Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

15: 2 (2015) 112-116

COMPOSITES THEORY AND PRACTICE

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Received (*Otrzymano*) *3.02.2015*

ACOUSTIC EMISSION IN MONITORING COMPOSITE BRIDGE STRUCTURES

The studies carried out were aimed at developing guidelines for the procedure of employing the Acoustic Emission (AE) method for ensuring the required manufacturing quality and operating safety of composite bridge structures. For the studies, the experience gathered in the studies of thin-walled components made for the aeronautics, automotive and boatbuilding sectors was used. The focus was components with a significant thickness (14÷16 mm) which are, by their nature, less homogeneous and can have more defects when compared to thin-walled composites. The studies carried out for the purpose of this work demonstrate the system for the acceptance tests of composite structures. The demonstrator model in question was developed based on laboratory tests of composite components and of parts of a prototypical structure under load, as described in this work. The recorded acoustic signals were analyzed using software enabling the authors to analyze numerous parameters of the signals and to locate the recorded acoustic emission artifacts. The developed procedures were verified in AE tests in four-point bending of a prototype composite beam with the length of 15.3 m. The nominal operating load and loads significantly exceeding the operating conditions were applied for the tests. The results obtained enabled the authors to study the destruction of composite beams. Based on the signal analyses, the sites of local composite damage were identified and the stage when the global structure damage took place was foreseen. Multiparameter analysis of the recorded acoustic signals made it possible to determine the kinetics of defect growth. The results of the tests carried out for this work helped to develop guidelines for the procedure of acoustic emission testing for composite road bridges at the stage of handing them over for use and in the periodic monitoring period for the used bridge structure.

Keywords: **reinforced fiber polymers, acoustic emission, composite bridge structures**

MONITOROWANIE KOMPOZYTOWYCH OBIEKTÓW MOSTOWYCH Z ZASTOSOWANIEM METODY EMISJI AKUSTYCZNEJ

Przeprowadzone badania miały na celu opracowanie wytycznych do procedury stosowania metody emisji akustycznej (AT) do zapewnienia wymaganej jakości produkcji oraz bezpieczeństwa eksploatacyjnego kompozytowych obiektów mostowych. W badaniach wykorzystano doświadczenia zebrane w badaniach cienkościennych elementów wytwarzanych na potrzeby lotnictwa, motoryzacji i szkutnictwa. Uwagę skupiono na badaniach elementów cechujących się znaczną grubością (14÷16 mm), które z natury rzeczy są mniej jednorodne i mogą zawierać więcej wad w porównaniu do kompozytów cienkościennych. Badania przeprowadzone w ramach pracy stanowią demonstrator systemu do badań odbiorczych obiektów kompozytowych. Przedmiotowy demonstrator opracowano na podstawie badań laboratoryjnych elementów kompozytowych i badań fragmentów prototypowej konstrukcji w warunkach obciążenia, opisanej w tej pracy. Do analizy zarejestrowanych sygnałów akustycznych zostało wykorzystane oprogramowanie pozwalające na wieloparametryczną analizę parametrów sygnałów oraz lokalizację rejestrowanych zdarzeń emisji akustycznej. Opracowane procedury poddano weryfikacji w badaniach AT podczas czteropunktowego zginania prototypowej belki kompozytowej o długości 13,5 m. W toku badań stosowano nominalne obciążenia eksploatacyjne oraz obciążenia znacznie przekraczające warunki eksploatacji. Uzyskane wyniki pozwoliły na zbadanie procesu zniszczenia belek kompozytowych. Na podstawie analizy sygnałów zidentyfikowano miejsca lokalnego zniszczenia kompozytu oraz przewidziano etap, w którym doszło do globalnego zniszczenia konstrukcji. Analiza wieloparametryczna zarejestrowanych sygnałów akustycznych pozwoliła na określenie kinetyki wzrostu uszkodzeń. Wyniki badań przeprowadzonych w ramach pracy pozwoliły na opracowanie wytycznych do procedury badania metodą emisji akustycznej kompozytowych obiektów drogowych na etapie oddawania do eksploatacji oraz w czasie monitoringu okresowego - eksploatowanego obiektu mostowego.

Słowa kluczowe: **kompozyty włókniste o osnowie polimerowej, emisja akustyczna, kompozytowe obiekty mostowe**

INTRODUCTION

For over a dozen years, growing interest has been observed in the global civil engineering sector in the application of reinforced fiber polymers for producing load-carrying components of road bridges and footbridges [1-4]. The development works devoted thereto have also been carried out in Poland, with an example being the projects financed by the National Centre for Research and Development, called "COM-BRIDGE

Innovative FRP Road Bridge" and "Development of the Technology to Manufacture and Implement Composite Footbridges". Due to safety requirements, the composite components used for the structures are significantly thick because of their large size and high load values. This makes it difficult to examine the components using standard non-destructive testing methods. For this reason, no non-destructive testing has been carried out so far to detect any defects before the composite civil engineering structures are handed over for use. Such tests, however, are routine in aeronautic structures, characterised by a smaller size, including but not limited to a smaller thickness. This is why this work was initiated to develop an effective non-destructive testing method for large composite components and structures used for road-building. Based on the experience of the authors related to the application of non-destructive testing for civil engineering structures, the Acoustic Emission method was selected as a leading technology for examining composite road bridge structures.

The Acoustic Emission method is perfect for examining engineering structures in the course of acceptance load tests and multiannual periodic inspections, as well as for monitoring their condition in real time [5-7]. This necessitates the development of a specific test method for those materials, including the selection of appropriate AE sensors, their distribution on the tested structure, of acoustic signal recording parameters, the application of suitable structure loading methods and the method of multi-parameter analysis of data collected in the course of measurements. The tests are also aimed at supporting the process of characterising the material and designing structures with respect to optimising their critical components.

MATERIALS AND METHODOLOGY

Composites differ from metals to a significant degree both with respect to their structure and mechanical properties. The mechanical properties of FRP composites are naturally non-homogeneous and display a certain degree of anisothropy depending on the fiber orientation and the sequence of their ordering in particular layers (of the textile). This is reflected in the acoustic properties such as the type and speed of waves propagating in the material and their damping. An additional impact on the acoustic properties of FRP composites is exerted by the shape and geometry of the examined structures, including but not limited to the type of materials used for their creation.

Due to the complex structure of composite composites reinforced with various fiber types, there are many mechanisms responsible for the damage found. Using the AE method [8], it is possible to detect and differentiate between most defects derived from those mechanisms. It is possible to determine the level of load values required for the development of specific defects and to monitor their development.

The mechanisms of defect creation, because of the nature of the generated acoustic emission, can be divided into: warp defects (micro and macro cracks of the warp, laminate splitting and delamination), fiber defects (breaks of single and multiple fibers) and combined mechanisms: fiber-warp (breaks of multiple fibers and the warp, border layer fiber-warp breaks (debonding) and fibers pulling out of the warp).

The defects created due to the specific load conditions generate acoustic emissions. Those defects are characterised by generating acoustic waves with variable activity and intensity. They are momentary emission signals but because of their measurement nature, they can also take the form of continuous emissions.

During the examinations, AE tests were carried out in the four-point bending of the demonstrator model of a span of the designed composite footbridge with a length of 13.5 m. The footbridge was produced by MOSTOSTAL Warszawa for the study project called "Development of the Technology to Manufacture and Implement Composite Footbridges". The company responsible for the design was the Materials Engineers Group. The test was carried out under a static load simulating standard loads characteristic of its operation and under loads significantly exceeding the realistic conditions of beam use. The footbridge was supported on sliding supports with a span of 12.00 m. Actuators were installed on the central footbridge ribs at a distance of 2.00 m from one another. The diagram of the footbridge test is presented in Figure 1.

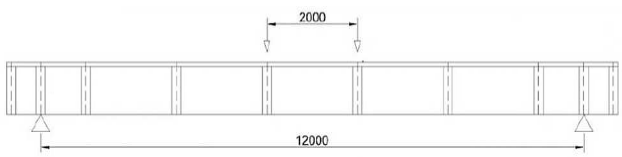

Fig. 1. Studied footbridge girder, including support and force application method

Rys. 1. Badana kładka wraz ze sposobem podparcia i przyłożenia siły

The footbridge was made from two components: a platform and girder. The box girder is composed of a glass and carbon-epoxy laminate.

The test bench, as presented in Figure 2, prepared for the measurements, was composed of two actuators installed on a dedicated frame, and of supports which the studied structure rested on. The actuators were controlled manually by changing the cross-beam setting. The compression force was applied to the studied structure via steel beams to ensure even distribution of the component tension over the entire cross-section.

The test was carried out at Rzeszow University of Technology, Faculty of Civil Engineering, Environmental Engineering and Architecture.

The multi-channel system Vallen AMSY-5 with Vallen AE-Suite R2011.1115.1 was used for the acoustic emission tests. The tests were carried out by means of 108 measurement channels, including AE sensors with preamplifiers, measuring cards and connecting cables. The signals were detected using resonant VS150-RIC sensors (1÷40) and VS30-SIC (41÷108) with integrated preamplifiers, amplifying at 36 and 46 dB respectively.

The sensor location on the tested component is shown in Figures 3 and 4. Such a distribution makes it possible to record AE signals from the entire footbridge as VS30-SIC sensors record low-frequency signals and VS150-RIC record high frequency ones generated in the most stressed zones and in the support zones, differing by means of structure and cement filling. The AE sensors were installed on the outer surface of the girders by means of dedicated clamps.

The diagram of the planned static load during the test is presented in Figure 5 [9]. The maximum test force adopted was 1260 kN. The load diagram contains three cyclic stages of loads and load-free conditions. The first cycle with a total load of 330 kN (25% of the maximum force value) is characterised by an approximated value of the maximum load of the footbridge in use. Consecutive cycles are to determine footbridge vulnerability to the loads applied and the maximum strength of the designed and produced structure.

Fig. 2. Tested structure installed on test bench with AE sensors attached

Rys. 2. Badany obiekt zamontowany na stanowisku badawczym z czujnikami AT

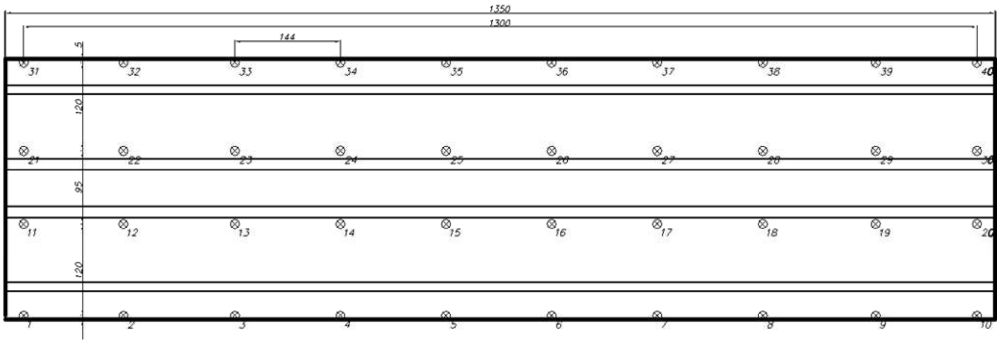

Fig. 3. Location of VS30-SIC on tested structure - expanded view

Rys. 3. Rozmieszczenie czujników VS30-SIC na badanym obiekcie - widok w rozwinięciu

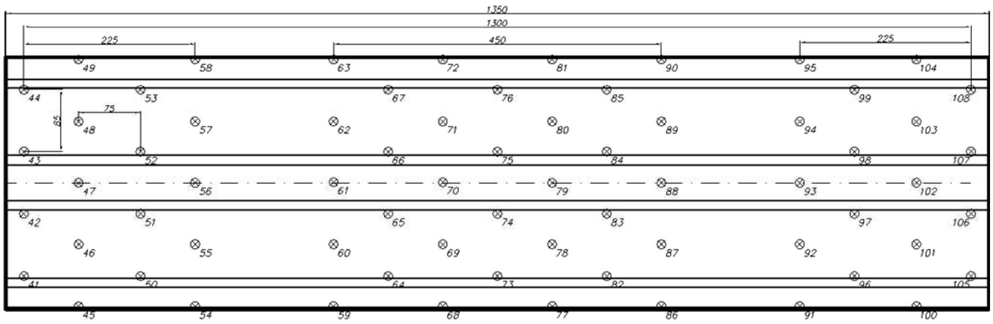

Fig. 4. Location of VS150-RIC on tested structure - expanded view

Rys. 4. Rozmieszczenie czujników VS150-RIC na badanym obiekcie - widok w rozwinięciu

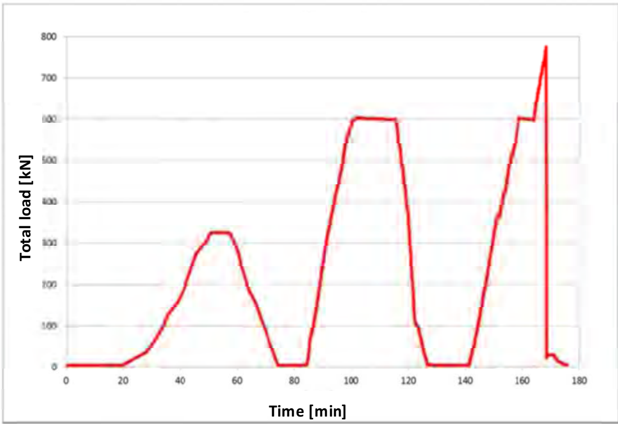

Fig. 5. Diagram of total load on footbridge girder during tests.

Rys. 5. Wykres sumarycznego obciążenia działającego na kładkę w czasie badania

TEST RESULTS

The analysis and interpretation of the acoustic signals recorded during the static bending test are presented for two deflection stages of the composite footbridge:

- 1st load cycle - typical of operating load;
- 2nd load cycle - typical of load values significantly exceeding the realistic operating conditions, not leading to global destruction of the footbridge structure.

Having analysed the acoustic signals recorded during the first cycle of the static bending tests, it was detected that there are AE artifacts in the central part of the girder in the lower strip. The detected artifacts, due to their passive nature, do not indicate that the footbridge was damaged but derive from the footbridge response to the first load applied. Referring to the results of the numerical analysis (MES) of the footbridge structure, the signals located in the lower strip of the footbridge are found in the area of the maximum tensile stress.

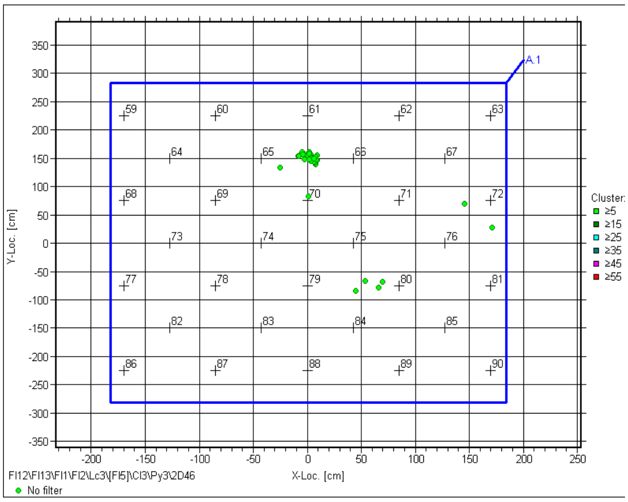

Fig. 6. Planar location of AE signals - central part, 1st load cycle

Rys. 6. Lokalizacja planarna sygnałów AE - część środkowa; I cykl obciążenia

In the second cycle of applying load to the footbridge, the AE signals were also located in this area - see the drawing. They are active and indicate footbridge damage in that zone. Cracks develop in the lower strip.

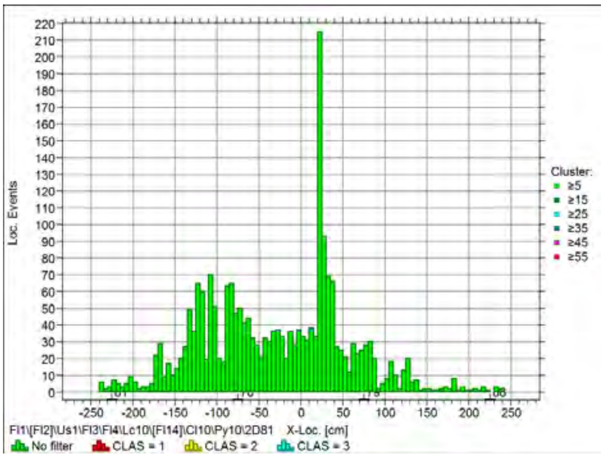

Fig. 7. Linear location of AE signals - central part, 2nd load cycle

Rys. 7. Lokalizacja liniowa sygnałów AE - część środkowa; II cykl obciążenia

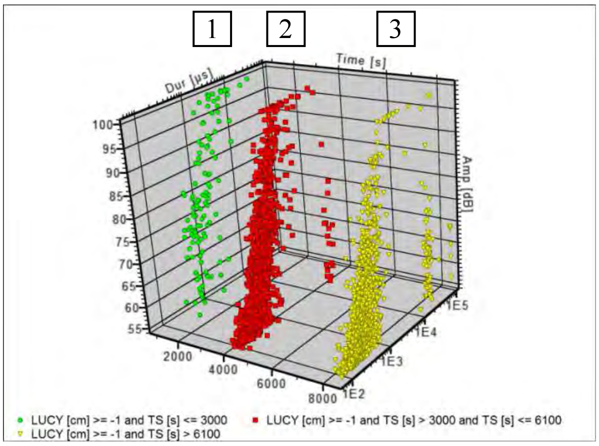

Fig. 8. 3D diagram - signal amplitude and duration versus measurement duration (1 - 1st cycle, 2 - 2nd cycle, 3 - girder decohesion).

Rys. 8. Wykres 3D - amplituda sygnałów oraz czas trwania sygnałów w funkcji czasu trwania pomiaru (1 - I cykl; 2 - II cykl; 3 - dekohezja dźwigara)

The location of acoustic signals in that area indicates high acoustic activity of the deflection processes of the composite material.

The above-mentioned results refer to the 1st and 2nd load cycle and present local defects of the composite structure, with no influence on the global load-carrying capacity of the structure. When the force was raised again to above 660 kN, global structure damage took place.

The process of composite damage was observed as rapid growth of the count rate for AE signals recorded by the AE sensors. Such a significant increase in the count rate of the recorded acoustic signals above 300 kN per actuator proves increased activity of the acoustic emission sources, that is material defects. This is also a criterion for assessing the technical condition of engineering structures enabling one to anticipate the critical development of defects.

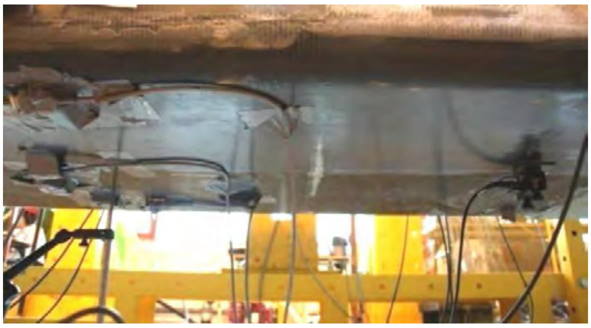

Fig. 9. Transverse defect in lower strip, in centre of girder span

Rys. 9. Wada poprzeczna w pasie dolnym w środku rozpiętości dźwigara

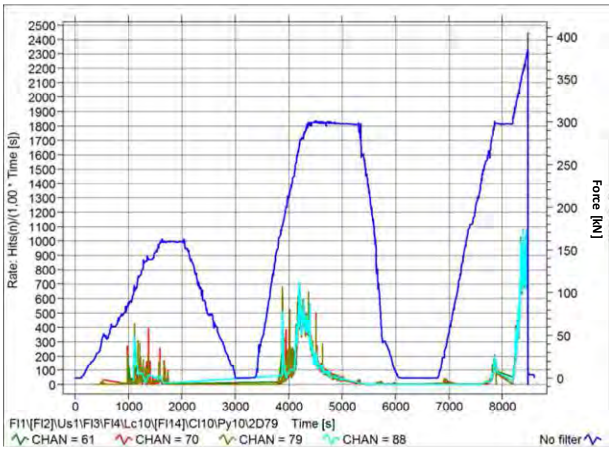

Fig. 10. Count rate for AE signals and force versus measurement duration

Rys. 10. Tempo zliczeń sygnałów AE oraz siła w funkcji czasu pomiaru

In Figure 11, the observed Felicity effect is presented. The Felicity effect is a criterion for assessing the technical condition of the tested structure. The effect was observed for the total load of 660 kN, amounting to 50% of the maximum load applied to the footbridge.

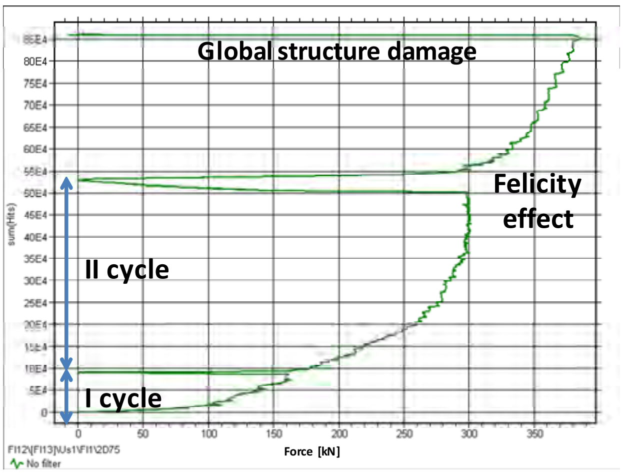

Fig. 11. Total number of signals versus history of force applied to sample (single actuator). Felicity effect

Rys. 11. Sumaryczna liczba sygnałów w funkcji historii działającej na próbę siły (pojedynczy siłownik). Efekt Felicity

This indicates that numerous damage processes and parallel relaxation processes take place for such a stress. The effect is not present for the load of 330 kN. This confirms that the composite footbridge structure was designed and made correctly and does not have any active defects likely to prevent its safe operation for the load levels applied.

SUMMARY AND CONCLUSIONS

Significant progress in the technology of manufacturing and testing large-size composite components has been achieved and its price makes it possible to apply it to the road infrastructure components. Such components can be used only if there are some non-destructive testing methods available to examine the development of the possible defects. Such opportunities are offered by acoustic emission measurements, requiring further development in line with the specific nature of large composite structures.

The developed bases of acoustic signals generated by various types of defects are the grounds for analysing and interpreting the load test results and the periodic monitoring of composite structures in operating conditions.

The developed procedures will be implemented for tests related to preventing any possible structure defects and determining the duration and scope of maintenance works.

Acknowledgments

This research was co-financed by The National Center for Research and Development within the frame of Applied Research Programme (PBS1/B6/2/2012)

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