaining life of orthopaedic plates after crack initiation.

2. EXPERIMENTAL INVESTIGATION

Tensile testing was conducted according to EN ISO 6891-1 [20], with the ± 100kN force range and in displacement control, under loading rate of 5 mm/minute. Test results are presented in Table 1, indicting low elongation, i.e. low plasticity.

Table 1. Tensile testing results

Specimen No.	Yield strength, $R_{p0,2}$ (MPa)	Ultimate strength R_m (MPa)	Elongation A (%)
1	1035	1089	7.7
2	1015	1062	6.0
3	1022	1071	6.6

Testing of crack growth rate (da/dN) was preformed on standard Charpy specimens, using three-point bending on resonant high frequency pulsator, according to ASTM E647 [21], in load control, with load ratio R=0.1, in 215 – 235 Hz frequency range. Average load and amplitudes were measured with ±0.03 Nm accuracy. Measurement system was based on indirect potential drop method, continuously indicating the measurement values

Results for all 3 tested specimens are given in Fig. 2, as dependence of fatigue crack growth rate, da/dN, vs. stress intensity factor amplitude, ΔK, and in Table 2, as coefficients for Paris law. Experimental results are presented in more details in [2].

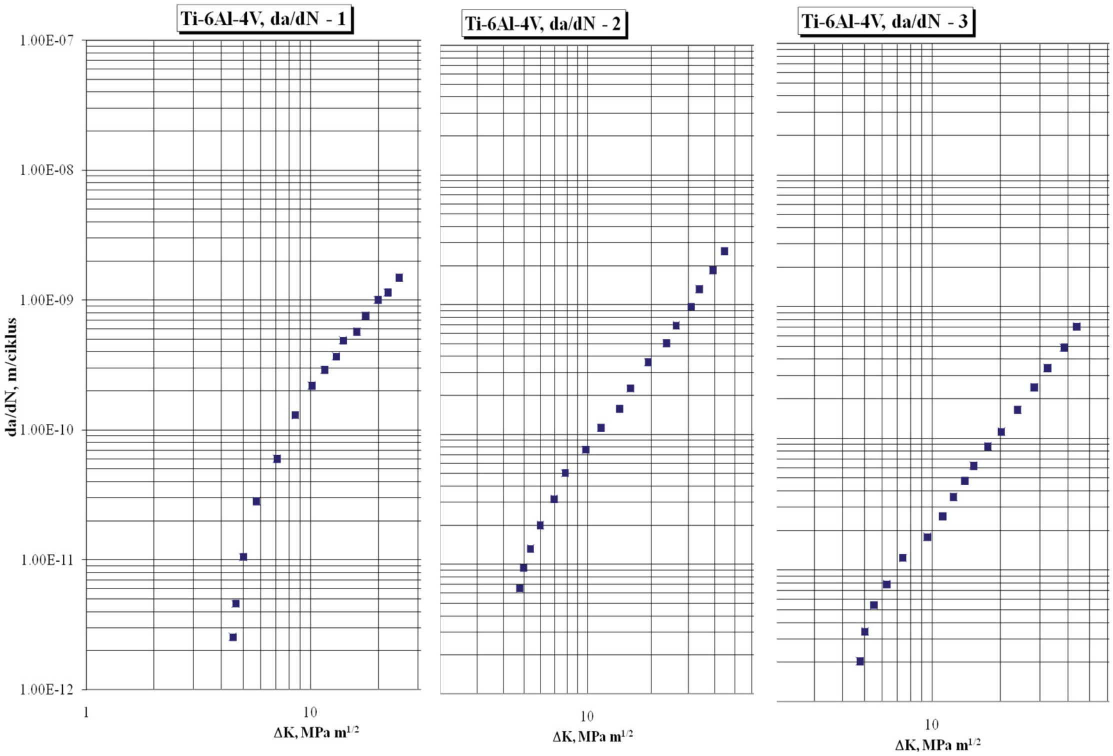

Figure 2. Fatigue crack growth rate vs. ΔK for all 3 specimens

Table 2. Fatigue crack growth parameters for data from Fig. 2

Specimen No.	Stress intensity factor threshold, ΔK_{th}, MPa√m	Coefficient C	Exponent m
1	4,5	$1.54 \cdot 10^{-12}$	2.15
2	4,8	$3.70 \cdot 10^{-13}$	2.31
3	4,7	$1.05 \cdot 10^{-13}$	2.32

3. NUMERICAL SIMULATION

Extended finite element method (xFEM) was used to simulate fatigue crack growth in orthopaedic LCPs. This simulation included 5 different plate geometries, as explained in more details in [TG], while here only the optimal one (“longest living”) is presented, Fig. 3.

Tetrahedral finite elements mesh with 108990 nodes, and 71599 elements of size 0.91 mm, was generated and used for calculation in ANSYS. Cracks were introduced as edge, quarter-circular, 2 mm in radius, located as shown in Fig. 3c.

Three different body weights have been considered for simulation of four-point bend testing, applying the maximal bending moments in upper tibia region, as calculated according to [22], and shown in Table 3. Total of 60 steps were set in ANSYS. The worst-case tensile properties and crack growth parameters were used (specimens No. 2 from Table 1 and 2, respectively).

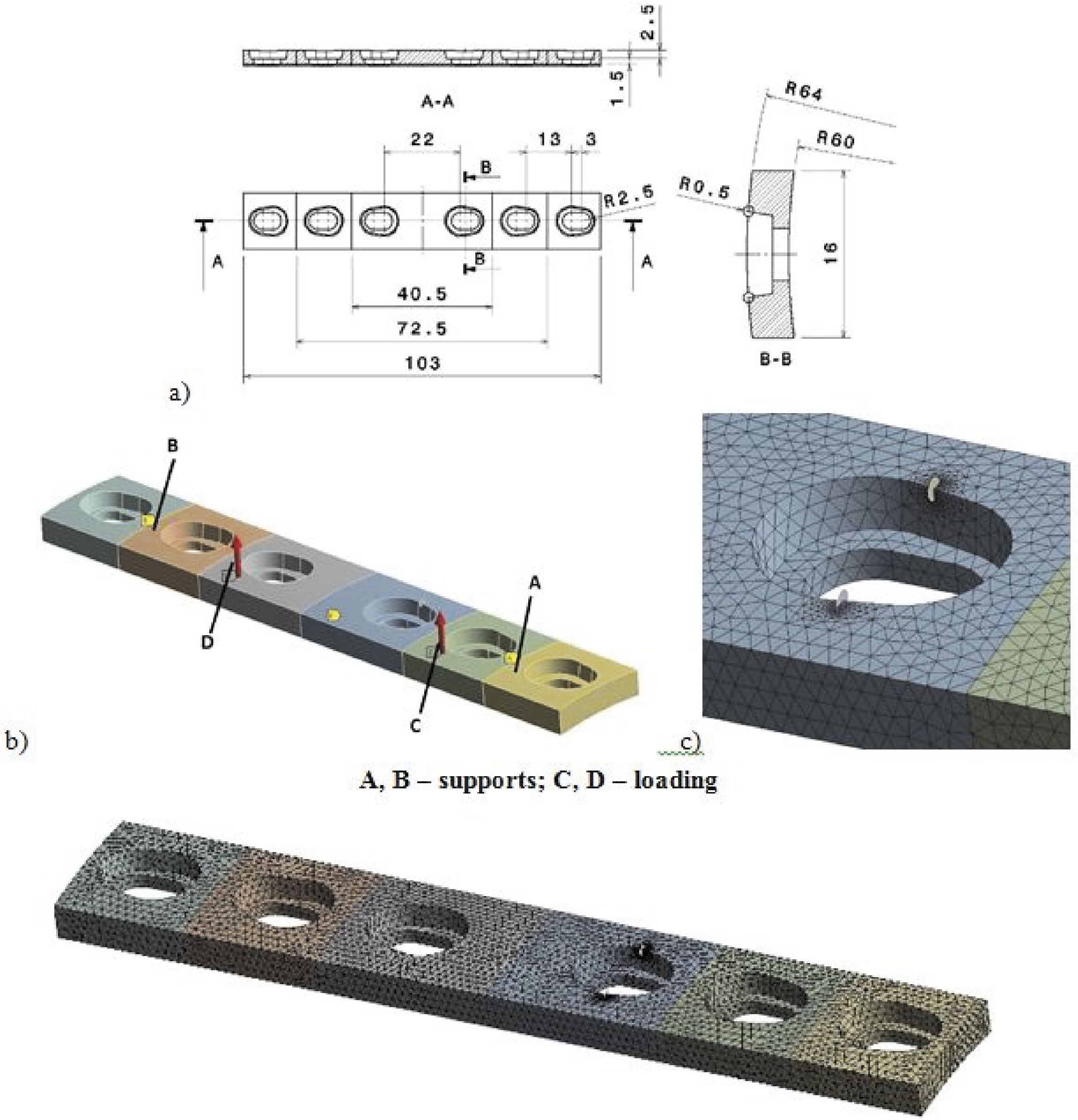

Figure 3. Plate: a) geometry, b) boundary conditions, c) mesh around the cracks, d) FE mesh

Table 3. Loading forces

Plate type	60 kg BW, kN	90 kg BW, kN	120 kg BW, kN
D	2.6	3.9	5.2

The optimal geometry from remaining life point of view, was plate D. Its results are presented in Fig. 4 (crack length, a, vs. number of cycles, N) for all 3 BWs, and in Table 4, indicating significant reduction in remaining life with body weight increase.

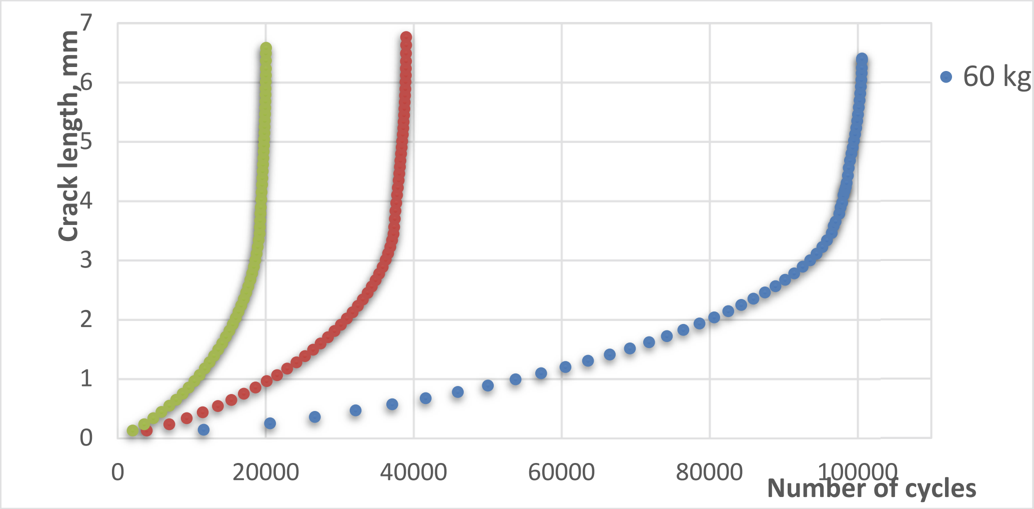

Figure 4. Crack length a vs number of cycles N for all 3 BWs

Table 4. xFEM results for three different BWs

BW, Kg	Number of cycles	Stress intensity factor / MPa mm$^{1/2}$	Maximal crack length mm	Number of walking days
60	100670	1748	6.39	200
90	39016	2672	6.76	78
120	20068	3563	6.58	40

Crack propagation path is more than 2 mm longer than the plate's thickness in all cases, since the crack stops propagating through thickness at one point and continues along plate surface only. When the surface propagation finishes, crack starts going through the thickness again, as shown in Fig. 5. This information can be taken in consideration when designing the plates in order to prolong the remaining life after crack initiation. It is obvious that more complex path crack has, the longer remaining life of a component will be.

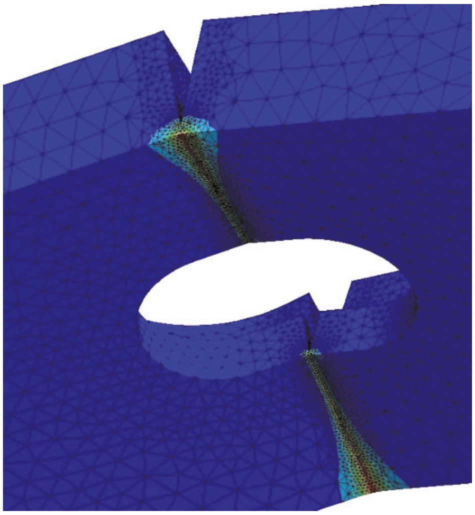

Figure 5. Crack propagation through LCP

4. CONCLUSIONS

Based on the results of remaining life assessment of LCPs, following conclusions can be drawn:

- Design of LCPs affects significantly their remaining life. The longest crack path in the most complex geometry is the best option from the remaining life point of view.
- Loading due to increased BW significantly reduces remaining life (cca 80% for 120 kg BW and cca 60% for 90 kg, compared to 60 kg BW case).
- Numerical simulation can contribute significantly to increasing structural integrity and life of LCPs, since it can provide reliable results for complex geometries in fast and efficient way.

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