DOI: 10.2478/fas-2019-0004
FATIGUE OF AIRCRAFT STRUCTURES
Volume 2019: Issue 11, pp. 28-38

COMPARATIVE STUDY ON FATIGUE LIFE OF CFRP COMPOSITES WITH DAMAGES

Marta Baran[1] • ORCID 0000-0002-7532-0215,
Piotr Synaszko[1] • ORCID 0000-0002-7884-0582,
Janusz Lisiecki[1] • ORCID 0000-0003-3069-3453,
Sylwester Kłysz[1,2] • ORCID 0000-0002-4521-4972.

[1]Air Force Institute of Technology, ul. Księcia Bolesława 6, 01-494 Warsaw, Poland
[2]University of Warmia and Mazury in Olsztyn, ul. Michała Oczapowskiego 2, 10-719 Olsztyn, Poland

marta.baran@itwl.pl, piotr.synaszko@itwl.pl, janusz.lisiecki@itwl.pl, sylwester.klysz@itwl.pl

ABSTRACT

In this work, the compressive residual strength tests results, Compression After Impact (CAI), are presented. The specimens were made of carbon-epoxy prepreg E722-02 UHS 130-14. Two variants of specimens were tested: samples undamaged and samples with damage that was centrally introduced by a drop-weight impact, as per the ASTM D7136/7136M standard. An impactor with potential energy equal to 15J and the type of support required by the standard were used. The size of impacted damages, defined as an area of damage on a plane perpendicular to the impact direction, and the equivalent diameter were specified using the flash thermography method.

The tests were performed using the fixtures manufactured according to the ASTM D7137/7137M standard. The specimens were compressed to determine the residual strength. This value was afterwards used to specify the force levels for the fatigue tests. The fatigue tests were carried out under force control – with a sinusoidal shape, stress ratio R equal to 0.1 and frequency f 1Hz. Maximum force in a loading cycle P_{max} was being increased after each thousand of cycles N until its value was close to the residual strength determined in the previously mentioned tests. In this work, the following relationships were presented: force-displacement P-δ for both static and fatigue tests and displacement-loading cycles δ-N for fatigue tests.

A method of conducting the fatigue tests of CFRP composite was proposed, in which both the CAI specimens and CAI fixture were used. This allowed researchers to accelerate making initial comparisons between the two groups of specimens with damages – grouped relative to the way of conditioning.

Keywords: CAI, CFRP, compression, Compression After Impact, damage, drop-weight impact test, fatigue test, residual strengt.

INTRODUCTION

Damages appear in both composite structures and other materials. It is important the aircraft structure be capable of carrying loads in a safe way despite the occurrence of damages of a specified size, until these are detected and repaired. In the case of composite materials, it is vital to establish during the certification process the Allowable Damage Limits (ADL) for the impact damage size.

Low energy impacts cause specific cone-shaped damages. Depending on energy, speed and stiffness – delamination and cracking of the fibers occur, primarily on the side opposite to the impact. Damages of this type are known as barely visible impact damages (BVID). They are particularly dangerous because they are un- or poorly-detectible with the naked eye. BVID detection often is only possible using non-destructive testing methods.

These damages reduce a structure's ability to carry loads that is quantitatively described by the residual strength. One of the methods used to investigate residual strength of composites is the technique developed by Boeing company and described in the ASTM D7137/D7137M standard [1]. In this technique, standard composite plate previously subjected to a drop-weight impact event [2] is compressed in a support fixture limiting the risk of bending and buckling occurrence (CAI test – Compression After Impact test). The properties obtained using this method may be listed in material specifications or used in development works. It allows for comparing residual strength of similar materials, but such results are generally not scalable to other supports and loadings configurations and should not be used for design of ADL.

The ASTM D7137/D7137M standard concerns static loading. Aircraft components, however, are generally subjected to cyclic loadings during exploitation. Research on fatigue of undamaged composites revealed an occurrence of significant non dimension stiffness (E/E_0) decreasing near the failure, shown in Fig. 1.

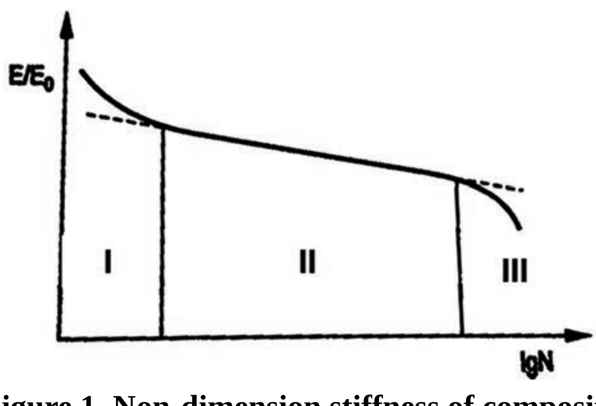


Figure 1. Non-dimension stiffness of composites during cyclic loading [3].

Impact damage causes the fatigue life to decrease. In the S-N chart it's clearly visible that the number of loading cycles to failure decreases with increasing the impact energy (Fig. 2).

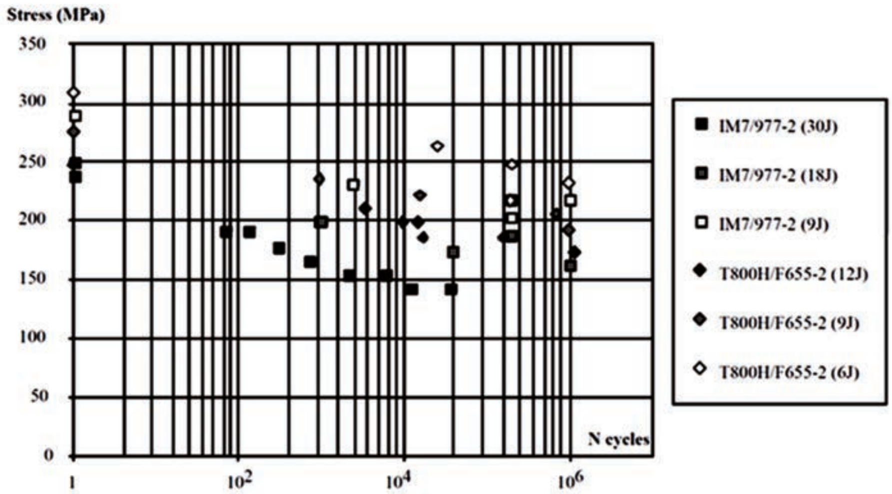


Figure 2. Stress versus number of cycles to failure for impact damaged laminates [4].

Investigations into fatigue behavior of composites with previously impacted damage in the conditions of constant force amplitude indicated that delaminations significantly grew until the end of tests, which is shown in Fig. 3. In the case of specimen loaded by a force equal to 0.8 of residual strength (circles on the chart), delamination propagation was observed to approximately $2 \cdot 10^5$ cycles, which is close to the number of cycles to failure.

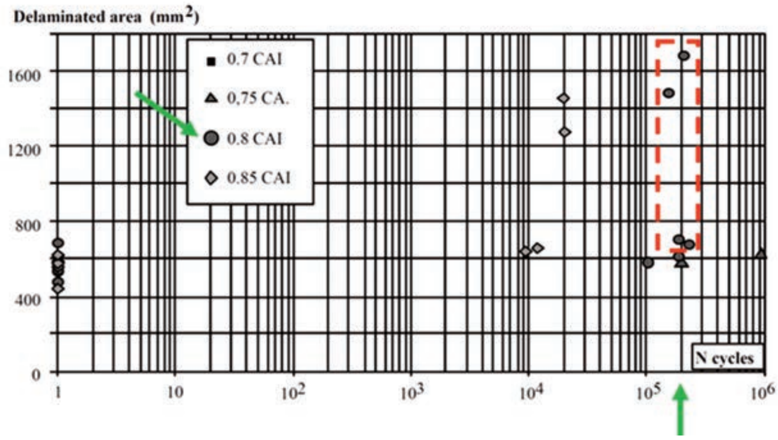


Figure 3. Post-impact delaminations size versus loading cycles [4].

The accelerated fatigue tests presented in this paper were undertaken because: i) it was time-consuming to determine the S-N curve and ii) delamination growing rapidly in the end of cycling hindered the parametrization of the S-N curve. The tests objective was to compare the CFRP composites in terms of fatigue life in three states:

- without damage,
- with damage,
- with damage and conditioning (executed after impact).

The research object was a composite material intended for repair of the composite skins of a MiG-29's vertical stabilizers. The tests were performed using the support fixtures and specimens made based on the ASTM D7137/D7137M standard. The specimen size established through Boeing method (100 × 150 mm) was similar to the area of a MiG-29's composite vertical stabilizer limited by the ribs and longerons [5]. Ribs and longerons inhibit buckling of the composite skin, which is close to support conditions provided by the CAI support fixture (Fig. 4).

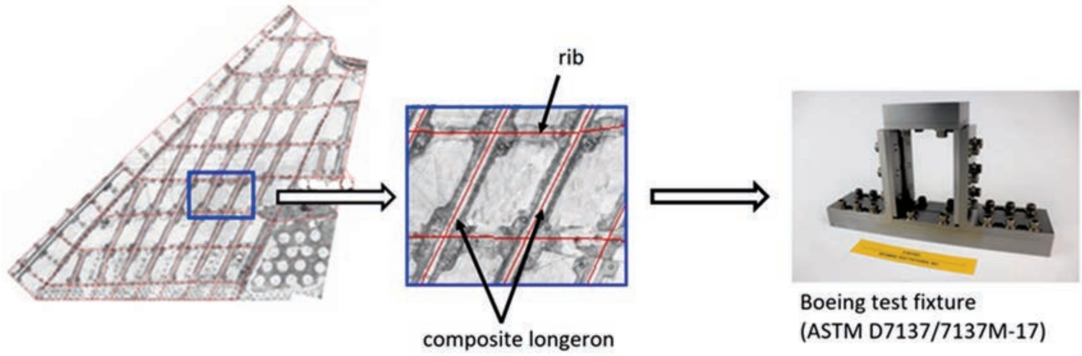


Figure 4. MiG-29 vertical stabilizer versus CAI support fixture.

METHOD

The block diagram of the research was shown in Fig. 5. The dotted arrow which connect the static CAI tests and fatigue CAI tests indicates data flow. The static CAI tests were carried out in order to obtain the residual force, which was the input value for the subsequent fatigue tests. The other arrows indicate the specimens flow.

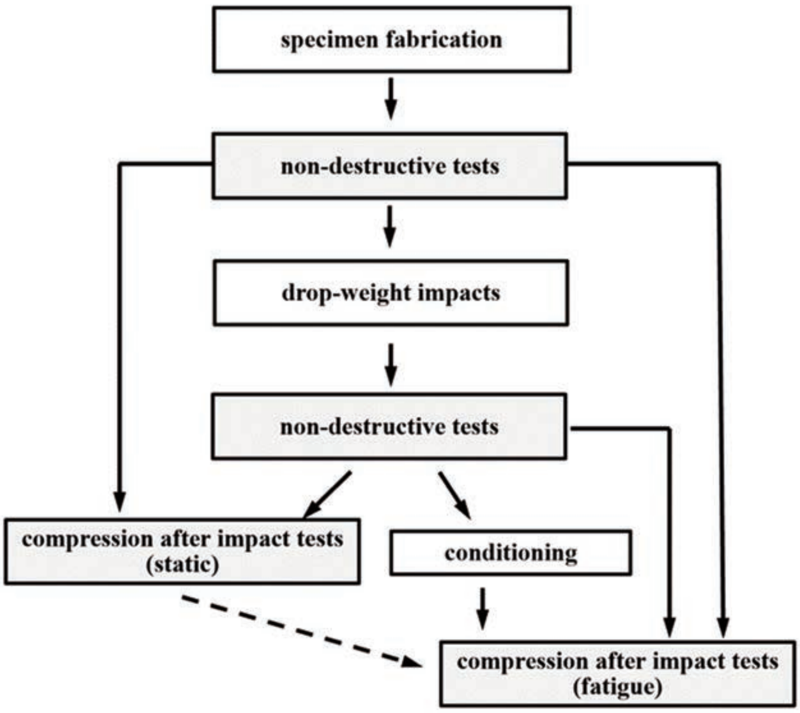


Figure 5. The scheme of the research.

The research stages shown in Fig. 5 are described above.

Specimen fabrication

Firstly, two panels were made of prepreg composed of E722 epoxy resin and ultra-high strength carbon fibers in technology of a vacuum bag in an autoclave. The multidirectional CFRP laminate construction consisted of 24 plies, which was equivalent to the stacking sequence exposed on a vertical stabilizer of a MiG-29 jet fighter. Plies orientation was specified in Table 1.

Table 1. Stacking sequence.

No. ply	Angle of ply	No. ply	Angle of ply	No. ply	Angle of ply
24	90^o	16	0^o	8	90^o
23	0^o	15	90^o	7	0^o
22	90^o	14	$+45^o$	6	-45^o
21	$+45^o$	13	-45^o	5	$+45^o$
20	0^o	12	0^o	4	90^o
19	90^o	11	0^o	3	0^o
18	$+45^o$	10	-45^o	2	0^o
17	-45^o	9	$+45^o$	1	-45^o

Secondly, the specimens were cut out using the water jet method. The geometry of the specimens was shown in Fig. 6. The specimens' thickness resulted from the number of plies (Table 1).

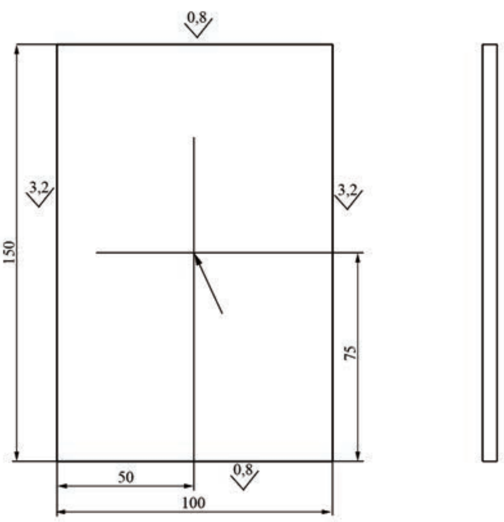


Figure 6. Geometry of Compression After Impact test specimen.

Non-destructive tests

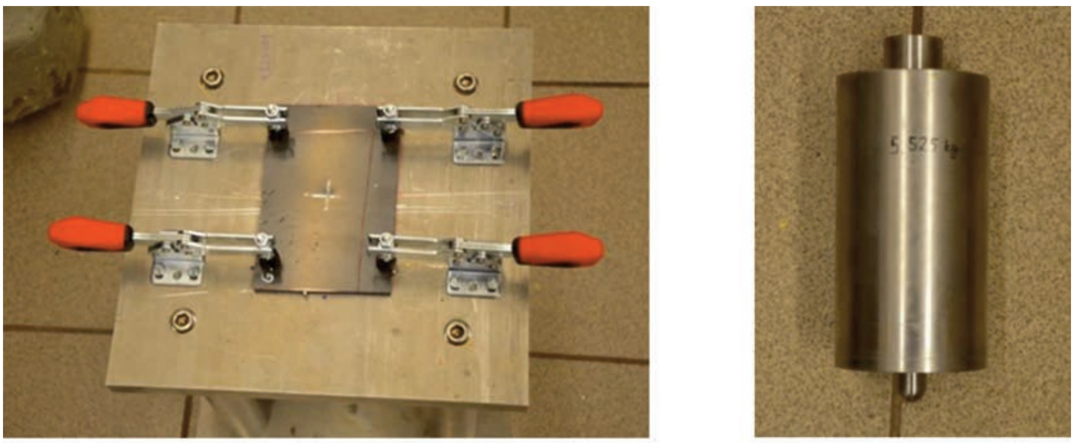
In order to control specimens' quality both immediately after cutting out and after introducing damage the flash thermography method was used. In the case of the specimens after impact both sides were tested. Data was recorded in the moment when the biggest area of damage was visible. The final area of damage was calculated by summing pictures of both sides of the specimen.

Drop-weight impacts

Damage was introduced according to the ASTM D7136/D7136M-15 standard [2]. The rigid impact support fixtures with the specimen placed were shown in Fig. 7a. The assumed impact energy value *E* was equal to 15 J. Drop-height needed to produce the energy *H* was calculated using the following equation:

$$H = \frac{E}{m \cdot g}$$

where E – potential energy of impactor prior to drop,
H – drop-height of impactor,
m – mass of impactor (Fig. 7b),
g – gravitational acceleration.



a) b)

Figure 7. a) Specimen placed in impact support fixtures, b) impactor (complied with [2]).

Conditioning

The pre-test conditioning process consisted of 18 cycles. Each cycle involved a 9 h 10 min UV exposure and 4 h 20 min water spraying.

Mechanical tests

The mechanical tests were carried out at the Laboratory of Strength Testing Materials of AFIT based on the ASTM D7137/D7137-17 standard [1]. The specimens were installed in compression after impact support fixtures (Fig. 8) and mounted on the mechanical universal testing machine MTS 810.23 (range of load cell ± 250 kN).

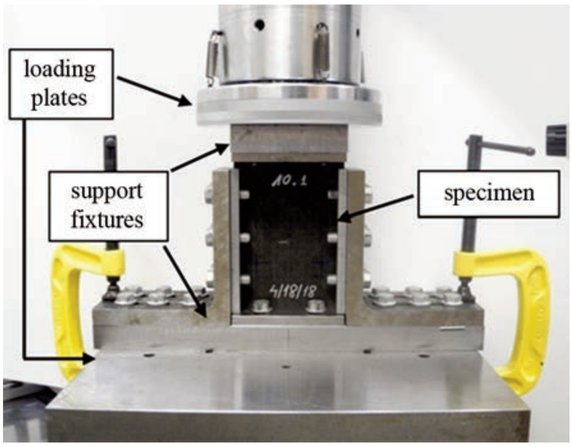


Figure 8. Specimen placed in compression after impact support fixtures (complied with [1]).

Static tests

The procedure of loading during static tests:

- pre-loading: loading to 5 kN with displacement rate equal to 0.5 mm/min,
- unloading,
- main test: compression of specimen with 0.5 mm/min displacement rate up to 30% decrease in maximum force.

Fatigue tests

The procedure of loading during fatigue testing:

- pre-loading: loading to 5 kN with displacement rate equal to 0.5 mm/min,
- unloading,
- main test:
  - control signal – force P,
  - shape of control signal – sinusoidal wave,
  - load frequency f – 1 Hz,
  - load ratio R – 0.1,
  - the initial level of force – assumed based on static tests results,
  - stepped rise of force – after each 1000 cycles increase of 5 kN up to the value limited by the maximum force obtained from static tests.

TESTS RESULTS

Fig. 9 shows a selected specimen after drop-weight impact. The damage was barely visible with the naked eye on the side which had contacted with the impactor tip (Fig. 9a). However, the pictures obtained using the flash thermography revealed the occurrence of a damage (Fig. 9b) that was reflected in a decreasing in maximum compressive force from (-78,1) ± 2,93 kN (specimens without damage) to (-67,8) ± 9,51 kN (specimens after drop-weight impact) (Fig. 10). Besides in the maximum force, these two types of specimens also differed in failure modes (Fig. 11). All specimens subjected to drop-weight impacts showed failures localized in the central parts of the specimens, where delaminations grew to the edges. In the case of initially undamaged specimens, the failures were observed near the top parts of the specimens.

Based on the static tests results, the initial level of loading in the fatigue tests was assumed such that was close to half the average maximum force for the specimens without drop-weight impact and equalled (-40) kN.

The fatigue tests results for all of the specimens were shown as a relationship between the maximum displacement δ in a loading cycle and the loading cycle number (Fig. 12 – 14). Moreover, the tables with the maximum force value during cycling P_{max}, number of cycles for P_{max} – N and total number of cycles to failure N_c were given. What is more, the failure modes views were added for each of the three types of composite states investigated.

The results obtained for the specimens without initial drop-weight impact damage were presented in Fig. 12. All of them became damaged at (-75) kN stage (last stage, below the maximum static compressive force). What is more, all of them exhibited the same mode of failure – localized near the top. In addition to similarities one of specimens obtained bigger number of cycles to failure (19852 cycles vs. about 7600). This indicates significant spread of results even for the group of initially undamaged specimens.

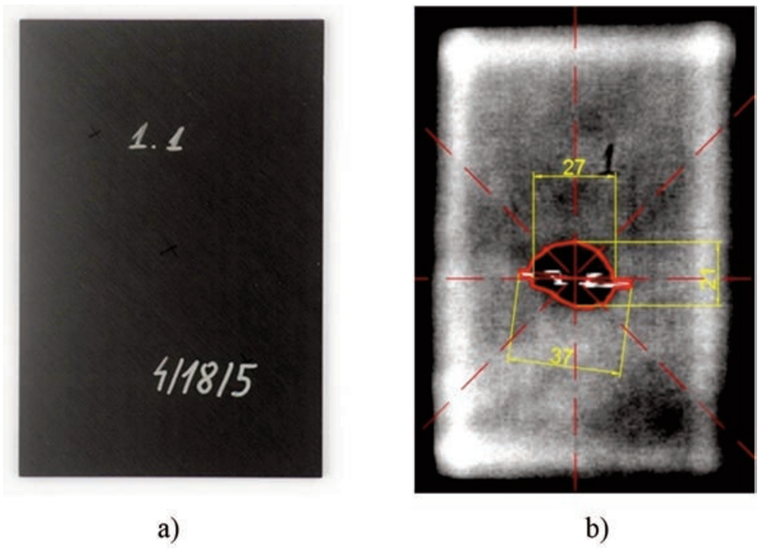


Figure 9. Specimen after drop-weight impact a) photo of the frontside of the impact, b) thermogram with dimensioning of impact.

type of specimen	$P_{max,av}$	$S_{n-1}(P_{max})$
	kN	kN
without damage	-78,1	2,93
with damage	-67,8	9,51

Figure 10. Static CAI tests results.

Fig. 13 and Fig. 14 present the results for the specimens after drop-weight impact, without and with conditioning, respectively. All of them had failure modes as in case of the specimens with initial damage subjected compression in static way (Fig. 11).

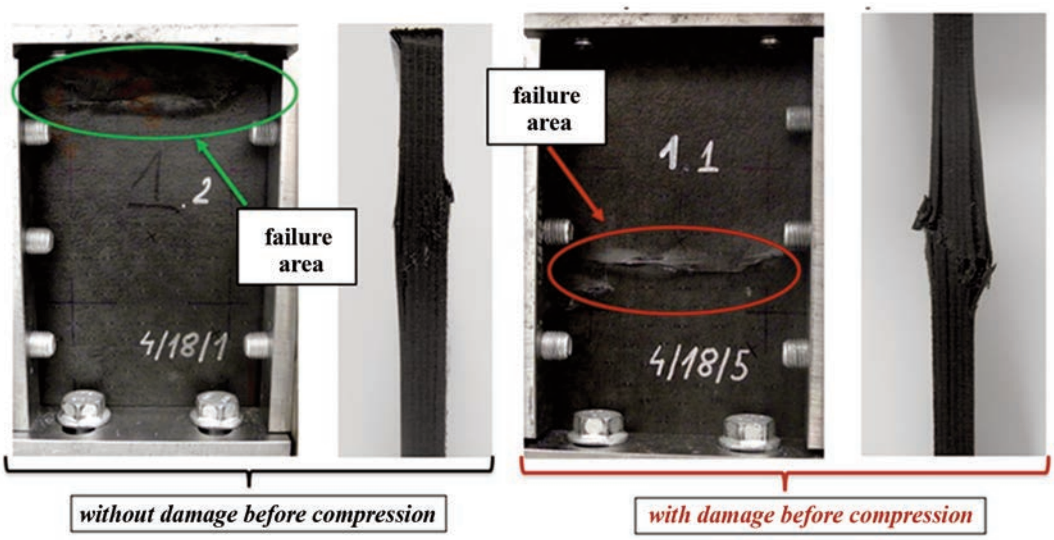
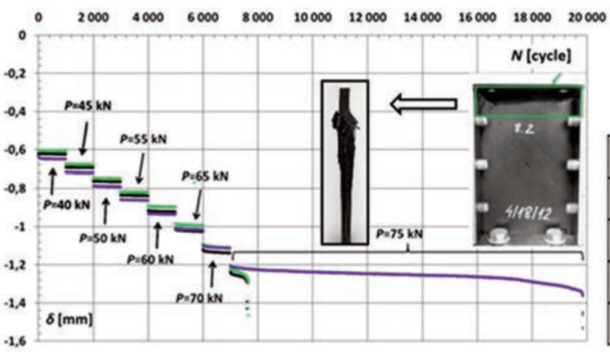
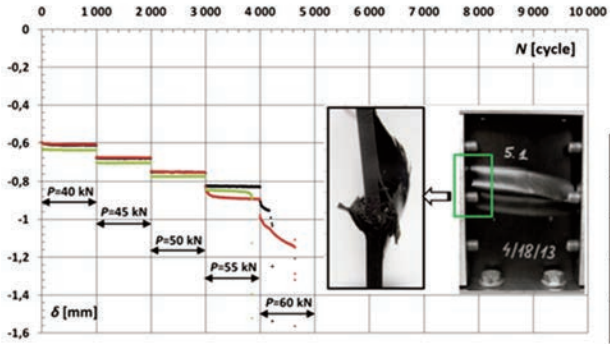


Figure 11. Failure modes obtained during static tests.



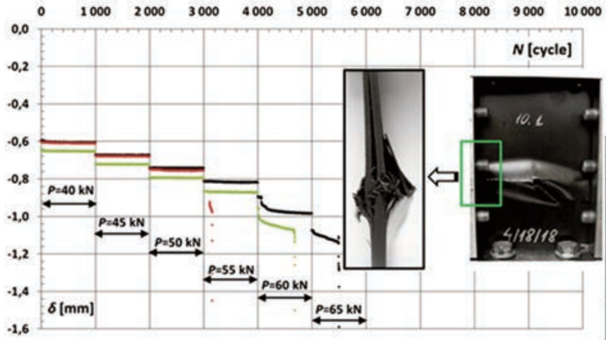
P_{max}	N	N_c
kN	cycle	cycle
-75	606	7606
-75	653	7653
-75	12852	19852

Figure 12. Specimens without damage before compression.



P_{max}	N	N_c
kN	cycle	cycle
-60	222	4222
-60	637	4637
-55	851	3851

Figure 13. Specimens with damage before compression without conditioning.



P_{max}	N	N_c
kN	cycle	cycle
-65	501	5501
-55	159	3159
-60	680	4680

Figure 14. Specimens with damage and conditioning before compression.

Specimens without conditioning (Fig. 13) failed for forces in the range of: (-55) – (-60) kN, whereas specimens after conditioning (Fig. 14) for: (-55) – (-65) kN. Given the similar value of displacement δ, the influence of conditioning on the fatigue tests results obtained cannot be stated.

Regardless of the presence of impact damage all of the tested specimens showed stiffness decreasing at the end of the fatigue loading as shown in Fig. 1. This was observed as changes in the displacement δ values at the same level of loading.

SUMMARY

The static Compression After Impact tests were performed on specimens that replicated the composite skins of a MiG 29's vertical stabilizers. Results obtained from these tests were used in accelerated fatigue tests.

The specimens without previously introduced damage accumulated a bigger number of cycles to failure compared to the specimens with damage. Nevertheless, both types of specimens - with and without the impact damage – showed a similar spread of results. Given the dispersion of test results mentioned above, the influence of conditioning on the fatigue tests results cannot be determined.

The magnitudes of displacement obtained for given force levels up to P_{max} = 50 kN show no significant differences between the investigated states of the material. Influence of impact damage occurrence or conditioning were not observed. This specimens' behavior corresponds to phase II of stiffness degradation during cycle loading of composites shown in Fig. 1, where degradation is gradual and linear. Some of the impact damaged samples both with and without conditioning were found in phase III of stiffness degradation for the force P_{max} level equal 55 kN. In the case of specimens without impact damage, rapid degradation was observed only for P_{max} = 75 kN, which equalled more than 95 % of the force obtained during static tests.

The presented approach to comparative accelerated fatigue testing, based on the results obtained from static tests for samples with and without impact damages, will be employed in further research on specimens cut out from the MiG-29's aircraft vertical stabilizers composite skins with repairs.

ACKNOWLEDGEMENTS

This work was prepared as part of the Air Force Institute of Technology project called "MiG" performed under a contract with the Ministry of National Defense. The main goal of the project was to develop a repair technology for CFRP and sandwich structures of a MiG-29 jet fighter, with verification in flight tests as the last stage.

REFERENCES

[1] ASTM D7137/D7137M-17. *Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates.*

[2] ASTM D7136/D7136M-15. *Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event.*

[3] Ochelski, S. (2019). *Metody doswiadczalne mechaniki kompozytow konstrukcyjnych*, Wydawnictwo Naukowe PWN, Warsaw. (in Polish)

[4] *Composite Materials Handbook. Volume 3. Polymer Matrix Composites Materials Usage, Design, And Analysis*, Department of Defense Handbook, 2002.

[5] Sałacinski, M., Synaszko, P., Olesinski D. and Samoraj, P., (2019). *Approach to Evaluation of Delamination on the MiG-29's Vertical Stabilizers Composite Skin.* ICAF 2019, Lecture Notes in Mechanical Engineering, Niepokolczycki A. and Komorowski J. (Eds.), pp. 865-873.

[6] *Compression After Impact Research,* Laboratory of Strength Testing Materials Report No SP-88/31/2018. AFIT Library. 2018. (in Polish)