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SENSITIVITY ANALYSIS OF THE NASGRO EQUATION BASED ON THE PZL-130 TC-II ORLIK TRAINER AIRCRAFT FULL SCALE FATIGUE TEST

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Abstract
The study investigates the sensitivity of numerical crack propagation estimations based on the Nasgro equation. The equation is widely used for crack propagation calculations since it considers the whole range of crack propagation speed from threshold to critical values of stress intensity factor range (ΔK). The presented investigation is based on the actual results of the full scale fatigue test (FSFT) of the PZL-130 'Orlik' TC-II aircraft. We provide a brief description of the test and the general approach followed in crack propagation estimations originally carried out after the test. The obtained results are verified in terms of variation of the input data. Overall results are compared and discussed.
Keywords: sensitivity analysis, crack propagation, full scale fatigue test
Article category: research article

Introduction

Fatigue cracks are one of the most common factors (beside corrosion) influencing structural integrity of aging aircraft over the course of operation (Daverschot et al., 2020; B. G. Nesterenko, Nesterenko, Konovalov, & Senik, 2020; Balicki, Głowacki, & Uchanin, 2021; Loroch, 2022). Variable loads that are exerted on the aircraft structure during flight result in variable stresses in the load paths, which therefore cause initiation and propagation of fatigue cracks. This is a very complex phenomenon driven by many factors, like the mentioned loads, material properties, geometry of the structure, and many more (Anderson, 2017). Numerical approaches toward defining the propagation of a fatigue crack are based on the stress intensity factor (SIF), which is defined as the potential of crack development due to the exerted loads and general properties of the structure.

Within this work, we focus on the Nasgro equation commonly used in numerical fatigue crack propagation estimations, which, in comparison to the analytical power laws derived from the Paris–Erdogan equation, defines the crack propagation speed as da/dN vs. the SIF range (ΔK) over the whole domain, from the threshold value of ΔK_{th}, where the crack propagation is infinitely slow, up to the critical propagation region defined by the K_c value (Anderson, 2017). The present investigation is based on the results of a full scale fatigue test (FSFT) of the PZL-130 'Orlik' TC-II trainer aircraft.

FSFT Description

The goal of the FSFT of the PZL-130 'Orlik' TC-II trainer aircraft was to determine the overall durability of the structure by achieving 12,000 simulated flight hours (SFH) with a safety factor of order 3. The secondary goal was to identify critical points (CP) in the structure, where cracks may occur and develop during operation, leading to catastrophic damage (Leski, Kurdelski, Reymer, Dragan, & Sałaciński, 2015). The test was executed in the Výzkumný a Zkušební Letecký Ústav (VZLU) in Czech Republic, Prague. During the test, a specially prepared specimen (a taken out of service aircraft) was instrumented with an array of strain gauges and placed in the test stand. The loads were exerted on the structure by means of 14 hydraulic actuators. The load spectrum was carefully designed based on the operational load monitoring (OLM) program, during which a second PZL-130 'Orlik' TC-II aircraft instrumented with an identical array of strain gauges performed a series of test flights in order to measure the actual loads. The configuration of the test specimen in the test stand as well as example strain gauges installed on the specimens' structure are presented in Figure 1.

Figure 1. Test specimen mounted in the test rig and the right front wing spar with installed strain gages.

The load spectrum during the test was a cycle-by-cycle spectrum (Leski, Reymer, & Kurdelski, 2011), which means that it was composed of individual load cycles arranged in the same order in which they occurred during flight, which contrasts with a blocked spectrum, where similar cycles are arranged in blocks and the time history is lost (this latter approach is used for durability tests, where linear damage cumulation phenomena are assumed). This was an important factor in terms of proper crack propagation during the test.

The load spectra for a single actuator used in the test are shown in Figure 2.

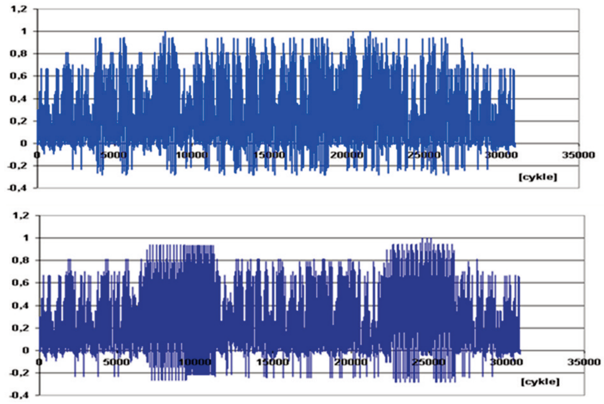

Figure 2. Depiction of the PZL-130 load spectrum used during the test.

CP Definition

The CP discussed within this article was defined as the lower flange of the rear spar in the left part of the wing near rib No. 2. The cracks were found in this location during the non destructive inspection (NDI) late in development (21,000 SFH) (Leski et al., 2015), and therefore the actual initiation location and direction of each crack had to be estimated. The general location of this CP as well as a close-up picture of the actual structure are shown in Figure 3.

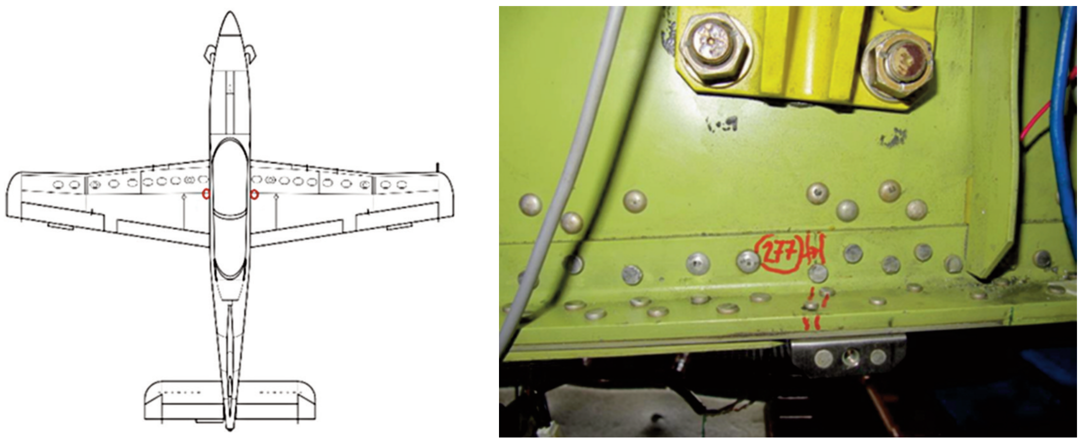

Figure 3. Location of the CP2 – lower flange of the rear spar near rib No. 2. CP2, critical point No. 2.

The crack initiated from one of the riveted holes (Figure 3) connecting the lower flange with the lower skin of the wing. However, the actual cracking scenario had to be defined based on the finite element method (FEM) model. Therefore, the FEM model was loaded according to the load conditions during the test (Figure 4) and the maximum hoop stresses around the holes were defined. The most stressed locations were selected as the crack initiation sites (Figure 5). The resulting crack propagation scenario in this CP is shown in Figure 6. The critical damage of CP was a result of a multisite fatigue damage (MFD), where several cracks occur in one section, leading to critical damage. In this paper, we will focus on section C of the cracked element, shown in Figure 6.

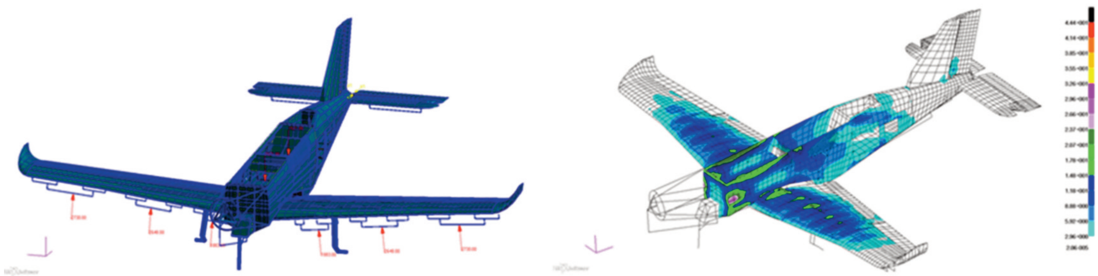

Figure 4. Global-local model approach.

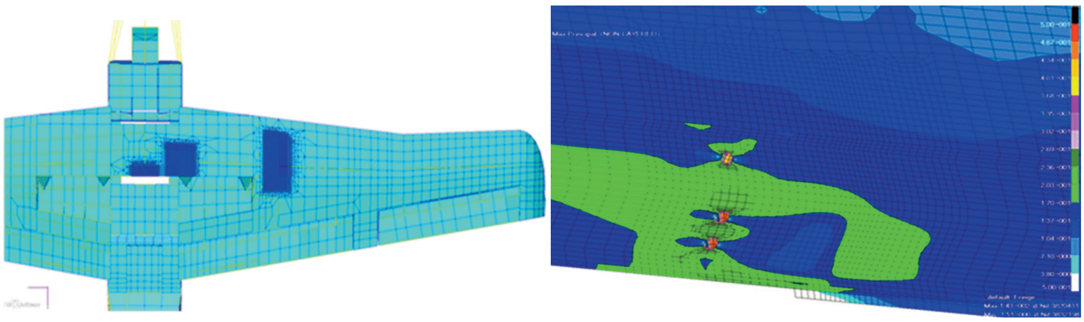

Figure 5. Global strain fields and local stresses indicating crack initiation locations.

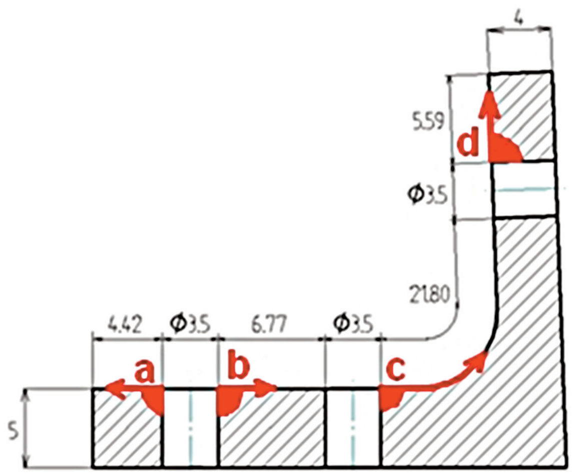

Figure 6. Cross section of the damaged structure with the initiation and assumed crack propagation.

Crack Propagation Calculations

Since the crack in the CP was found late in development, numerical calculations were used in order to determine the crack propagation process. The global model shown in Figure 5 allowed for definition of displacement fields, which were then used for loading the local model of the CP shown in Figure 5 (Reymer, Leski, & Dziendzikowski, 2022)

Using the virtual crack closure technique (VCCT), the values of energy release rate were defined along the crack path (Atluri & Nishioka, 1986; Leski, 2003, 2007; Wilk, 2016), allowing for SIF calculation and therefore the dimensionless geometry factor β (Figure 7).

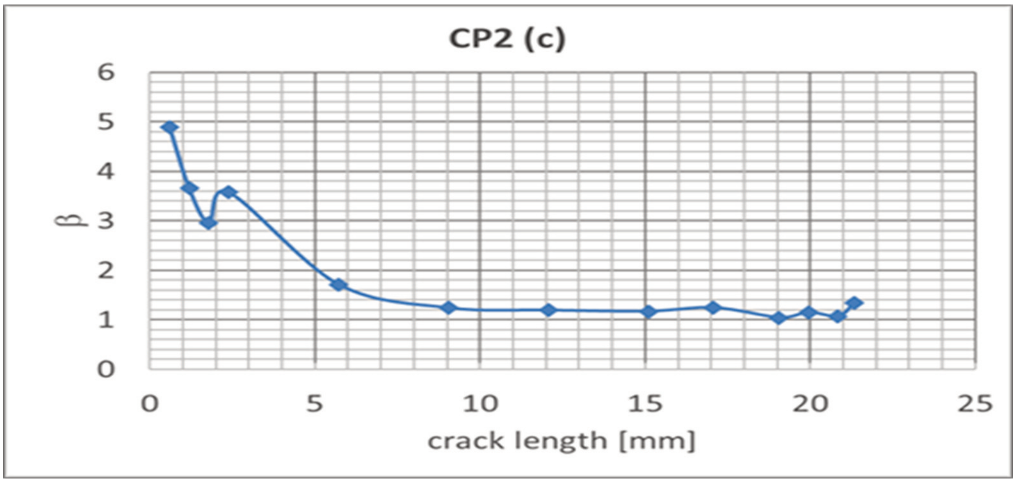

Figure 7. Estimated β factor along crack length.

Sensitivity Analysis

The sensitivity analysis calculations were performed using the AFGROW software (LexTech, Centerville, Ohio USA) which allows for crack propagation estimations based on the input data provided. The initial data used in calculations are shown in Table 1.

The geometric properties (the width *W*, and thickness *T*) were given by the aircraft manufacturer based on the 3D model. The stress multiplication factor (SMF) corresponds to the maximum stress level in the load spectrum. The load spectrum presented previously in Figure 2 was normalized (as a result of which the maximum value in the whole spectrum was 1); therefore, by multiplying the whole load sequence by SMF, a resultant value is obtained that corresponds with the maximum stress level in the whole spectrum.

The material properties were reckoned as E, v, and *yield stress* (YLD), and were determined during laboratory tests (Lisiecki & Bochenek, 2013; Lisiecki, Bochenek, & Nowakowski, 2013). The Nasgro equation coefficients C, n, p, q, C_{th}, and Alpha were taken from the AFGROW material database for the 2024 T351 aluminum alloy (Harter, 2008).

Table 1. Initial data used in the analysis

initial data		
[m]	W	0.0218
[m]	T	0.005
[-]	SMF	0.072
[MPa]	E	72000
[-]	ν	0.33
[MPa]	YLD	319
[MPam-2]	KIC	36.75
[MPam-2]	KC	74.722
[-]	C	1.71E-10
[-]	n	3.353
[-]	p	0.5
[-]	q	1
[-]	Cth	1.5
[-]	Alpha	1.5
[h]	**SFH**	**7454.96**

SFH, simulated flight hours.

The model used in AFGROW software was a simple flat bar with a side through crack. Using the β values obtained from FEM calculation using VCCT method allowed us to consider the actual SIF distribution along the crack length, which is attributable to the complex element geometry as well as the connected structural elements, even in such a simple model. For the initial input data, the crack propagated from the initial crack length of 0.6 mm to the critical length (for which a rapture crack occurs due to exceedance of K_c in the net section) in just under 7,455 SFH.

Similar calculations were carried out for the set of input data shown in Figure 1 with one of the parameters changed by 5% in the −10% to +10% range. This allowed us to show the influence of the changed parameter on the final result in the vicinity of the original results. For most of the parameters it was enough to change the single value. In the case of β, which is a crack length dependent parameter, the value was changed throughout the whole crack length domain.

Table 2 shows exemplary results for the variation of β factor.

Table 2. Exemplary results obtained for β value variations

input data			**β-10%**	**β-5%**	**β**	**β+5%**	**β+10%**
[m]	W	0.0218	0.0218	0.0218	0.0218	0.0218	0.0218
[m]	T	0.005	0.005	0.005	0.005	0.005	0.005
[-]	SMF	0.072	0.072	0.072	0.072	0.072	0.072
[MPa]	E	72000	72000	72000	72000	72000	72000
[-]	n	0.33	0.33	0.33	0.33	0.33	0.33
[MPa]	YLD	319	319	319	319	319	319
[MPam-2]	KIC	36.75	36.75	36.75	36.75	36.75	36.75
[MPam-2]	KC	74.722	74.722	74.722	74.722	74.722	74.722
[-]	C	1.71E-10	1.7073E-10	1.7073E-10	1.71E-10	1.7073E-10	1.7073E-10
[-]	n	3.353	3.353	3.353	3.353	3.353	3.353
[-]	p	0.5	0.5	0.5	0.5	0.5	0.5
[-]	q	1	1	1	1	1	1
[-]	Cth	1.5	1.5	1.5	1.5	1.5	1.5
[-]	Alpha	1.5	1.5	1.5	1.5	1.5	1.5
[h]	**SFH**	**7454.96**	**11040.33**	**9026.14**	**7454.96**	**6240.39**	**5251.65**
		7454.96	48.09%	21.08%	0.00%	-16.29%	-29.55%

As can be seen, the β factor, since it is a linear coefficient of the SIF, does significantly influence the overall result. A change of 5% corresponds with a 20% change in estimated crack length (16% in case of increase) and an even greater change by 10% results in a nearly 50% increase in estimated crack life (30% in the case of increase). As shown in Figure 7, the values of β in a relatively complex geometry are relatively versatile, and therefore a 10% difference in values obtained from numerical estimations is not that uncommon.

The same procedure was carried out for rest of the parameters shown in Table 1, and the ones showing significant influence in the total estimated crack length are shown in Figure 8.

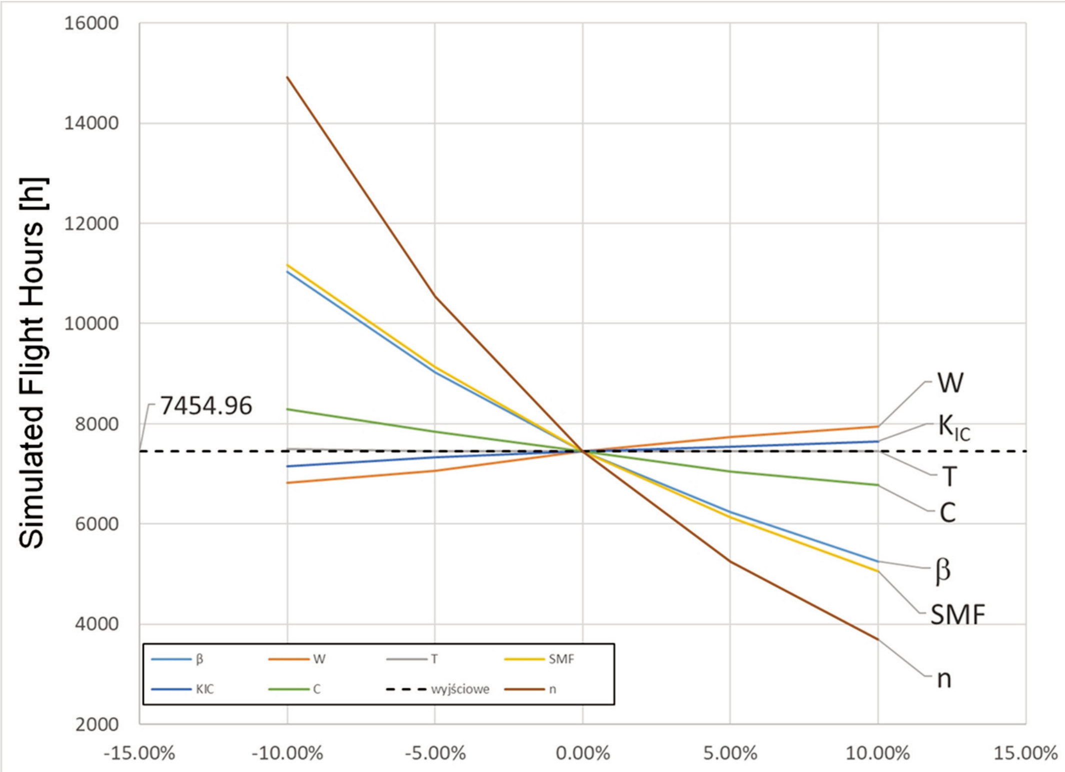

Figure 8. Final results depicting sensitivity of the estimation on input data change. SFH, simulated flight hours; SMF, stress multiplication factor.

The greatest change was observed for the material constant n, which is the power of the main element of the Nasgro equation. The second one was the SMF, which directly corresponds with the maximum values of stress in load cycles. While the geometry parameters and KIC showed some influence, it was not very significant in comparison with that shown by other parameters.

Summary

The presented analysis allowed us to examine the influence of individual parameters on the overall results of crack propagation estimation using the Nasgro equation. The analysis was based on actual crack propagation calculations carried out after a FSFT of a trainer military aircraft. Initial data were obtained from numerical calculations, delivered by the aircraft manufacturer, or obtained from a series of laboratory tests. The carried out comparative analysis shows that some parameters have a more significant influence on the final results of crack propagation estimation than the others. As a preliminary result, it can be assumed that these parameters should be defined with the highest level of confidence in order to prepare a conservative analysis.

Further investigation, including laboratory tests using different load spectra and C(T) specimens, will be carried out as the doctoral thesis of the main author.

Author Biography

The main author graduated from the Faculty of Power and Aeronautical Engineering at the Warsaw University of Technology in 2009 and ever since worked in the Air Force Institute of Technology. Throughout over a decade of professional activity he participated in preparation and execution of several full scale fatigue tests of aircraft structures as well as definition and introduction of individual aircraft tracking programs for military aircraft. Currently as a PhD student at the Military University of Technology, he investigates the sensitivity of numerical crack propagation estimations, in order to prepare a comprehensive methodology, suitable for assessment of cracks, found in military aircraft during operation.

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