Evaluation of the Destruction Process of Metal-Composite Cylinders with Use of Acoustic Emission Method

Jerzy SCHMIDT 1, Marek NOWAK 1, Ireneusz BARAN 1

1 Cracow University of Technology
al. Jana Pawla II 37, 31-864 Krakow, Poland;
tel/fax+48 12 374-37-45; schmidt@m6.mech.pk.edu.pl

Abstract
The problem of determining the level of safe operation of the hybrid cylinder under high internal pressure loading (Mode III) can be examined using the AE method. The tests realized under the project funded by Polish Ministry of Science and Higher Education were carried out on metal–composite cylinder samples with an internal diameter of 60mm, thickness 7.5mm (3 mm metal + 4mm overwrapped composite) and 260mm length. The samples were loaded with the special testing equipment by internal pressure up to burst. The two types of fibers - basalt and carbon - were used but in this article only basalt-fiber case will be presented. Also two directions of fibers were used. The first type of samples had circumferential winding fibers and the second type had a ±10° winding. The analysis of AE signals recorded during burst of hybrid cylinders allowed to determine the level of internal load useful for technical purposes, mainly for the construction of cylindrical systems. The paper presents the results of a comparative analysis to test the material of the hybrid cylinders with different winding direction. The parametric and frequency analysis as well as the analysis with VisualClass application were used.

Keywords: hybrid cylinder, composite, burst tests

Test Background
The use of composite overwrappings in the construction of high-pressure cylinder applicable to the special structures needs to develop their assessment of non-destructive methods under stress. Due to the planned industrial application of the metal cylinder with reinforced composite overwrappings the laboratory tests were carried out on samples with an internal diameter of 60mm using AE method to evaluate the processes. Because the cylinders will be used in the mining industry, the matrix resin EPOLAM 2500 (Axon) and basalt fibers with a diameter of 0,013 mm (TEXBAS) and strength of 3000 MPa were used. It was wound circumferentially and ±10° on the steel cylinder (material 32 HA, strength 905-935 MPa). The cylinders were loaded by internal pressure (Mode III) on a special stand with use of the testing machine Zwick Z100. For AE measurement the AMSY-6 Vallen system and resonant sensors SE25-P were used.

Preliminary Tensile Tests
At the build-up stage of database for the purpose of analysis and classification, the tensile tests on the composite specimen were conducted and AE signals were monitored. The results from tensile test are presented on figure 1. On a flat composite sample, three sensors were used allowing for effective elimination of grip noise with two outside sensors. The sensors 1, 2 and 3 were located at X-loc = 0, 4.5 and 7.5 cm, respectively. The graphs presented are for the results of signals located in the mid-section of X-loc = 2 to 6 cm. Signal amplitude ranged from 28 dB (threshold) to 94 dB, indicating mechanisms of matrix/interface cracks or debonds for lower amplitude range, while fiber and fiber bundle fracture for higher amplitude range. These fibers are expected to behave similarly to common glass fibers and amplitude for such fibers was ~70 dB [1]. For these high amplitude signals, duration was over 1000 µs, which is longer than typical single fiber fracture. Multiple fiber and matrix related AE mechanisms appear to take part. The dominant frequency was found to be between 300 and...
370 kHz. The sensor used has relatively flat response between 50 and 400 kHz with slightly (5 dB) higher sensitivity at 280 and 370 kHz. This finding is consistent with the fiber fracture as the main mechanism of the AE generation.

**Test on cylinders**

Next step of tests were the destructive tests of the cylinder samples. On figure 2 the schematic drawing of cylinder, the photo of metal composite cylinder with AE sensors on stand and layout of sensors are presented. The cylinder was internally pressurized hydraulically.

![Fig 1. The results of tensile test composite specimen](image1)

![Fig. 2 The schematic drawing, photo and layout of AE sensors on metal composite cylinder](image2)
AE signals, obtained during the loading of the cylinders, were associated with local failure processes for damage of the composite components. The geometry of the specimens permitted the performance of microscopic examination for different levels of internal pressure. These studies allowed the identification of failure mechanisms and correlation with classes of AE signals after analysis using VisualClass application.

The first studies were carried out to destructively test the cylinder samples. In some cases the capacity of system was not enough to finish the test so it was necessary to unload the specimen and fill the system again. Figures 3-5 show the results of loading up to the damage for metal cylinder (fig. 3) and metal-composite cylinder with fiber wound ±10° (figs. 4 and 5).

In this metal cylinder test, it started to yield at 700 MPa and expanded at 800 MPa (at 80 MPa pressure). Hit rates and amplitude are low throughout, from the elastic to the end of test. During unload-reload at 2100 sec, AE continued at similar low amplitude levels to those at the elastic or yielding range. Thus, most of these AE below 50 dB appear to be noise from the loading system. Signals have low frequency content below 100 kHz and long duration, both consistent with noise. In the last part of test, the highest AE activity was seen by channels 3 and 5 sensors (light blue and blue curves, respectively), caused by large deformation in this region where final failure occurred.

Figure 4 presents the AE data of loading up to the destruction of a metal-composite cylinder with fibers wound ±10°. Until the yielding starts at 100 MPa pressure, AE amplitude is mostly below 50 dB and these are noise. Above this pressure, load-hold AE start to appear and higher amplitude (50-85 dB) emissions are observed. This is the start of some fiber breaks, though the hit rates are less than ten, a very low value. When unload-load step is introduced at 3100 sec, Kaiser effect is essentially followed, but 150-MPa load hold or above produces many load-hold AE. Still the total number of high amplitude AE above 70 dB is not high. Thus, the extent of fiber breaks is limited. When the final fracture load (193 MPa pressure) is
approached, the hit rates finally exceed 10 at 5000 sec, increasing exponentially to fracture even during the final load hold at 180 MPa. This is the stage of massive fiber failure. It appears that many events overlap and not counted as separate events. From amplitude-duration diagram, most above 50 dB AE have less than 2000 µs duration. In comparison to fig. 3, this clearly shows the feature of fiber-related AE in this metal-composite cylinder sample. The main frequency is within 350-450 kHz, where one of the sensor resonances at 370 kHz exists. In this case the locations of failures were at different places as shown in fig. 5
The high AE activity areas are shown by red points that show high amplitude (>60 dB) AE locations. In contrast, low amplitude emissions (green points, below 60 dB) are spread relatively uniformly. The test was finished when the fibers were broken and started to spread out.

The main purpose of these tests was to get the strength characteristics with the load vs. time data. From the maximum pressure levels, we determined relevant behavior of composite structures under conditions of industrially anticipated loads. For the adopted geometry of the samples, we selected the design pressure level of 100 MPa, and the analysis and assessments of the development of damage were performed. Below there are shown the results obtained during testing of metal composite cylinders up to the load level 100 MPa pressure with load hold. See Figs. 6 and 7 with circumferential overwrapping and with ±10º windings.

In the case of a metal composite cylinder with circumferentially wound fibers tested up to 100 MPa, few strong emissions were observed (Fig. 6). Over 90% of AE events observed were below 45 dB and under 30 µs duration. Some deformation was noted above 70 MPa pressure, but the stress level is <300 MPa and no fiber damage is expected. AE is mainly expected from resin. When the fiber winding is ±10º angle, Fig. 7 shows a larger AE activity (about twice hit counts and rates) and higher signal amplitudes up to 85 dB. Events with >65 dB amplitudes were seen and duration of 100-1000 µs became abundant. With this winding angle, the process of deformation of the composite structure starts to involve interfiber matrix shear cracking and the fracture strength changes from that of fiber to matrix shear. The fracture strength value is reduced by about a factor of two [2]. The observed AE is connected with more numerous and more intense process of the matrix shear cracks and fiber debonding components, caused by the effects of strain in the axial and radial direction. Friction is also expected once shear and debonding develop. In the process of loading the composite overwrappings, three distinct frequency ranges of signals were found in both cases (Figs. 6 and 7). The low frequency (20-50kHz) peak was present in the steel cylinder case as well (Fig. 3) and associated with noise, while the processes of friction may also produce noise-like signals. The two high frequency peaks, 350-430kHz and 560-590kHz, are found in both cases (0º and ±10º overwraps), though the highest frequency peak was much less intense since it is beyond the range of calibrated sensor sensitivity. The main high frequency peak is slightly higher than that found in the flat specimen test (300-350 kHz, Fig. 1). Still at this stage it is difficult to assign specific failure mechanisms. It seems all strong AE events with short rise times, fiber fracture, matrix cracks and fiber debonding, produce this peak. Thus, we need to utilize pattern recognition analysis to try to classify detected AE hits. We used Vallen’s VisualClass application, designed to distinguish and identify groups of signals with similar characteristics which occur during increasing of pressure.

On figures 8 and 9 the results of using VisualClass application are presented for the data obtained during the loading of two different kinds of cylinders, (0º and ±10º overwraps). Developed classes represent groups of features corresponding to the levels of deformation and defects of the component structure (classes 1,2,6). They are separated from the signals coming from the process of loading. Due to the occurrence of radial and circumferential strain, the mechanisms of cracking as well matrix cracking of fiber are accompanied by intense process of friction in the matrix and on the fiber-matrix boundary. At the present stage of studies carried out by AE method it is stated that the class 1 is related to the mechanism of friction and matrix cracking, class 2 is associated with the process of friction on the boundary of matrix and fiber and matrix damage, class 6 is responsible for the processes of deformation of the steel cylinders. At this stage of testing, it is believed that no fiber or fiber bundle cracking,
the most serious damage of all, is not occurring under 100-MPa pressure. Metallographic examination, necessary for the assignment of classes to kinds of damage or deformation, are currently performed with electron microscopy methods. Therefore, the assignment presented is not final and will be verified.

![Fig. 6 The results of loading up to 100 MPa metal composite cylinder with circumferentially wound fibers](image1)

![Fig. 7 The results of loading up to 100 MPa metal composite cylinder with fibers wound ±10°](image2)

Classes 3,4,5 are associated with the load operation, e.g. class 5 is related to the filling process. In assessing the behavior of the classes relating with defect of composite
components, it could be possible to see an increase of intensity of AE signals, corresponding to the growth of plastic deformation of metal cylinder. For the composite structure with cross-winding (±10º) fibers, there occurs throughout the loading process significantly higher activity of the events responsible for the process of friction and the matrix cracking associated with the mechanism of mezo-level damage for the border of the matrix and fibers.

Fig. 8 The results of VisualClass classification for metal composite cylinder with circumferentially wound fibers

Fig. 9 The results of VisualClass classification for metal composite cylinder with cross-wound fibers

Conclusions

The tests with use of AE method during the deformation processes of the steel cylinder overwrapped with reinforced composite were performed using internal pressure loading by Mode III. The analysis of AE signals allowed for preliminary identification of the types of defect in composite structure. Using of VisualClass application we developed signal classifiers corresponding to the failure and process mechanisms, and determined their activity changes during the loading of steel cylinders as well the metal composite cylinders. No deleterious fiber damage has been found in the loading condition used.

References