MEASUREMENT OF THE STRAIN AND BENDING MOMENT ON THE WING OF AN AIRCRAFT AND USING OF THESE FINDINGS FOR FATIGUE TEST

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Abstract

The goal of measurement was to set curves of bending moment on the wing of a small aircraft and establishing of the strain in dependence on a flight conditions. The results were used for design of the fatigue test of the connection between the center wing and outer wing.

1 In Flight Measurements

Values measured during in flight testing:

- Responses from installed strain gauges (left wing)
- Load factor at center of gravity
- Load factor at left wing
- Load factor at rear part of fuselage
- Static pressure
- Overall pressure
- Deflection of elevator
- Deflection of left aileron

Totally there were installed 35 strain gauges [1] in 5 cuts along the wingspan. Typical example of strain gauges placing is on Fig. 1.

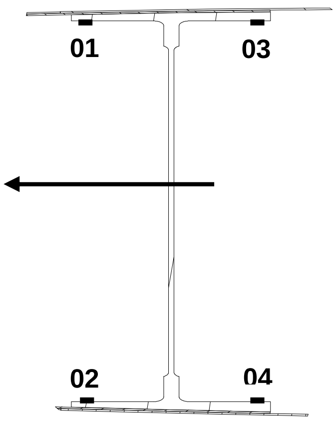


Fig. 1 Placing of strain gauges

Indicated air speed Vias was calculated by this equation:

$$Vias = \sqrt{\frac{2\Delta p}{\rho}} \qquad (1)$$

and pressure altitude:

$$h = \frac{\sqrt[5{,}256]{\frac{p}{p_0}} - 1}{\frac{-0{,}0065}{T_0}} \qquad (2)$$

where p is measured pressure, ρ is air density and p_0 and T_0 is pressure and temperature at the middle see level.

Data acquisition system ESAM Traveller Static was used for recording of all needed values. Data acquisition mounting is on Fig. 2.

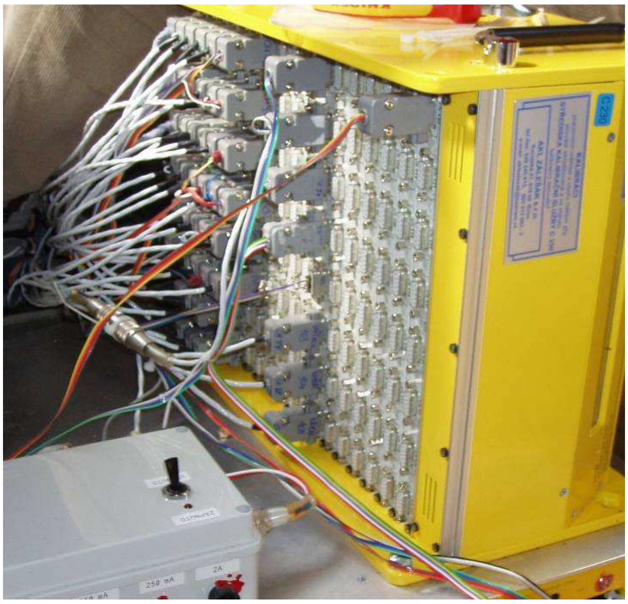


Fig. 2 Mounting of data acquisition system

1.1 Calibration of Strain Gauges

Definition of a relation between forces (moments) effecting the wing and responses from strain gauges was needed for our purposes. It was done by loading of collets placed on the wing in two cuts (see Fig. 3).

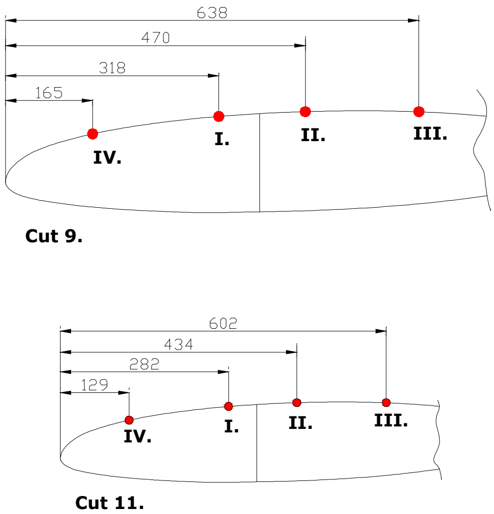


Fig. 3 Positions of applied calibration loads

The loading from 196,1N up to 1569N (at 196,1N) was applied on cut no. 9 in all four points I., II., III. and IV. along chord of the wing. Similar calibrations forces were applied on cut no. 11 up to 785N. Total number of calibration loads was 80.

1.2 Calculating of Calibration Coefficients

The strain gauges were installed by the producer to the positions, where there is no possibility to determine all components of loading. For this reason the calibration was done for bending moment and shear force only.

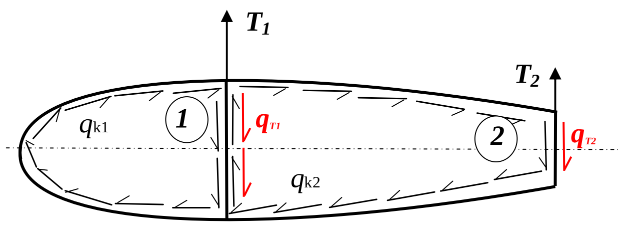


Fig. 4 Shear stress in wing structure

On Fig. 4 there is a shear stress in the wing structure. If we take shear flow q_{T1} a q_{T2} as a result forces $\mathbf{T_1}$ a $\mathbf{T_2}$ divided by an effective height of spars, then we can write for total shear flow in the webs:

$$q_{v1} = q_{k1} + q_{k2} + q_{T1} \qquad (3)$$

and

$$q_{v2} = q_{k2} + q_{T2} \qquad (4)$$

Strain gauges were installed on the webs of spars and it is clear that the shear flow q_{k1} and q_{k2} are affecting some total accuracy of measurement, because they are not in continual proportion with overall loading of wing. Relation between response $\boldsymbol{m}$ of strain gauge and overall loading of structure is done by equation [3]:

$$\left\| \begin{matrix} T \\ Mo \\ Mk \end{matrix} \right\| = \left\| \begin{matrix} b_{11} & b_{12} & .... & b_{1j} \\ b_{21} & b_{22} & .... & b_{2j} \\ b_{31} & b_{32} & .... & b_{3j} \end{matrix} \right\| * \left\| \begin{matrix} m_1 \\ m_2 \\ .... \\ m_j \end{matrix} \right\| \qquad (5)$$

In our case we do not study a torque moment (wrong placement of strain gauges), but we are looking for the shearing force and bending moment.

And now it is possible to deduce an equation for calculating wanted coefficients $\boldsymbol{b}$:

$$\left\|\mathbf{b}_{\mathbf{ij}}\right\| = \left\| \left\|\mathbf{m}_{\mathbf{nj}}\right\|^{\mathbf{T}} * \left\|\mathbf{m}_{\mathbf{nj}}\right\| \right\|^{-1} * \left\|\mathbf{m}_{\mathbf{nj}}\right\|^{\mathbf{T}} * \left\|\mathbf{T}'_{\mathbf{n}}\right\| \qquad (6)$$

where $\boldsymbol{n}$ is loading of calibration force $\boldsymbol{T_n}'$ and this force is applied at $\boldsymbol{n}$ places of structure

And probable error of estimate of shear values gives this equation:

$$P.E.(T) = 0.6745.\sqrt{\frac{\sum \epsilon_V^2}{n-(q+1)}} \qquad (7)$$

where

n number of loads applied
q number of terms in calibration equation
$\sum \epsilon_V^2$ sum of squares of the residuals

which may be calculated from the relationship:

$$\sum \epsilon_V^2 = \sum \left(T_n\right)^2 - \left\|\mathbf{b}_{\mathbf{ij}}\right\| * \left\|\left\|\mathbf{m}_{\mathbf{nj}}\right\|^T * \left\|\mathbf{T}_{\mathbf{n}}'\right\|\right\| \quad (8)$$

We can use the similar relationships for calculating of calibration coefficients of bending moment and their probable error of estimate.
Only suitable placed strain gauges were used in all cuts and these were summarized. Next the bending moment was calculated and calibration coefficients were determined from applied calibration force:

Cut	C3	R3	R5	R7	R8
Coeff. Mo	18,73	22,98	16,08	13,29	5,08
Coeff. T	-18,02				

Tab. 1 Calibration coefficients in each cut along wingspan

Probable error of estimate of shearing force and bending moment are in Table 2.

	C3	R3	R5	R7	R8
P.E.(bmo)=	0,103	0,135	0,100	0,108	0,071
P.E.(bT)=	0,221				

Tab. 2 Probable error of estimate of shearing force and bending moment

Now we can write equations in each cut for calculating of shearing force and bending moment with appropriated probable errors:

$$T = (-18,02 \pm 0,22)(m_{t1C3} + m_{t2C3}) \quad (9)$$

$$M_{OC3} = (18,73 \pm 0,10) m_{C3} \quad (10)$$

$$M_{OR3} = (22,98 \pm 0,14) m_{R3} \quad (11)$$

$$M_{OR5} = (16,08 \pm 0,10) m_{R5} \quad (12)$$

$$M_{OR7} = (13,29 \pm 0,11) m_{R7} \quad (13)$$

$$M_{OR8} = (5,08 \pm 0,07) m_{R8} \quad (14)$$

where $\boldsymbol{m}_{..}$ is a response from given cut

For bending moments calculating were used calibration coefficients calculated this way.

1.2 Measured Data

Totally there were done 26 in flight measurements with different conditions (different load factor, speed and others) with continuous data recording. Data were recorded with sampling frequency 25 samples per second. Measured data was recorded from internal memory of data acquisition system ESAM Static. From each performed flight there was taken a part of data where the needed values were correct and some mean values were calculated from this part (Fig 5).

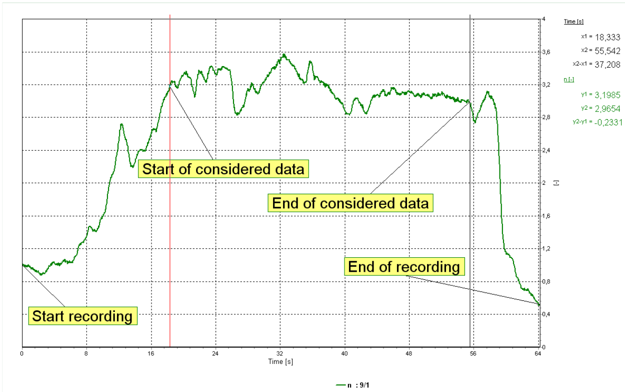


Fig. 5 Fundamentals of choosing measured data (needed load factor 3)

Calculated bending moment and shearing force was compared with measured and calculated values. Typical graph of comparison is shown on Fig. 6.

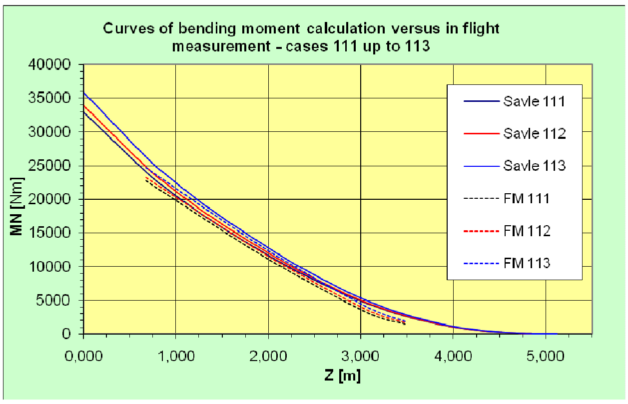
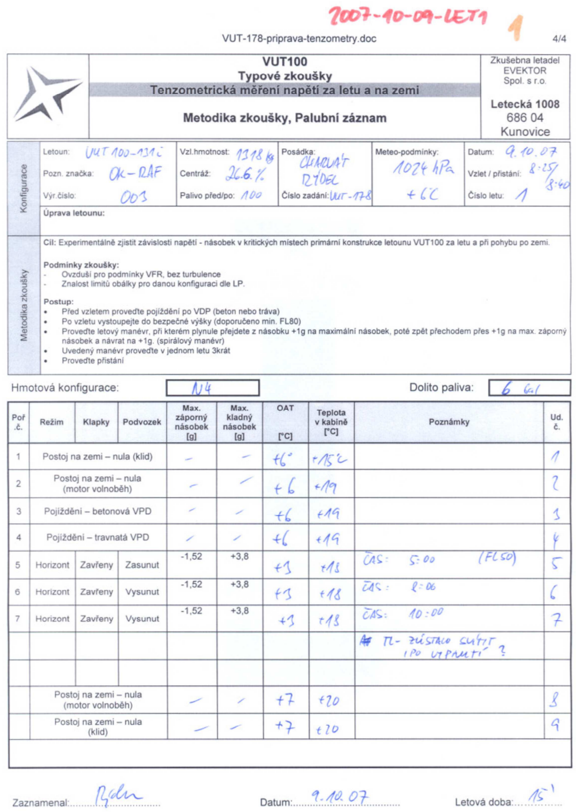


Fig. 6 Comparison of calculated bending moment with measured bending moment

This way I confirmed calculating methods using in a company that aircraft produce and methodology of measurement of bending moments too.

2 In Flight Strain Measurement

For the strain measurement there was used totally 15 strain gauges in cuts on the wing and midsection wing. The in flight measurements were done from minimal (-1,52) to maximal (3,8) load factor in different weight configurations. Totally were performed 22 in flight measurements at 4 weight configurations. Typical flight plan is on Fig. 7.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VUT-178-priprava-tenzometry.doc 4/4

	VUT100 Typové zkoušky Tenzometrická měření napětí za letu a na zemi Metodika zkoušky, Palubní záznam	Zkušebna letadel EVEKTOR Spol. s r.o. Letecká 1008 686 04 Kunovice

Konfigurace

Letoun: VUT 100-131i	Vzl.hmotnost: 1318 kg	Posádka: CHARVÁT RYDEL	Meteo-podmínky: 1024 hPa	Datum: 9.10.07
Pozn. značka: OK-RAF	Centráž: 26.6 %			Vzlet / přistání: 8:25/8:40
Výr.číslo: 003	Palivo před/po: 100	Číslo zadání: VUT-178	+6°C	Číslo letu: 1

Úprava letounu:

Metodika zkoušky

Cíl: Experimentálně zjistit závislosti napětí - násobek v kritických místech primární konstrukce letounu VUT100 za letu a při pohybu po zemi.

Podmínky zkoušky:
- Ovzduší pro podmínky VFR, bez turbulence
- Znalost limitů obálky pro danou konfiguraci dle LP.

Postup:
- Před vzletem proveďte pojíždění po VDP (beton nebo tráva)
- Po vzletu vystoupejte do bezpečné výšky (doporučeno min. FL80)
- Proveďte letový manévr, při kterém plynule přejdete z násobku +1g na maximální násobek, poté zpět přechodem přes +1g na max. záporný násobek a návrat na +1g. (spirálový manévr)
- Uvedený manévr proveďte v jednom letu 3krát
- Proveďte přistání

Hmotová konfigurace: N4 Dolito paliva: 6 Gal

Poř .č.	Režim	Klapky	Podvozek	Max. záporný násobek [g]	Max. kladný násobek [g]	OAT [°C]	Teplota v kabině [°C]	Poznámky	Ud. č.
1	Postoj na zemi – nula (klid)			–	–	+6°	+15°C		1
2	Postoj na zemi – nula (motor volnoběh)			–	–	+6	+19		2
3	Pojíždění – betonová VPD			–	–	+6	+19		3
4	Pojíždění – travnatá VPD			–	–	+6	+19		4
5	Horizont	Zavřeny	Zasunut	-1,52	+3,8	+3	+18	ČAS: 5:00 (FL50)	5
6	Horizont	Zavřeny	Vysunut	-1,52	+3,8	+3	+18	ČAS: 8:06	6
7	Horizont	Zavřeny	Vysunut	-1,52	+3,8	+3	+18	ČAS: 10:00	7
								TL- ZŮSTALO SVÍTIT I PO VYPNUTÍ ?	
	Postoj na zemi – nula (motor volnoběh)			–	–	+7	+20		8
	Postoj na zemi – nula (klid)			–	–	+7	+20		9

Zaznamenal: Rydel Datum: 9.10.07 Letová doba: 15'

Fig. 7 Typical flight plan

From this measurement the maximal strain (stress) was established for each cut and then recalculate on load factor n = 1. In Aircraft Testing Facility at Institute of Aerospace Engineering we realized a static strength tests both the wing and fuselage of the same aircraft as we tested in flight.

This way we get tree sources of strain and stress and we could prepare a fatigue test of connection between the wing and center wing (see Table 3). For this fatigue test there were used only spar from all wing structures. Strain gauges were installed on the same places as on the flying aircraft and then we could easily to set up the fatigue test correctly but during the tuning the right values of the strain in each cuts we found problems and the five loading forces had to by dramatically changed to get a good values on the strain gauges.

Cut R3	In flight meas. [MPa]	Strength test meas. [MPa]	Calculating [MPa]	For fatig. test [MPa]
Upper hinge	-9,5	-25,0	-16,5	-17,0
Lower hinge	14,5	20,5	14,4	15,0

Tab. 3 Input data for fatigue test (example for cut R3)

2.1 Fatigue Test

The test arrangement contains fifth hydraulic actuators for loading that were connecting to the collets. The test arrangement is on Fig. 8. The test specimen contains only main spars of the left, right and center wing. To elude the turning the spars, that spars were blockaded with one-directional vehicles.

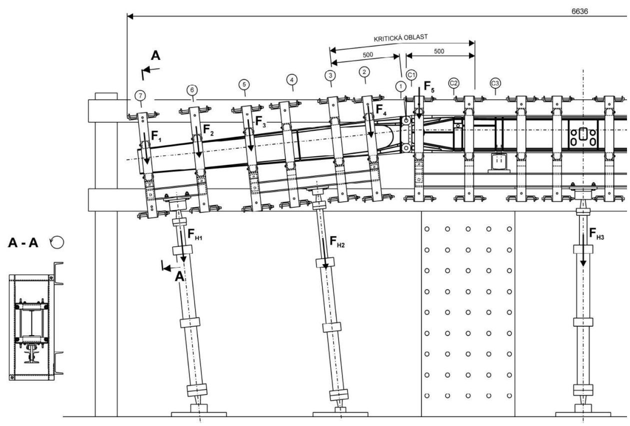

Fig. 8 Fatigue test arrangement

The forces at collets are shown in Table 4 for in flight case.

F_1	F_2	F_3	F_4	F_5
[N]	[N]	[N]	[N]	[N]
1730	1730	520	552	550

Tab. 4 Forces at collets

2.2 Spectrum of Loading and Loading Sequence

The load sequence was specified as a sequence of type flight by flight with stochastic order of loading levels. The sequence contains 216 flights which represents 144 flight hours if we consider that the average flight takes 40 minute. The main parameters of the test sequence are in Table 5.

Count of cycles		Count of cycles			Count of cycles	
guest + man.	total	guest + man.	rolling	total	guest + man.	total
[1]	[1]	[1/fl.]	[1/fl.]	[1/fl.]	[1/FH]	[1/FH]
5184	5400	24	1	25	36	37,5

Tab. 5 Main parameters of the test sequence

Spectrum of the gusts and maneuvers for the test were substituted by 11 levels marked I to XI. Total count of cycles was about 750 cycles per flight hour. Needed shortening was done by cutting out of the cycles from the lowermost levels X and XI to get optimal length of the test. A modified spectrum used for the testing is shown on Table 6.

Loading level	n_h	n_d	Frequency	Cumulative frequency
	[1]	[1]	[1/sequence]	[1/sequence]
I	4,500	-1,12	1	1
II	4,315	-1,02	1	2
III	3,946	-0,83	3	5
IV	3,585	-0,64	5	10
V	3,249	-0,49	13	23
VI	2,890	-0,32	32	55
VII	2,533	-0,15	103	158
VIII	2,170	0,05	446	604
IX	1,812	0,27	4580	5184

Tab. 6 Spectrum of the gusts and maneuvers

Rolling sequence was substituted with stepwise form with eight levels containing 620 cycles per hour (Table 7).

Δn	Frequency	Cumulative frequency
[1]	[1/sequence]	[1/sequence]
0,543	1	1
0,508	11	12
0,432	123	135
0,354	1089	1224
0,276	6833	8057
0,198	27035	35092
0,120	57236	92328
0,042	41592	133920

Tab. 7 Rolling spectrum

There were planed an inspection during the testing. All inspections were done by direct visual method only.
After all 30th finished loading sequence was strain measurement done with step of 0,25g up to +3g and -1g.
The fatigue test is continuously running from April 2009 up to these days (June 2010) and during the inspection we found a three fatigue cracks. Now we are watching the speed of the propagation of the cracks.

3 Conclusion

If we look at the test setup (Fig. 8 and 9) we can see that the test takes a very small space in a testing laboratory but needed preparations (vehicles and collets) are too much.

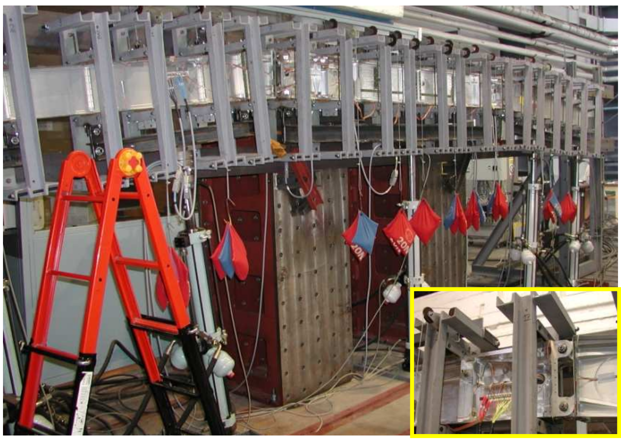

Fig. 9 Real test arrangement

In the Table 8 there are advantages and disadvantages of this type of test. Between other possibilities of the test arrangement is only using complete structure of the center wing and outer wings.

	Advantages	Disadvantages
Only the center spar with wing spars	a little needed space in a testing laboratory	many preparations (vehicles) for the test
	easy inspection	not the best system of loading
	lower price for the specimen	necessity to tune the test on the right strain
Whole structure of the wing	better conformity with real structure	higher price for the specimen
	easy loading of all loads component	problem with substitution of the fuselage (stiffness and others)
	lower number of the test preparations	poor inspection possibilities

Tab. 8 Advantages and disadvantages of the testing procedure

Process of the fatigue testing of the wing of a small fourth seats aircraft or any similar is shown on Fig. 10. This proposed procedure is suitable as a complete (static and fatigue) certification tests under the civil aircraft authority. It depends on the money placed for the testing but some parts should be omitted. For example the validation of the calculation methods it is not necessary to do it.

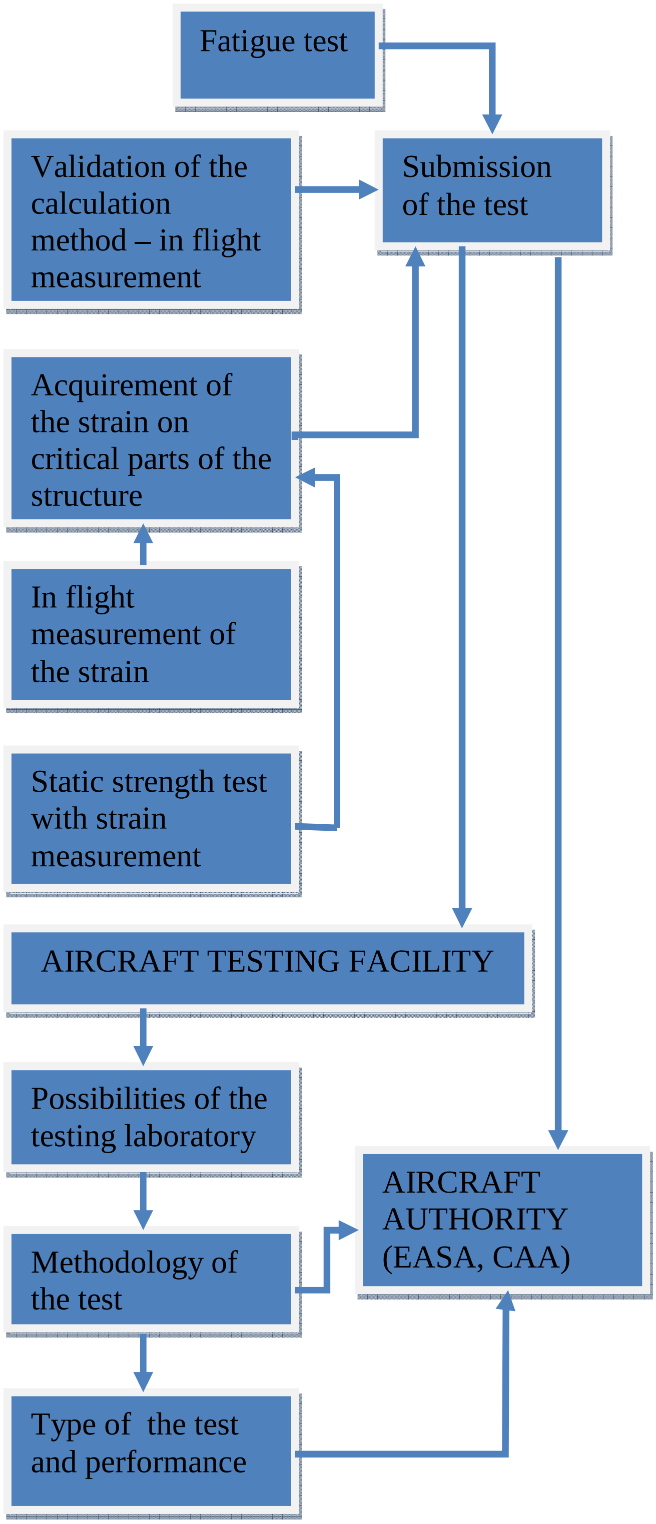

Fig. 10 Process of the fatigue testing of the wing

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