Fatigue Life of Al-Honeycomb Core Composites Construction

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Polymer composite honeycomb sandwich panels (PCHSPs) are used in many sectors of industry, such as in aerospace, defense and public transport factory. Sandwich panels consist of two facing skins and the core. Products of all industry sectors have to meet requirements on their dependability. This research paper deals with a proposal of the most appropriate methodology for dependability testing of PCHSPs products used in transport industry. Dependability is a global concept that includes terms such as availability, reliability, durability, maintainability, supportability, etc. The experiments have shown S-N curves with damages and without damages of PCHSPs. An important part of dependability is to be fonded the limit states of the studied object, which are for PCHSPs are characterized by fiber cracking and (core) delamination. Dependability evaluation consists of analysis and tests. For every test, it is necessary to be developed its test plan. Facing skin components of the sandwich panels may particularly be damaged. There are several methods of non-destructive testing, which can be used to determine the damage of facing skins of sandwich panels. Infrared thermography (IRNDT) is one of them. IRNDT utilizes thermo-physical properties of the materials, including thermal diffusivity.

Keywords: composite sandwich panel, honeycomb core, three-point bending, S-N curve, fatigue life

1 Introduction

The composite materials (CM) are increasingly replacing conventional structural and building materials. A special type of composite material is the polymer composite sandwich panel with a honeycomb core (PCHSP).

PCHSPs have been used in aviation since the 1960s. First on tertiary structures, later on secondary and nowadays on primary structures. At present, PCHSPs are also used in the construction of land vehicles (cars and buses, railway trains, etc.). The design of the aircraft and land vehicles is stressed by flight and ground loads (surface loads: aerodynamic, volume loads: own weight, etc.). These are always random processes. This work deals with statistical analysis of PCHSP testing. The substance of evaluation is in the determination of PCHSP´s lifetime.

The issue of fatigue loading of PCHSPs is not fully explored and general conclusions have not been formed yet. Unlike metallic materials, where two standards [1] and [2] for metal fatigue testing used in the Czech Republic, however, there is no specialized standard describing testing and statistical evaluation of PCHSP´s fatigue lifetime. There is only ISO 13003:2003 standard [3], which is applicable to composite materials (laminates) and the military standards; MIL-HDBK-23A [4]. There is a relatively small number of scientific publications dealing with the life fatigue test of PCHSPs. Only static tests on sandwich panels are included in the book [5] and fatigue tests of composite structures are described in [6] (laminates only). There is also a limited number of scientific articles dealing with PCHSPs fatigue tests [7, 8, 9, and 10]. The issue of fatigue testing of sandwich panels was solved in Czechoslovakia already in 1972 [11].

A PCHSP has specific fatigue life properties. The problem is complicated by the different properties of each of sandwich components. The PCHSPs tests are always tests of the structural element. Therefore, the complications resulting from the demands of adhesive bonding technology are increasing due to the known factors affecting the number of the achieved cycles, ie. stress values, structure of the individual components, geometric shape and dimensions. This also explains non-existent standard for the PCHSP ´s fatigue test. The fatigue testing methodology have to always include a statistical approach for the evaluation of the test results and with respect to the loading and conducted cycles itself we differ between low and high-cycle fatigue [12-16]. The statistical evaluation of the PCHSPs fatigue tests results is in a graphical representation using the classic S-N (Wöhler) curve and it determinines the reliability of the estimates of statistical variables. As a result, median of lifetime, the shortest life and the lower limit of fatigue life were investiquded in this work.

During fatigue testing, it is advisable to monitor the formation and propagation of the sample´s damage by infrared thermography. This non-destructive testing method is very well suited in CM and PCHSP testing and it has been validated in other experiments, eg. in [17].

2 Experiment

2.1 Materials

For the static and fatigue tests, the same samples were manufactured. Three prepreg layers in each side of facings were used for the fabrication of the experimental samples. Prepreg from company G. Angeli was used, having trademark: IMP503Z / VV 192 T. The glass fiber fabric had twill weave with density of 202 g/m^2. The resin content in the prepreg was 33 vol. %. Aluminum honeycomb from EURO-COMPOSITES, trademark: ECM 6.4-60, was used as the core with thickness of 8 mm. The aluminum alloy was Alu-Alloy 3003 (AlMnCu) coated with zirconia. Density of this honeycomb was 60 kg/m^3 having cell size of 6.4 mm. The sandwich sample cut by water jet from manufactured panel is shown in Fig. 1.

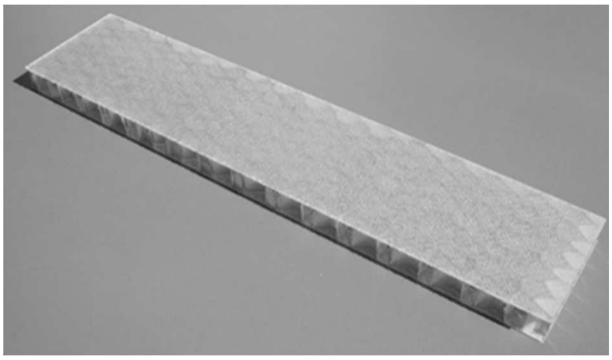

Fig. 1 *Sample of Polymer composite honeycomb sandwich panels (PCHSPs)*

The connection of the prepreg with the honeycomb was achieved by compression molding technology, which was carried out at 125° C (with a hour start and subsequent cooling). Prepared sandwich samples dimensions were following; l = 200 mm, b = 43 mm and h = 9 mm. Used dimensions was inaccordance with ČSN EN 2374 standard [18].

2.2 Experimental apparatus, equipment and methods

The three-point bending static test was performed in accordance to ČSN EN 2562 and ČSN EN ISO 14125 [19, 20] on Universal testing machine Zwick 1456. Testing temperature was 23 °C. Test speed was set to 5 mm/min with support span equal to 178 mm.

The test is based on the fact that the sample is bent at a constant speed to its fracture. During the test, the force at failure of $F_{B,i}$ and deflection of $f_{B,i}$ were measured (Tab. 1). A Equation (1) was used to calculate the stress in the sample at damage and for each fatigue loading level:

$$\boldsymbol{\sigma_{fb}} = \frac{\boldsymbol{3 \cdot F_B \cdot L}}{\boldsymbol{2 \cdot b \cdot h^2}} \text{ [MPa]} \tag{1}$$

Where:
σ_{fb}…Maximal stress of the sample at fracture point [MPa],
F_B…Size of the force [N] applied to the sample at its fracture in N-cycle,
L…Distance [mm] between the supports of the test instrument (178 mm)
b…Sample width [mm] (43 mm),
h…The height of the sample (9 mm).

The fatigue tests were carried out on a proprietary test device. This device has a classic, adjustable crank mechanism with a piston rod driven by gears with an electromotor with variable speed. The device is not capable of measuring load force Fmax, i. However, at known engine speeds and gear ratios, the number of the measured cycles can be achieved by the time measuring.

The fatigue test was performed at three stress levels. The levels were determined as a percentage of the force obtained from static three-point bend test (F_B). According to Tab. 2, it was 75%, 55% and 45% of the arithmetic mean F_B. Despite the impossibility of controlling the load force, a soft loading was used. The load waveform for each level was cyclic, sinusoidal, and passing (lower stress $\sigma_{min} = 0$, coefficient of cycle asymmetry R = 0). The maximum stress was set to the specified levels by changing the configuration of the test device. The time until the complete sample failure was measured.

The results of the fatigue tests were statistically evaluated at each level separately. The tests results sets were assumed to have the number of cycles logarithms according to the normal distribution. For each level, the arithmetic mean of the number of measured cycles $\bar{x}$,the median of the measured cycles $\tilde{x}$, the standard deviation of the measured cycles s and the variation coefficient V_x (Tab. 3) were calculated. In order to calculate other statistical characteristics, the sample mean, as the best estimation of the mean value of the base set E, was calculated according to equation (2):

$$\boldsymbol{\hat{\mu}} = \frac{\boldsymbol{\sum_{i=1}^{n} X_i}}{\boldsymbol{n}} \text{ [-]} \tag{2}$$

Where:
$\hat{\mu}$…The sample mean [-],
X_i…The i-th value of the observed test file (in $\log_{10}$) [-],
n…The number of data sets [-]. The "^" means that it is an estimate based on the test file. The sample standard deviation was calculated according to Equation (3):

$$\boldsymbol{\sigma} = \sqrt{\frac{\boldsymbol{\sum_{i=1}^{n}(X_i - \hat{\mu})^2}}{\boldsymbol{n-1}}} \text{ [-]} \tag{3}$$

Where:
σ…Te sample standard deviation [-],
X_i…The i-th value of the observed test file (in log10) [-],
$\hat{\mu}$…The sample mean [-],
n…The number of data sets [-] (n = 5). Median of lifetime was calculated according to Equation (4):

$$\boldsymbol{\hat{N}_{(P;1-\alpha;v)}} = \boldsymbol{10^{\hat{x}_{(P;1-\alpha)}}} \text{ [-]} \tag{4}$$

Where:
$\hat{N}_{(P;1-\alpha;v)}$…The median of lifetime in the number of cycles at the probability by P (predictive reliability) [%],
1-α…The confidence level of reliability, and v is the number of degrees of freedom [-] (n - 1 = 4). The estimate of cycles number of the shortest lifetime that survives 95% of all samples was calculated according to Equation (5):

$$\boldsymbol{\hat{N}_0} = \boldsymbol{10^{\hat{\mu} - 1{,}645 * \sigma}} \text{ [-]} \tag{5}$$

Where:
$\hat{N}_0$ …The shortest lifetime in numbero of cycle [-],
$\hat{\mu}$…The sample mean [-],
σ…The sample standard deviation [-],
and the constant of 1.645 was determined from the tables in [1] to survive 95% of all samples. The lower limit of fatigue life for x-th % probability of failure at a confidence level x%, where the unilateral tolerance limit of the normal distribution $k_{(P;1\text{-}\alpha;v)}$ was calculated (Equation (6)).

$$\boldsymbol{\hat{x}_{(P;1-\alpha)}} = \boldsymbol{\hat{\mu}} - \boldsymbol{k_{(P,1-\alpha,v)}} * \boldsymbol{\sigma} \text{ [-]} \tag{6}$$

Where:
$\hat{x}_{(P;1-\alpha)}$…The lower limit of fatigue life in the number of cycles [-],

$\hat{\mu}$...The sample mean [-], $k_{(P,1-\alpha,v)}$ is the unilateral tolerance limit of the normal distribution, and σ is the sample standard deviation.

By combining the calculated values, the Wöhler curve (S-N curve) was obtained, representing a 95% survival limit in this particular experiment. A regression nonlinear least squares method was used to compensate for the S-N curve.

3 Results and Discussion

3.1 Static test - three-point bending

The results of the static three-point bending test of the five samples are shown in Tab. 1. The standard deviation complies with Sillen's rule (the estimated parameter should be greater than three times its standard deviation value).

***Tab. 1** Static test results in three-point bending*

	Sample No.:					Arithmetic mean $\bar{x}$ [-]	Standard deviation *s* [-]
	1	***2***	***3***	***4***	***5***		
Strength at failure $F_{B,i}$ [N]	712	946	843	887	1068	891	117.2
Bend at failure $f_{B,i}$ [mm]	4.6	6.5	5.7	6.2	7.3	6.1	0.9
Stress at failure σ_{fB} [MPa]	**Calculated accord. to equation (1):**					67.5	

3.2 Fatigue test

According to the methodology which is referred in paragraph 2.3.2, and by using the Equation (1) the three load levels $\sigma_{max,i}$ = 50, 37 and 30 MPa, were determined. These levels are given in Tab. 2 and 3. According to the description of the test equipment in paragraph 2.2.2, the number of (measured) N_i cycles and the calculated statistical characteristics (Tab. 3) were specified.

***Tab. 2** Determination of load levels*

Level No.	% from $F_{B,i}$ [%]	Force $F_{max,i}$ [N]	Bend $f_{max,i}$ [mm]	Maximum stress $\sigma_{max,i}$ [MPa]	Stress amplitude $\sigma_{a,i}$ [MPa]
1	75	668	4.6	50	25.0
2	55	490	3.4	37	18.5
3	45	400	2.1	30	15.0

Tab. 3 shows that for each stress level the difference between the arithmetic mean of the measured cycles number $\bar{x}$, the median of the measured cycles $\tilde{x}$, and the median of lifetime $\hat{N}_{(10)}$ is insignificant. This is evidence of correctly performed fatigue tests including samples fabrication.

The median of lifetime $\hat{N}_{(10)}$ means that in further tests at the same stress level, about half of the samples will have a lifetime of less than 181, 30509, and 1157910 cycles. In order to assess the reliability of the structure, the shortest lifetime of $\hat{N}_0$ (106, 25704, and 829688 cycles) is most important, surviving 95% of all samples.

In fact, either the mean value or the scattering reliably is not known, because they were determined from five samples at each level. The coefficient of 1.645 in Equation (5) can be replaced by another coefficient for the unilateral tolerance limit $k_{(P;1-\alpha;v)}$ of Equation (6) and determining the lower limit of fatigue life $\hat{x}_{(10)}$ (45, 19702, and 494196 cycles). It is quite obvious that the lower limit of the fatigue life $\hat{x}_{(10)}$ is considerably lower than the shortest lifetime $\hat{N}_0$. This difference shows that the fatigue test was performed with a small number of samples.

***Tab. 2** Fatigue test results and statistical characteristics*

	Level No.1 $\sigma_{max,1}$ = 50 MPa	Level No. 2 $\sigma_{max,2}$ = 37 MPa	Level No.3 $\sigma_{max,3}$ = 30 MPa
Number of measured cycles N_i [-]	158	32712	1055090
	197	28274	1418403
	283	31082	1453173
	116	26708	1036366
	189	34429	923536
Arithmetic mean of the number of measured cycles $\bar{x}$ [-]	189	30642	1177314
Median of measured cycles $\tilde{x}$ [-]	189	31082	1055090
Standard deviation of measured cycles *s* [-]	61,6	3159	241573
Variation coefficient V_x [%]	32.7	10.3	20.5
Median of lifetime $\hat{N}_{(10)}$ [-]	181	30509	1157910
Shortest lifetime $\hat{N}_0$ [-]	106	25704	829688
Lower limit of fatigue life $\hat{x}_{(10)}$ [-]	46	19702	494196

3.3 S-N (Wöhler) curve

The Wöhler curve (S-N curve) was obtained by combining the calculated median lifetime $\widehat{N}_{(10)}$ and the values of the individual stress levels, representing a 95% survival limit in this particular experiment. Fig. 2 shows the graphical representation of the Wöhler curve. For the clarity of the chart, there are no other statistical characteristics mentioned (eg. lower limit). For the regression analysis, the Solver from MS Office-Excel was used. The confidence value $R^2 = 0.9946$ is very close to 1. This confirms the appropriately chosen regression method (regression nonlinear least squares method). Uniform scales (x and y axes) were used intentionally.

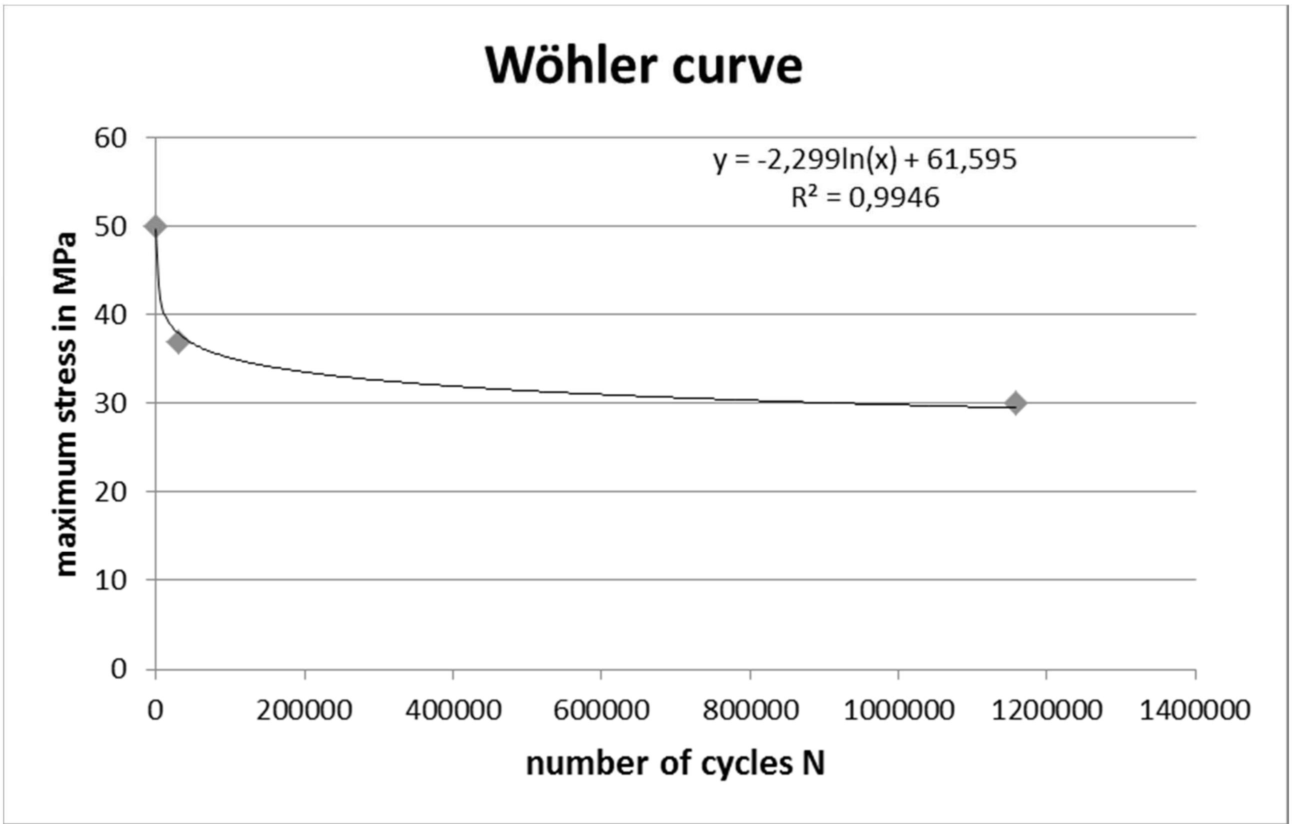

Fig. 2 *S-N (Wöhler) curve*

4 Conclusion

In the research, static bending properties and fatigue life of prepared honeycomb core sandwich samples have been investigated. Conducted tests and used statistical evaluation provided interesting results that are applicable PCHSP evaluation and design. From obtained Wöhler curve shape, it is observed that the stress level $\sigma_{max,3} = 30$ MPa is very close to the fatigue limit σ_c, where the sample would theoretically withstand an infinite number of cycles.

All kinds of means of transport are designed for a given lifetime. This article describes the method that can be used to determine the basic lifetime characteristics of PCHSP´s. The knowledge of these characteristics is necessary in order the to be designed not only for static strength but also for the required fatigue life.

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