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SFBM S.p.A.
Rome, Italy

Specific tests on CNG4 cylinders

Provider 2

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Rev.	2
Description	1st Issue-
Prepared by	P. Lombardi, E. Bertelli
Controlled by	E. Mecozzi
Approved by	M. Di Biagio
Date	19/03/2018

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2	First Issue	P. Lombardi E. Bertelli	E. Mecozzi	M. Di Biagio	19/03/2018

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EXECUTIVE SUMMARY

The experimental activity has been focused on the execution of tests on CNG4 type cylinders according to Paragraphs A11/2 and A20 of Annex 3 of the ECE ONU Regulation 110.

First part of the activity included the following tests:

- ✓ hydraulic pressure test at 300 bar
- ✓ impact damage test;
- ✓ hydraulic pressure test at 300 bar;
- ✓ pressure cycling fatigue test between 260 bar and 20 bar, for 20,000 cycles, at 0.16 Hz (> 10 cycles/min).

Only 2 cylinders out of the 12 initially considered have passed the first part of the activity.

At the end of the first part, a second part of activity has been added, including the following phases:

- ✓ protection domes removal;
- ✓ impact damage test;
- ✓ pressure cycling fatigue test between 260 bar and 20 bar, for 20,000 cycles, at 0.16 Hz (> 10 cycles/min).

None of the 2 cylinders completed the 20,000 cycles foreseen by the fatigue test of the second phase.

All of the cylinders showed a mechanical failure in the area where the impact occurred during the drop impact damage test.

In the end, 1 cylinder has been cut in order to measure the wall thickness. Measurements showed a strong difference of the thickness of the composite layer between the dome and the cylindrical zone.

1 CYLINDERS PREPARATION

The activities on cylinders started on April 10th, 2017; cylinders looked like having been well packed as shown in Figure 1-1.

Figure 1-1: Packed cylinders before inspection

When the external packaging was opened, also the impact protection system appeared to be well assembled; the cylinder was suspended in the middle of the box as shown in Figure 1-2.

Figure 1-2: Impact protection system

When cylinders have been taken out of the packaging, the low pressure gas mixture inside them was purged out, then each cylinder has been traced along the four main generatrixes, named 0°, 90°, 180° and 270°. Each cylinder has been assigned an identification number, as reported in Table 1.1.

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Table 1.1: Identification numbers and Serial Numbers of the cylinders

CSM ID	Serial Number
1	1419200152
2	1423200230
3	1423200222
4	1419200164
5	1423200250
6	1419200188
7	1423200241
8	1423200224
9	1423200236
10	1419200185
11	1423200154
12	1423200213

1.1 PRELIMINARY INSPECTION

Some cylinders showed the protection dome of the capped side damaged. In particular, the damage consisted in a fracture of the dome (from Figure 1-3 to Figure 1-8).

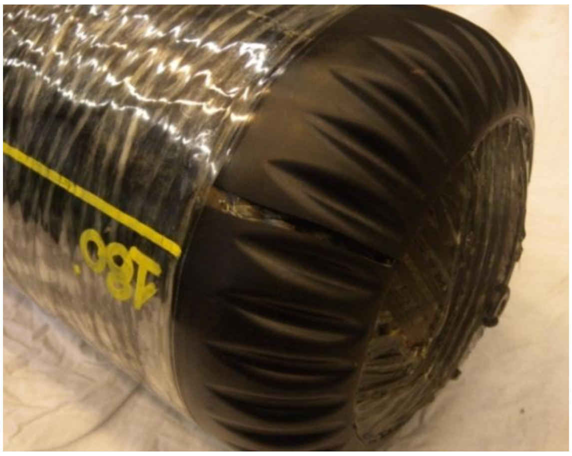


Figure 1-3: Damaged dome – Cylinder 1

Figure 1-4: Damaged dome – Cylinder 2

Figure 1-5: Damaged dome – Cylinder 5

Figure 1-6: Damaged dome – Cylinder 6

Figure 1-7: Damaged dome – Cylinder 10

Figure 1-8: Damaged dome – Cylinder 11

The following additional defects have been observed about fiber wrapping:

- ✓ exposed fibers in the dome of the capped side of cylinder 3 (Figure 1-9);
- ✓ exposed and frayed fibers on both side domes of cylinder 5 (Figure 1-10 and Figure 1-11);
- ✓ partially exposed fibers for cylinder 12 (Figure 1-12).

Figure 1-9: Exposed fibers – Cylinder 3

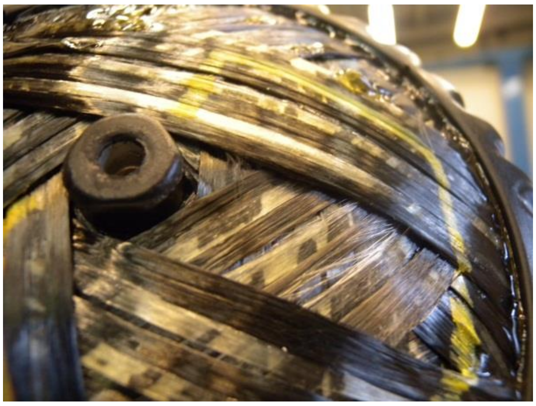


Figure 1-10: Exposed and frayed fibers – Cylinder 5

Figure 1-11: Partially exposed fibers – Cylinder 5

Figure 1-12: Partially exposed fibers – Cylinder 12

2 FIRST HYDRAULIC TEST

Each cylinder has been hydraulically tested according to Regulation ECE ONU R110 A11 Option 2. The test requested the pressurization with water up to 300 bar (equivalent to 150% of working pressure). Once reached the target pressure, the pressurization line has been closed in order to be able to read with the pressure transducer possible pressure variations only related to the cylinder and not to other parts of the pressurization system. The test also foresaw to maintain the target pressure for at least 60 s. At the end of the holding time, the pressure was discharged down to ambient pressure. The experimental setup is reported in Figure 2-1.

Figure 2-1: Experimental setup for Hydraulic test

An AEP® LabTP14BL53R pressure transducer has been used for the test, having a 500 bar full scale and the serial number 908685. Calibration certificates are reported in Appendix A of the present Report. The measurement chain has been additionally verified by means of a known pressure applied with a dead weight tester Manotherm Armaturenbau PD2500 (Calibration certificate No. MA-RTI-1282-2014).

All of the cylinders successfully passed the hydraulic test. Pressure-time plots recorder during the tests are presented in the following figures.

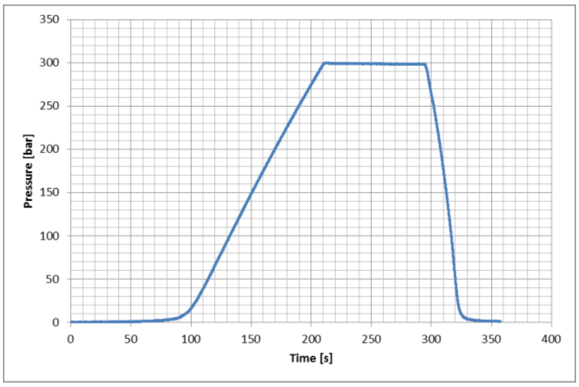


Figure 2-2: Hydraulic test – Cylinder 1

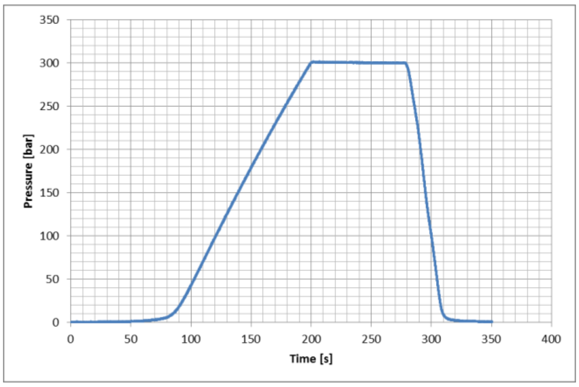


Figure 2-3: Hydraulic test – Cylinder 2

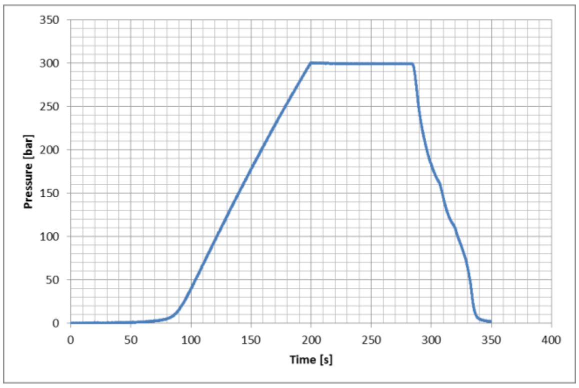


Figure 2-4: Hydraulic test – Cylinder 3

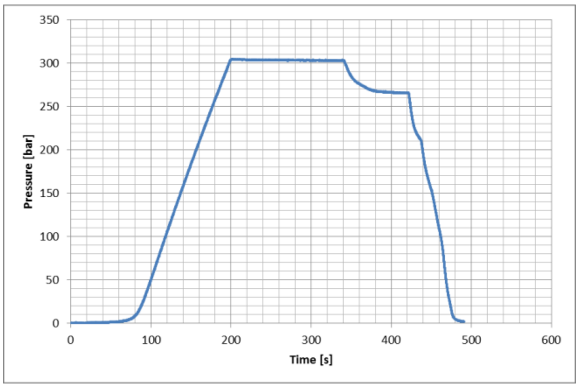


Figure 2-5: Hydraulic test – Cylinder 4

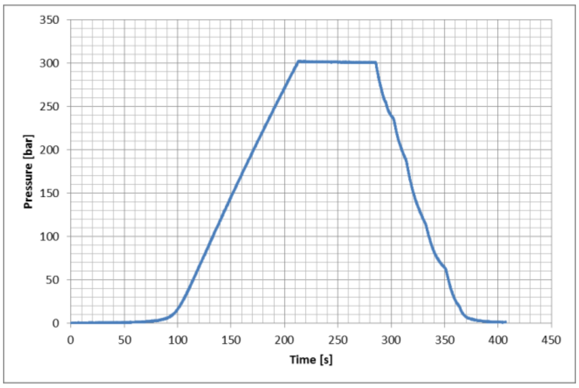


Figure 2-6: Hydraulic test – Cylinder 5

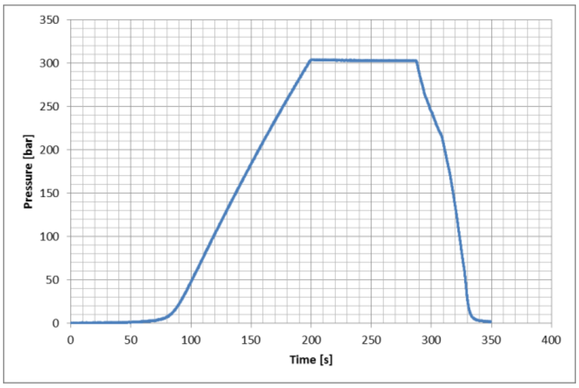


Figure 2-7: Hydraulic test – Cylinder 6

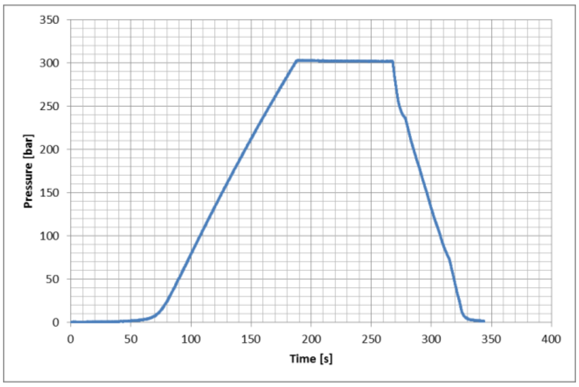


Figure 2-8: Hydraulic test – Cylinder 9

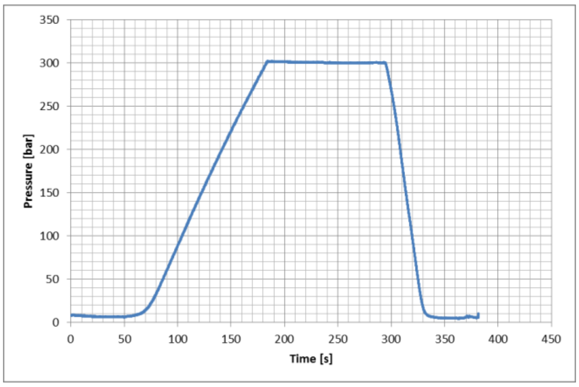


Figure 2-9: Hydraulic test – Cylinder 10

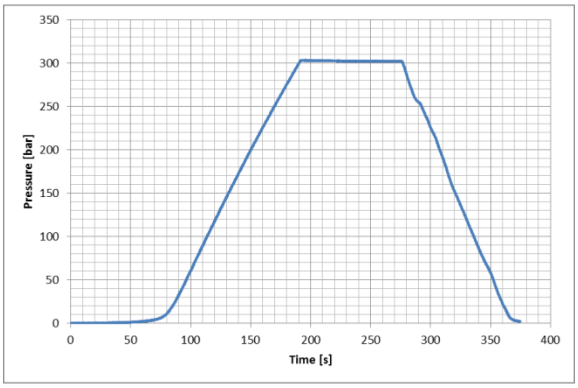


Figure 2-10: Hydraulic test – Cylinder 11

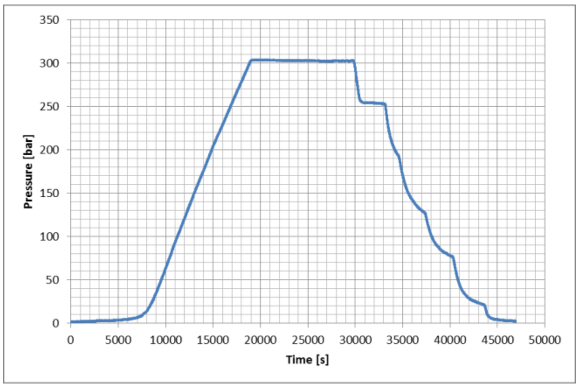


Figure 2-11: Hydraulic test – Cylinder 12

After the hydraulic test, a visual inspection has been carried out in order to verify if new damages have occurred on the cylinders: no new damages were detected.

3 DROP IMPACT DAMAGE TESTS

The cylinders, emptied and without valve, has been subjected to the series of drop impacts foreseen by Regulation ECE ONU R110. The drop tests have been performed from the height of 1.8 m and each cylinder was tested with a specific drop position following the requirements of ECE ONU R110:

- ✓ horizontal drop test (dropping height measured from inferior generatrix of the cylinder);
- ✓ vertical drop test on the valve side followed by vertical drop test on the capped side (dropping height measured from the lowest cylinder point);
- ✓ 45° angle drop test on the valve side (dropping height measured from the cylinder center of gravity);
- ✓ 45° angle drop test on the capped side (dropping height measured from the cylinder center of gravity);

All of the drop tests, except the vertical ones, had the 180° generatrix as first impact point.

After the drop test, a visual inspection has been carried out on each cylinder in order to observe possible new damages related to the drop test itself.

3.1 CYLINDER 1

Cylinder 1 was horizontally drop tested on the 180° generatrix. After the test, an increment of the initial fracture on the dome of the capped side was observed, as shown in Figure 3-1.

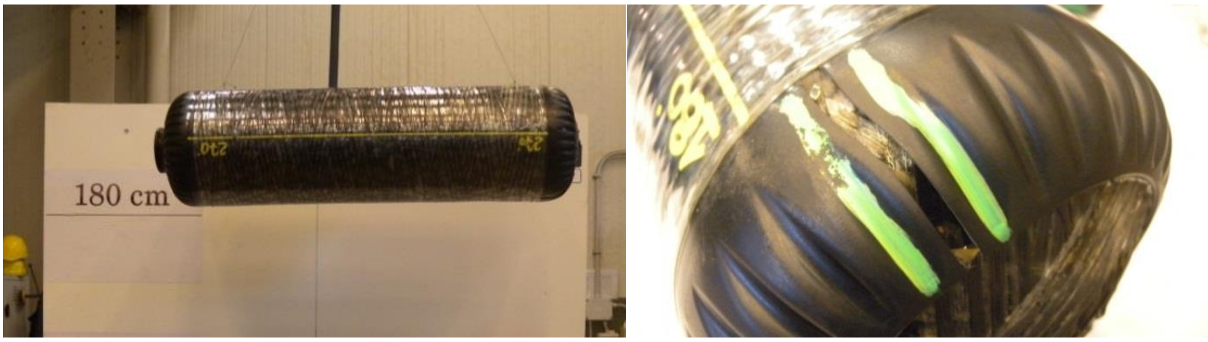


Figure 3-1: Horizontal drop test and dome damage – Cylinder 1

3.2 CYLINDER 2

Cylinder 2 was vertically drop tested on both sides. After the test on the valve side, an abrasion of the border of the cylinder connection was observed, as shown in Figure 3-2. The test on the capped side produced an abrasion of the fibers close to the cap, as reported in Figure 3-3.

Figure 3-2: Connection abrasion after vertical drop – Cylinder 2

Figure 3-3: Fibers abrasion after vertical drop on capped side – Cylinder 2

3.3 CYLINDER 3

Cylinder 3 was 45° angle drop tested on capped side. Visual inspection after the test showed fibers fraying as reported in Figure 3-4.

Figure 3-4: Fibers fraying in the dome area after 45° angle drop on capped side – Cylinder 3

3.4 CYLINDER 4

Cylinder 4 was 45° angle drop tested on valve side. Visual inspection after the test did not show any damage (Figure 3-5).

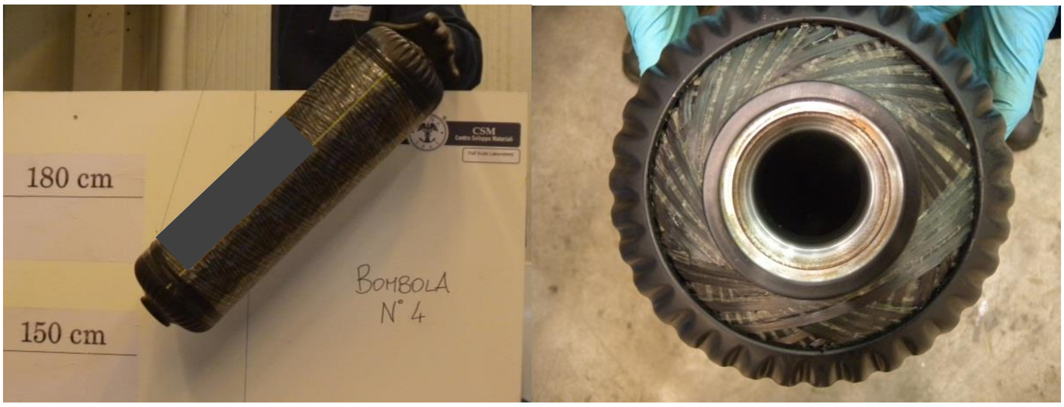


Figure 3-5: No damages after 45° angle drop on valve side – Cylinder 4

3.5 CYLINDER 5

Cylinder 5 was horizontally drop tested. Visual inspection after the test did not show any damage (Figure 3-6).

Figure 3-6: No damages horizontal drop – Cylinder 5

3.6 CYLINDER 6

Cylinder 6 was vertically drop tested on both sides (Figure 3-7). The test on the capped side produced an abrasion of the fibers as reported in Figure 3-8; the test on the valve side showed an abrasion of the border of the cylinder connection, as shown in Figure 3-9.

Figure 3-7: Vertical drop on capped side – Cylinder 6

Figure 3-8: Fibers abrasion on the dome after vertical drop, capped side – Cylinder 6

Figure 3-9: Connection abrasion on the valve side after vertical drop – Cylinder 6

3.7 CYLINDER 7

Cylinder 7 was 45° angle drop tested on capped side. Visual inspection after the test showed a damage on the dome of the valve side due to a cylinder rebound (Figure 3-10).

Figure 3-10: Damage after 45° angle drop on the capped side and subsequent rebound – Cylinder 7

3.8 CYLINDER 8

Cylinder 8 was 45° angle drop tested on valve side. Visual inspection after the test showed a damage on the dome of the valve side (Figure 3-11).

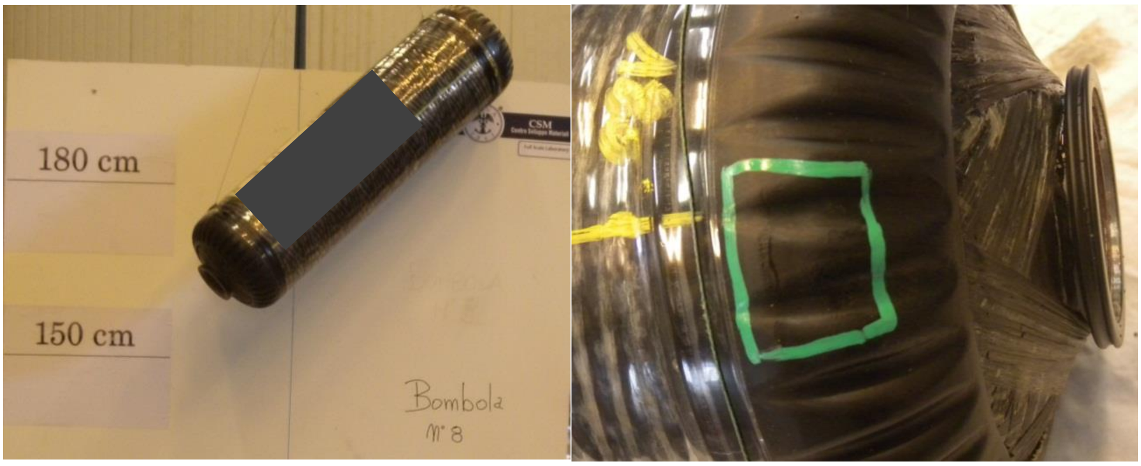


Figure 3-11: Damage on the dome after 45° angle drop on the valve side – Cylinder 8

3.9 CYLINDER 9

Cylinder 9 was horizontally drop tested. Visual inspection after the test did not show any damage (Figure 3-12).

Figure 3-12: Horizontal drop – Cylinder 9

3.10 CYLINDER 10

Cylinder 10 was vertically drop tested on both sides (Figure 3-13 and Figure 3-14). Visual inspections after the tests did not show any damage.

Figure 3-13: Vertical drop on valve side – Cylinder 10

Figure 3-14: Vertical drop on capped side – Cylinder 10

3.11 CYLINDER 11

Cylinder 11 was 45° angle drop tested on capped side. Visual inspection after the test showed a damage on the dome of the valve side due to a cylinder rebound (Figure 3-15).

Figure 3-15: Damage after 45° angle drop on the capped side and subsequent rebound – Cylinder 11

3.12 CYLINDER 12

Cylinder 12 was 45° angle drop tested on valve side (Figure 3-16). Visual inspection after the test showed a damage on the dome of the valve side due to a cylinder rebound.

Figure 3-16: 45° angle drop on the valve side – Cylinder 12

Observations relevant to all of the cylinders before and after drop tests are reported in Table 3.1.

Table 3.1: Results of the drop impact tests

CSM ID	Horizontal drop	Vertical drop side 1	Vertical drop side 2	45° drop	Observations before drop	Observations after drop
1	√ *[180°]*				Initial defect on the dome (180° ; capped side)	Initial defect incremented
2		√	√			Abrasion of the fibers around the capped side and of the connection on the valve side
3				√ (capped side) *[0°-90°]*	Exposed fibers on capped side	Fibers fraying on the dome (capped side)
4				√ (valve side) *[0°]*	No defect	
5	√ *[180°]*			√ (valve side) *[180°]*	Initial defect on the dome (270° capped side) Exposed and frayed fibers on capped side Partially exposed fibres on valve side	
6		√	√		Initial defect on the dome (0° capped side)	Abrasion of the fibers around the capped side and of the connection on the valve side
7				√ (capped side) *[180°]*		Damage on dome valve side (dent)
8				√ (valve side) *[180°]*		Damage on dome valve side (dent)
9	√ *[180°]*					
10		√	√		Initial defect on the dome (210° capped side)	
11				√ (capped side) *[180°]*	Initial defect on the dome (45° and 90° capped side))	Damage on dome valve side (dent)
12				√ (valve side) *[180°]*	Partially exposed fibres on capped side	

4 SECOND HYDRAULIC TEST

After the drop tests, each cylinder has been hydraulically tested according to Regulation ECE ONU R110 A11 Option 2. Tests have been performed with the same procedure described in Chapter 2. Cylinder 3 blew up once the target pressure of 300 bar was achieved; cylinder 8 blew up after 23 s holding at 300 bar. Remaining cylinders passed the test, although all of them were creaking at pressure values over 200 bar. Pressure-time plots of each test are reported in the following.

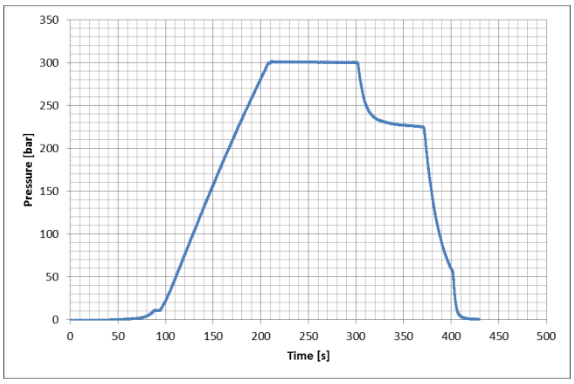


Figure 4-1: Second hydraulic test – Cylinder 1

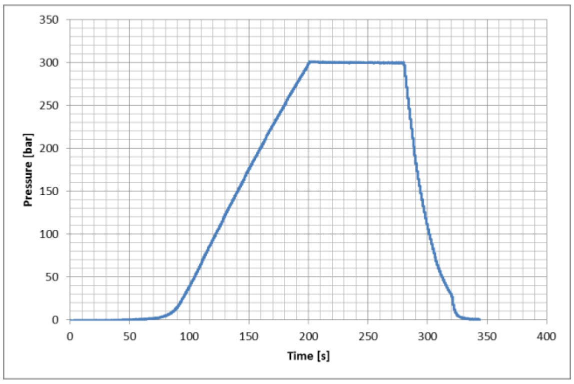


Figure 4-2: Second hydraulic test – Cylinder 2

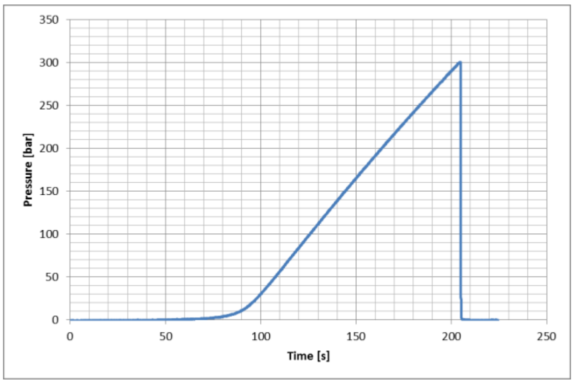


Figure 4-3: Second hydraulic test – Cylinder 3

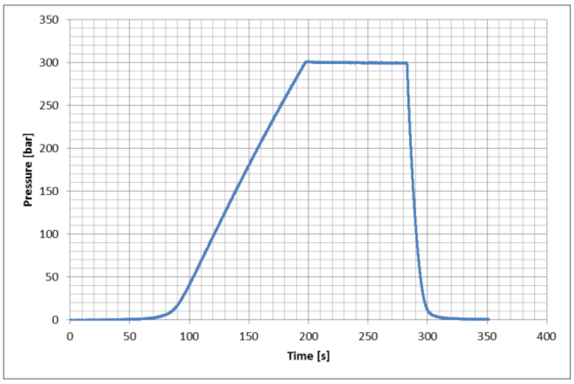


Figure 4-4: Second hydraulic test – Cylinder 4

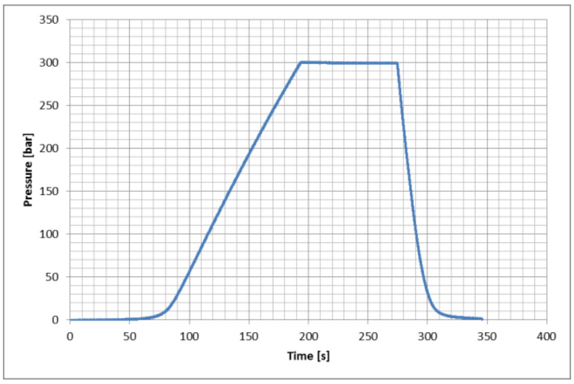


Figure 4-5: Second hydraulic test – Cylinder 5

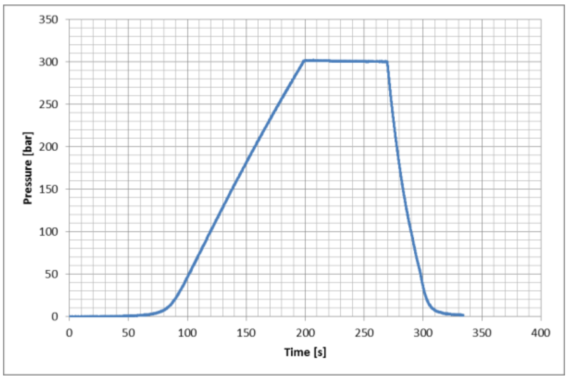


Figure 4-6: Second hydraulic test – Cylinder 6

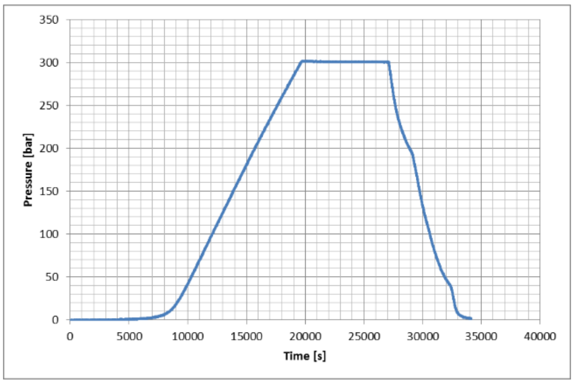


Figure 4-7: Second hydraulic test – Cylinder 7

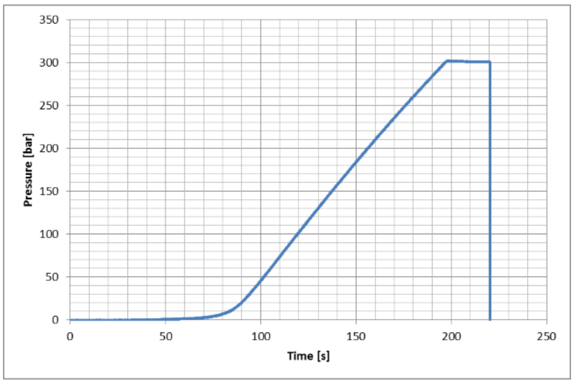


Figure 4-8: Second hydraulic test – Cylinder 8

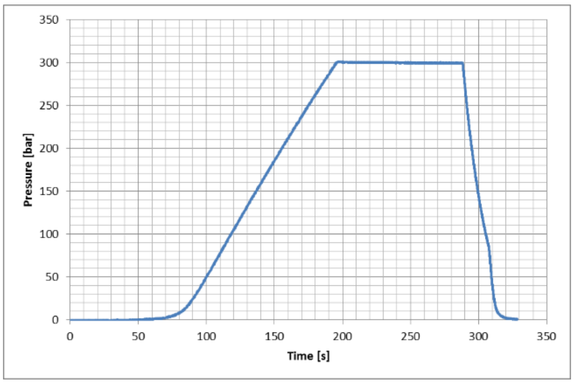


Figure 4-9: Second hydraulic test – Cylinder 9

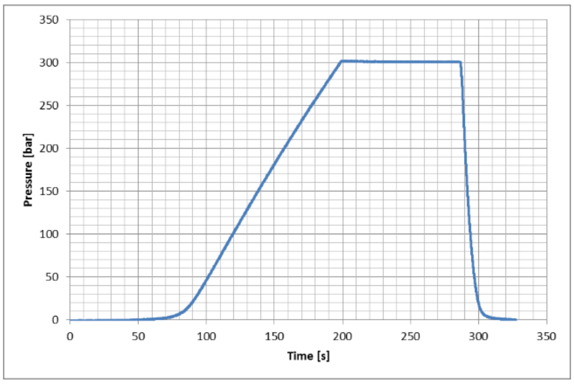


Figure 4-10: Second hydraulic test – Cylinder 10

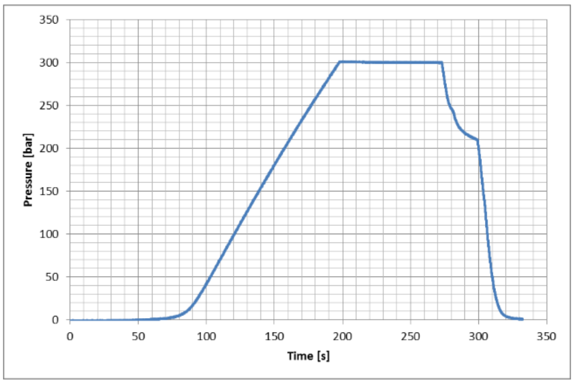


Figure 4-11: Second hydraulic test – Cylinder 11

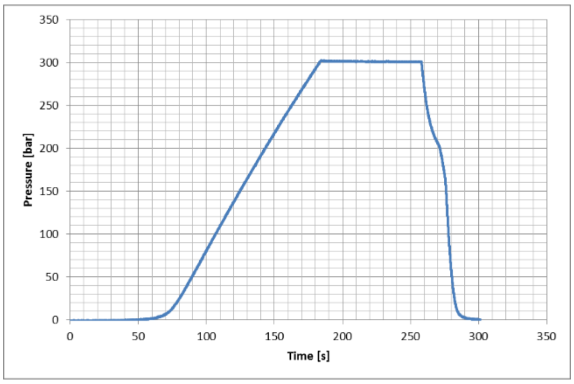


Figure 4-12: Second hydraulic test – Cylinder 12

4.1 FAILURE ANALYSIS

A failure analysis has been carried out on the cylinders which had failed the second hydraulic test (i.e. cylinders 3 and 8). Both cylinders showed failure in the area where the first impact had occurred during the drop test. Main remarks are reported in the following.

4.1.1 Cylinder 3

In the cylinder 3 the failure occurred in the dome area on the capped side, as shown in Figure 4-13. This area corresponds to the area where the first impact occurred during the drop test.

Figure 4-13: Cylinder 3 blown up during the second hydraulic test

After a deeper analysis, two failure mechanism can be identified:

- ✓ in the impact area the fibers are sharply truncated as shown in Figure 4-14;
- ✓ in the area close to the impact the fibers are frayed as shown in Figure 4-15.

Figure 4-14: Detail of sharply truncated fibers after the second hydraulic test- Cylinder 3

Figure 4-15: Detail of frayed fibers after the second hydraulic test - Cylinder 3

4.1.2 Cylinder 8

In the cylinder 8 the failure occurred in the dome area on the valve side, as shown in Figure 4-16. This area corresponds to the area where the first impact occurred during the drop test.

Figure 4-16: Cylinder 3 blown up during the second hydraulic test

Also in this case two failure mechanism can be identified:

- ✓ in the impact area the fibers are sharply truncated as shown in Figure 4-17;
- ✓ in the area close to the impact the fibers are frayed as shown in Figure 4-18.

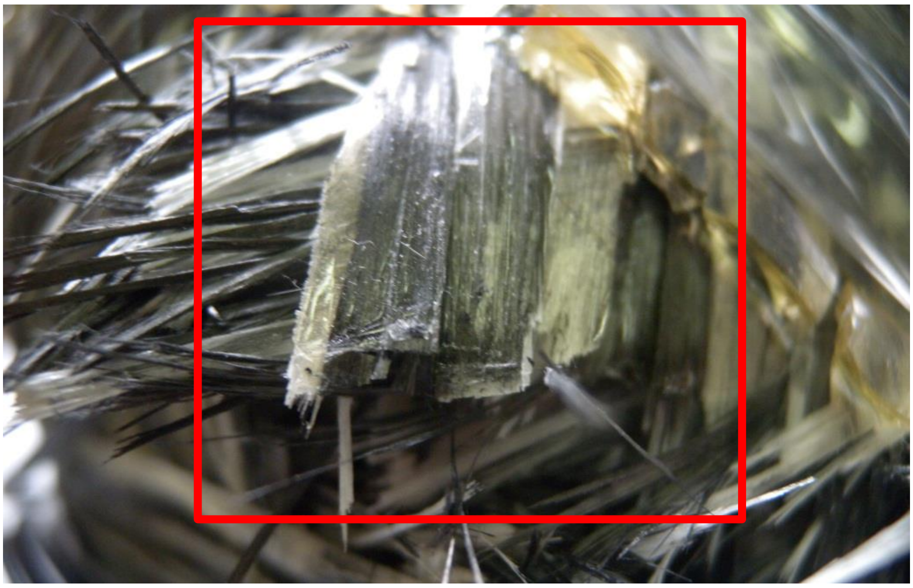


Figure 4-17: Detail of sharply truncated fibers after the second hydraulic test- Cylinder 8

Figure 4-18: Detail of frayed fibers after the second hydraulic test - Cylinder 8

5 FATIGUE TESTS

Each cylinder has been subjected to a pressure cycling fatigue test. Oil has been used as pressurizing medium, varying pressure from a minimum value of 20 bar to a maximum value >260 bar, having a target of 20,000 cycles.

Tests have been performed by means of the cycling system Italsigma X-CSM-1505, composed by:

- ✓ hydraulic power unit (6 litres/minute, max pressure 700 bar);
- ✓ chiller for oil cooling (max temperature 40 °C);
- ✓ National Instruments system for remote control and number of cycles acquisition;
- ✓ pressure monitoring system
  - PC Desktop
  - National Instrument NI-9215 card at 16 bit
  - pressure transducer AEP® LabTP14BL53R
  - data acquisition and pressure monitoring software (frequency 5 Hz).

The plot of the pressure variation during the fatigue test is reported in Figure 5-1.

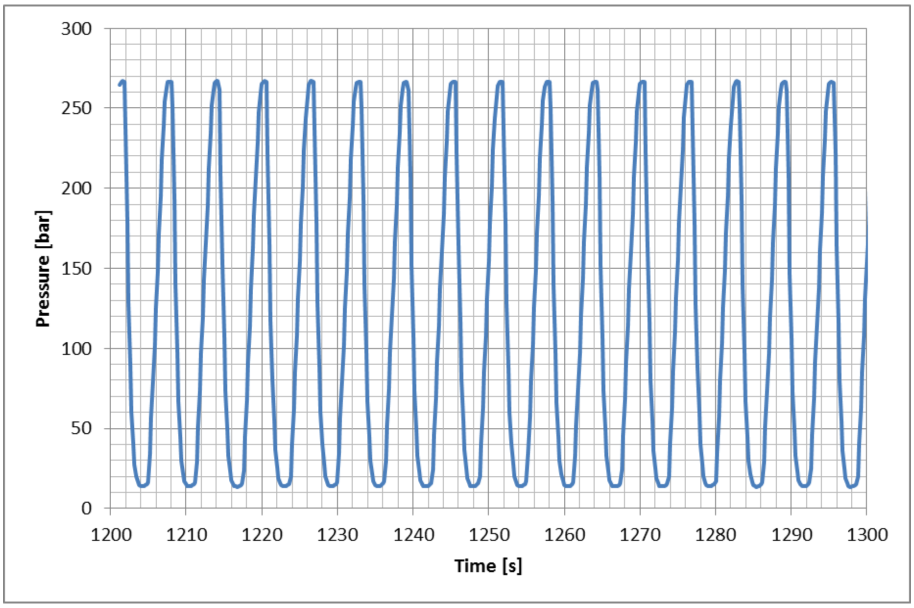


Figure 5-1: Example of pressure variation plot during fatigue test (cylinder 6)

According to Section A.6 of ECE ONU R110, cycling frequency has been set equal or lower to 10 cycles/minute (i.e. 0.16 Hz). The same data acquisition system of the hydraulic tests has been used also for the fatigue tests.

Fatigue test results are reported in Table 5.1.

Table 5.1: Results of the first fatigue tests

CSM ID	Fatigue Test Result	Failure Zone (Side/Generatrix)
1	**Negative:** **Failure after 1,125 cycles** *	Valve / 180°
2	Positive, no leak detected	NA
3	NA	NA
4	**Negative:** **Failure after 615 cycles**	Valve / 180°
5	**Negative:** **Failure after 120 cycles**	Valve / 180°
6	**Negative:** **Failure after 12,515 cycles**	Valve / 90°
7	**Negative:** **Failure after 2,685 cycles**	Capped / 180°
8	NA	NA
9	**Negative:** **Failure after 190 cycles**	Valve / 180°
10	Positive, no leak detected	NA
11	**Negative:** **Failure after 709 cycles**	Capped / 180°
12	**Negative:** **Failure after 5,345 cycles**	Valve / 180°

5.1 FAILURE ANALYSIS

In all of the tested cylinders, with the only exception of cylinder 6, failure occurred in the area of first impact during the drop test.

5.1.1 Cylinder 1

In the cylinder 1 the failure occurred in the dome area on the valve side, as shown in Figure 5-2. This area corresponds to the area where the first impact occurred during the drop test. Failure happened after 1,125 cycles.

Figure 5-2: Cylinder 1 blown up during the fatigue test

Figure 5-3 shows the two failure mechanisms previously observed. Red arrows indicate the sharply truncated fibers; these fibers are located in the impact area during the drop test (180° generatrix). Close to this area, the green arrows are pointing to the frayed fibers, which have likely been ripped off during the blow up.

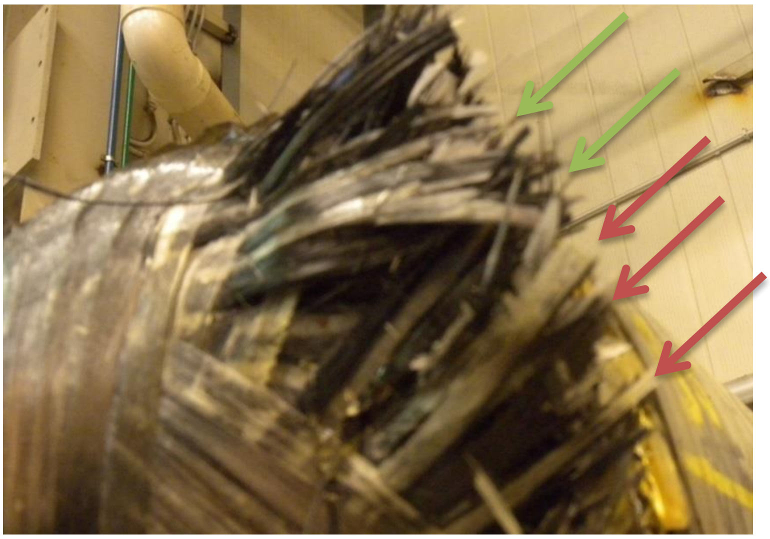


Figure 5-3: Cylinder 1 – Details of broken fibers after the fatigue test

5.1.2 Cylinder 4

In the cylinder 4 the failure occurred in the dome area on the valve side, as shown in Figure 5-4. This area corresponds to the area where the first impact occurred during the drop test. Failure happened after 615 cycles.

Figure 5-4: Cylinder 4 blown up during the fatigue test

Also in his case it is possible to see the sharply truncated fibers located in the impact area during the drop test (Figure 5-5).

Figure 5-5: Cylinder 4 – Details of broken fibers after the fatigue test

5.1.3 Cylinder 5

In the cylinder 5 the failure occurred in the dome area on the valve side, as shown in Figure 5-6. This area corresponds to the area where the first impact occurred during the drop test. Failure happened after 120 cycles.

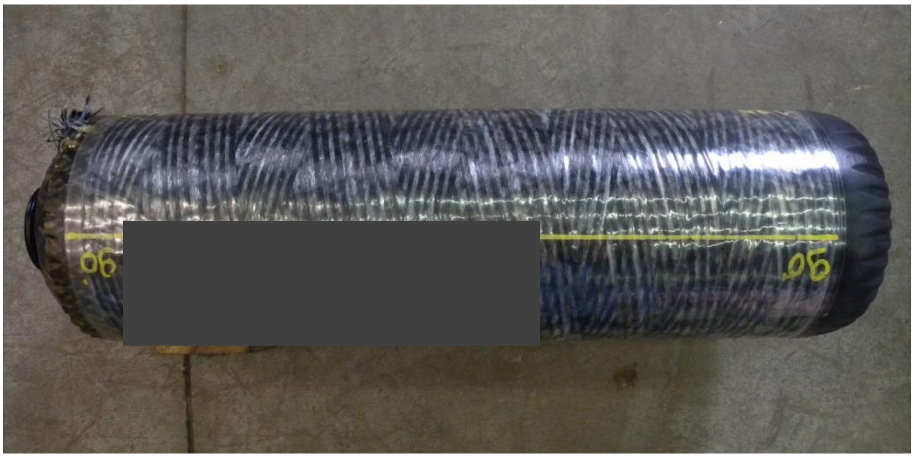


Figure 5-6: Cylinder 5 blown up during the fatigue test

Also in this case, as for the hydraulic tests, two failure mechanisms can be pointed out:

- ✓ in the impact area of the drop test, fibers are sharply truncated (Figure 5-7);
- ✓ in the area close to the impact, fibers are frayed (Figure 5-8).

Figure 5-7: Cylinder 5 – Details of sharply truncated fibers after the fatigue test

Figure 5-8: Cylinder 5 – Details of frayed fibers after the fatigue test

As already reported in Paragraph 1.1, fibers of cylinder 5 in the capped side were observed to be highly damaged during the preliminary visual inspection; nevertheless cylinder 5 did not failed in that area. Final state of the fibers in the capped area, after the fatigue test, is reported in Figure 5-9.

Figure 5-9: Cylinder 5 – Finale state on the fibers after fatigue test in the dome of capped side

5.1.4 Cylinder 6

In the cylinder 6 the failure occurred in the dome area on the valve side, along 90° generatrix, as shown in Figure 5-10. This cylinder was vertically drop tested, then it should not be subjected to an impact along the generatrix. Nevertheless, the video of the drop test demonstrates that the cylinder had a strong rebound impact exactly where the failure occurred. Failure happened after 12,515 cycles.

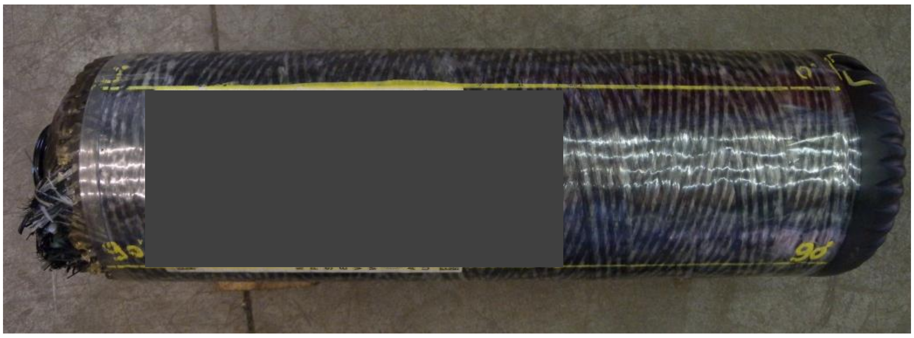


Figure 5-10: Cylinder 6 blown up during the fatigue test

Also in this case, as for the hydraulic tests, two failure mechanisms can be pointed out:

- ✓ in the impact area of the drop test, fibers are sharply truncated (Figure 5-11);
- ✓ in the area close to the impact, fibers are frayed (Figure 5-12).

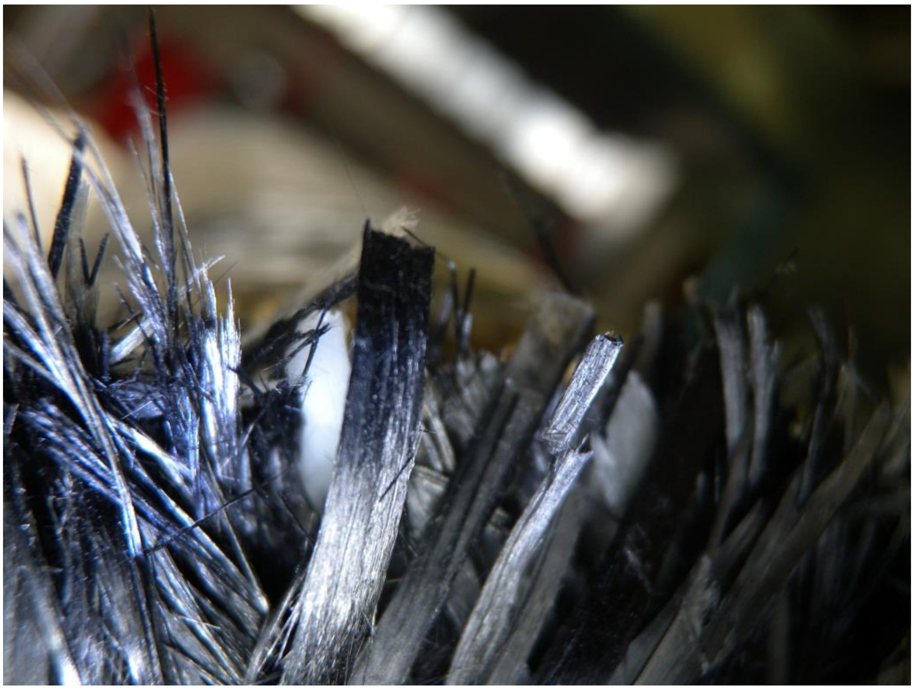


Figure 5-11: Cylinder 6 – Details of sharply truncated fibers after the fatigue test

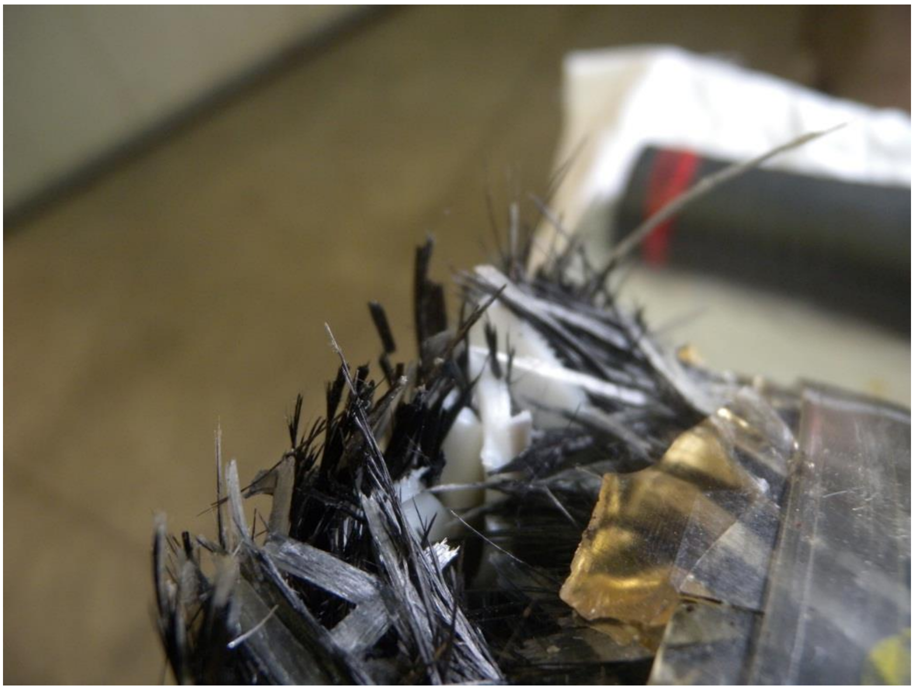


Figure 5-12: Cylinder 6 – Details of frayed fibers after the fatigue test

5.1.5 Cylinder 7

In the cylinder 7 the failure occurred in the dome area on the capped side, as shown in Figure 5-13. This area corresponds to the area where the first impact occurred during the drop test. Failure happened after 2,685 cycles.

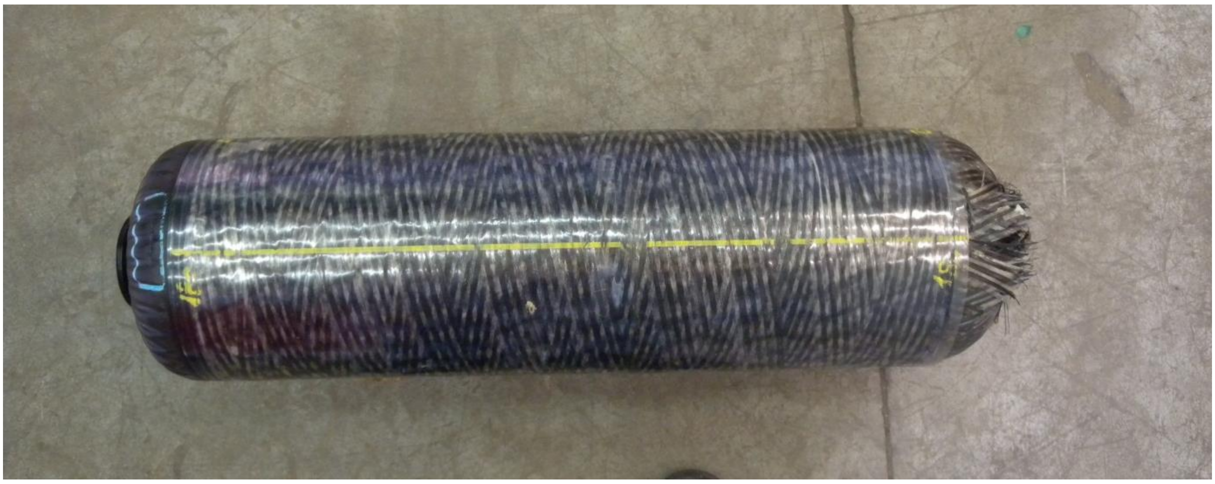


Figure 5-13: Cylinder 7 blown up during the fatigue test

Also in this case, as for the hydraulic tests, two failure mechanisms can be pointed out:

- in the impact area of the drop test, fibers are sharply truncated (Figure 5-14);
- in the area close to the impact, fibers are frayed (Figure 5-15).

Figure 5-14: Cylinder 7 – Details of sharply truncated fibers after the fatigue test

Figure 5-15: Cylinder 7 – Details of frayed fibers after the fatigue test

5.1.6 Cylinder 9

In the cylinder 9 the failure occurred in the dome area on the valve side, as shown in Figure 5-16. This area corresponds to the area where the first impact occurred during the drop test. Failure happened after 190 cycles.

Figure 5-16: Cylinder 9 blown up during the fatigue test

Also in this case, as for the hydraulic tests, two failure mechanisms can be pointed out:

- ✓ in the impact area of the drop test, fibers are sharply truncated (Figure 5-17);
- ✓ in the area close to the impact, fibers are frayed (Figure 5-18).

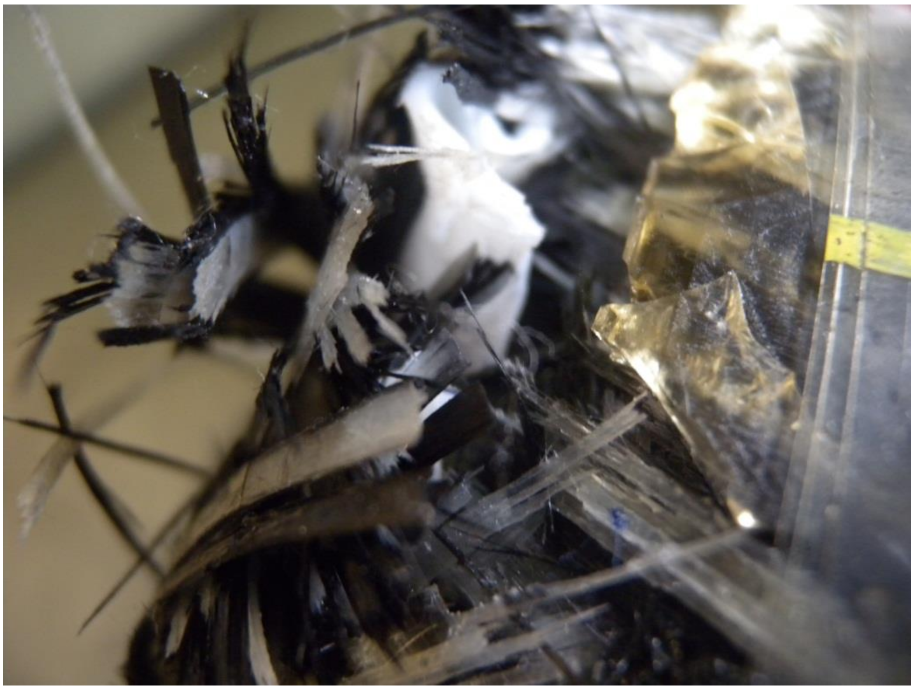


Figure 5-17: Cylinder 9 – Details of sharply truncated fibers after the fatigue test

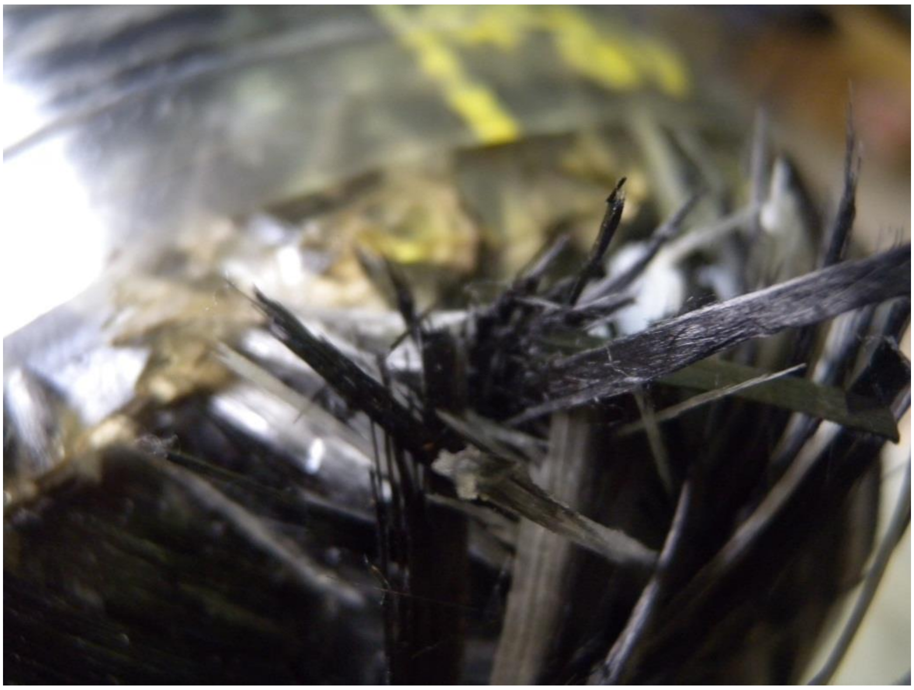


Figure 5-18: Cylinder 9 – Details of frayed fibers after the fatigue test

5.1.7 Cylinder 11

In the cylinder 11 the failure occurred in the dome area on the capped side, as shown in Figure 5-19. This area corresponds to the area where the first impact occurred during the drop test. Failure happened after 709 cycles.

Figure 5-19: Cylinder 11 blown up during the fatigue test

Also in this case, as for the hydraulic tests, two failure mechanisms can be pointed out:

- ✓ in the impact area of the drop test, fibers are sharply truncated (Figure 5-20);
- ✓ in the area close to the impact, fibers are frayed (Figure 5-21).

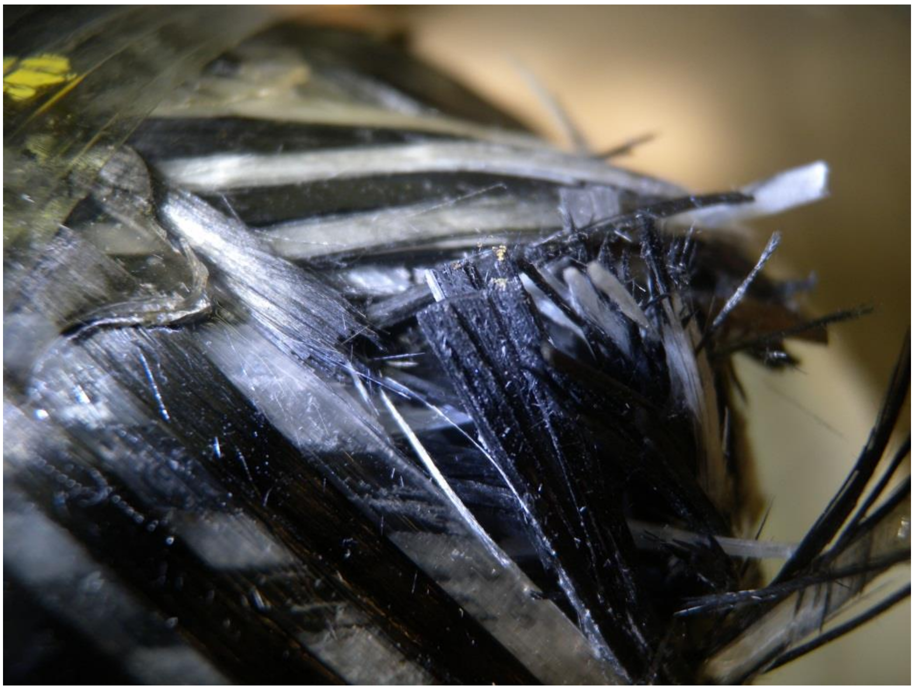


Figure 5-20: Cylinder 11 – Details of sharply truncated fibers after the fatigue test

Figure 5-21: Cylinder 11 – Details of frayed fibers after the fatigue test

5.1.8 Cylinder 12

In the cylinder 12 the failure occurred in the dome area on the valve side, as shown in Figure 5-22. This area corresponds to the area where the first impact occurred during the drop test. Failure happened after 5,345 cycles.

Figure 5-22: Cylinder 12 blown up during the fatigue test

Also in this case, as for the hydraulic tests, two failure mechanisms can be pointed out:

- ✓ in the impact area of the drop test, fibers are sharply truncated (Figure 5-23);
- ✓ in the area close to the impact, fibers are frayed (Figure 5-24).

Figure 5-23: Cylinder 12 – Details of sharply truncated fibers after the fatigue test

Figure 5-24: Cylinder 12 – Details of frayed fibers after the fatigue test

6 DROP TEST WITHOUT PROTECTIVE DOMES

The two cylinders which had passed the fatigue test (i.e. cylinders 2 and 10) have been subjected again to the drop test after having removed the protective domes. Both cylinders underwent the vertical drop test, both on the capped and the valve sides.

6.1 CYLINDER 2

Cylinder 2 has been tested with both sides vertical drops. After both tests the cylinder does not appear to have damages.

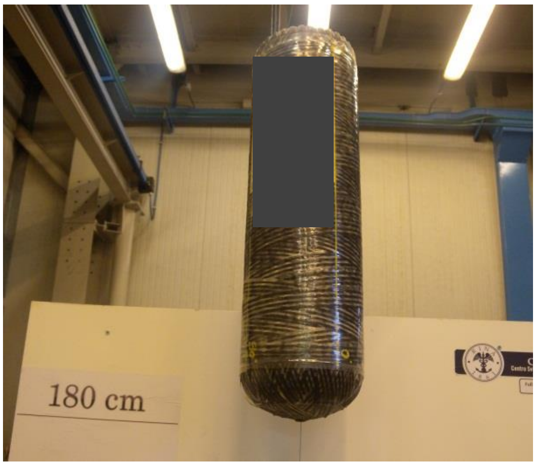


Figure 6-1: Cylinder 2 – Vertical drop, capped side

Figure 6-2: Cylinder 2 after the vertical drop, capped side

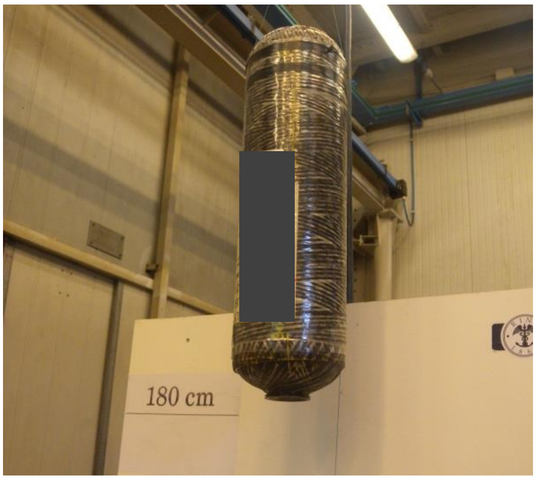


Figure 6-3: Cylinder 2 – Vertical drop, valve side

Figure 6-4: Cylinder 2 after the vertical drop, valve side

6.2 CYLINDER 10

Cylinder 2 has been tested with both sides vertical drops. As shown in Figure 6-7 and Figure 6-8, the cylinder has been highly damaged in the dome area of the capped side.

Figure 6-5: Cylinder 10 – Vertical drop, capped side

Figure 6-6: Cylinder 10 – After vertical drop, capped side

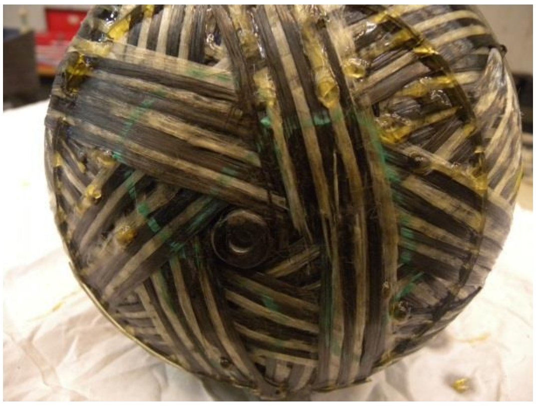


Figure 6-7: Cylinder 10 – Details of damaged fibres after Vertical drop, capped side

Figure 6-8: Cylinder 10 – Details of damaged fibres after vertical drop, capped side

No further damage was observed after the vertical drop test on the valve side.

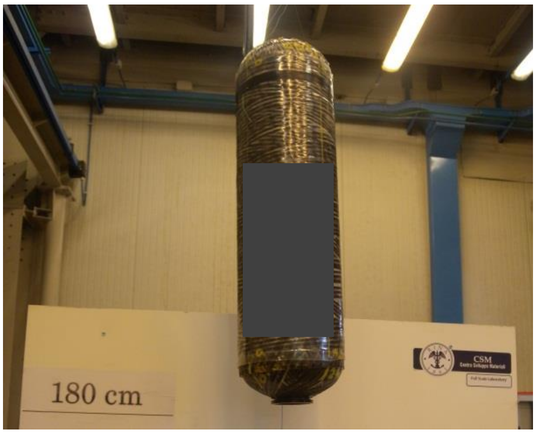


Figure 6-9: Cylinder 10 – Vertical drop, valve side

Figure 6-10: Cylinder 10 – After vertical drop, valve side

7 SECOND FATIGUE TEST

Each one of the two remaining cylinders underwent once again the fatigue test. Test procedure was the same already described at Chapter 5. Test results are summarized in Table 7.1.

Table 7.1: Results of the second fatigue tests

CSM ID	Test Results	Failure Zone
2	**Negative:** **Failure after 83 cycles**	Dome, capped side
10	**Negative:** **Failure during first cycle**	Dome, capped side

7.1 FAILURE ANALYSIS

For both cylinders the failure zone was located in the dome area of the capped side.

7.1.1 Cylinder 2

In the cylinder 12 the failure occurred in the dome area on the capped side, as shown in Figure 7-1. Failure happened after 83 cycles.

Figure 7-1: Cylinder 2 blown up during the second fatigue test

The failure area corresponds to the top of the dome, capped side, as shown in Figure 7-2.

Figure 7-2: Cylinder 2 – Detailed view of the blown up area

Figure 7-3 reports the inner surface of cylinder 2. It is possible to see that part of the liner at the top of the dome is missing; this kind of damage can be related to the vertical drop.

Figure 7-3: Cylinder 2 – View of the blown up area from inside

7.1.2 Cylinder 10

In the cylinder 12 the failure occurred during the first cycle (Figure 7-4) at the top of the dome area on the capped side, as shown in Figure 7-5.

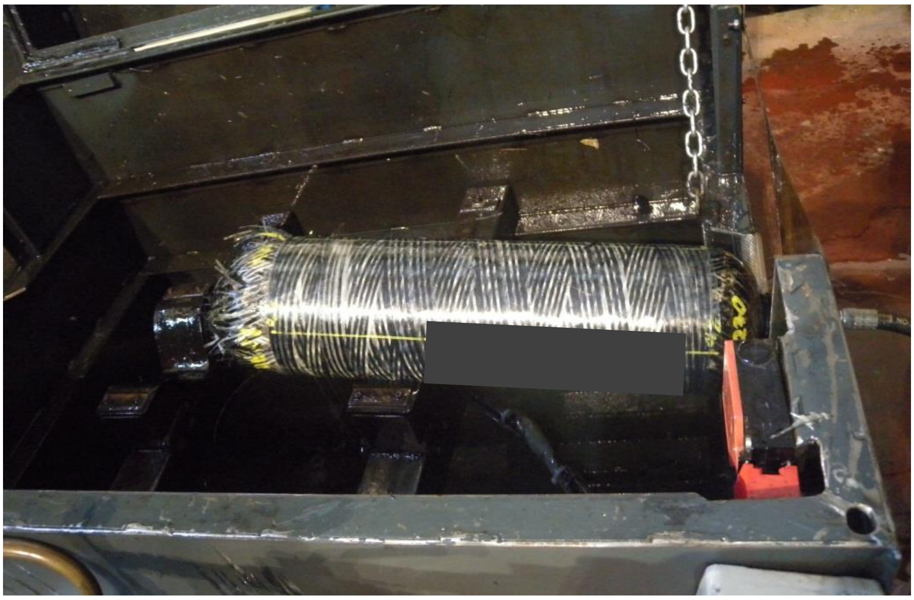


Figure 7-4: Cylinder 10 blown up during the second fatigue test

Figure 7-5: Cylinder 10 – Detailed view of the blown up area

Figure 7-6 reports the inner surface of cylinder 10. It is possible to see that the damage extends to the whole dome. In this case, no part of the liner was missing. This kind of damage can be related to the vertical drop.

Figure 7-6: Cylinder 10 – View of the blown up area from inside

8 WALL THICKNESS MEASUREMENTS

In order to evaluate the wall thickness distribution in the cylinders used for the tests, specific measurements have been taken on cylinder 7.

Cylinder 7 has been cut under optimal cooling conditions and with a low speed, in order to avoid damages to the composite during cutting operations.

Wall thickness measurements have been taken using a Mitutoyo instrument with an accuracy of 0.005 mm and able to take the measure far from the cut edge.

The cylinder has been longitudinally cut along directions at 90° and 270°. For each measure position, 4 measurement have been taken.

After cutting the plastic liner was easily detached from the cylindrical surfaces.

Measurements showed a non-uniform thickness. Particularly in the cylindrical area the composite thickness was constantly of 5 mm (Figure 8-1). In the dome areas, the thickness was higher close to the cylindrical zone and at the top of the dome, whilst a strong thinning was observed in the intermediate zone. In that area, the wall thickness can be lower than 2.5 mm. In some cases, also a lack of superimposition of the fibers was observed (Figure 8-2). In Figure 8-3 a picture of the valve connection area after cutting is presented.

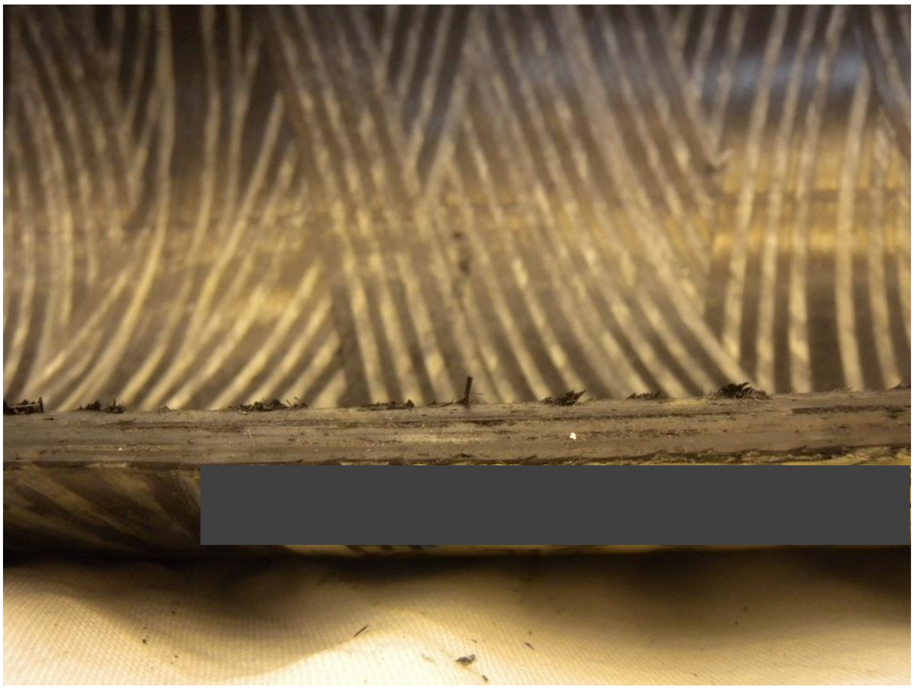


Figure 8-1: Cylinder 7 – View of the cutting along the cylindrical area

Figure 8-2: Cylinder 7 – Detailed view of the lack of fibers superimposition

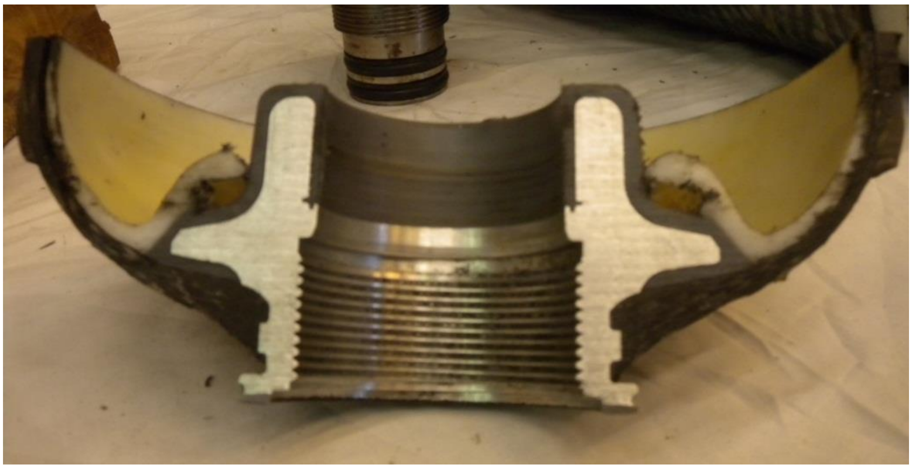


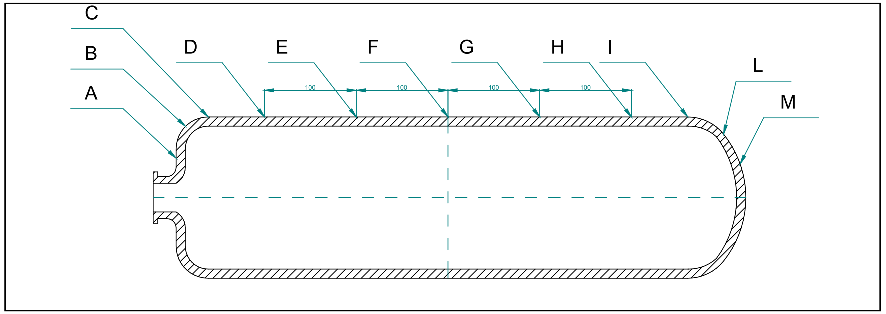
Figure 8-3: Cylinder 7 – Detailed view of the valve connection area

The results of the measurements taken on cylinder 7 are reported in Figure 8-4.

Hexagon thickness measurement

Specimen	Manufacturer		CSM ID		Date of Test:	29/09/2017
	SN	1423200241	Nom. Outside Diameter D [mm]:	178,0	Standard	ECE R110
Material		Carbon/glass fiber	Specimen Lenght [mm]	650,0	Test Pressure [bar]	300,0
Empty mass [kg]		4,2	Working Pressure [bar]	200,0		
Water Capacity		12,5	Maximum Op. Pressure [bar]	260		

A Beginning of curved shape - Valve side
B Minimum dome thickness - Valve side
C End of curved shape - Valve side
D 200 mm distance from F - Valve side
E 100 mm distance from F - Valve side
F Central section of cylinder
G 100 mm distance from F - Capped side
H 200 mm distance from F - Capped side
I Beginning of curved shape - Capped side
L Minimum dome thickness - Capped side
M End of curved shape - Capped side



Thickness measurement

tc - Wall Thickness [mm]											
SEZ	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**L**	**M**
tc 90°	4,860	2,430	3,625	4,990	4,950	4,885	5,370	5,250	4,380	2,460	8,555
tc 90°	4,675	2,390	3,725	5,195	4,885	4,945	5,265	5,545	4,300	2,160	8,865
tc 270°	7,770	2,475	3,680	5,055	4,980	4,900	5,255	5,210	4,395	2,695	9,405
tc 270°	4,560	2,350	3,705	4,960	5,055	4,870	5,255	5,505	4,525	2,135	8,740
$tc_{average}$	5,47	2,41	3,68	5,05	4,97	4,90	5,29	5,38	4,40	2,36	8,89
tc_{max}	7,77	2,48	3,73	5,20	5,06	4,95	5,37	5,55	4,53	2,70	9,41
tc_{min}	4,56	2,35	3,63	4,96	4,89	4,87	5,26	5,21	4,30	2,14	8,56

$tc_{average}$	4,80	mm
tc_{max}	9,41	mm
tc_{min}	2,14	mm

Figure 8-4: Cylinder 7 – Results of the wall thickness measurements

9 CONCLUSIONS

An experimental activity has been performed on 12 cylinders type CNG4 according to Regulation ECE ONU R110, Annex 3, Paragraphs A11/2 and A20.

None of the 12 tested cylinders passed the whole testing program.

Cylinders resulted to be seriously affected by the first drop impact tests performed. In fact, during the subsequent hydraulic tests, all of the cylinders creaked at pressure values over 200 bar and two of them blew up at target pressure (300 bar).

Eight cylinders failed during the first fatigue test, while the two remaining failed during the second fatigue test, after the drop test performed without the protective domes.

In all cases, a relation has been detected between the impact zone, with or without protective domes, and the failure zone.

The 45° angle drop test revealed to be the most severe one: two cylinders out of six, subjected to this type of test, failed just after the drop. In terms of severity, the horizontal drop test follows the 45° one; all of the cylinder horizontally dropped failed during the first fatigue test.

The less severe drop test is the vertical one. In this case, out of three cylinders, one failed after 12,515 cycles of the first fatigue test and two cylinders passed the first fatigue test and then failed at the beginning of the second fatigue test, performed after having carried out the drop test without the protective domes. In this two final cases, the failure was very significative and involved the entire dome on the capped side.

In some cases, although severe defects were observed in the preliminary visual inspection (strong exposition of the fibers), cylinders failed in the impact zone even if it did not show evident damage.

The analysis of the failed areas led to put in evidence two failure mechanisms:

- ✓ in the impact areas, fibers are sharply truncated as if they were indented in the impact test;
- ✓ in the areas close to the impact, fibers appear to be frayed and/or ripped off.

Unfortunately, the inspection of the impact damaged zones was not easy at all, due to the presence of the protective domes which, anyhow, do not appear to be particularly effective.

Wall thickness measurements performed on the cut cylinder (number 7) put in evidence a strong non-uniformity of the composite material between the cylindrical part and the dome areas. The thickness varies from 5 mm in the cylindrical area to 2.5 mm in the dome. After having cut the cylinder is also possible to see that in the dome the resin is present in areas where fibers should be; this never occurs in the cylindrical zones.

The whole experimental activity and the relevant main results are resumed in Table 9.1 and Table 9.2, respectively for cylinders 1-6 and cylinders 7-12.

Table 9.1: Experimental activities and results for cylinders 1-6

Cylinder ID	1	2	3	4	5	6
SN	1419200152	1423200230	1423200222	1419200164	1423200250	1419200188
Preliminary Visual Inspection	Performed	Performed	Performed	Performed	Performed	Performed
Hydraulic Test @ 300 bar	Performed OK	Performed OK	Performed OK	Performed OK	Performed OK	Performed OK
Visual Inspection after Hydraulic Test	Performed	Performed	Performed	Performed	Performed	Performed
Drop Test from 1.8 m Height	Horizontal Performed	Vertical (capped & valve sides) Performed	45° angle (capped side) Performed	45° angle (valve side) Performed	Horizontal Performed	Vertical (capped & valve sides) Performed
Visual Inspection after Drop Test	Performed	Performed	Performed	Performed	Performed	Performed
Hydraulic Test @ 300 bar	Performed OK Creaking @ P>200 bar	Performed OK Creaking @ P>200 bar	Performed Failed Failure @ 300 bar *	Performed OK Creaking @ P>200 bar	Performed OK Creaking @ P>200 bar	Performed OK Creaking @ P>200 bar
Visual Inspection after Hydraulic Test	Performed	Performed	Performed	Performed	Performed	Performed
Fatigue Test (20.000 cycles)	Performed Failed Failure after 1,125 cycles *	Performed OK	NA	Performed Failed Failure after 615 cycles *	Performed Failed Failure after 120 cycles *	Performed Failed Failure after 12,515 cycles
Visual Inspection after Fatigue Test	NA	Performed	NA	NA	NA	NA
Protective Domes Removal	NA	Performed	NA	NA	NA	NA
Visual Inspection	NA	Performed	NA	NA	NA	NA
Drop Test from 1.8 m Hight	NA	Performed	NA	NA	NA	NA
Visual Inspection after Drop Test	NA	Performed	NA	NA	NA	NA
Fatigue Test (20.000 cycles)	NA	Performed Failed Failure after 83 cycles	NA	NA	NA	NA
Cylinder Cutting	NA	NA	NA	NA	NA	NA

** Failure occurred in the impact zone*

Table 9.2: Experimental activities and results for cylinders 7-12

Cylinder ID	7	8	9	10	11	12
SN	1423200241	1423200224	1423200236	1419200185	1423200154	1423200213
Preliminary Visual Inspection	Performed	Performed	Performed	Performed	Performed	Performed
Hydraulic Test @ 300 bar	Performed OK	Performed OK	Performed OK	Performed OK	Performed OK	Performed OK
Visual Inspection after Hydraulic Test	Performed	Performed	Performed	Performed	Performed	Performed
Drop Test from 1.8 m Height	45° angle (capped side) Performed	45° angle (valve side) Performed	Horizontal Performed	Vertical (capped & valve sides) Performed	45° angle (capped side) Performed	45° angle (valve side) Performed
Visual Inspection after Drop Test	Performed	Performed	Performed	Performed	Performed	Performed
Hydraulic Test @ 300 bar	Performed OK Creaking @ P>200 bar	Performed Failed Failure after 20 s @ 300 bar *	Performed OK Creaking @ P>200 bar	Performed OK Creaking @ P>200 bar	Performed OK Creaking @ P>200 bar	Performed OK Creaking @ P>200 bar
Visual Inspection after Hydraulic Test	Performed	Performed	Performed	Performed	Performed	Performed
Fatigue Test (20.000 cycles)	Performed Failed Failure after 2,685 cycles *	NA	Performed Failed Failure after 190 cycles *	Performed OK	Performed Failed Failure after 709 cycles*	Performed Failed Failure after 5,345 cycles
Visual Inspection after Fatigue Test	NA	NA	NA	Performed	NA	NA
Protective Domes Removal	NA	NA	NA	Performed	NA	NA
Visual Inspection	NA	NA	NA	Performed	NA	NA
Drop Test from 1.8 m Hight	NA	NA	NA	Performed	NA	NA
Visual Inspection after Drop Test	NA	NA	NA	Performed	NA	NA
Fatigue Test (20.000 cycles)	NA	NA	NA	Performed Failed Failure during first cycle	NA	NA
Cylinder Cutting	Performed	NA	NA	NA	NA	NA

** Failure occurred in the impact zone*

APPENDIX A

Appendix A

Calibration Certificates

Doc. No. 19500-R Rev. 2 – March 2018

CSM
Centro Sviluppo Materiali

Rapporto di Taratura N° 17/01

(Calibration report N°)

Data delle misure *(Date Of Measurement)*	**28/03/2017**
Temperatura di Prova *(Room Temperature)*	22°C
Pratica di Taratura di riferimento *(Laboratory Reference)*	T.CPE.01 Rev.0

Apparecchiatura Utilizzata

(Standard System)

Strumento *(Device)*	Bilancia Manotherm
Costruttore *(Manufacter)*	Armaturenbau
Tipo *(Type)*	Pd 2500
N° Serie *(Serial Number)*	187
Certificato Di Taratura N° *(Calibration Certificate)*	MA-RTI-1282-2014
Scadenza Certificato *(Validity)*	01/12/2018
Strumento *(Device)*	Multimetro Digitale
Costruttore *(Manufacter)*	Agilent
Tipo *(Type)*	34401 A
N° Serie *(Serial Number)*	MY53004473
Certificato Di Taratura N° *(Calibration Certificate)*	15MC098
Scadenza Certificato *(Validity)*	15/10/2017
Strumento *(Device)*	Alimentatore
Costruttore *(Manufacter)*	Tti
N° Serie *(Serial Number)*	406877

Trasmettitore di Pressione ☑ **Manometro**

Strumento *(Device)*	Trasmettitore di pressione
Costruttore *(Manufacter)*	AEP
Tipo *(Type)*	LabTP14BL53R
N° Serie *(Serial Number)*	**908685**
Fondo Scala *(Pressure Ranges)*	500 BAR
Alimentazione *(Power Supply)*	7-25,5Vdc
Segnale Uscita *(Output Signal)*	4-20mA 2 wires

Misure (Measurement)

	Valore applicato [bar]	Valore misurato [bar]	Errore [%]
1	0	0,0	
2	50	50,4	0,8
3	100	100,5	0,5
4	150	150,8	0,6
5	200	200,8	0,4
6	250	251,0	0,4
7	300	301,0	0,3
8	350	350,9	0,3
9	400	401,1	0,3
10	450	451,3	0,3
11	500	501,0	0,2

Tecnico *(Technical Operator)* **Mario Sacchetto**

Resp. Laboratorio *(Lab. Manager)* **Emanuele Bertelli**