USE OF AE FOR CHARACTERIZATION OF DAMAGE MECHANISMS IN COMPOSITE ACCUMULATOR

Oriane COLAS¹, Catherine HERVE², Christophe BRIANCON¹, Alain HOUSSAIS³

¹ CETIM, 74 route de la Jonelière, 44000 NANTES
² CETIM, 52 Avenue Félix Louat, 60300 SENLIS
³ PARKER OLAER, 16 Rue de Seine, 92700 COLOMBES

Abstract:

This study presents the results of a collective study performed at CETIM for industrials of the hydraulic transmissions profession. The purpose is to develop an accumulator made of composite material, carbon fiber and thermosetting resin, and to characterize the behavior of this accumulator by both static and cyclic pressure tests.

Knowledge of the damage mechanisms evolution occurring during these tests is studied by Acoustic Emission monitoring combined by strain gage measurements.

The AE monitoring results are compared to the failure criteria used in the design model in order to correlate the different damage mechanisms occurring in each layer with the detected AE signals.

Further mechanical tests were carried out on samples taken from accumulators tested at different pressure levels. Visual observations by video camera combined with AE data recording during these tests validated the identification and the progression of the different damage mechanisms in different layers.

1. Introduction

In the scope of hydraulic transmission needs, a study is currently conducted at CETIM to better understand damage mechanisms of accumulators made from carbon fiber-reinforced thermosetting matrix. For that purpose, several accumulators and more specifically their pressure envelopes, have been designed, manufactured and tested. This paper is mainly focused on the results of the static tests. The tests were divided in two parts; operational tests with proof testing at different pressure levels and residual mechanical characterization with tensile tests on samples cut from tested accumulator. The aim of the tests analysis is to characterize the behavior of the structure during the proof test through AE monitoring and strain measurement combined with ultrasonic inspection performed before and after the proof test. The mechanical tests are then performed in order to give the residual strength in axial direction and the damage mechanisms are observed with a camera combined with AE monitoring.
2. Description of work

2.1 Accumulator design

The accumulator is composed of a 5 mm plastic liner, a 6 mm layer of composite material and 2 metallic nozzles. The working pressure of the accumulator is 300 bar. The composite design is made up of 6 different orientation layers (circumferential and helicoidal layers) containing various ply number. Each ply is composed of epoxy resin and carbon fiber with a fiber volume fraction of 50%.

Six accumulators have been manufactured by filament winding process.

2.2 Proof tests

Different proof pressure levels have been applied in order to analyze their influence on the accumulator damage mechanisms. The tests have been performed at $P_s$ (300 bar), $1.5P_s$ (450 bar) and $2P_s$ (600 bar) (Table 1). The test device consists of a water booster with a range of 0-1000 bar. The proof test cycle used is presented Figure 1.

<table>
<thead>
<tr>
<th>Accumulator reference</th>
<th>Proof test pressure (bars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP8</td>
<td>300</td>
</tr>
<tr>
<td>ESP9</td>
<td>450</td>
</tr>
<tr>
<td>ESP12</td>
<td>600</td>
</tr>
<tr>
<td>ESP13</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 1: Proof test description

![Figure 1: Pressure test cycle](image)

A strain measurement has been performed with 4 unidirectional strain gages located around a circumference on the center of the accumulator (90° apart). The strain measured is the circumferential strain.
All the proof tests are monitored by Acoustic emission. Ten sensors are located on the accumulator as described in Figure 2. They are 150kHz resonant sensors, coupled by cement to the composite surface.

Non-destructive inspection is performed before and after the proof test by phased array ultrasonics.

### 2.3 Mechanical tests

The tensile mechanical tests are performed to determine the residual mechanical characteristics in axial direction on tested accumulators. To do this, specimens are taken from the central part along the axis of the accumulator, their location being determined from AE and ultrasonic inspection results.

The tensile tests are realized with a tensile test machine equipped with self-fastening hydraulic clamps. Tabs are glued on the specimens to the specimens so as to obtain a flat surface in contact with the hydraulic jaws. The test velocity is 1 mm/min according to the ISO527-4, the strain measurement is performed by an extensometer and there is a monitoring by acoustic emission (Figure 3).

These tests do not stress the composite in the main direction of stress induced by internal pressure, i.e. in the circumferential direction. Nevertheless, they provide valuable information on the pressure damage induced in the helicoïdal layers.
3. Results

3.1 Proof tests results

3.1.1 acoustic emission analysis

The first step of the analysis is to evaluate the AE signal evolution during the tests in terms of activity (hit number) and intensity (hit amplitude or energy).

- Global analysis with acoustic energy parameter

It can be seen on Figure 4 that signal energy for high amplitudes signals (superior to 85 dB) increases regularly with the pressure with local acceleration around 150 to 200 bar and after 400 bars (cumulative energy slope changes suddenly after these steps).
These punctual accelerations can be linked to the progression of the damages during the pressure holds. The acceleration for high amplitude signal is sudden compared to lower amplitude signals acceleration (Figure 5). This can be explained by the fact that high amplitude signals correspond to high energy damage phenomena such as fiber strand breaks, which occur randomly.

Another observation linked to the signal amplitude is that for the 4 accumulators the signal amplitude doesn’t exceed the following values:

- 70dB for the 100 bar increase
- 80 à 85dB for the 200 bar increase
- 90dB for the 300 bar increase
- 95dB for the 400 bar increase

These characteristics have been observed on all the 4 accumulators. What can be also noted is that the accumulators have the amount of acoustic emission activity related to the same pressure level. The results for 400 bars are shown below in Figure 6.
Given the energy evolution and the signal amplitude progression, these two parameters could be linked in order to define a damage starting point. This will have to be consolidated by further tests leading to critical damages and their impact on signal energy level.

- **Local analysis**

Zonal analysis makes it possible to identify the areas where acoustic emission is concentrated. In the conducted tests, several areas where identified, principally on the bottom shell junctions and on the center of the shell (Figure 7). These observations helped us to select the mechanical tests and micrographic observation samples.

![Figure 7: Zonal analysis of the accumulator ESP12](image)

**Pressure holds analysis**

The AE activity during the different holds (10 min for intermediate holds every 100 bar and 30 min for the final hold) has been analyzed. From the 400 bar steps, the acoustic activity doesn't decrease during the holds but has a stable level. No activity increase was detected during the holds, which means that there is no significant damage progression occurring when the accumulator is stabilized in pressure.

**3.1.2 ultrasonic testing analysis**

The ultrasonic inspection of the 4 accumulators showed that there was no significant evolution of the indications initially detected, knowing that the purpose of the inspection is to detect defects such as delamination. Moreover, no significant defects created by the proof
test was detected, which means that proof test until 600 bar doesn’t lead to severe damages between the composite layers.

### 3.1.3 micrographic analysis

For the accumulator tested at 300 bar, matrix cracking is observed in the helicoidal layers. A more severe damage is noted in the layer ±10° compare to the ±30° and ±55° layers. The ±10° layer presents over the thickness cracks whereas discontinuous cracks are in the ±30° and ±55° layers (Figure 8).

For the accumulators tested at 450 bars, the cracking state of the ±10° layer is more severe than for the 300 bar accumulator, particularly due to cracks appearing through all the thickness (Figure 8). The cracks from the ± 30° et ±55° seem also more developed in length and density.

As for the 600 bar accumulator, the cracking in the ±10° layer is comparable to the one present in the 450 bar accumulator. The cracks in the ± 30° ±55° layer are also more developed.

<table>
<thead>
<tr>
<th>Micrographic observations location</th>
<th>± 55°</th>
<th>± 30°</th>
<th>± 10°</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8: Micrographic observations**

### 3.2 Mechanical tests results

#### 3.2.1 residual strength

The tensile tests show a decrease of 19-22% of material stiffness after the tests at 300 and 450 bar. This can be explained by the transverse cracking observed in the helicoidal layers.
The stiffness decrease doesn’t generate a decrease on the residual strength which means that the high energy AE signals detected before 450 bars don’t affect the breaking load.

### 3.2.2 damage mechanisms

During the tensile tests, a monitoring by AE and a camera gave us information about the chronology of damage occurring during the load increase.

What has been observed thanks to the camera is that the onset of damage occurs with transverse cracking in the ±90° plies around 57MPa (13kN) (Figure 9). Then these cracks multiplicate and at 271MPa (65kN) the damage of internal plies oriented at ±10° begins. Internal damage continued to propagate until the final failure at 340MPa (82kN). Then, a delamination propagates along the oriented plies. All the specimen tested (x21) have a similar behavior.

The AE data have been analyzed in parallel and what can be noted is that before the final failure of the specimen, two AE accelerations occur. The first one happens around 10kN and the second one between 70 and 80kN (Figure 10). These two accelerations could be linked with the initiation of damages in the ±90° and ±10° layers as described above.
4. Discussion

The different results obtained by the tests leaded were brought together with the design criteria, the Hashin criteria. Hashin criteria is used to determine the criticity of tensile loads for unidirectional fibers [reference?]. The criteria allow to differentiate the damage mechanisms of:

- tensile fibre breakage
- compression fibre breakage
- tensile matrix breakage
- compression matrix breakage

Once the value of the criteria reaches 1 for each damage mechanism, the break is likely to occur. For 300 and 450 bars levels an evaluation of this criteria has been realized.

At 300 bar, this criteria shows the following:

The helicoidal ply ±10° is in a breaking state which means that the fibre transversal strain exceed the layer transversal strain. The ±30° layer has a high probability of through thickness cracks. The ±55° has also a probability of cracks presence.

Figure 10 : AE energy cumulate for tensile tests
This Hashin criteria observations can be linked to the experimental results. Indeed, the AE data showed that an acceleration of acoustic activity took place around 200 bar which means that some damage mechanisms have already appeared and are propagating until reaching the proof test pressure. In addition to that, micrographic observations validate the fact that there is damage in the ±10° layer but also in the ±30° and ±55° layers.

At 450 bar, the criteria has evolved:

The helicoidal ply ±10° must have several through thickness cracks, and the first through thickness cracks appear in the ±30° layer. In the ±55° layer the cracks are longer and denser.

In the case of the accumulator tested at 450 bar, the experimental results can also be linked with the Hashin criteria. In micrographic observations cracks through the thickness of the layer at ±10° are more numerous. In the ±30° and ±55° layers, cracks are denser and have a higher length than in the accumulator tested at 300 bar. Moreover, AE signal amplitude are getting higher which may correspond to the multiplication of through thickness cracks.

5. Conclusion

The present project has given us an approach on how to study the behavior under pressure of a composite material accumulator. As far as the Acoustic Emission analysis is concerned, the energy criteria have given us important information about the evolution of the damages during the proof tests. Moreover, the possibility to locate the areas where the activity was the most intense was also an asset to evaluate the zones with the highest stress and to analyze
them after with micrographic observations and tensile tests. AE provides valuable information for the manufacturer in evaluating the safety and the residual life of this pressure equipment.

The micrographic observations were useful to link the AE observations with the Hashin design criteria evaluation and so to the actual damage mechanisms occurred during the proof tests. (It gave a good information of what had been induced by the proof tests).

The possibility of performing tensile tests allowed to give information of the criticality of the damage present in the accumulators.