DOI: 10.2478/fas-2023-0010
FATIGUE OF AIRCRAFT STRUCTURES
Volume 2023: Issue 15, pp. 155–165

CRACK PROPAGATION TESTS FOR LOAD SEQUENCES DEVELOPED USING DIFFERENT FLIGHT PARAMETERS OF A TRAINER AIRCRAFT

Piotr Reymer[1,2], Kamil Kowalczyk[1], Marta Baran[1],
Dominik Nowakowski[1], Michał Dziendzikowski[1], Andrzej Leski[2,3]
[1] Air Force Institute of Technology,
Ks. Bolesława 6, 01-494 Warsaw, Poland
[2] Military University of Technology,
gen. Sylwestra Kaliskiego 2, 00-908 Warsaw, Poland
[3] Lukasiewicz Research Network – Institute of Aviation,
al. Krakowska 110/114, 02-256 Warsaw, Poland

piotr.reymer@itwl.pl, kamil.kowalczyk@itwl.pl, marta.baran@itwl.pl,
dominik.nowakowski@itwl.pl, michal.dziendzikowski@itwl.pl,
andrzej.leski@ilot.lukasiewicz.gov.pl

Abstract

Military aircraft are subjected to highly variable and unpredictable loads due to diverse mission profiles, armament configurations, and individual piloting styles. This variability complicates the definition of precise load spectra, particularly in cases where data loss occurs due to Flight Data Recorder (FDR) malfunctions or data mishandling. This paper investigates the use of different flight parameters, such as load factor (n_z), barometric height (H_b), and horizontal velocity (V_p), to define load sequences for the PZL-130 "Orlik" TC-II military trainer aircraft. These sequences were then used to evaluate crack propagation using Compact Tension (CT) specimens. The results show that the incorporation of additional flight parameters improves the accuracy of crack propagation predictions when compared to direct strain measurements. This study highlights the potential of using available flight data to develop reliable load spectra for fatigue life estimation in military aircraft, even when direct load measurements are not financially feasible.

Keywords: fatigue crack propagation, flight parameters, load sequence
Article category: research article

INTRODUCTION

Compared to commercial aviation, military aircraft experience loads that are highly variable and hard to predict, due to the diverse range of missions, various armament configurations, and the individual piloting style of military aviators. These factors complicate the process of defining the actual loads exerted on the aircraft structure without direct in-flight measurements. Additionally, estimating load sequences in the event of data loss, due to a malfunction of the onboard Flight Data Recorder (FDR) or data mishandling, is challenging. On the other hand, instrumenting an entire fleet of aircraft with direct load measuring sensors and the necessary recording equipment is also difficult to justify financially.

This study investigated the possibility of defining load spectra for the PZL-130 "Orlik" TC-II turbopiston propeller military trainer aircraft based on available flight parameters recorded by the onboard FDR during regular operations, comparing the crack propagation potential of these load spectra to that obtained from direct strain measurement of the lower wing spar during a Operational Load Monitoring (OLM) program.

In military aircraft, the primary driver of operational loads is the load factor, defined as the ratio of the current lift force to the actual weight of the aircraft. This load induces a bending moment in the wing structure, leading to high tension in the lower wing spar flange. This structural element has been shown to be the critical part of the PZL-130 structure using the Full Scale Fatigue Test (FSFT) (Leski et al., 2015) as well as other fatigue tests carried on aircraft structures e.g. (Reymer et al., 2017).

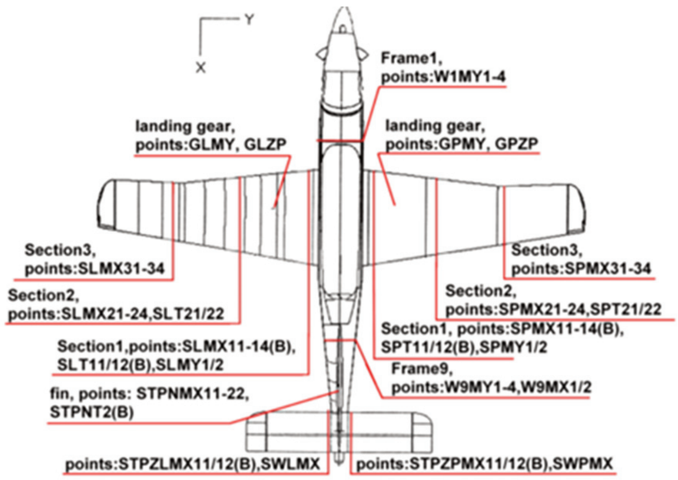
Modern military aircraft operation relies on a damage-tolerance approach, which is based on the crack propagation phenomenon. This approach is sensitive to the actual loads exerted on the structure during flight (U.S. Department of Defense, 2016), making it crucial to detect the actual cracks during scheduled inspections after they become detectable, yet before they reach critical sizes (Jiao et al., 2018; Reymer et al., 2012; Gillet & Bayart, 2020). This is only possible when crack propagation estimates are accurate for the considered location.

To assess an aircraft's overall structural integrity, FSFTs are often carried out. These tests provide detailed information about the structure's critical points and crack development during operation in a controlled environment (Nesterenko et al., 2020; Molent et al., 2009; Daverschot et al., 2020; Reymer & Leski, 2011). However, the load spectrum used for a FSFT can vary based on which of the available flight data processing methods is employed. This paper therefore examines how different processing approaches to flight data influence crack propagation estimations.

FLIGHT DATA ACQUSITION AND INITIAL ANALYSIS

The data used to prepare the load sequences were recorded during the OLM program carried out as part of the Service Life Extension Program (SLEP) of the PZL-130 "Orlik" TC-II aircraft. The OLM was focused on capturing the real strain signals from over 100 strain gauges installed on the aircraft structure, simultaneously with actual flight data recorded by the onboard FDR. These data were then used to define the load sequence for the FSFT of the aircraft structure (Kottkamp et al., 1976). Figure 1 illustrates the overall strain gauge array on the PZL-130 aircraft structure during OLM.

a)



b)

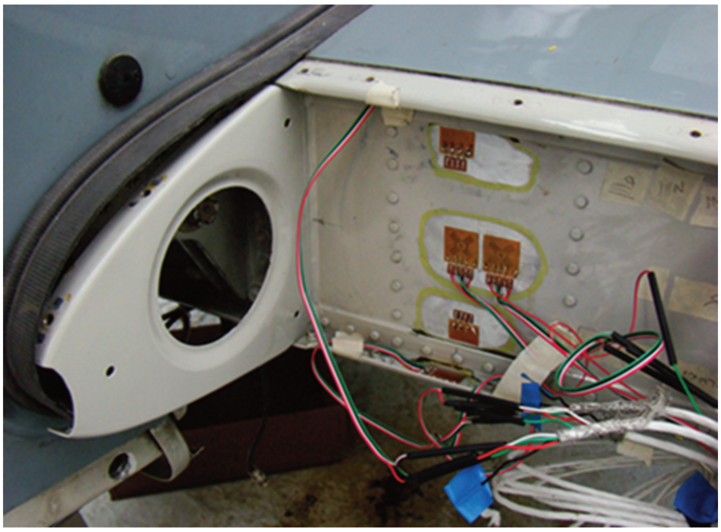


Figure 1. Location of strain gauges during the OLM
and the SLM14 sensor

Direct strain measurement during flight provides comprehensive information about the load state of a structural element, independent of the load condition (Jenkins & DeAngelis, 1997; Skopionski et al., 1954). Therefore, the comparative load spectrum used in this study was based on the *SLMX14* strain gage signal, which was installed on the lower flange of PZL-130 aircraft (Fig. 1a). The strain gauge was a tee rosette half bridge (Fig. 1b), which allowed for temperature compensation (crucial for measurements on a structure being operated in variable ambient temperature) and resulted with elevated sensitivity ($1+v$, where v is the Poisson's ratio of the material) (Jiao et al., 2018; Reymer et al., 2012; Gillet & Bayart, 2020). Other available flight parameters recorded by the onboard FDR were:

- load factor – n_z [-],
- horizontal speed – V_p [km/h],
- barometric height – H_b [m],
- horizontal stabilizer angle – *dh* [°],
- flaps extension – *dkl* [%],
- ailerons angle – *dl* [°],
- vertical stabilizer angle – *dv* [°].

The OLM was divided into three phases. In the first, the aircraft carried out planned flights in order to capture strain data corresponding to particular exercises and maneuvers. In the second phase, the aircraft returned to the 42nd Training Air Force Base in Radom (42 TAFB), where it was operated according to standard training schedule. Lastly, in the third phase, the measurement system was reduced to 8 strain gauges (4 on the wings, including *SLMX14*) and the aircraft continued regular flights at 42 TAFB.

Throughout these three phases, 350 records were collected. Of these, two were identified as ground tests and 1 duplicate record was found, which resulted in a total of 347 recorded flights of varying intensity (in terms of the maximum load factor range during the flight), altitude, and speed.

Further analysis revealed that 29 flight records (8.4% of the total) had damaged n_z signals; however, the *SLMX14* signal remained intact and fully usable. To validate data quality and identify potential discrepancies caused by a malfunction of the sensors or recording equipment, the following physical thresholds of the signals were determined:

- load factor: from -2 to 7,
- SLMX14 strain gauge: from 0 to 2100 μStr,
- barometric height: from 0 to 10 000 m,
- horizontal speed: from 0 to 440 km/h.

The characteristic values of *SLMX14* strain gauge in specific flight states were as follows:

- on the ground – 60 μStr,
- level flight with n_z = 1 - 320 μStr.

Preliminarily, it was assumed that flight data would be extracted from overall records based on the weight on wheels signal. However, due to unreliable values of this sensor, alternative criteria were determined based on changes in air speed and height. The following values were used:

- take off – $V_p > 100$ km/h, $H_b > 300$m,
- landing – $V_p < 100$ km/h, $H_b < 300$m.

These defined thresholds allowed the gathered data to be prepared for further analysis and load sequence definition.

LOAD SEQUENCE DEFINITION

After the initial verification, the gathered data were analyzed to identify correlations between individual parameters. The initial correlation matrix for the available parameters is shown in Table 1. Since the *SLMX14* strain signal is considered to be the parameter most reliably corresponding with the actual tensile strain state in the lower spar, correlations of all the other parameters to *SLMX14* were considered. As previously mentioned, the load factor (and thus indirectly the lift force) is considered as the primary driver of wing loads, therefore resulting in the highest 0.93 correlation coefficient with the strain value. Additionally, the horizontal speed V_p and flight height H_b showed noticeable correlations with the strain signal, resulting in 0.61 and 0.43 correlation factors, respectively.

The control surface deflection parameters did not show clear linear correlation with neither the *SLMX14* signal or the load factor, and so were excluded from this analysis. While more complex flight mechanics dependencies could potentially yield more useful correlations between the parameters, such an approach is beyond scope of the present study.

Table 1. Correlation matrix for the available flight parameters

Variable	**SLMX14**	**n_z**	**H_b**	**V_p**	**dh**	**dkl**	**dl**	**dv**
SLMX14	1.00	0.93	0.43	0.61	0.37	-0.30	-0.03	-0.07
n_z	0.93	1.00	0.29	0.39	0.28	-0.14	-0.08	-0.03
H_b	0.43	0.29	1.00	0.30	0.42	-0.49	0.09	0.17
V_p	0.61	0.39	0.30	1.00	0.22	-0.46	-0.08	-0.15
dh	0.37	0.28	0.42	0.22	1.00	0.08	-0.04	0.22
dkl	-0.30	-0.14	-0.49	-0.46	0.08	1.00	-0.00	0.15
dl	-0.03	-0.08	0.09	-0.08	-0.04	-0.00	1.00	-0.15
dv	-0.07	-0.03	0.17	-0.15	0.22	0.15	-0.15	1.00

Based on these findings, the load sequence definitions were based on four parameters: strain value *SLMX14*, load factor n_z, horizontal speed V_p and barometric height H_b. Since the *SLMX14* strain signal was considered the most accurate measure of the actual strain state of the structure, and given that it is not available in the regular FDR data from operation (only being available for the data recorded during the OLM program), it was decided to define the comparative load sequence based on the *SLMX14* signal from all of the flights. Additionally the remaining parameters, which are recorded during regular operation, would be used to define three types of load spectra, each more complex than the previous.

The first load spectrum was based solely on the load factor n_z, whereas the second incorporated the load factor n_z and the barometric height H_b. The third used both of these parameters plus the horizontal velocity V_p. Linear regression analysis defining the values of *SLMX14* using the above defined sets of parameters was carried out in STATISTICA software. The resulting linear regression models are shown in Table 2.

Table 2. Linear regression model parameters for the SLMX14 equations using flight parameters

Independent variables	R	R^2	free coefficient	a	b	c
n_z	0.9320	0.8686	-64.1018	388.8242	-	-
n_z, H_b	0.9459	0.8947	-113.747	368.296	0.046	-
n_z, H_b, V_p	0.9742	0.9491	-231.156	332.524	0.032	0.726

As can be observed in the table, the addition of H_b and subsequently V_p did increase the overall coefficients of determination of the consecutive models. These differences in predicting a single value of *SLMX14*, although relatively small, are expected to have a more significant impact when evaluating the total fatigue life of a specimen, which is the ultimate goal of the presented research.

To facilitate load spectrum preparation for this study and to enable spectra generation from current flight data, dedicated software was created. This software automated the processing of flight data by defining of flight states based on the aforementioned criteria, selection of desired regression model and other parameters like low bypass filtration. Moreover, to enable comparison of the test results obtained for each of the four spectra, the load cycles in each sequence corresponded to so called Simulated Flight Hours (SFH). This approach meant that executing a certain portion of each sequence represented a defined number of flight hours of the PZL-130 aircraft. The number of cycles and corresponding SFH for each sequence are given in Table 3.

Table 3. Load sequence characteristics

Sequence	SLMX14	n_z	n_z+H_b	$n_z+H_b+V_p$
Number of cycles	52894	30434	28241	25348
SFH	270.6	266.7	267.7	271

Each spectrum was filtered with a 5% low bypass filter in order to speed up the laboratory tests and to comply with the relevant standards (ASTM International, 2024). Additionally, due to potential problems with transitions from negative to positive values, all low values were truncated below 100 N.

TEST PREPARATION AND EXECUTION

Crack propagation tests using the obtained spectra were carried on CT samples designed in accordance with the relevant standards (ASTM International, 2024). The overall sample dimensions are shown in Figure 2 and detailed in Table 4. Samples were placed in specially designed clamps, adhering to standard requirements, and loaded in tension on an electromechanical MTS Acumen 12T strength testing machine using the prepared load sequences (Fig. 3).

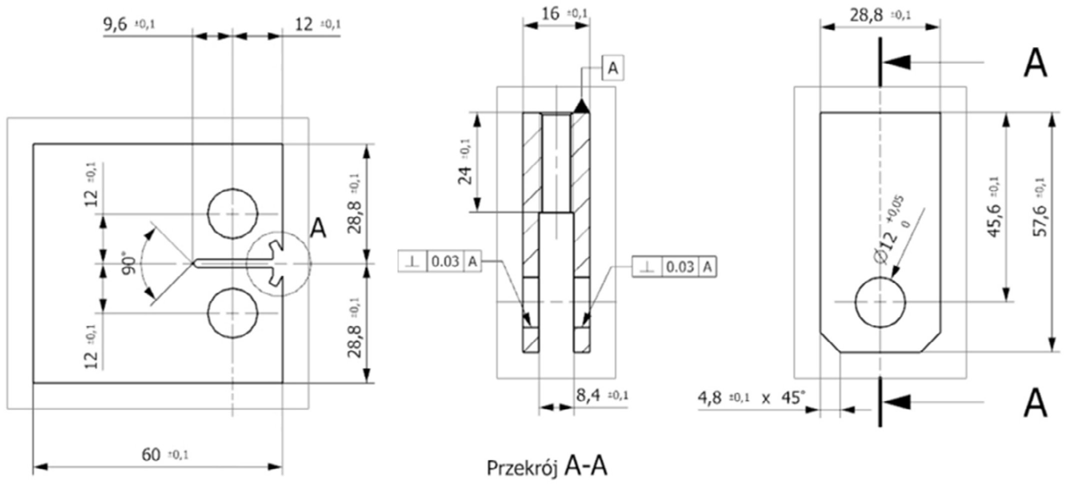


Figure 2. Technical drawing of the CT samples used in the test and the mount

Table 4. Dimensions of the CT specimens used in the test

W [mm]	B [mm]	Width [mm]	Height [mm]	Holes [fi_mm]	Notch [mm]	CS [mm2]	Precrack [mm]	H [mm]
48	8	60	57.6	12	21.6	307.2	1	3

Before the start of each test, a precracking procedure was carried out, aiming to create an initial crack of identical length (approximately 3 mm) for each specimen. The overall crack length throughout the test was derived using the susceptibility method, which requires monitoring of several test parameters to derive the actual crack length using the equation provided in the relevant standards (ASTM International, 2024):

- *W* – characteristic dimension of each CT sample measured from the pin holes center to the rear of the sample,
- *B* – thickness of each specimen,
- *E* – Young's modulus – defined during the precracking stage,
- *P* – load force applied by the machine,
- *u* – crack displacement measured with a Crack Opening Displacement (COD) gauge (Fig. 3).

Each test was carried out using a different load sequence until the defined test limits were achieved, which were defined as the maximum displacement of the machine piston under the current load. The maximum load in each load sequence was around 4kN and it appeared several times per cycle. Whenever this load caused the piston displacement to exceed the set value, the test was halted and the specimen was considered fractured.

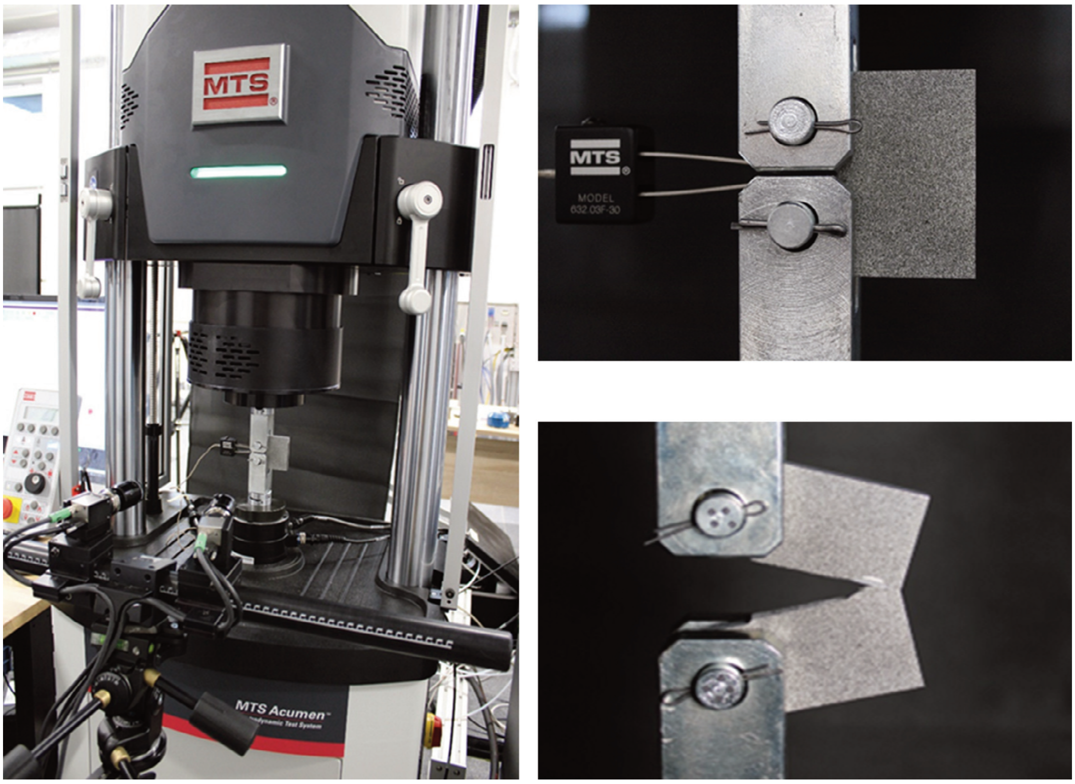


Figure 3. Test specimen mounted in the test stand, shown during (with a COD gauge) and after the test.

In addition to the crack length measurement method outlined in the relevant standards (ASTM International, 2024), an additional approach based on surface deformation measurements (Digital Image Correlation) was used during the test. For this, the surface of each sample was covered in a special pattern. Correlation of crack length defined using the method described in the standard and using the DIC method is beyond scope of this paper.

TEST RESULTS AND DISCUSSION

Crack propagation tests for the four defined load spectra were carried out and the obtained results are presented in Figure 4. The initial test using the load sequence based solely on the *SLMX14* strain gauge values resulted in a 22.13 mm crack after 12 079 SFH. The test using the load sequence based only on the n_z load factor halted after reaching crack length of 28.50 mm after completion of 21 348 SFH, which is almost double the fatigue life of the comparative sequence. The n_z+H_b sequence sample reached 26.07 mm in 17 664 SFH whereas the most complex, n_z+H_b+V_p sequence was the closest to the comparative *SLMX14* sequence, with 27.38 mm crack length and 13 401 SFH.

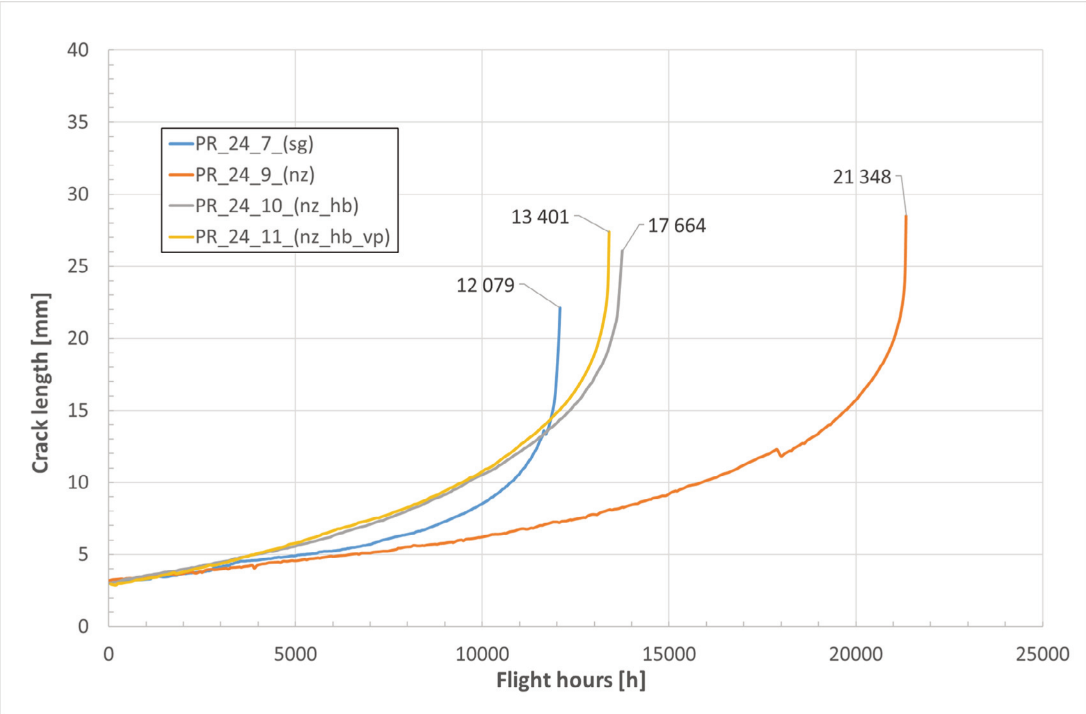


Figure 4. Crack propagation curves obtained for different load spectra

Preliminary results indicate that using more detailed models, incorporating more flight parameters with higher correlations to the main driving parameter, leads to crack propagation estimates that more closely resemble those obtained with the comparative *SLMX14* load sequence. Small improvements in terms of a single load value definition tend to result in higher fidelity in terms of additive crack propagation phenomena.

When direct load measurements are not financially justified, using properly defined models based on the available data may result in more reliable crack propagation estimations. Although the load factor is the primary driver of wing loading, it may be beneficial to incorporate more available flight data, as this improves the accuracy of fatigue life predictions.

CONCLUSIONS

This study confirms that incorporating additional flight parameters, such as barometric height and horizontal velocity, improves the accuracy of crack propagation predictions for the PZL-130 "Orlik" TC-II military trainer aircraft. Further research will focus on mitigating data loss due to mishandling or malfunction of the recording devices. Moreover, the omitted control surface data could be taken into account, when specific flight mechanics formulas are incorporated. The missing data can be reconstructed using different techniques, such as linear regression models based on other available parameters or machine learning techniques.

Rerefences

ASTM International. (2024). *Standard test method for measurement of fatigue crack growth rates* (ASTM E647-24).

Daverschot, D., Mattheij, P., Renner, M., Ardianto, Y., De Araujo, M., & Graham, K. (2020). Full-scale fatigue testing from a structural analysis perspective. In A. Niepokolczycki & J. Komorowski (Eds.), *ICAF 2019 – Structural Integrity in the Age of Additive Manufacturing. Lecture Notes in Mechanical Engineering*. Springer, Cham. https://doi.org/10.1007/978-3-030-21503-3_62

Gillet, O., & Bayart, B. (2020). Fatigue crack growth approach for fleet monitoring. In A. Niepokolczycki & J. Komorowski (Eds.), *ICAF 2019 – Structural Integrity in the Age of Additive Manufacturing. Lecture Notes in Mechanical Engineering*. Springer, Cham. https://doi.org/10.1007/978-3-030-21503-3_78

Jenkins, J. M., & DeAngelis, V. M. (1997). A summary of numerous strain-gage load calibrations on aircraft wings and tails in a technology format. *NASA Technical Memorandum 4804*. NASA, Edwards, California.

Jiao, R., He, X., & Li, Y. (2018). Individual aircraft life monitoring: An engineering approach for fatigue damage evaluation. *Chinese Journal of Aeronautics, 31*(5), 1000–1009. https://doi.org/10.1016/j.cja.2018.02.002

Kottkamp, E., Wilhelm, H., & Kohl, D. (1976). NATO Advisory Group for Aerospace Research and Development. *AGARDograph No. 160* (Vol. 7).

Leski, A., Kurdelski, M., Reymer, P., Dragan, K., & Sałaciński, M. (2015). Fatigue life assessment of PZL-130 Orlik structure – Final analysis and results. In *Proceedings of the 28th ICAF Symposium* (Helsinki, June 5-5, 2015).

Molent, L., Barter, S. A., White, P., & Dixon, B. (2009). Damage tolerance demonstration testing for the Australian F/A-18. *International Journal of Fatigue, 31*(7), 1163–1171. https://doi.org/10.1016/j.ijfatigue.2008.05.009

Nesterenko, B. G., Nesterenko, G. I., Konovalov, V. V., & Senik, V. Y. (2020). Russian practice to provide safe operation of airplane structures with long-term operation. In A. Niepokolczycki & J. Komorowski (Eds.), *ICAF 2019 – Structural Integrity in the Age of Additive Manufacturing. Lecture Notes in Mechanical Engineering*. Springer, Cham. https://doi.org/10.1007/978-3-030-21503-3_22

Reymer, P., & Leski, A. (2011). Flight loads acquisition for PZL-130 Orlik TCII full scale fatigue test. *Fatigue of Aircraft Structures, 1*(1), 78–85.

Reymer, P., Kurdelski, M., Leski, A., Leśniczak, A., & Dziendzikowski, M. (2017). Introduction of an individual aircraft tracking program for the Polish Su-22. *Fatigue of Aircraft Structures, 9*(1), 101–108. https://doi.org/10.1515/FAS-2017-0008

Reymer, P., Leski, A., & Kurdelski, M. (2012). Introduction of a structure integrity program for a military trainer aircraft. In *Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences (ICAS 2012)* (Vol. 6).

Skopionski, T. H., Aiken, W. S., & Huston, W. B. (1954). Calibration of strain-gage installations in aircraft structures for the measurement of flight loads. *NACA Report No. 1178*.

U.S. Department of Defense. (2016). *Department of Defense standard practice: Aircraft structural integrity program (ASIP)* (MIL STD-1530D).