INVESTIGATION OF DELAMINATED COMPOSITES BY DIC AND AE METHODS

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ABSTRACT

Carbon fiber reinforced epoxy specimens were manufactured by vacuum infusion and they were tested by tensile test with additional NDT tests. The recorded AE signals which originated from the opening of the delaminated zone and the break of elementary fibers were synchronized with DIC measurement, so we could analyze the data simultaneously. The location of the delaminated zone was clearly identified in the strain field, the results correlated well with the AE localization results. However, bigger elongation was required for AE localization than DIC measurement, which indicated the fault from as low as 0.1% strain.

1 INTRODUCTION

In the 21st century, there are more and more high value, load bearing structures made of fiber-reinforced polymer composites, due to their excellent specific mechanical properties. For example, they can be found in air-, land- and water vehicles, wind turbines, pressure vessels and sport equipment, which are critical in personal safety [1]. After reaching the maximal load capacity the failure of these structures happens suddenly and almost without any signal, as a result of several failure processes (fiber breakage, matrix fracture, fiber-matrix debonding/pullout and delamination) [2]. However, this catastrophic failure mode is not acceptable. Therefore, there are two hot topics closely related to solve the problem: composites with improved toughness and non-destructive testing (NDT) of composites to detect and monitor the damage [1, 3].

In this study, two NDT methods are used to collect data during tests, about carbon/epoxy specimens which contain artificial delaminations. One of them is acoustic emission (AE) which is an excellent health monitoring tool, where at least one microphone is placed on the examined object. The microphone is used to detect sounds, which come from deformation or damage of structures in real-time [4]. Analyzing the amplitude and accumulation of the noises, the type of the damage can be determined [4, 5]. If more microphones are used, the location of the source of the events can be computed. It can be used on large objects such as bridges or wind turbines, but there are also two disadvantages. Usually it cannot detect the depth and the geometry of the damage or imperfection between the layers and it can only collect data when the damage is being generated or progressing [5].

The second one is digital image correlation (DIC), which is a powerful, optical imaging based tool to obtain deformation and strain fields from the surfaces of the composite structures. The basic experimental setup consists of a digital camera which records the deformation of the loaded specimen, a computer with DIC software and last, but not least high-performance illumination. The non-contact method can also be applied to large objects, without material restriction so there are many possibilities of applications [6]. In most of the cases it is used as a tool for obtaining accurate longitudinal and transverse strain or to follow the crack accretion during mechanical tests, but it is able for much more. For example, detection of hidden structural damage and finite element (FE) validation.

Sztefek and Olsson [7] analyzed low velocity impact damaged carbon/epoxy composite plates by DIC. During the test, the plates' deviation from flatness was determined on both sides, which allowed to track opening of the delamination. Moreover, the local buckled zones were imported to the FE model, which results in a more accurate simulation.

The aim of our research was to combine and compare the capabilities of these two powerful testing methods to get a deeper understanding of the mechanical behaviour of delaminated composite structures, on an emphasis to characterize the effects of interlaminar friction between the two delaminated layers.

2 EXPERIMENTAL

2.1 Production of specimens

Composite plates were produced by vacuum infusion at room temperature. IPOX ER 1010 (IPOX Chemicals Kft., Budapest, Hungary) epoxy resin with IPOX MH 3124 curing agent was used as the matrix of the composite laminates. The mixing weight ratio was 100:35. As fiber reinforcement PX35FBUD030 (Zoltek Zrt., Nyergesújfalu, Hungary) type unidirectional carbon weave (surface weight 309 g/m2), was used. The artificial delaminations were created by 20 mm wide, 0.02 mm thick PTFE foil strips placed between layers before curing (Table 1). The layup sequence was selected based on our preliminary FEA tests, because in case of this structure, the delamination formation and propagation is well visible in the DIC strain fields. Thereafter 250 mm long, 25 mm wide specimens were prepared with a diamond disc cutter. Finally, the specimens got a random surface pattern by white paint spray, which ensured sufficient contrast for DIC.

Type of specimens	Stacking sequence of specimens
Reference	[90°, 45°, -45°, -45°, 45°, 90°]
A	[90°, /, 45°, -45°, -45°, 45°, 90°]
B	[90°, 45°, /, -45°, -45°, 45°, 90°]
C	[90°, 45°, -45°, /, -45°, 45°, 90°]

Table 1: Location of PTFE foil ("/") in different specimen types.

2.2 Test methods

Tensile tests were conducted at room temperature using a Zwick Z250 universal testing machine equipped with a 250 kN load cell. Free length of the specimens was 150 mm. The applied crosshead speed was 1 mm/min. The displacement was computed from DIC which was not connected to the tensile machine, so the measurement was stopped manually when the measured value approached 0.4% average strain.

The AE signals were recorded by a Sensophone AEPC-40/4 (Gereb es Tarsa Ltd., Budapest, Hungary) device with two Micros30s (Physical Acoustic Corporation, Princeton Junction, USA) microphones placed on the surface of the specimens. Distance of microphones was 100 mm (Fig.1), the coupling agent was Oxett silicon grease (T-silox Ltd., Budapest, Hungary), threshold was 30 dB, dead time was 5 msec and the applied average sound velocity was 2100 m/s.

The full field surface deformation was investigated by a Mercury Monet 3D DIC (Sobriety Sro., Kurim, Czech Republic) tracking system with two 5 Mpix resolution cameras and 10 Hz data acquisition rate. After calibration, the resolution of the optical system was 0.2 mm/pixel. The images were collected and analyzed simultaneously by Mercury RT-v2.6 software run on a computer with an Intel Core i7-7700K processor, 8 GB of RAM and a Patriot Hellfire 480GB M.2 SSD. The following parameters were set in the software for evaluation: 40 × 40 pixel windows, 0.2 confidence interval, high correlation quality, fast speed and full affine transformation. The region of interest (ROI) (shown in Fig.1) which included the PTFE foil was analyzed by full field method with 20-pixel grid space.

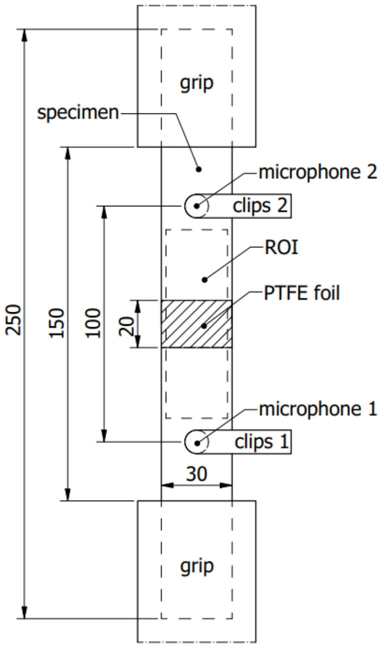
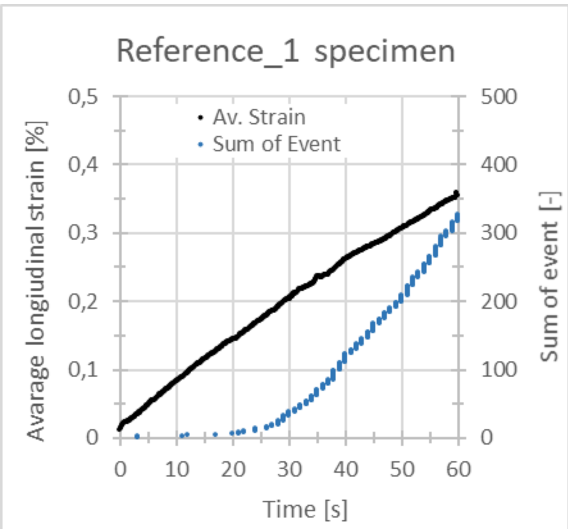


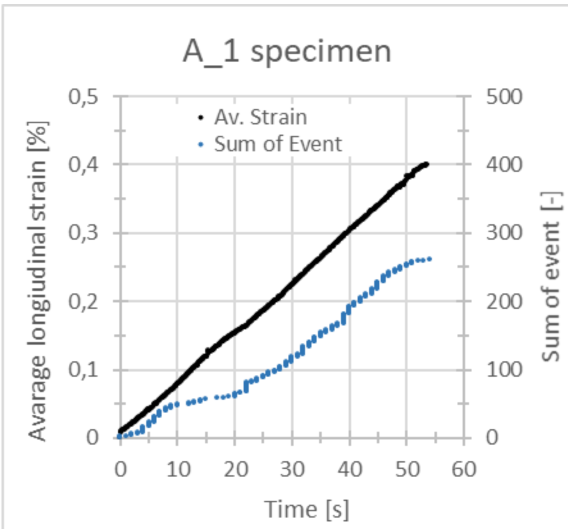
Figure 1: Geometry of specimen and location of measuring systems.

3 RESULTS

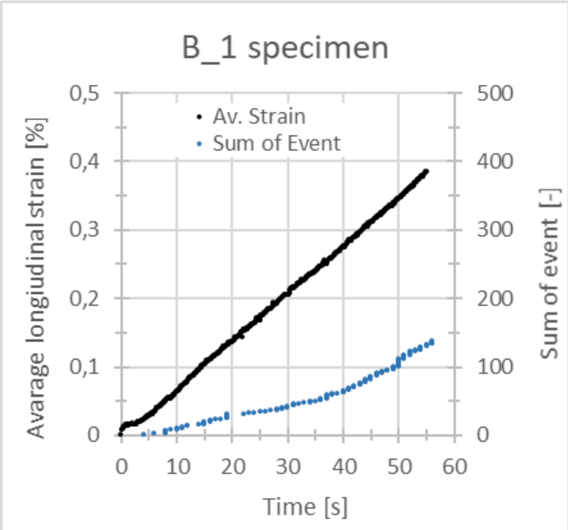
Three specimens were tested from each type of composites, but because of their similar results only one sample from each type is shown in the figures. The recorded AE signals mainly originated from breakage of weak or originally stretched fibers but the number of events did not exceed 350. It means that the test did not involve significant structural damage because one roving contained tens of thousands of elementary fibers, and there were a lot of rovings in the specimen. Furthermore, as shown in Fig. 2 the strain of the specimens remained in the linear section of the strain curve, which also indicates no residual damage. In the case of the reference, the events came from 0.15% strain continuously, while in the case of delaminated specimens (type A-C), they occured continuously from the beginning of the measurement, although fewer events occured in total.



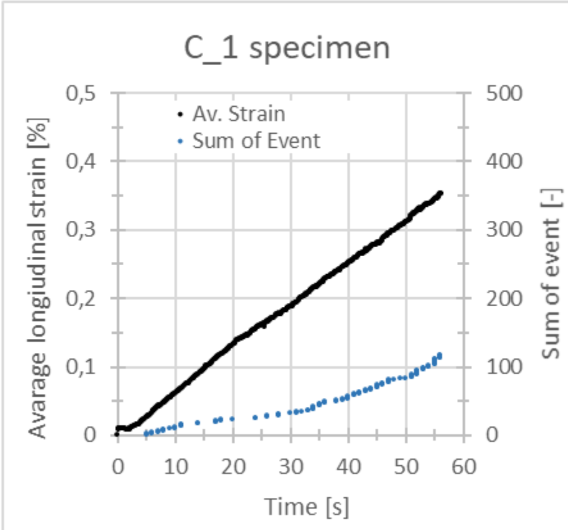
a)



b)



c)



d)

Figure 2: Elongation-time and sum of event-time correlation of different types of specimens: a) reference, b) A_1, c) B_1, d) C_1 specimens.

The reason of this phenomenon could be the mix of many effects. For example, the friction or opening of the delaminated zone and the effect of PTFE foil edges which focused the stress on a line and the appearance of the shear load in the delaminated zone which was caused by cessation of symmetry.

Evaluating the results of the DIC measurements helped to understand the phenomenon. Fig. 3 shows the strain maps of the reference and specimen A_1 under different loads. The reference specimen with 0.1% average strain showed a little area in the middle of the sample which had higher strain. This was an imperfection but not an artificial one, which also means that the DIC method is highly sensitive. This specimen with 0.3% average strain continued to show the fault with 0.6 % local strain, which caused further breakages in that little area. It also appeared on the AE localization map between 40 and 50 mm. There were lots of events between 10 and 20 mm too, which did not show up on the strain map. Perhaps the source of the events coluld have been seen from the other side of specimen by DIC.

The type A specimens showed a very clear signal of their artificially delaminated zones (Fig. 3 down) by DIC at all load levels, which had a god correlation with the AE localization results. The pre-layered PTFE foil was twice as large as the area which indicated higher strain on the strain map, which means that the delamination did not develop along the entire area of the foil.

The specimen B and C had totally different strain maps because of their stacking sequence but the effect of the PTFE foil was already visible at 0.1% strain. AE localization of imperfections in these specimens were not clear. A third of events were localized and the deviation was high.

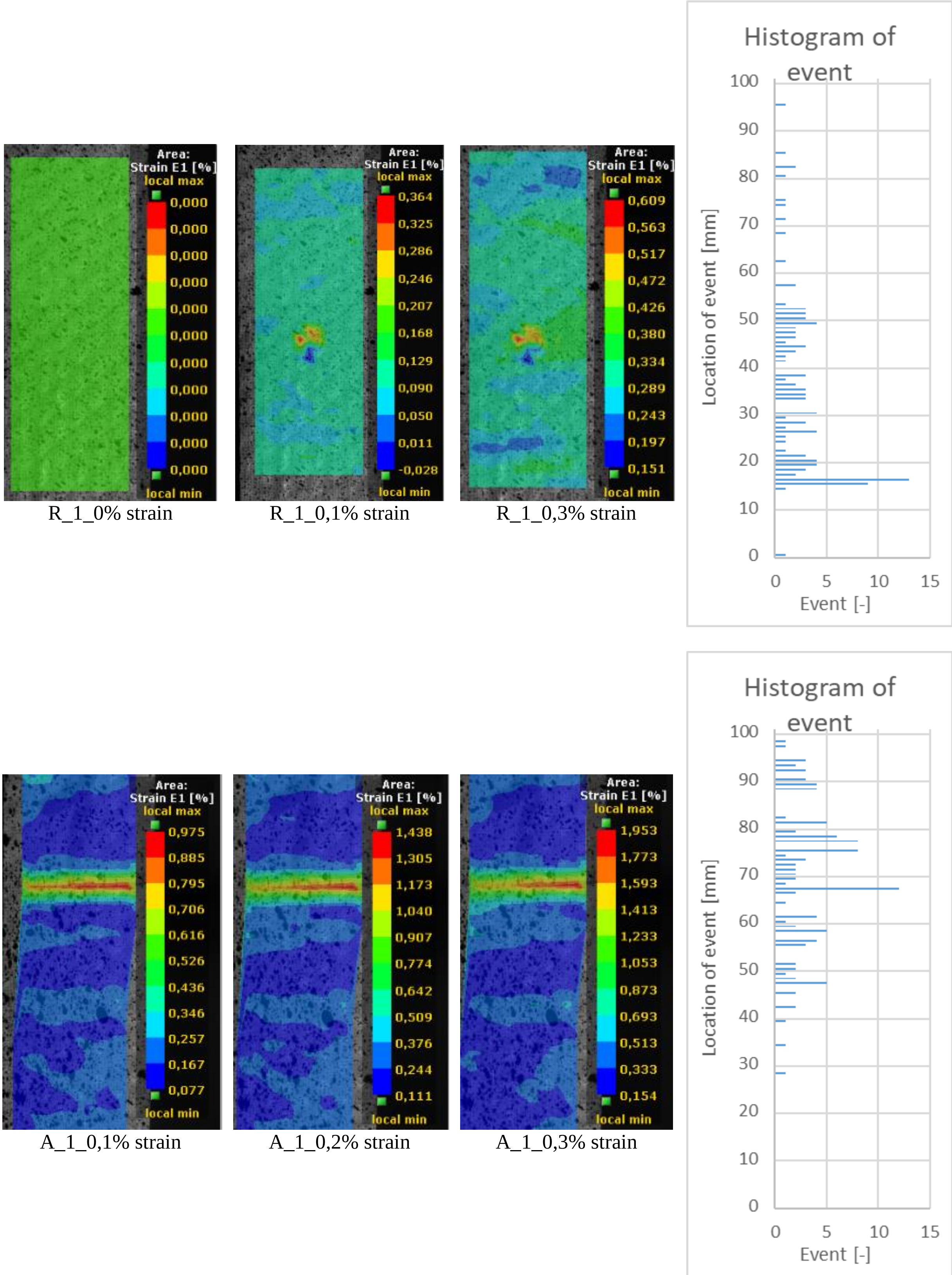
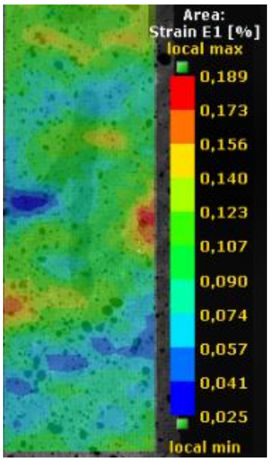
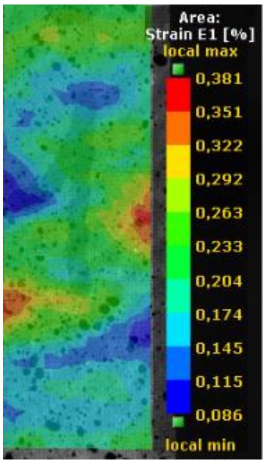


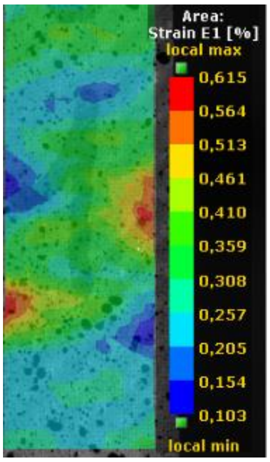
Figure 3: Strain map of reference specimen in different load level and the AE localization (up), strain map of specimen A in different load level and the AE localization (down).



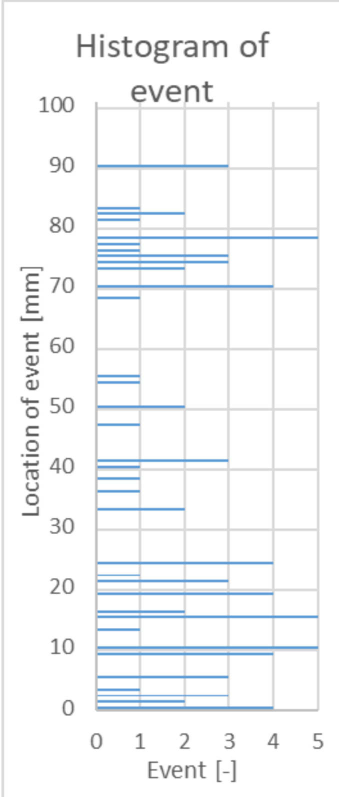
B_1_0,1% strain

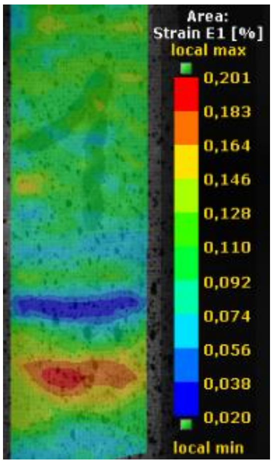


B_1_0,2% strain

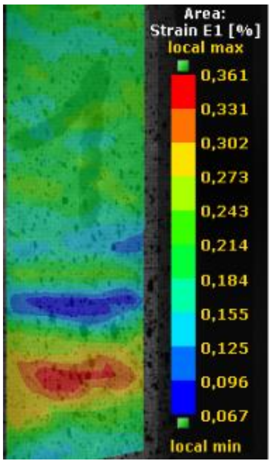


B_1_0,3% strain

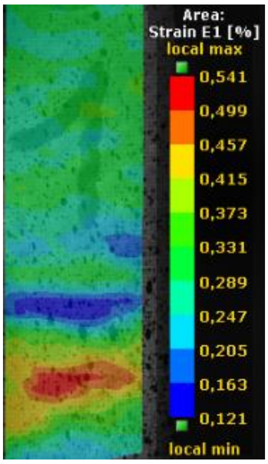




C_1_0,1% strain



C_1_0,2% strain



C_1_0,3% strain

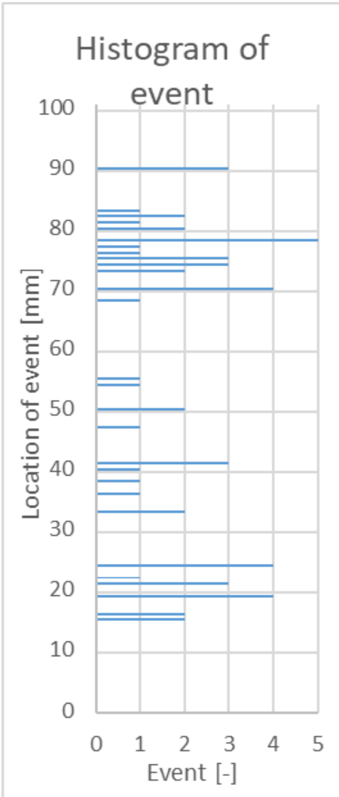


Figure 4: Strain map of specimen B (up) and C (down) in different load level and the AE localization.

4 CONCLUSIONS

The location of the artificially delaminated zones could be clearly identified in the strain field. The pattern of the strain map mainly depended on the positon of the delamination in the stacking sequence, but it indicated the imperfection at a very low load level (0.1% strain), which did not cause structural damage based on AE signs. In this case the delamination could not be localized by AE. Using a higher load (0.3% strain) the AE localization results often correlated well with DIC. In some cases AE events occurred in other positions too, which could came from the back side of the specimen which was not visible by DIC. In conclusion, DIC method was an efficient NDT for detecting delamination. The result of AE tests indicated that it was not suitable to observe such a thick specimen from a single side by DIC. Moreover, the AE method is a useful equipment to define the acceptable loading level which did not cause structural damage.

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