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Acoustic Emission Monitoring of Thin Ply Hybrid Composites under Repeated Quasi-Static Tensile Loading

This paper investigates the applicability of the acoustic emission (AE) technique for identification of the damage onset and accumulation in S-Glass/TR30-Carbon hybrid laminates under repeated quasi-static tensile loading. The samples were made of 2 layers of unidirectional thin carbon prepreg plies which were sandwiched between 2 standard thickness S-glass prepreg plies. Analysis of the AE results shows that there are two types of events regarding energy and amplitude ranges of the AE signals. The signals with low values are found to be related to the delamination of the carbon/glass interface whereas the signals with high values are linked with the carbon layer fragmentation. There are more friction related AE signals during the unloading stage than the loading stage due to collision and rubbing between existing crack faces. Increasing the strain level increases the number of fragmentations and the AE technique is able to quantify this. It is concluded that the AE technique can be used to evaluate the number of fragmentations and can identify the damage evolution of the hybrid laminate under repeated quasi-static tensile loading.

Keywords: *Carbon/glass hybrid, Pseudo ductility, Acoustic emission, Fragmentation, Delamination.*

1. INTRODUCTION

Polymer matrix composites consist of fibres in a polymer matrix, where the high modulus fibres [1] overcome the low modulus and temperature limitations of the polymer; be reinforced with synthetic or natural fibers [2-5]. These reinforced polymers are strong and stiff and they have high specific strength and specific stiffness. In addition, they have improved fatigue resistance and higher creep resistance than similar structures made from steel [6,7]. As a result, reinforced polymers find extensive use in many fields [8-11], such as aerospace, automobiles, sports and corrosion-resistant equipment.

However, a fundamental and yet unsolved limitation of conventional high performance polymer matrix composites is their brittle and catastrophic failure. The failure happens with no significant damage or warning. As an example, the barely visible impact damage (BVID) caused by low-velocity impacts, such as bird strikes and tool drops [12], BVID can cause internal damage [13-15] (e.g. delamination) which is not visible from the surface. Therefore, structures that satisfy a visual inspection, can fail suddenly at loads much lower than expected. To ensure safe operation, currently a much greater safety coefficient is applied for composites, than for more ductile materials. These design limitations prevent the designer to regard composites as suitable for many applications in which there are unpredictable loading conditions and catastrophic failure is not accepted. Due to these limitations of currently available high performance composites, pseudo-ductile composites that can fail gradually are of exceptional interest and could potentially offer a notable increase in the applications of composites.

Hybridising different fibres and in many previous works, carbon and glass layers, is a successful approach to address the lack of ductility in composite laminates [16-20].

High performance carbon fibre composites offer exceptional stiffness- and strength-to-weight ratios, but suffer from brittle failure. Recently, gradual failure and pseudo-ductile stress-strain response were observed in carbon/glass composite materials [21-25]. Their results showed that as the failure strain of carbon fibres is lower than that of the glass fibres, the first damage occurs in the carbon layer and the following failure mechanisms in the specimen are influenced by the interfacial toughness, material properties, and the thickness of the layers. In those studies, it was observed that in pseudo-ductile laminates, made from hybrid of high modulus thin-ply carbon and standard thickness glass prepregs, delamination of the carbon/glass interface and fragmentation of the carbon layer were the main damage modes.

Characterising the damage modes which have caused pseudo-ductility can be useful to optimise the

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Received: March 2017, Accepted: December 2017
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doi:10.5937/fmet1802238F

design of more general layups. But the characterisation of these damage modes is a complicated matter, especially in thick and non-transparent laminates.

Acoustic emission (AE) as an online monitoring technique has good potential to identify active damage mechanisms.

The AE technique is the phenomenon of radiation of transient elastic waves (acoustic events) released by a sudden redistribution of stress in a material due to crack formation, plastic deformation, etc. This technique has been used by different researchers for damage characterisation of composite materials. Successful results have been reported for damage characterization of composite laminates using the AE parameters. Different frequency, energy and amplitude ranges were observed for different damage mechanisms such as fibre breakage, matrix cracking and delamination [26-32].

In our previous work, the AE technique was found to be an applicable method to characterise the damage mechanisms in thin-ply carbon/S-Glass laminates under tension loading [33,34]. It was found that energy and amplitude ranges of the AE signals are different for the pseudo-ductile damage mechanisms. The results were also verified by direct visual observations of the corresponding damage mechanisms.

The aim of this study is to investigate the applicability of the AE technique for identification of the damage onset and accumulation in S-Glass/TR30-Carbon hybrid laminates under repeated quasi-static tensile loading. For this reason, pseudo-ductile hybrid laminates were subjected to a repeated quasi-static tensile loading and the generated failure mechanisms were monitored using the AE technique.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

The utilised materials are standard thickness glass/ epoxy prepreg and thin carbon/epoxy prepreg. Table 1 gives more information on the characteristics of the prepregs. UD S-glass/913 epoxy prepreg with the fibre tensile modulus of 88 GPa and the fibre failure strain of 5.5% was used as the high strain material of the hybrid laminate. The low strain material is a thin carbon prepreg from SK Chemicals (South Korea) under the trade name of SkyFlex USN020A. The fibre failure strain and modulus of the carbon fibre are 1.9% and 234 GPa, respectively. More information regarding the prepregs are given in Table 1. K50 epoxy resin which is a SK Chemical's type resin is the corresponding matrix in the thin USN020A prepreg.

Table 1. Properties of the utilised prepregs.

Type of Prepreg	TR30/epoxy	S-glass/epoxy
Nominal thickness of the prepreg after curing (mm)	0.029	0.155
Volume fraction of fibre (%)	41	50

2.2 Specimen design

As illustrated in Figure 1, the lay-up was designed using the damage mode map [12] in order to have a combination of both stable delamination and fragmentation in the carbon layer. From Figure 1, different failure modes may occur by changing the percentage of the carbon layers thickness to the thickness of the laminate (relative thickness) and absolute thicknesses of the carbon layer. From Figure 1, the laminate was designed in a way to have fragmentation and dispersed delamination damage mechanisms. Due to the translucent nature of the glass/epoxy surface ply, the failure modes were observable and it was possible to correlate the obtained AE signals to the actual damage accumulation appeared during the test i.e., ply fragmentation and carbon/glass interface delamination.

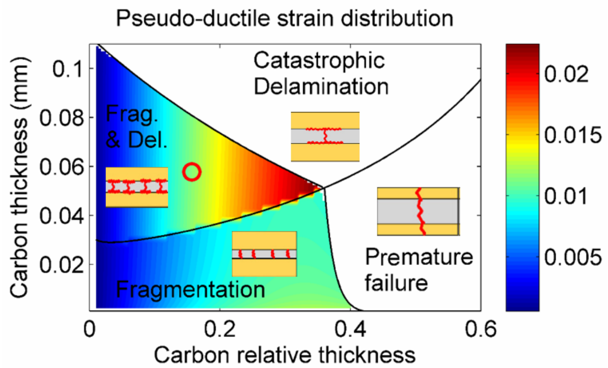

Figure 1. Pseudo-ductile strain distribution for the laminate made with 2 plies of TR30 carbon prepregs sandwiched between 2 S-glass plies.

The pseudo-ductile strain, as shown in Figure 2, is defined as the extra strain between the final failure point and the initial slope line at the failure stress level.

2.3 Specimen manufacturing

The laminate was fabricated by sandwiching 2 TR30 carbon plies between 2 S-glass plies. As the glass prepreg was translucent it was possible to observe the damage visually. The laminate was cured for 60 minutes at 125 °C and 0.7 MPa as recommended by the suppliers. A diamond cutting wheel was used to cut the specimens. Finally, 40 mm long tabs of glass fabric/epoxy were bonded to the ends of the specimens with a two component epoxy adhesive.

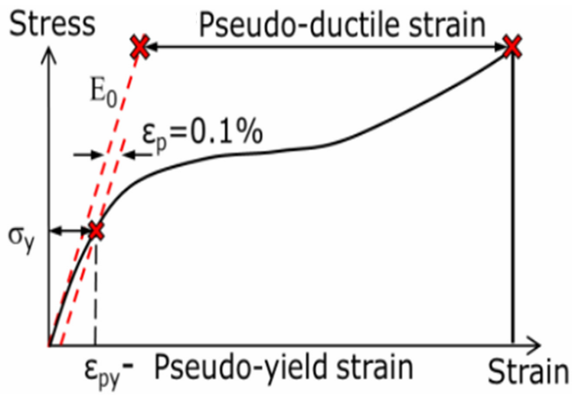

Figure 2. Schematic of the typical stress–strain graph of a thin-ply hybrid with pseudo-ductility.

The specimens tested within the study were parallel edge end-tabbed tensile specimens, as shown in Figure 3. Nominal specimen dimensions were overall length:

240 mm, gauge length: Lg=160 mm, width: W=20 mm, variable thickness: h for the UD sublaminates and overall length: 120 mm, gauge 12, length: Lg=64 mm, width: W=16 mm.

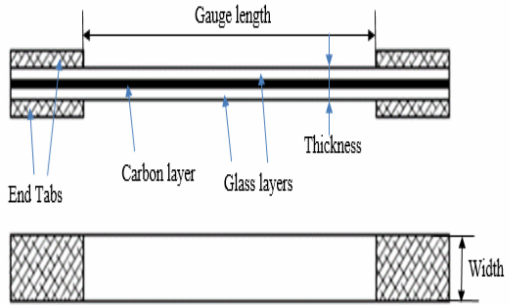

Figure 3. Specimen schematics.

2.4 Test procedure

Repeated quasi-static tests were carried out using a universal hydraulic computer controlled Instron 8801 with a 25 kN load cell. The test was conducted under displacement control at a cross-head speed of 2 mm/min for both the loading and unloading phases, with immediate reloading. Seven cycles were chosen, each with a certain displacement limit, after which the load returns to zero. The nominal length, width and thickness of the investigated specimens were 240, 160 and 20 mm, respectively. An Imetrum video gauge system was utilised to measure the strains by tracking the white points painted over a particular gauge length on the laminate face.

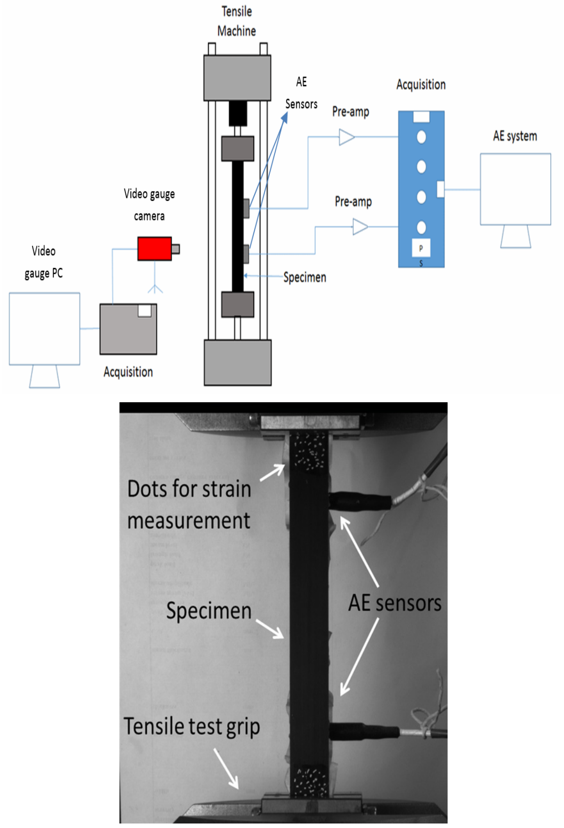

Figure 4. Schematic of the experimental setup, schematic and experimental picture.

A PCI-2 made by PAC Company was used to record the AE signals. The maximum sampling rate of the device was 40 MHz. The threshold and the gain selector of the preamplifier value were set to 40 dB. The AE sensors were two PAC R15 resonant-type and single-crystal with the frequency range of 20–900 kHz. The test sampling rate was 5 MHz. The surface of the sensor was covered with silicon grease to provide good acoustic coupling between the specimen and the sensor. The test sampling rate was 5 MHz. A pencil lead break procedure was used to calibrate the data acquisition system for each of the specimens. After the calibration step, the AE signals were recorded during the tests as illustrated in Figure 4. Schematic definition of the features of an AE signal such as duration, rise time, amplitude, energy and count are presented in Figure 5.

All tests were conducted under standard and stable temperature and humidity conditions to preserve the integrity of the coupons [35].

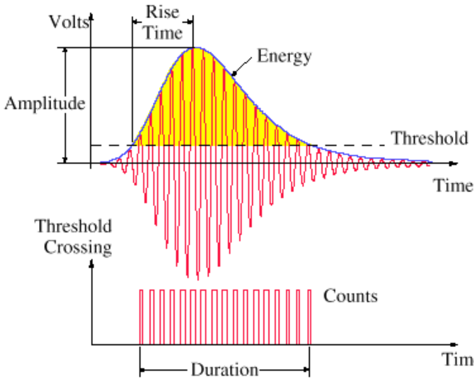

Figure 5. The definitions for acoustic-emission parameters [36].

3. RESULTS AND DISCUSSION

3.1 Quasi-static tensile test results:

Figure 6 shows a typical stress–strain graph and its relationship with AE energy for a typical hybrid specimen, whose loading was interrupted before the final failure. The graph shows that the specimen fails in the desired pseudo-ductile manner, with carbon ply fragmentation and stable delamination.

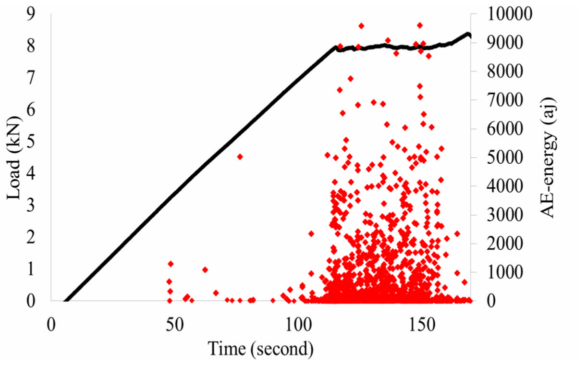

Figure 6. Stress–time and AE event energy distribution for a typical tested specimen. Red dots are showing the AE energies.

From Figure 6, AE events with different energy levels can be observed for different damage evolution. At the early stage of the loading process the load-time diagram is linear and there is no significant damage in the specimen. At this stage, there are some weak AE events that might be related to some micro-scale damage around the edges of the sample e.g. single fibres coming off the edge and/or grip rubbing effects. These damage mechanisms do not have a considerable effect on the specimen’s integrity.

The first significant AE energy signals were registered near the plateau where the onset of macroscopic damage happened. This means that the obtained AE signals that appeared in this region were due to fragmentation and dispersed delamination. The specimen’s appearance also changed from fully black to a tiger striped pattern, as shown in Figure 7. The well bonded areas appear black, and within the locally delaminated light areas, the cracks in the carbon layer are visible as sharp bright lines. The observed damage modes agreed with the expectations from the damage mode maps.

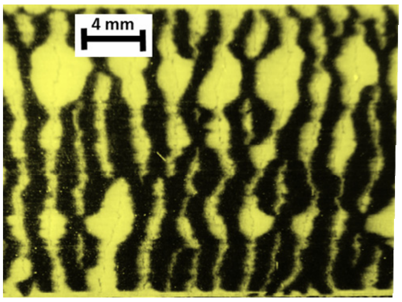

Figure 7. Microscopic images from the surface of a typical tested sample, interrupted before final failure, showing the fragmentation path and delaminated areas around the cracks.

3.2 Quasi-static cyclic tensile test results:

Figure 8 shows a typical load-strain curve for repeated quasi-static tensile tests of the investigated layup. The chosen strains, calculated from the video gauge were: C1: 1.33 %, C2: 1.63 %, C3: 1.89 %, C4: 2.07%, C5: 2.32%, C6: 2.71 %, and C7: 3.12 %, where C stands for “Cycle”. Until the third cycle, the applied strain is lower than the failure strain of the carbon layer (i.e. 1.9 %) and there is an appearance of a plateau in the fourth cycle, which then evolved in the other cycles. After the third cycle, there is a residual strain or permanent deformation at zero load and by increasing the strain level the initial tensile modulus decreases. The important factor responsible for the changes in the stress-strain diagram is the occurrence of delamination of the carbon/glass interface and the carbon ply fragmentation.

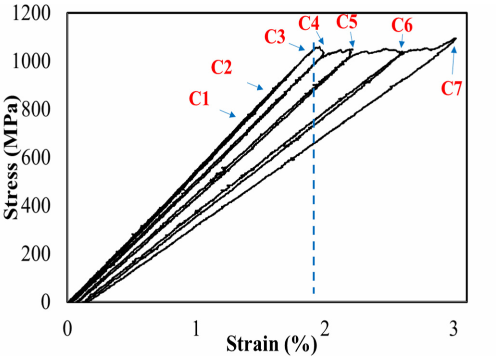

Figure 8. Stress-strain curve for a typical specimen subjected to cyclic loading. The dashed line corresponds to the damage initiation.

In order to extract more useful information about the damage mechanisms of the tested specimens, the AE technique was used. A previous study reported that it is possible to characterise certain mechanisms by studying the energy and the amplitude of the AE events during the damage accumulation [33,34]. It is concluded that higher amplitudes and energies represent fibre fragmentations, medium values are mostly in connection with delamination, while the lower ones are noise. It was found that delamination between the carbon/glass interface occurred between 60-85 dB amplitude and 30-800 aJ energy, while these values were 75-100 dB and 800-65000 aJ in the case of carbon fibre fragmentation.

Using this classification technique, the AE signals were separated into three clusters. The results are illustrated in Figures 9 and 10. As illustrated, the damage mechanisms are identified by the AE events with different energy and amplitude levels. The clear and significant AE events start when the plateau on the stress-strain curve begins. There are also some fragmentation and delamination related events before cycle 4, due to the relaxation of the internal stresses developed due to issues such as free fibres at the edges of the specimens.

Around the peak loads there are higher intensity AE signals, whereas the lower amplitude and energy signals appear between the load peaks as well as when unloading the sample. The lower intensity signals, i.e. the noise, could be friction due to existing damage mechanisms. There are more noise related AE signals during the unloading stage than the loading stage.

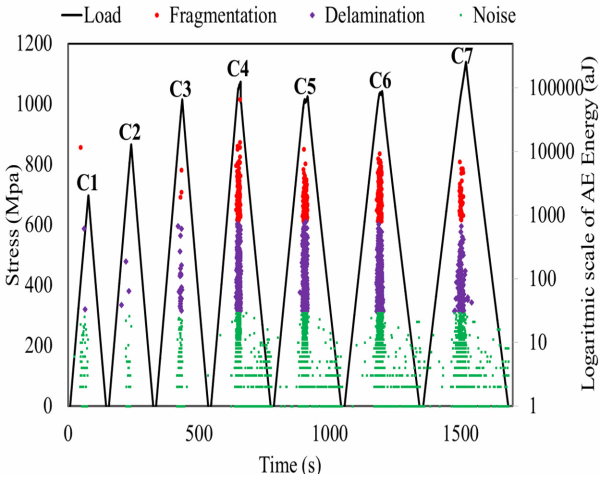

Figure 9. Stress-time and distribution of AE event energy for the hybrid laminate.

Cumulative AE energy of the AE signals is shown in Figure 11. Before reaching the failure strain of the carbon layer, i.e. in cycles 1, 2 and 3, there is no significant increase in the cumulative AE trends. After that, in each cycle, there is significant increase. Between the peaks, the rate of damage accumulation stays relatively constant. Fragmentation related cumulative AE energy is higher than the delamination related ones. The noise signals occur continuously with some small steps near the peak stresses which could have been caused by reflection of high energy signals or more friction related events.

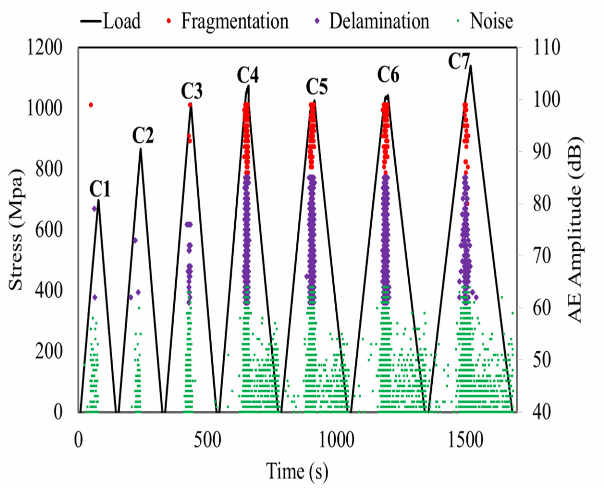

Figure 10. Stress-time and AE event amplitude distribution for the hybrid laminate.

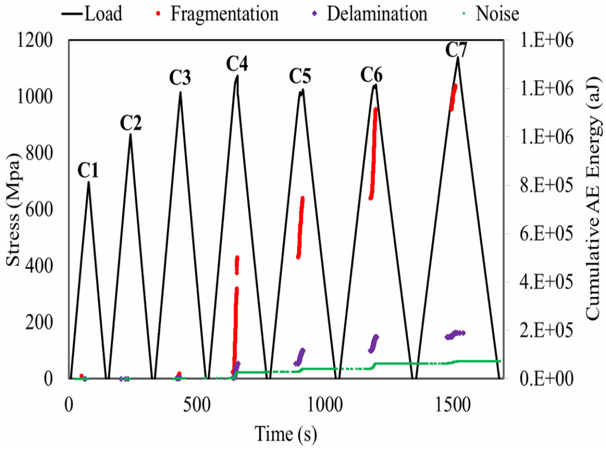

Figure 11. Cumulative AE event energy for each class of AE signal for a typical hybrid laminate.

Each AE event is regarded as one damage event. The number of damage events is illustrated in Figure 12. This number of fragmentation events prior to the final peak point and the average energy content for each of them are 495 and 2445 aJ, respectively.

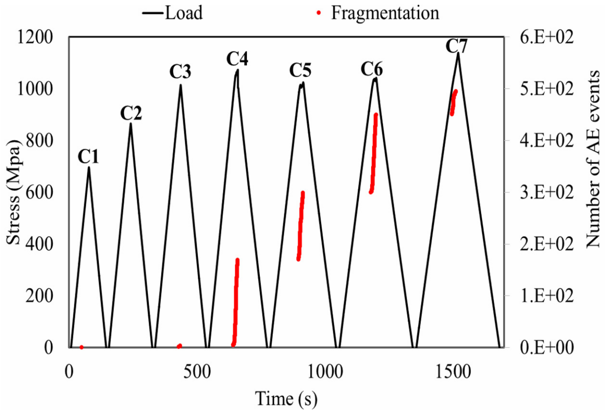

Figure 12. Number of fragmentation type AE events for the hybrid laminate.

4. CONCLUSION

In this paper, the AE technique is utilised to identify the damage modes in thin-ply UD carbon/glass hybrid laminates under repeated quasi-static tensile loading. Fragmentation of the carbon plies and delamination of the carbon/glass interfaces are found to be the main damage sources for the AE signals. It is concluded that the AE technique can be used to evaluate the number of fragmentations and can identify the damage evolution of the hybrid laminate under repeated quasi-static tensile loading.

The proposed method is very useful as an effective way to accurately detect fibre fragmentation and to track the damage progression and accumulation in more complex loading conditions such as cyclic loading.

ACKNOWLEDGMENT

This work was funded under the UK Engineering and Physical Sciences Research Council Programme Grant EP/I02946X/1 on High Performance Ductile Composite Technology in collaboration with Imperial College, London. Gergely Czél acknowledges the Hungarian Academy of Sciences for funding through the Post-Doctoral Researcher Programme fellowship scheme, the János Bolyai scholarship and the Hungarian National Research, Development and Innovation Office - NKFIH, for funding through grant OTKA K 116070. The authors acknowledge Hexcel Corporation for supplying materials for this research. All underlying data are included in full within this paper.

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ПРАЋЕЊЕ АКУСТИЧНЕ ЕМИСИЈЕ ТАНКИХ СЛОЈЕВА ХИБРИДНИХ КОМПОЗИТА ПОД ПОНОВЉЕНИМ КВАЗИ-СТАТИЧКИМ ЗАТЕЗАЊЕМ

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Овај рад истражује применљивост технике акус–тичке емисије (АЕ) за идентификацију оштећења и акумулације у S-Staklu/TR30-Grafitnim хибридним ламинатима под поновљеним квази-статичним опте–рећењем. Узорци су направљени од 2 једносмерна танка слоја угљеничног препрега која су била постав–љена између 2 стандардне препрег плоче С-стакла. Анализа резултата АЕ показује да постоје две врсте догађаја који се односе на опсеге енергије и ампли–туде сигнала АЕ. Утврђено је да су сигнали са нис–ким вредностима повезани са деламинацијом повр–шине угљеника/стакла, док су сигнали са високим вред–ностима повезани са фрагментацијом слоја уг–љеника. Постоји више сигнала АЕ везаних за трење током фазе растерећења од фазе учитавања због су–дара и трљања између постојећих површина пуко–тина. Повећавање нивоа напрезања повећава број фрагментација и АЕ техника је у стању да га ква–нтификује. Закључено је да се техника АЕ може користити за процену броја фрагментација и може идентификовати еволуцију хибридног ламината под поновљеним квази-статичним оптерећењем затезањем.