ACOUSTIC EMISSION OF COMPOSITE WING SEGMENT DURING FATIGUE TESTS

Jaroslav JURACKA
Brno University of Technology, Institute of Aerospace Engineering
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Abstract

Acoustic emission is a technique to monitor defect formation and failures in structural materials used in services or laboratories. Moreover, the method has been developed and applied in numerous structural components for monitoring and failures localization.

Article describes fatigue tests of wing segments and static wing test and their results. Mainly the process and results of monitoring by acoustic emission are described.

Possibility of method application on large structures, advantages and disadvantages are presented.

1 Introduction

The Institute of Aerospace Engineering of Brno University of Technology takes a share in development of several airplanes in the framework of its research and development activities. Composite sailplane from the HPH, ltd. company from Kutna Hora, Czech Rep. marked as 304S was one of them. This sailplane development demanded a number of technological and construction changes as well as number of development and certification tests realized such small company with difficulties. Therefore the Institute of Aerospace Engineering participated in the wing construction development as a certified laboratory implementing structural tests of wing segments and whole wing structure test after all. Acoustic emission was also a part of development tests as an NDT method for structure state monitoring. Application of this method should have confirmed its applicability for global structure monitoring, localization of structure critical areas and structure state description. The test program was entered with the knowledge of the acoustic emission method, experience on metal structures, but with limited experience on composite structure. Another reason for application of this method was a faulty experience with application of ultrasound for combination of GFRP and CFRP on structures.

2 Description of tests

The wing root segment was manufactured after the wing construction was designed for preliminary load and with respect to previous experience. This choice reflects the experience with frequent compressive failures of upper flange in a root area of the wing as a result of secondary loading caused by stiffness difference between the GFRP web and CFRP flange and sudden change of shear force caused by the cantilever.

Therefore, three wing root segments were manufactured and subsequently tested during the technological process development. The tests series included the static-loading test of the segment at elevated temperature, fatigue-loading tests of two segments (with regard to different loading spectra). Finally the whole wing was manufactured and tested.

2.1 Static load test of specimen X-05

Test specimen mark X-05 was attached to the fixing jig and segment tip was supported. The fixing jig enabled to test just one half of the wing with cantilever without a assembling with the other wing half. This test arrangement allows through a hinge at the end of the fixing jig produced complex specimen loading (bending moment and shear force) by just one loading force.

Strain gauges and potentiometers were attached for measuring of strains and wing deflections. The segment was heated to 54°C and then tested. The test confirmed a load-carrying capacity 154% of limit load.

2.2 Fatigue test of specimen X-06

Fatigue-loading test of wing segment marked X-06 run through period 09/2007-04/2008 and covered two fatigue test lives.

The specimen loading corresponded to stochastic spectrum coming out of spectrum KoSMOS2 modified by actual sailplane measurement results. Basic life consisted of 6000 flight hours divided into 17 blocks. Static measurements were done three times during the test together with wing deformation evaluation, each time at 80% of maximum loading for stiffness monitoring. The test was running at average frequency 0.4 Hz without a visible damage of specimen. The test was interrupted after the second life due to significant time demand.

On the specimen a system of acoustic emission sensors from DAKEL Company was attached. Measurement description is mentioned in chapter 3.2.

2.3 Fatigue test of specimen X-07

The test of specimen X-07 was passed through period 05/2008-06/2008 after the experience from previous test of specimen X-06.

The specimen was loaded by a constant amplitude spectrum with coefficient of asymmetry $R = \frac{-2.613}{5.57} = -0.47$, where the maximum forces corresponded to the maximum positive and negative limit loads of wing. The test was running at average frequency 0.15 Hz. The final number of test cycles was 60 576, when the lower flange was pulled out of the cantilever (i.e. failure of bonded joint web-flange at the cantilever area).

This specimen was also monitored by system of acoustic emission. Results are described in chapter 3.3.

2.3 Wing static test (specimen S-08Z)

The static-loading test of wing structure was prepared on February 2010 after the previous experience and with knowledge of previous segments tests results with a goal of proving the static load carrying capacity of structure.

Monitoring by a set of acoustic emission sensors was done in a framework of this test with a goal of detail description of structure progressive failure and localization of construction critical area. Also a using of method for fast failure was verified.

The specimen S-08Z contained inner and outer part of the left half of wing and was nine meters long. The root of wing was joined to the mounting bracket through a fixing jig. Loading force was primary generated by a hydraulic actuator at the end of the fixing jig and secondary by a crane through a load distribution system to the wing structure. Forces, deflection and strains were measured continuously during the test. The wing was monitored by acoustic emission currently by nine sensors.

First, the test up to limit load was performed at room temperature. Than the wing was preheated to 54 – 60 °C in heating chamber before the ultimate load test took place. The heating procedure was performed during seven hours before the test procedure. The heating box from polystyrene panels was assembled around the wing and temperature was raised and controlled by the heating unit. For better temperature control the box was divided into six zones along the wing span.

The loading sequence was performed at two steps. After opening the heating box the limit load was applied continually followed by short hold and than unloading. Then the load was increased up to the limit load with 3 seconds holding period again. Then the load was increased on ultimate load (150%) and then until failure occurred. After reaching of the ultimate load, the damage of construction occurred between collets number 7 and 8 as a result of technological defect in compressive flange.

3 Defectoscopy method and measurement equipment

Acoustic Emission, according to ASTM, refers to the generation of transient elastic waves during the rapid release of energy from localized sources within a material. The source of these emissions in metals is closely associated with the dislocation movement accompanying plastic deformation and the initiation and extension of cracks in a structure under stress. Other sources of Acoustic Emission are: melting, phase transformation, thermal stresses cool down cracking and stress build up.

3.1 Monitoring method description

The Acoustic Emission technique is based on the detection and conversion of these high frequency elastic waves to electrical signals. This is accomplished by directly coupling piezoelectric transducers (sensors) on the surface of the structure under test and loading the structure. For composite structures the sensors are mostly coupled to the structure by adhesive bonds. The output of each piezoelectric sensor (during structure loading) is amplified through a low-noise preamplifier, filtered to remove any extraneous noise and furthered processed by suitable electronic equipment.

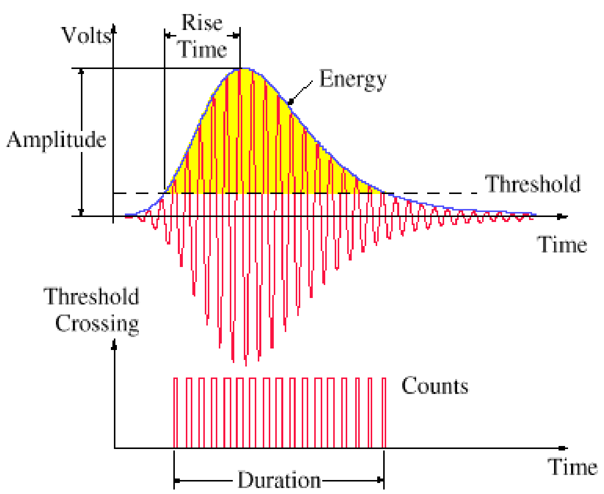

Fig. 1. The definitions for acoustic-emission events [2].

The instrumentation of Acoustic Emission must provide some measure of the total quantity of detected emission for correlation with time and/or load.

Figure 1 shows a burst AE signal and the commonly used parameters of AE techniques. When the AE transducer senses a signal over a certain level (i.e., the threshold), an AE event is captured (called as hit). The amplitude of the event is defined at the peak of the signal. The number of times the signal rises and crosses the threshold is the count of the AE event. The time period between the rising edge of the first count and the falling edge of the last count is the duration of the AE event (length). The time period between the rising edge of the first count and the peak of the AE event is called the rise time. The area under the envelope of the AE event is the energy [2].

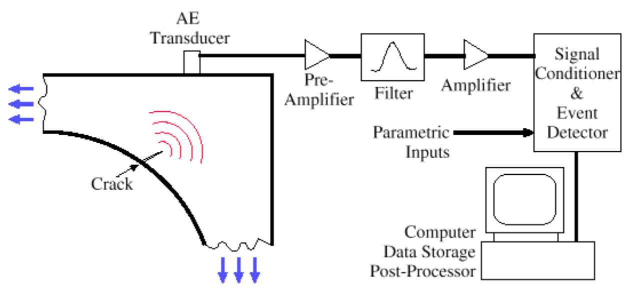

Fig. 2. A typical AE system setup [2].

Figure 2 presents a typical AE system setup. The AE transducers are generally very sensitive piezoelectric sensors. Because the traditional AE technique only uses AE features, the actual waveforms are not critical to this method. During investigations, other parameters, such as load, deformation, pressure, and temperature, can also be recorded as parametric inputs for interpretations.

3.2 Measurement equipment

The realized measurement was done by a system DAKEL-XEDO-3, designated for measuring and evaluating of AE parameters, localization of AE sources and digital recording of emission events (hits). It is a modular system which can be connected with almost every PC via Ethernet connection. The device can be easily extended without any software or hardware modification and thus connected with other measurement systems with unlimited number of units. Wide range of automatically associable modules (pulsars, parametric inputs, operating outputs, tensometric modules, low frequency modules for acoustic and vibration measurement) extend system application possibilities significantly. Every measurement channel does emission signals sampling in addition to measuring of acoustic emission basic parameters. Therefore, it can be used as transient effect recorder (storage oscilloscope).

Measuring channel unit XEDO-AEv32 enabling connection of passive piezoceramic sensors without preamplifier or active sensors with integrated preamplifier is the base of the system. The principal of system measuring activity is: analogue signal from the sensor is increased in the amplifier after filtration and is converted into 10 bit A/D convertor input. Following signal processing goes exclusively in digital form in programmable gate array, where threshold crossings are tested and emission events detected.

Fig. 3. Measurement data unit XEDO-AEv32.

Control software (DeaMon) is designated for configuration and controlling of attached channels, it also performs and controls the data collection, display and storing. An analysis of general noise background is the basis of parameters evaluation. Following parameters are available in Xedo system for this purpose: number of threshold crossings for two adjustable threshold levels (Count1 and Count2) and time averaged AE signal (RMS).

The system also evaluates a number and shape parameters of AE events, which exceed common background noises:

- Time of event beginning
- Event duration
- Number of threshold crossings for two thresholds levels during the event
- Maximum amplitude
- Risetime
- Number of threshold crossings for two thresholds levels until a maximum is reached

AE event can be localized by evaluation of time data from multiple sensors. A user of Xedo system can control the measuring process, display of mentioned parameters and storing frequency by the DeaMon software. The sw also enables calibration and automatic setting of measuring channel units.

DeaShow software is used for graph creation and measured data evaluation. It enables processing as export of binary files, time dependency graph creation and localization of AE sources measured by AE sensors.

The graphs contain a legend (see Figure 4), from which the source of displayed data can be recognized. In the frame the first line contents a date and time of time axis beginning. Time axis is then described relatively to this point. Next lines describe the data series. First two numbers separated by a dot identify a measuring unit, from which the data come from, in format BOX.SLOT. Data type identification follows after the next dot: c1 and c2 = counts on corresponding threshold level, rms = time averaged signal, evn = registered hits, ain = analog input.

3.3 Results on X-06 specimen

AE sensors were attached to the wing skin in the root area of the wing segment by Loctite glue. Sensors placing are apparent from figures 5 and 6. The whole measuring chain function was verified by internal pulse source after assembling the measuring device. Velocities of acoustic waves and ability to localize an AE source were verified by pentests (lead HB, diameter 0.5 mm).

The greatest velocity (8720 m/s) was measured in the direction of wing axis in the area of stiffened carbon spar between the sensors. The lowest velocity (2308 m/s) was measured in the direction perpendicular to the wing axis between the sensors.

The monitoring runs continuously during the wing segment fatigue test. Results of evaluation by DAKEL-XEDO-3 were observed and stored during the fatigue test. Observed quantities were Count1, Count2, RMS and acoustic emission events localization between selected pairs of sensors.

A filtration of localized events was done for next evaluation in dependence on force time behavior. Localization maps and trends for defined intervals of loaded force were available (as example see Figure 6). Emission sources were relocating in the observed part of wing segment during the time. Acoustic emission of each source was characterized by increase of events and following slow decrease of emission events. The highest rate of localized events,

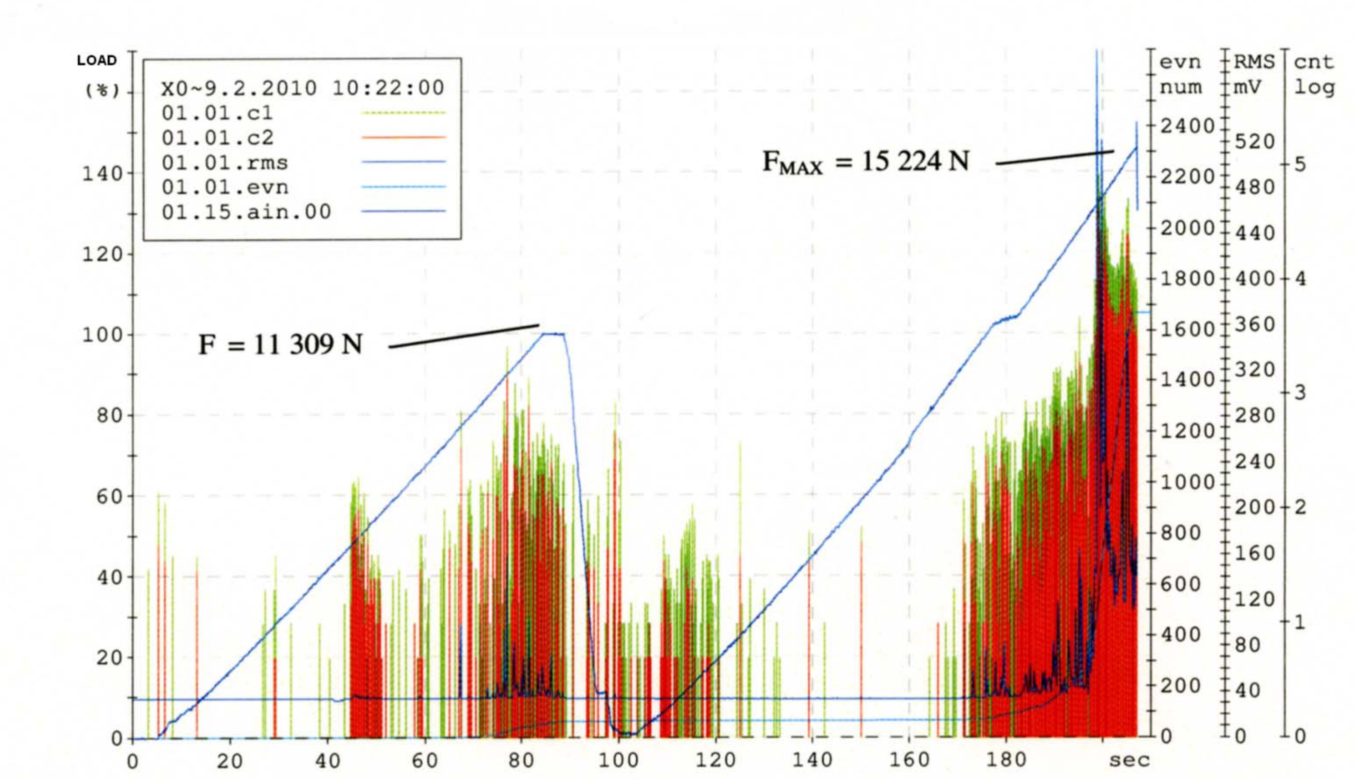

Fig.4. Time record of hits, record with Count1, Count2, RMS and acoustic emission events

After the beginning of the fatigue test it was obvious that detectable acoustic emission events are occurring after exceeding force values already reached during past stiffness test. This phenomenon is well known and is called the Kaiser effect. Localized events had greater amplitude during the beginning phase of fatigue test and at higher forces; they were short with a short risetime.

The evaluation included primary emission sources localization, definition of time trends of localized emission sources in the regions of localized map and observation of events occurring in the time period.

occurred during higher values of loading force, was observed in the scope of localization map grid in G area near the root on the upper wing skin. It amounts to 2054 events. Localized events distribution in the wing main spar (see Figure 7) corresponds to the occurrence of three emission sources in the surrounding of carbon flanges of wing main spar.

3.4 Results on X-07 specimen

Measuring and evaluation was consistent with X-06 specimen. In addition, the filtration of hits was done for loading force lower than 10 kN and higher than 25kN. Discovered emission sources were not significant and they were identified during the initial and middle phase of test. Therefore, they are not emission sources connected with the wing destruction.

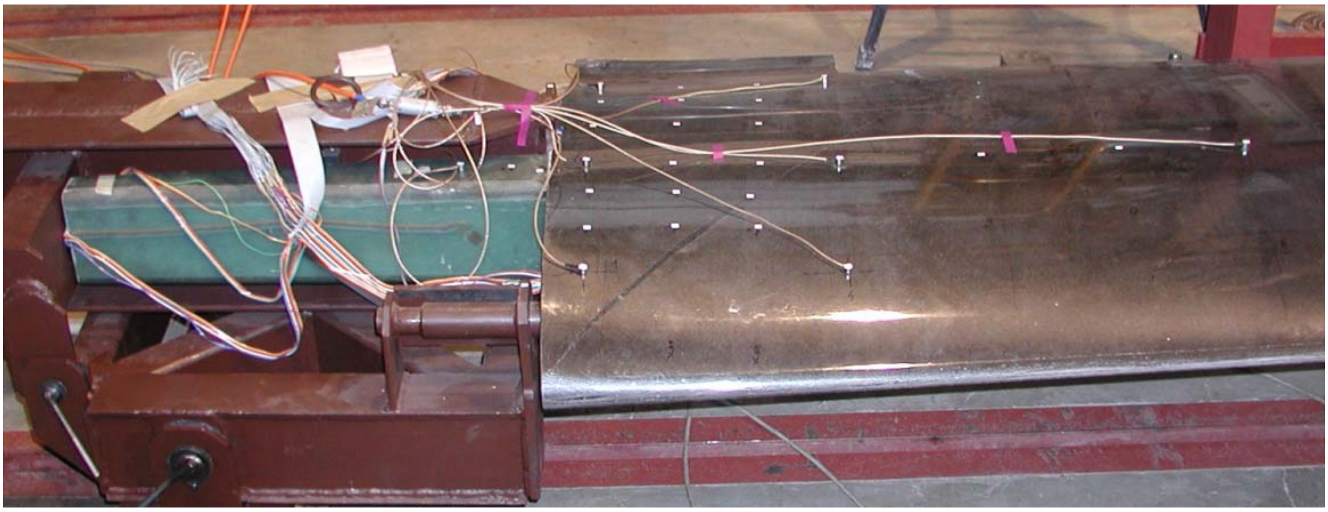

Fig. 5. Sensors position on specimen X-06.

Localization maps between the sensors on the upper and bottom side of spar are on Figure 8. In both cases of filtration the sources appears to be near the sensor 9 on the bottom skin. It is also important to mention that these maps can be affected by a high inaccuracy with respect to high dissipation of acoustic waves or decrement of velocities between sensors on upper and bottom skin and high acoustic signal absorption because of construction design of the spar. Emission events registered on the bottom skin between the sensors 9 and 12 also occurred.

Only the times of detection and their differences between each sensor are used in the program DeaShow for a localization of emission sources (with 1µs accuracy). Parameters of all hits from all sensors are stored in the memory (time of beginning, duration, maximum, risetime, counts, number of counts until maximum reaching).

Theoretically, it is possible to use the set of parameters of AE to identify particular sources, which correspond with certain mechanism of construction degradation and in consequence even to make the localization more accurate. A set of AE parameters from the sensor 9 on the bottom skin was used as a basis. Sensor 9 is closest to the area of spar collapse and also to emission source evaluated by the standard procedure. We also assumed a separation of hits, which were detected in according with the wing structural failure and identification of their parameters, i.e. duration of event (length), rise time of maximum amplitude (rise) and maximum amplitude (max). Suspected result of sorting the hits from the sensor 9 was a fact that some group according to mentioned parameters will be localized together with unsorted events from other sensors into one area.

Also a standard clustering algorithm with expectation maximization from software WEKA 3.5.7 was applied on 390 chosen events. This software compared to other algorithms provided the strongest allocation into six clusters.

Emission events from particular clusters were used for a standard localization with a complete set of events from other sensors, both unsorted and sorted for condition of force higher than 25 kN. However, the results are not very significant with respect to the number of localized events. More likely, they imply a possible relevance.

The system DAKEL-XEDO also stores a synchronized data from an external channel – in this case the time behavior of the loading force. It is possible to obtain information about context of loading force and emission events occurrence.

An algorithm, which assigns a magnitude of the loading force to each emission event at the time of its detection, was created. We obtain in coordinates time vs. loading force “star charts”- with emerging “nebulae” - belts with higher events concentration. These belts with higher concentration of AE events get decline after their detection in the next time behavior. This analysis was done for the last hour of the test first (Figure 9 for sensor no. 9).

is happening at lower magnitudes of loading force during the cycling, until they disappear. Evidently, there is a stress redistribution happening in the loaded construction and degradation process is relocating. Results from

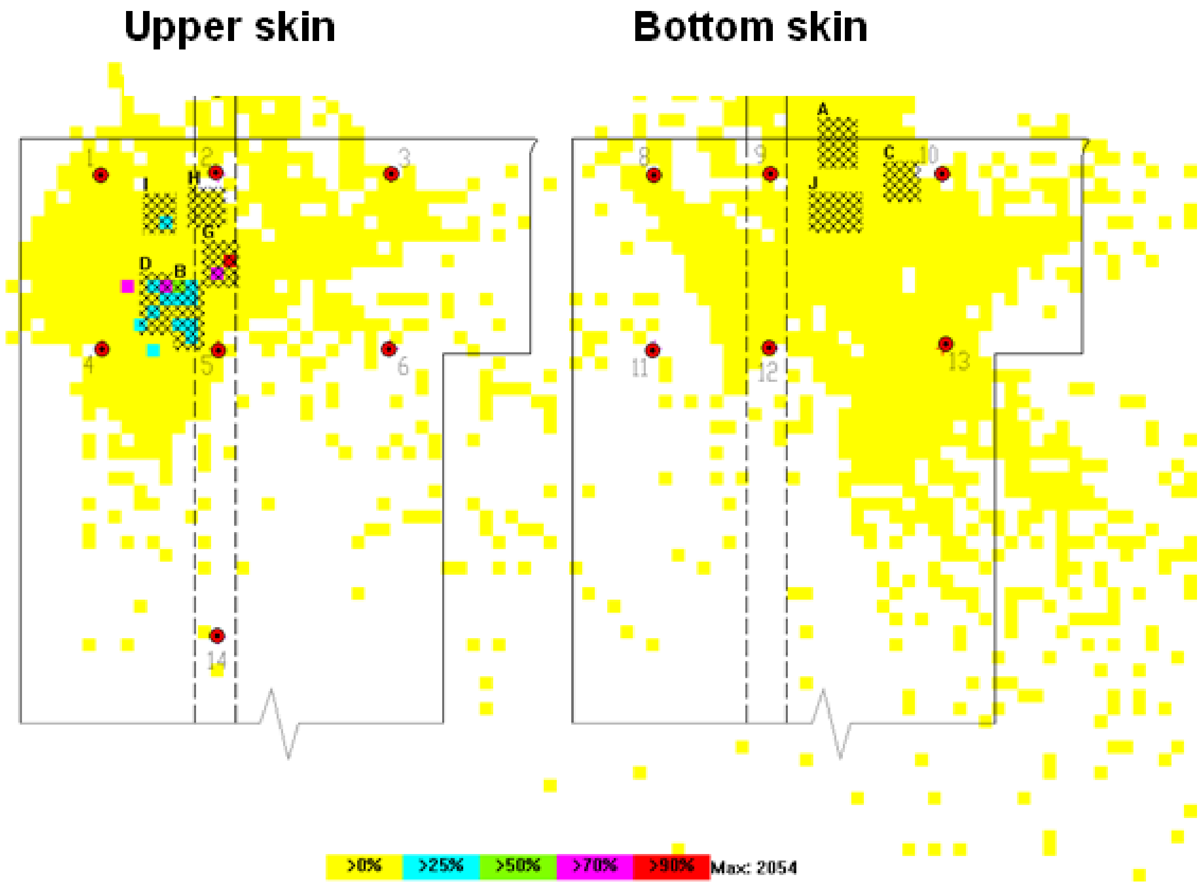

Fig. 6. EU localization map for of X-06 segment.

Sets of emission events were highlighted in color belts and these sets were used again for the standard localization with complete data from other sensors. It appears that red set (maximum force ~26kN) is jointed with the spar structural failure. Green, blue and dark green sets are then joined with the area of the front pin. Complete data from the whole measurement was processed in this way. Belts with higher AE concentration are also obvious here. After their detection they have mainly decreasing character (similar to the Wöhler curve) and they disappear after a certain number of load cycles. If these belts are derived by some kind of degradation process, this process

the test of specimen X-06 indicate the same observations.

3.5 Results on S-08Z specimen

Measurement on the static loaded wing was run in the same way as on previous specimens. Sensors placing are shown on Figure 9 together with the localization maps of emission events. Sensors were placed only on the upper skin. This placing was chosen for better description of degradation process but it appeared to be ineffective. Unfortunately, the wing failure occurred near the sensor 9 (between collets 7 and 8), i.e. in the area of maximum sensors distance.

It was not possible to evaluate the Kaiser effect from the comparison of the first loading up to limit load and repeated loading because of change of temperature condition from 20°C to 54°C. Although, it is obvious that emission activity has higher intensity already at 80% of load and temperature has negative effect.

The lowest emission activity was observed at sensor 9, where the parameters are more than two orders lower compared to other sensors.

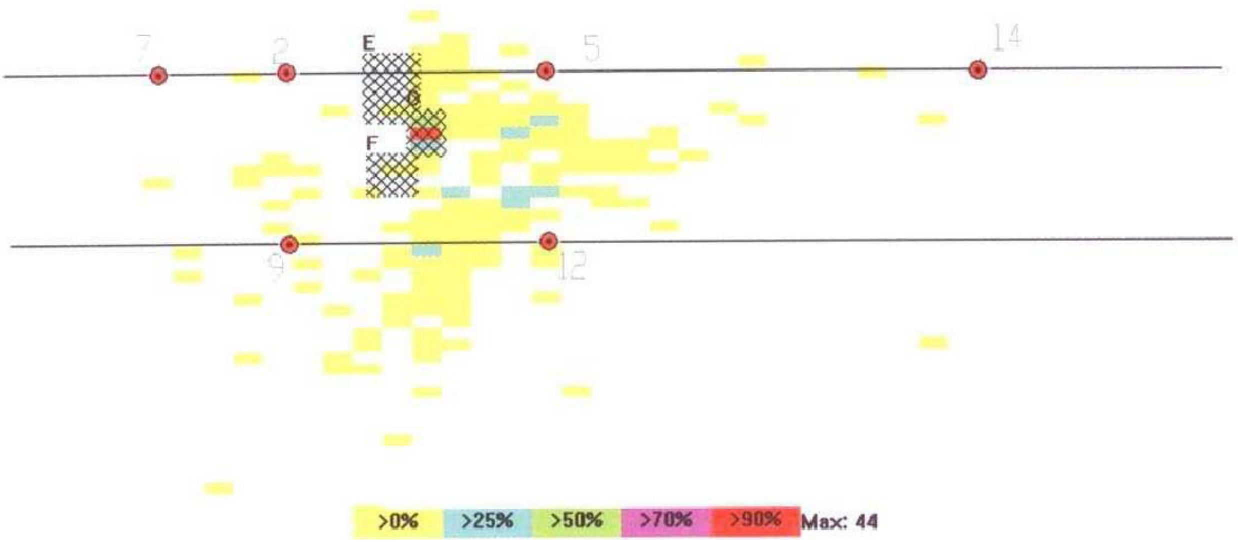

Fig. 7. EU localization at spar of X-06 segment.

During the second loading cycle (until failure) we can observe an upraise of emission activity at 90% of limit load. This is weak Felicity effect, which shows that wing degradation process continued. We can assume the beginning of wing degradation process already before reaching the limit load. The localizations from all sensors are in Figure 10. There is also confirmed an emission source at the distance 700 mm from the wing root. The distribution of maximum amplitudes in dependence on their localization is on Figure 11.

4 Results discussion

Acoustic wave velocity is highly dependent on the measurement area. Anisotropy of acoustic waves velocity is observed on the wing skin. Orientation of the composite reinforcing material and local thickness are probably the reason. Acoustic waves spread 3.76 times faster along the carbon flange of the wing than on the wing skin. The ability to localize emission events is very good, which was proven by pentests.

The Kaiser effect was observed during the initial stage of the X-06 wing segment fatigue test. During the next progress, the quality of

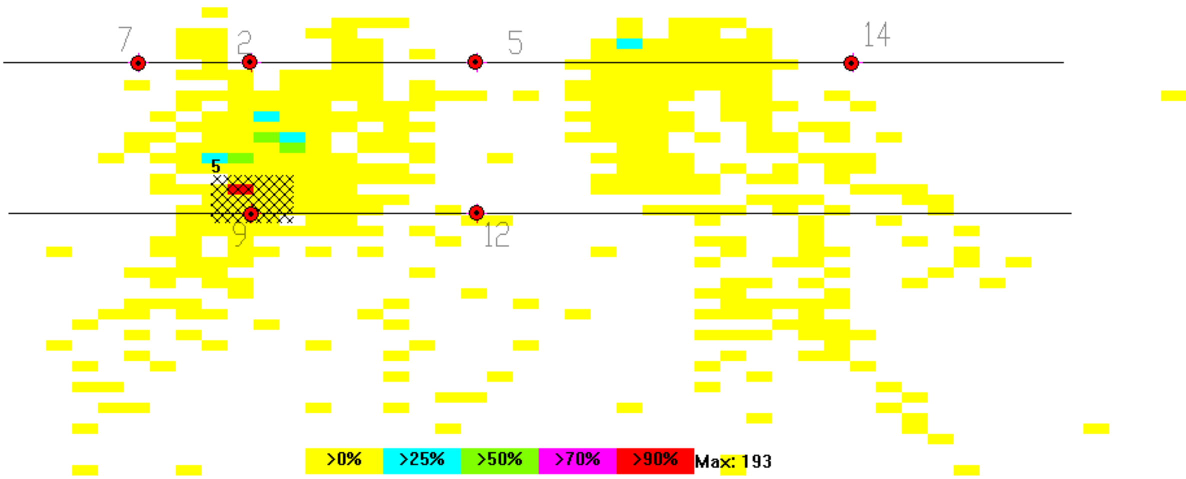

Fig 8. EU localization at spar of X-07 segment.

fixing jig friction joints was decreasing which was accompanied by higher emission activity. The highest number of localized events emitted at higher load levels was observed in the area of carbon flange of the main spar on the upper wing skin near the root. This area corresponds to the results of previous tests (specimens X-01 to X-04). Relocation of acoustic emission sources was observed during the realized part of the fatigue test (one third of planned durability). The acoustic emission occurrence at particular places of the localization map is characterized by increase and following decrease of emission count.

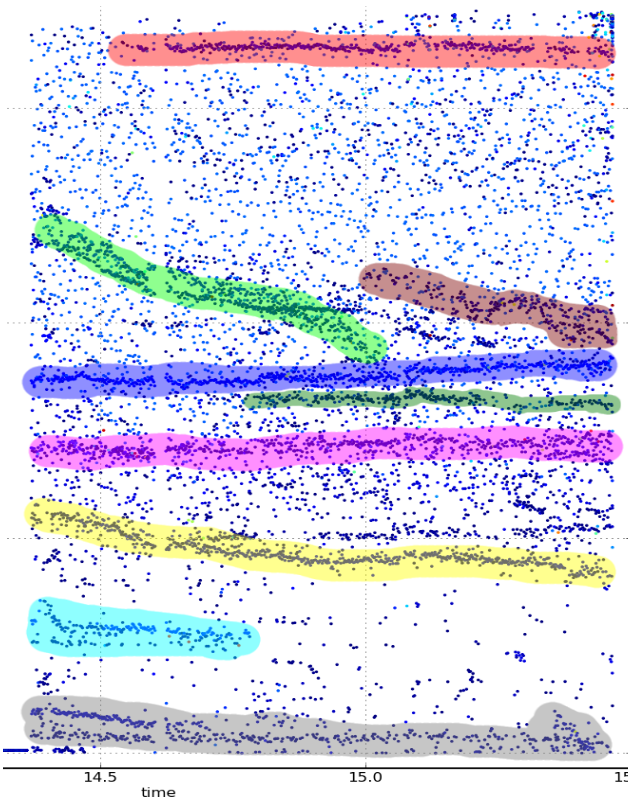

Fig 9. EU distribution at Chart load-time for X-07 specimen.

The X-07 results imply that high amount of emission events are generated when the loading force was passing the zero value, which is caused by a higher clearance in fixing jig joints. These emission events was localized on the whole observed area of the wing and they overlay emission sources connected with the construction makrofailures.

Emission sources evaluation is very demanding and time-consuming because of large volume of data files. It was necessary to use a filtration with regard to the loading force for better localization of failure area. Emission events were considered only when the loading force was higher than 95% of limit load. These events marked as “outliners” are massive with high maximum amplitude, long maximum amplitude risetime and long duration.

The procedures based on the cluster analysis enabled the separation of events connected with the loading mechanism and events connected with the final failure of the wing spar between the sensors 9 and 12.

Degradation processes are generated in certain areas of the wing construction during the fatigue test, they are followed by localized emission sources which gradually disappear after stress (deformation) redistribution and finally they are localized at a different area of the wing. This hypothesis is supported by a newly developed process of force-time correlation of detected events, which shows a generation of clusters and their disappearing connected with the decreasing force during the progress of the acoustic event. The last cluster was observed at maximum force of ~26kN just before the end of the test. At this case the decrease during the next progression was not observed and the wing structural failure followed.

Concerning the static test, the number of sensors was small for this type of strength test and area of the spar failure could not be localized exactly. The number of sensors would be sufficient, if the failure have occurred at the predicted area with a higher concentration of sensors. Optimum number of sensors for localization for this type of test is 30 to 35. Next, it would be suitable to use equipment enabling the complete sampling of AE signal with 2 MHz frequency with storing into PC for following analysis.

A significant emission source was evaluated at the distance 700 mm from the wing root (the same as on segments), i.e. on the main spar closer to the leading edge. With regard to the sharp increase of AE events number at this source we can say that the failure would probably occurred if the loading force kept rising.

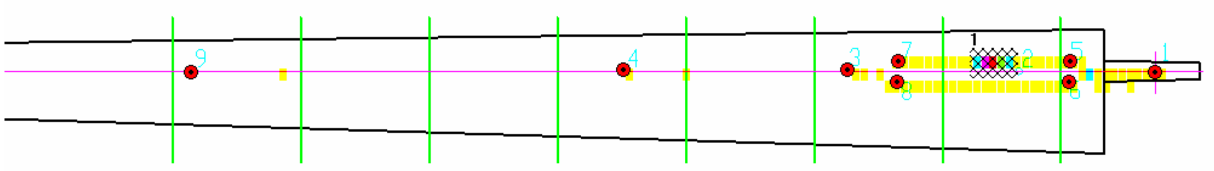

Fig. 9. Sensors position on specimen S-08Z with EU localization.

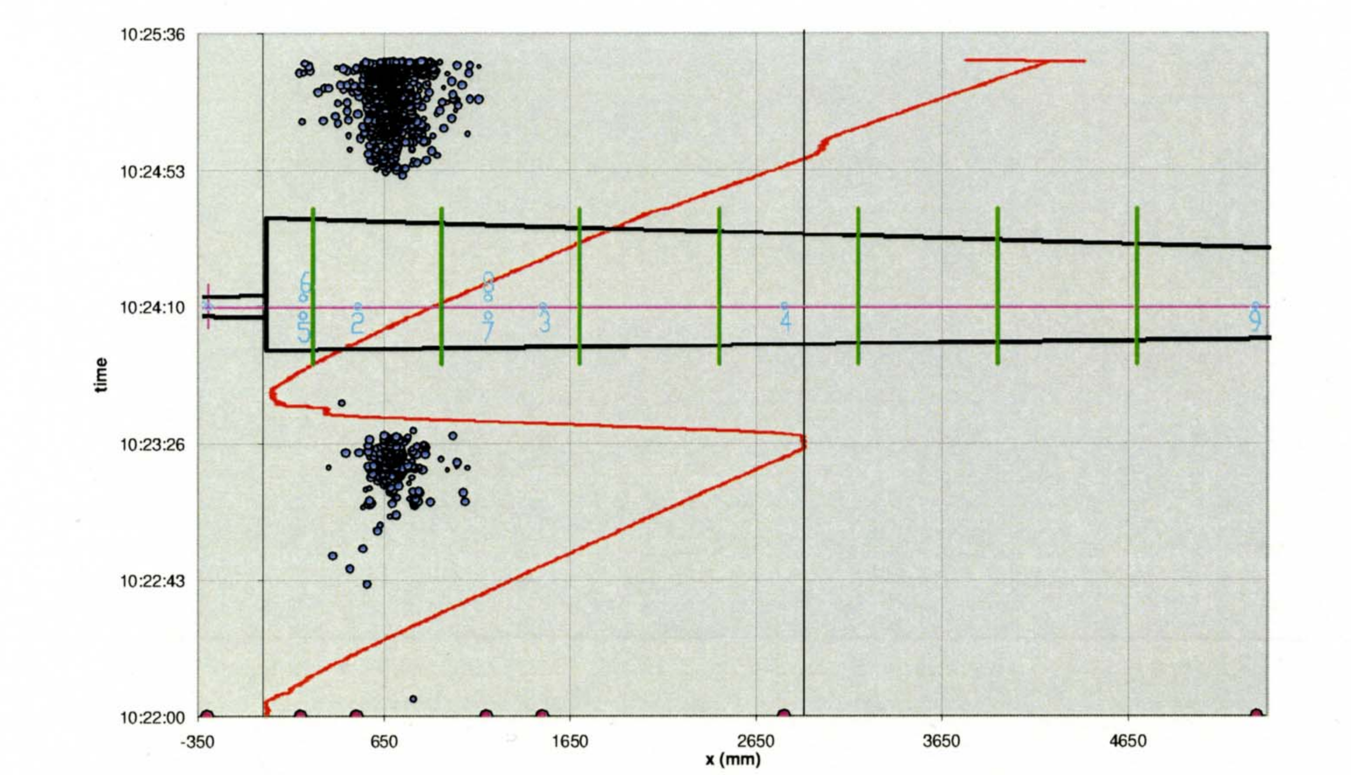

Fig. 10. EU amplitude distribution along wing.

5 Conclusion

In conclusion we can say that the method of acoustic emission can be utilized for large and complex composite structures monitoring. However, it is necessary to use higher concentration of sensors for satisfactory results. The evaluation of measuring outputs requires a work with a large volume of data.

6 References

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