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Specific tests on CNG4 cylinders

Provider 1

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Description	1st Issue
Prepared by	P. Lombardi, E. Bertelli
Controlled by	E. Mecozzi
Approved by	M. Di Biagio
Date	March 2018

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2	First Issue	P. Lombardi E. Bertelli	E. Mecozzi	M. Di Biagio	March 2018

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EXECUTIVE SUMMARY

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

Before starting the proper experimental activity, a set of preliminary tests, including drop test and hydraulic test, has been performed on a dummy cylinder in order to setup the experimental procedure.

First part of the proper experimental activity included the following tests:

- ✓ impact damage test;
- ✓ hydraulic pressure test at 300 bar;
- ✓ pressure cycling fatigue test between 260 bar and 20 bar, for 20,000 cycles, at 0.15 Hz (≤ 9 cycles/min).

At the end of the first part, a second part of activity has been added, after having removed the protective domes:

- ✓ impact damage test;
- ✓ hydraulic pressure test at 300 bar;
- ✓ pressure cycling fatigue test between 260 bar and 20 bar, for 20,000 cycles, at 0.15 Hz (≤ 9 cycles/min).

In 11 cases out of 12, with the only exception of cylinder 7, a relation has been identified between the impact zone of the drop test without protective domes and the failure zone.

The 45° angle drop test revealed to be the most severe one: none of the cylinders subjected to this type of test was able to pass the following hydraulic test. In terms of severity, the horizontal drop test follows the 45° one: only one cylinder, out of the three tested with horizontal drop, managed to pass the hydraulic test.

The less severe drop test is the vertical one. In this case, all of the three tested cylinders passed the subsequent hydraulic test; two of them failed during the last (second) fatigue test and one cylinder (number 2) managed to complete the whole test program, although showing the same kind of damages (discolored area on the domes) that led to failure in all of the other cases.

On the basis of the observed results, it is possible to state that the mechanism that leads to the failure of the cylinders is related to the breaking of the fibers in the dome areas, due to the impact caused by the drop test. The fibers breaking is put in evidence by discoloured (turned white) areas. The protective domes removal is a key element in order to be able to perform a correct visual inspection of the domes and to detect possible damages.

1 SCOPE OF THE WORK AND ACTIVITY PROGRAM

Scope of the present work is to perform a series of experimental activities on type CNG4 all composite cylinders for automotive natural gas, according to Paragraphs A11/2 and A20 of Annex 3 of the ECE ONU Regulation 110.

The activity program consisted of the following tests:

- ✓ impact damage test;
- ✓ hydraulic pressure test at 300 bar;
- ✓ pressure cycling fatigue test between 260 bar and 20 bar, for 20,000 cycles, at 0.15 Hz (≤ 9 cycles/min).

Furthermore, in order to make the test sequence more similar to the actual cylinder working life, a second series of tests (the same listed above, foreseen by ECE ONU R110) has been carried out on the same cylinders, after having removed the protective domes.

It was also agreed to perform a preliminary set of tests, including drop test and hydraulic test, in order to setup the experimental procedure. These tests were performed on a dummy cylinder having serial number 1002200066 and internal CSM ID 0. In particular, the dummy cylinder underwent all of the drop tests foreseen by ECE ONU R110 Annex 3, Paragraph A20.

The experimental procedure setup by means of the preliminary tests was then applied to a set of 12 cylinders.

2 PRELIMINARY TESTS

2.1 DUMMY CYLINDER PREPARATION

The dummy cylinder has been marked along 4 main generatrices, named 0°, 90°, 180° and 270°. The preliminary visual inspection did not show any kind of damage (dent, crack, etc.).

The dummy cylinder before drop tests is shown in Figure 1-1.

Figure 1-1: Dummy cylinder before drop tests

2.2 DROP TESTS

2.2.1 Test Procedure

The dummy cylinder, empty and without valve, underwent two series of drop tests: the first series from the height of 1 m, the second one from 1.8 m.

Each one of the two series included the following tests:

- ✓ No. 3 horizontal drop tests;
    - o each test was performed changing the impact generatrix, namely 0°, 90° and 270°;

- the drop height was measured at the lowest cylinder generatrix;

- ✓ No. 3 vertical drop tests on the valve side (drop height measured at the lowest cylinder point);
- ✓ No. 3 vertical drop tests on the capped side (drop height measured at the lowest cylinder point);
- ✓ No. 3 drop tests at 45° angle, on three different generatrices (0°, 90° and 270°);
  - the drop height was measured at the centre of gravity of the cylinder;
  - the lowest side was the valve one.

A total number of 24 drop tests was then performed on the dummy cylinder.

Different setups for each of the mentioned drop tests are reported in Figure 1-2 for the height of 1.8 m case.

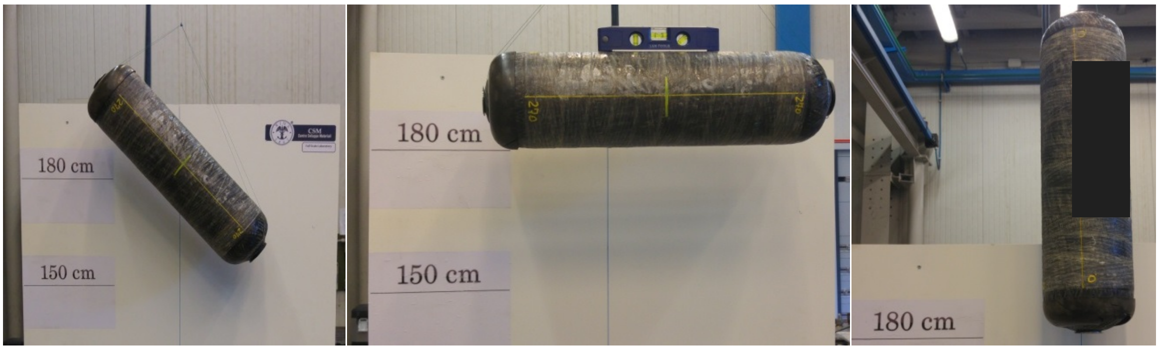

Figure 1-2: Drop tests different setups (drop height 1.8 m)

2.2.2 Preliminary drop test results

The protective dome on the valve side was lost after the 45° angle drop test at 1 m height; the following tests from 1.8 m height were then performed without it. The protective dome on the capped side presented several cracks and missing parts, as reported in Figure 2-3, after both 1 m and 1.8 m drop tests, but it was not separated from the cylinder body.

Figure 2-3: Dummy cylinder - Damages on the capped side protective dome after drop tests

The cylinder also showed abrasions and dents on the external resin, but the most evident damage consisted in the diffused discoloration of the impact zone on both domes.

2.3 HYDRAULIC TEST

2.3.1 Test Procedure

After having completed the two series of drop tests from different heights, the dummy cylinder underwent the hydraulic test, according to ECE ONU R110 Annex 3, Paragraph A11 option 2. The cylinder ready for the test is shown in Figure 2-4.

Figure 2-4: Dummy cylinder – Hydraulic test setup

The test foresaw pressurization up to 300 bar (i.e. 150% of the cylinder working pressure), with some intermediate holding at 30 bar, 50 bar and 100 bar in order to verify the whole hydraulic circuit.

According to the test procedure, once reached the target pressure the cylinder should be isolated from the rest of the circuit, so that any possible pressure variation revealed by the transducer could be directly related to the cylinder behavior.

2.3.2 Hydraulic Test Results

The dummy (spare) cylinder blew up at 150 bar, before achieving the target pressure (300 bar); the failure is put in clear evidence by the pressure collapsing in the plot reported in Figure 2-5.

The dummy cylinder consequently did not pass the hydraulic test after drop tests.

As shown in Figure 2-6, cylinder failure occurred on the dome at valve side, in correspondence of 90° generatrix. In the failure zone, fibers are at about 30° angle with the longitudinal axis of the cylinder.

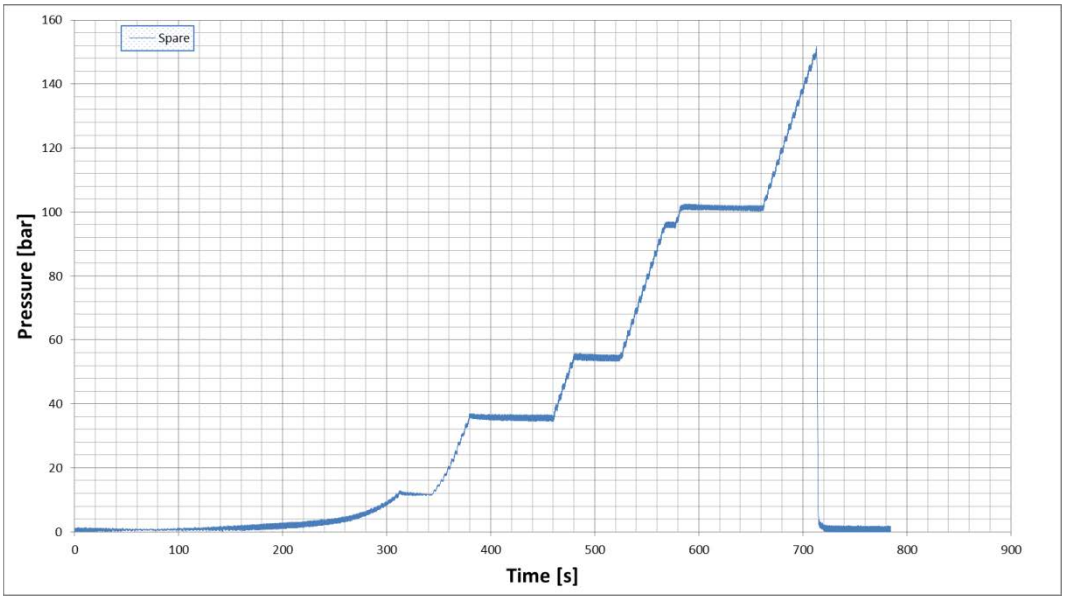

Figure 2-5: Dummy cylinder – Hydraulic test pressure-time plot

Figure 2-6: Dummy cylinder – Failure after the hydraulic test

3 OFFICIAL TESTS

After having completed the test procedure setup by means of the preliminary tests, the official test program was started following the test sequence reported in Figure 3-1, in accordance with ECE ONU R110, Annex 3, Paragraphs A11/2 and A/20.

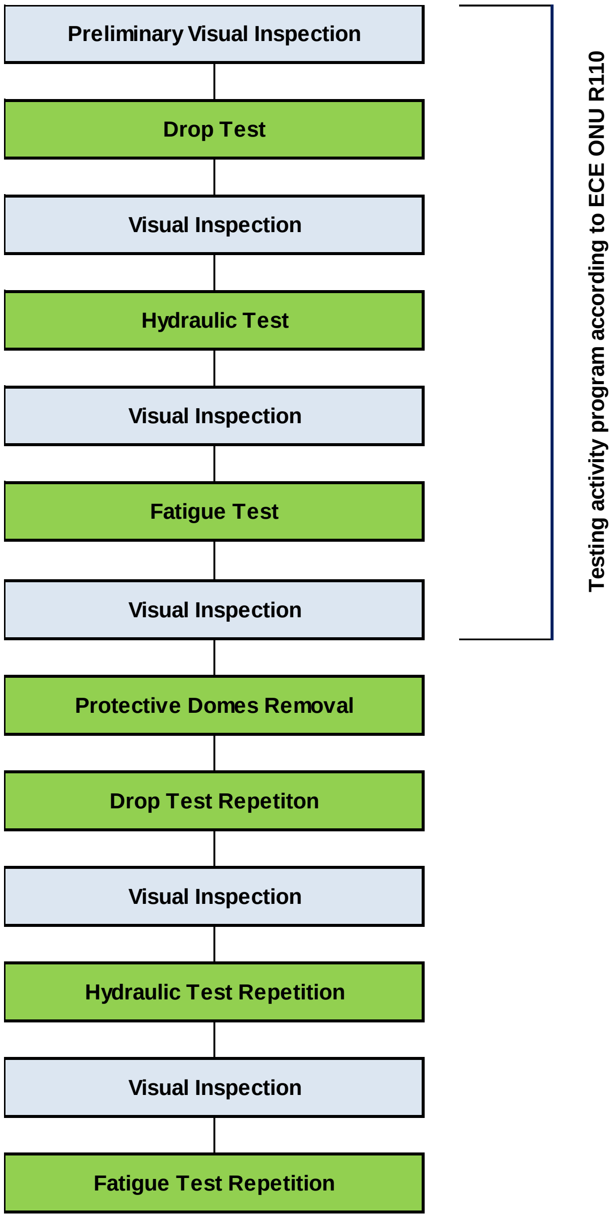

Figure 3-1: Activities sequence of the official test program

Tests execution and results for each cylinder are reported in details in the following Paragraphs.

3.1 DROP TESTS

Before starting the official tests, each cylinder has been assigned an internal CSM ID for ease of reference; the correspondence between each cylinder serial number and the relevant CSM ID is reported in Table 3.1.

Table 3.1: CSM Identification numbers and Serial Numbers of the cylinders

CSM ID	Serial Number
1	1007600053
2	0927900020
3	1002600016
4	1002600059
5	0911900022
6	1002600039
7	0908400029
8	1002200057
9	0904700059
10	0927400061
11	0927400070
12	0911900045

Each cylinder, empty and without valve, was subjected to a specific drop test, among those foreseen by ECE ONU R110, from the height of 1.8 m:

- ✓ horizontal drop tests (the drop height was measured at the lowest cylinder generatrix);
- ✓ vertical drop tests on the valve side followed by vertical drop test on the capped side (drop height measured at the lowest cylinder point);
- ✓ 45° angle drop tests on the valve side (the drop height was measured at the centre of gravity of the cylinder);
- ✓ 45° angle drop tests on the capped side (the drop height was measured at the centre of gravity of the cylinder).

The drop test program and the relevant results of the visual inspection performed before and after tests (observed defects are reported in reference to the main generatrices marked on the cylinders, as per dummy cylinder example) are reported in Table 3.2 and Table 3.3, respectively for cylinders 1-5 and cylinders 6-12.

Table 3.2: Results of the drop impact tests (cylinders 1-5)

CSM ID	Horizontal drop	Vertical drop side 1	Vertical drop side 2	45° drop	Observations before drop	Observations after drop
1	√ *[180°]*				✓ Light abrasion at 180° ✓ Small crack between 90° and 180°, on the valve side protective dome ✓ Valve side protective dome slightly unglued ✓ Capped side protective dome slightly unglued	✓ Impact evidence on the protective dome at 270°
2		√	√		✓ Capped side protective dome damaged at 90° ✓ Valve side protective dome slightly unglued (4 mm gap) ✓ Capped side protective dome slightly unglued (2 mm gap) ✓ Abrasion on capped side at 0° ✓ Oblique scratch at 270° ✓ Protective dome on capped side chipped	✓ Impact evidence on the edge of valve connection ✓ Protective dome on capped side chipped between 180° and 270°
3				√ (capped side) *[0°-90°]*	✓ Dent on protective dome capped side at 0° ✓ Dent on protective dome valve side between 270° and 0°	✓ Crack at 90° on the valve side protective dome ✓ Protective dome capped side broken between 0° and 90°
4				√ (valve side) *[0°]*	✓ Exposed fibers on valve side ✓ Protective dome valve side flatted ✓ Valve side protective dome slightly unglued (4 mm gap)	✓ Crack at 0° on the valve side protective dome ✓ Protective dome valve side broken between 0° and 270°
5	√ *[180°]*			√ (valve side) *[180°]*	✓ Scratch at 0° on cylinder body ✓ Valve side protective dome unglued ✓ Marks on protective dome capped side at 0° ✓ Marks on protective dome valve side at 90°	✓ Marks on protective dome valve side at 180° ✓ Crack at 180° on the valve side protective dome

Table 3.3: Results of the drop impact tests (cylinders 6-12)

CSM ID	Horizontal drop	Vertical drop side 1	Vertical drop side 2	45° drop	Observations before drop	Observations after drop
6		√	√		✓ Exposed fibers at 0° close to capped side ✓ Exposed fibers at 270° on both capped and valve sides ✓ Discontinuous fibers at 180° and 270° ✓ Gaps between cylinder and protective domes	✓ Protective dome on valve side strongly cracked ✓ Protective dome on capped side cracked
7				√ (capped side) *[180°]*	✓ Abraded protective domes ✓ Gaps between cylinder and protective domes	✓ Protective dome on capped side broken
8				√ (valve side) *[180°]*	✓ Discontinuous fibers at 180° on both capped and valve sides ✓ Gaps between cylinder and protective dome on capped side	✓ Protective dome on capped side broken
9	√ *[180°]*				✓ Protective dome on capped side cracked ✓ Gaps between cylinder and protective dome on valve side	✓ Both protective domes broken
10		√	√		✓ Cylinder body dented at 0° ✓ Abrasions on valve side at 180° and 270° ✓ Gaps between cylinder and protective domes	✓ No further observation
11				√ (capped side) *[180°]*	✓ Protective dome on valve side partially unglued ✓ Gaps between cylinder and protective domes ✓ Strong abrasions on both protective domes	✓ Both protective dome damaged at 180°
12				√ (valve side) *[180°]*	✓ Discolored fibers at 180° ✓ Frayed fibers	✓ Protective dome capped side damaged at 180°

3.2 HYDRAULIC TEST

Each cylinder, after the drop test, underwent the hydraulic proof test, performed by applying a pressure equal to 150% of the cylinders working pressure (I.e. 300 bar) and maintaining the pressurization for at least 120 s, according to ECE ONU R110, Annex 3, Paragraph A/11 option 2. Water was used as pressurizing medium.

According to the test procedure, once the target pressure was reached, the cylinder was isolated from the rest of the circuit, so that any possible pressure variation revealed by the transducer could be directly related only to the cylinder behavior.

Hydraulic test results are reported in Table 3.4.

Table 3.4: Hydraulic test results

CSM ID	Result
1	Positive: no leak observed
2	Positive: no leak observed
3	Positive: no leak observed
4	Positive: no leak observed
5	Positive: no leak observed
6	Positive: no leak observed
7	Positive: no leak observed
8	Positive: no leak observed
9	Positive: no leak observed
10	Positive: no leak observed
11	Positive: no leak observed
12	Positive: no leak observed

No further damages were observed on the cylinders after the hydraulic test.

3.3 FATIGUE TEST

Fatigue test, by means of cycling pressure, was performed on the cylinders. Mechanical oil was used as pressurizing medium; pressure cycled between a minimum (<20 bar) and a maximum value (>260 bar). Target of the test was to reach 20,000 cycles. In accordance with ECE ONU R110, Annex 3, Paragraph A6, the test frequency was ≤9 cycles/minute (0.15 Hz).

Fatigue test results are reported in Table 3.5.

Table 3.5: Fatigue test results

CSM ID	Result	Failure zone
1	Positive: no leak observed	NA
2	Positive: no leak observed	NA
3	Positive: no leak observed	NA
4	Positive: no leak observed	NA
5	Not performed	NA
6	Positive: no leak observed	NA
7	Negative: failure after 12,935 cycles	Failure located on the top of the valve dome (far from impact area)
8	Positive: no leak observed	NA
9	Positive: no leak observed	NA
10	Positive: no leak observed	NA
11	Positive: no leak observed	NA
12	Positive: no leak observed	NA

NA = Not Applicable

3.4 PROTECTIVE DOMES REMOVAL

Before repeating the drop tests, the protective dome were removed and a further visual inspection was performed on each cylinder.

The removal of the domes was carried out with great care, in order to avoid to make any damage on the external surface of the cylinders. Depending on the resistance opposed by the glue, the domes removal was performed by hands or using a PTFE wedge (Figure 3-2).

Figure 3-2: Protective dome removal using a PTFE wedge

In some cases, the protective domes were broken during removal; in this case, each part of the dome was collected and marked as shown in Figure 3-3.

Figure 3-3: Parts of a broken protective dome collected and marked after removal

3.5 SECOND DROP TEST

Cylinders which had passed the hydraulic test, after the protective domes removal, were subjected again to the drop test, adopting exactly the same procedure already applied in the first part of the test program (§3.1), in terms of drop height, initial inclination and impact generatrix.

The second drop test program and the relevant results of the visual inspection performed before and after tests are reported in Table 3.6 and Table 3.7, respectively for cylinders 1-5 and cylinders 6-12.

Table 3.6: Results of the second drop impact tests (cylinders 1-5)

CSM ID	Horizontal drop	Vertical drop side 1	Vertical drop side 2	45° drop	Observations before drop	Observations after drop
1	√ *[180°]*				✓ Light abrasion at 180°	✓ Part of fiber, between 90° and 270°, about to be detached from cylinder body ✓ Discolored fibers on the impact zones (valve dome)
2		√	√		✓ Abrasion on capped side at 0° ✓ Oblique scratch at 270° ✓ Impact evidence on the edge of valve connection	✓ No further observation
3				√ (capped side) *[0°-90°]*	✓ No observation	✓ Broken fiber on the dome capped side at 90° ✓ Part of 3 fibers, between 0° and 180°, detached from cylinder body
4				√ (valve side) *[0°]*	✓ Exposed fibers on valve side ✓ Crack at 0° on the valve side protective dome	✓ No further observation
5	√ *[180°]*			√ (valve side) *[180°]*	✓ Scratch at 0° on cylinder body ✓ Discolored fibers on capped side ✓ Thin exposed fibers	✓ Discolored fibers on the impact zones (both domes)

Table 3.7: Results of the second drop impact tests (cylinders 6-12)

CSM ID	Horizontal drop	Vertical drop side 1	Vertical drop side 2	45° drop	Observations before drop	Observations after drop
6		√	√		✓ Exposed fibers at 0° close to capped side ✓ Exposed fibers at 270° on both capped and valve sides ✓ Discontinuous fibers at 180° and 270° ✓ Unglued fibers at 270°	✓ Several discolored fibers areas on capped side
7				NA	✓ NA	✓ NA
8				√ (valve side) *[180°]*	✓ Discontinuous fibers at 180° on both capped and valve sides	✓ Discolored fibers on the capped dome at 180°
9	√ *[180°]*				✓ Detached fibers on valve side between 0° and 270°	✓ Discolored fibers on the impact zones (both domes at 180°)
10		√	√		✓ Cylinder body dented at 0° ✓ Abrasions on valve side at 180° and 270° ✓ Unglued fibers ✓ Broken fibers on domes	✓ Discolored fibers on the dome capped side (around the cap) ✓ Discolored fibers on the dome valve side
11				√ (capped side) *[180°]*	✓ No observation	✓ Discolored fibers on the impact zones (both domes at 180°)
12				√ (valve side) *[180°]*	✓ Discolored fibers at 180° ✓ Frayed fibers	✓ Discolored fibers on the impact zones

NA = Not Applicable

3.6 SECOND HYDRAULIC TEST

After the second drop test, the cylinders were subjected to a second hydraulic test, performed with the same procedure already described at §3.2.

Test results are reported in Table 3.8.

Table 3.8: Second hydraulic test results

CSM ID	Result	Failure zone
1	Negative: failure at 167.4 bar	Discolored zone on valve side dome at 180°
2	Positive: no leak observed	NA
3	Negative: failure at 228.8 bar	Discolored zone on capped side dome at 0°
4	Negative: failure at 210.0 bar	Discolored zone on valve side dome at 0°
5	Positive: no leak observed	NA
6	Positive: no leak observed Creaking from 250 bar	NA
7	NA	NA
8	Negative: failure at 171.0 bar	Discolored zone on valve side dome at 180°
9	Negative: failure at 240.0 bar	Discolored zone on valve side dome at 180°
10	Positive: no leak observed Creaking from 280 bar	NA
11	Negative: failure at 280.0 bar	Discolored zone on capped side dome at 180°
12	Negative: failure at 170.0 bar	Discolored zone on valve side dome at 180°

NA = Not Applicable

Visual inspection on cylinders which passed the second hydraulic test did not show neither new damages nor the evolution of pre-existing ones.

3.7 SECOND FATIGUE TEST

The 4 cylinders which passed the second hydraulic test (i.e. cylinders 2, 5, 6 and 10) were subjected to a second fatigue test, performed with the same procedure already described at §3.3.

Test results are reported in Table 3.9.

Table 3.9: Second fatigue test results

CSM ID	Result	Failure zone
1	NA	NA
2	Positive: no leak observed	NA
3	NA	NA
4	NA	NA
5	Negative: failure after 375 cycles	Failure located on impact area of capped side dome at 180°
6	Negative: failure after 390 cycles	Failure located on the top of the capped dome (impact side)
7	NA	NA
8	NA	NA
9	NA	NA
10	Negative: failure after 975 cycles	Failure located on the top of the capped dome (impact side)
11	NA	NA
12	NA	NA

NA = Not Applicable

4 FAILURE ANALYSIS

4.1 CYLINDER 1

Cylinder 1 failed during the second hydraulic test. Visual inspections put in evidence that the main damages on the cylinder were a strongly discolored area (180°) and the detached fibers close to the valve dome, due to the drop tests. Details of these defects are reported in Figure 4-1.

Figure 4-1: Cylinder 1- Main damages before second hydraulic test: a) discolored area; b) detached fibers

Failure during second hydraulic test occurred, at a pressure of 167 bar, where the discolored area was located, as reported in Figure 4-2.

Figure 4-2: Cylinder 1 – Failure location after second hydraulic test

4.2 CYLINDER 2

Cylinder 2 passed all of the performed tests, as foreseen by the test program. This cylinder passed two series of vertical drop tests on valve and capped sides. In Figure 4-3 and Figure 4-4 the discolored areas appeared in these zones after the drop tests are reported.

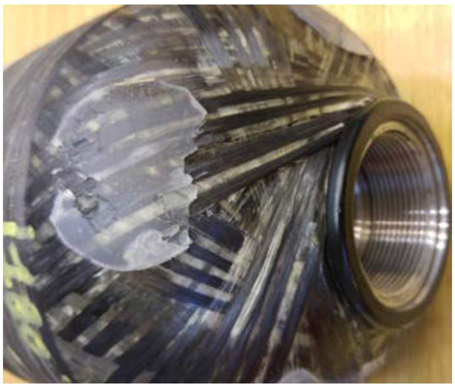

Figure 4-3: Cylinder 2 – Discolored area on valve side

Figure 4-4: Cylinder 2 – Discolored area on capped side

Some unglued fibers observed after the fatigue test are shown in Figure 4-5.

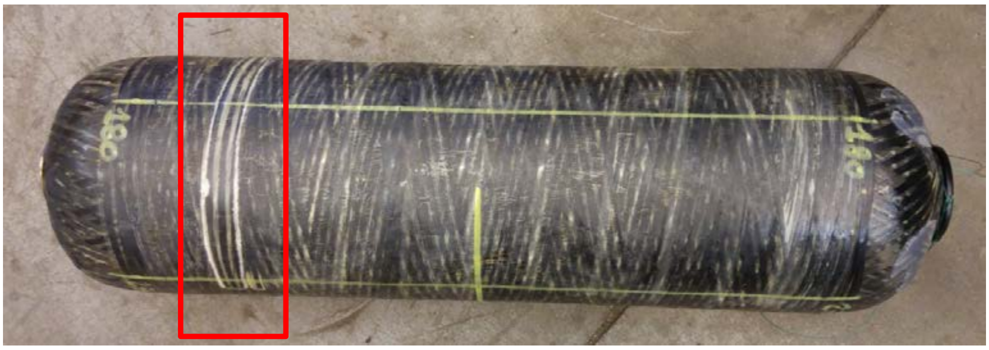

Figure 4-5: Cylinder 2 – Unglued fibers after fatigue test

4.3 CYLINDER 3

Cylinder 3 failed during the second hydraulic test, at a pressure value of about 229 bar. Visual inspections put in evidence that the main damage on the cylinder was a strongly discolored area (0°) close to the capped dome, due to the drop tests. Details of these damage are reported in Figure 4-6.

Figure 4-6: Cylinder 3 – Discolored area close to capped side (0°)

Failure during second hydraulic test occurred where the discolored area was located, as reported in Figure 4-7.

Figure 4-7: Cylinder 3 – Failure location after second hydraulic test

4.4 CYLINDER 4

Cylinder 4 failed during the second hydraulic test, at a pressure value of 210 bar. Visual inspections put in evidence that the main damage on the cylinder was a strongly discolored area (0°) close to the valve dome, due to the drop tests. Details of these damage are reported in Figure 4-8.

Figure 4-8: Cylinder 4 – Discolored area close to valve side (0°)

Failure during second hydraulic test occurred where the discolored area was located, as reported in Figure 4-9.

Figure 4-9: Cylinder 4 – Failure location after second hydraulic test

4.5 CYLINDER 5

Cylinder 5, as requested by the Client, did not perform the first fatigue test. After the protective domes removal, this cylinder was subjected to a horizontal drop test (on 180° generatrix). The drop test caused a strongly discolored area on the capped dome (Figure 4-10). The subsequent hydraulic test at 300 bar did not cause any other damage.

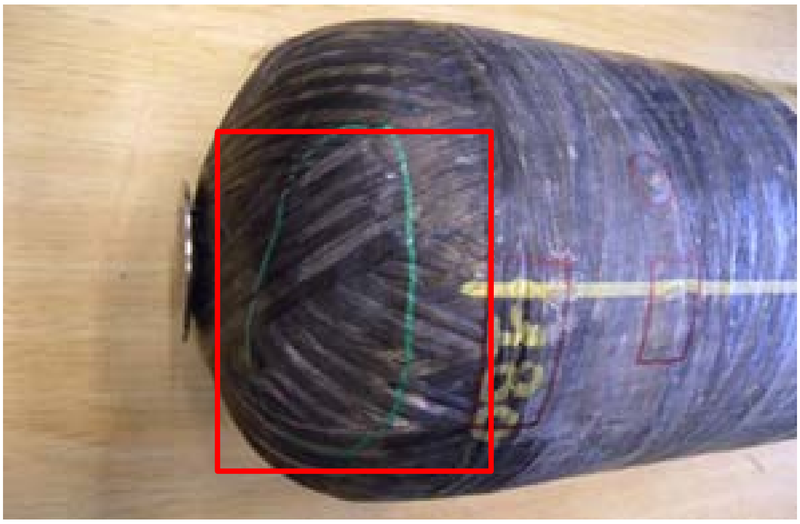

Figure 4-10: Cylinder 5 – Discolored area close to capped side (180°)

Failure occurred during the second fatigue test, after 375 cycles, where the discolored area was located, as reported in Figure 4-11.

Figure 4-11: Cylinder 5 – Failure location after second fatigue test

4.6 CYLINDER 6

Cylinder 6, failed during the second fatigue test, after 390 cycles. Visual inspections before this test put in evidence two main damages: the first one consisted in some unglued fibers observed after the first fatigue test (Figure 4-12); the second was a strongly discolored area close to the capped side (Figure 4-13). It is worthwhile to remember that the cylinder started creaking at 250 bar during the second hydraulic test.

Figure 4-12: Cylinder 6 – Unglued fibers

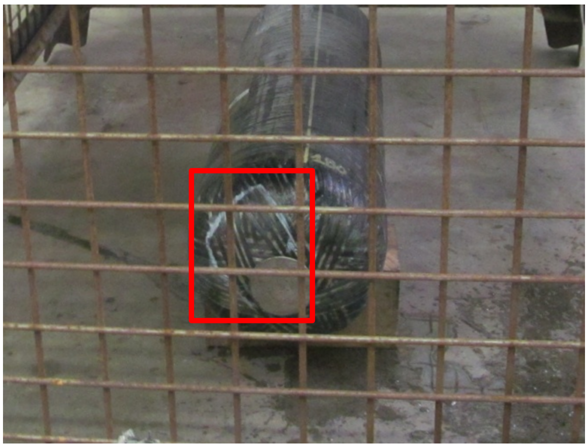

Figure 4-13: Cylinder 6 – Discolored area

Failure occurred during the second fatigue test where the discolored area was located, as reported in Figure 4-14.

Figure 4-14: Cylinder 6 – Failure location after second fatigue test

4.7 CYLINDER 7

Cylinder 7 is the only one where it was not possible to correlate the impact area of the drop test (45° angle, on the capped dome) and the failure zone. The cylinder also did not show any damage after the drop test but it was the only one to fail after the first fatigue test. Probably the removal of the protective domes after the first drop test could have revealed a possible damage. The state of both protective domes after the drop test is reported in Figure 4-15.

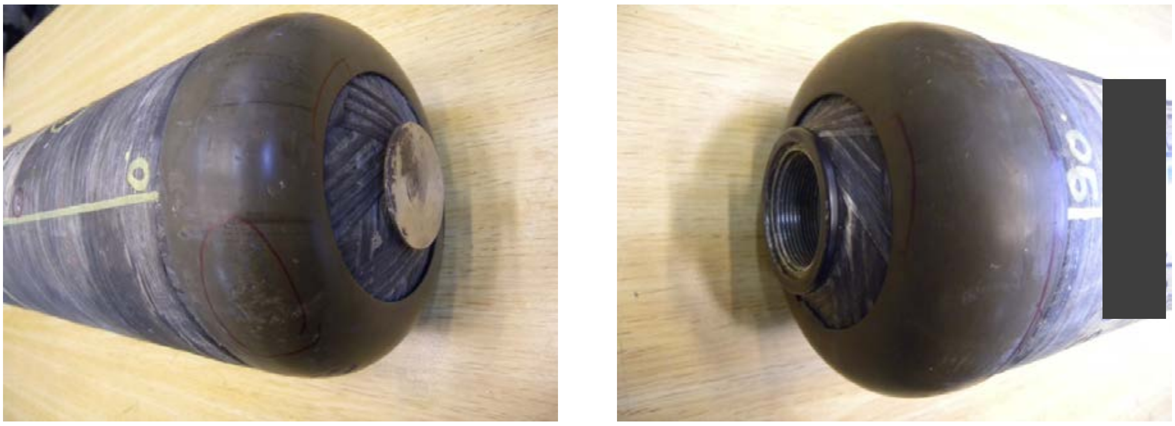

Figure 4-15: Cylinder 7 – Protective domes after the first drop test

Failure occurred during the first fatigue test, after 12,935 cycles and at 250 bar. In this case the failure consisted in the full ejection/separation of the valve connector from the cylinder (Figure 4-16 and Figure 4-17). Such an event did not occur in any other cylinder and could be likely referred to a pre-existing defect covered by the protective dome.

Figure 4-16: Cylinder 7 – Failure after first fatigue test

Figure 4-17: Cylinder 7 – Valve connector

4.8 CYLINDER 8

Cylinder 8 failed during the second hydraulic test. Visual inspection before this test showed a strongly discolored area in the valve side dome, at 180°, caused by the drop test performed at 45° angle. Pictures of the drop test and of the damaged area are reported in Figure 4-18 and Figure 4-19.

Figure 4-18: Cylinder 8 – Drop test

Figure 4-19: Cylinder 8 – Damaged area

Failure occurred in correspondence of the discolored area, at 171 bar, as shown in Figure 4-20.

Figure 4-20: Cylinder 8 – Failure location after second hydraulic test

4.9 CYLINDER 9

Cylinder 9 failed during the second hydraulic test. Visual inspection before this test showed a strongly discolored area in the valve side dome, at 180°, caused by the horizontal drop test performed on 180° generatrix (Figure 4-21).

Figure 4-21: Cylinder 9 – Discolored area close to valve capped side (180°)

Failure occurred in correspondence of the discolored area, at 240 bar, as shown in Figure 4-22.

Figure 4-22: Cylinder 9 – Failure location after second hydraulic test

4.10 CYLINDER 10

Cylinder 10 failed during the second fatigue test. Visual inspection before this test showed three main defects: some unglued fibers observed after the first fatigue test (Figure 4-23), a strongly discolored area in the capped side dome, at 270°, caused by the vertical drop test (Figure 4-24) and some broken fibers on the valve side dome, as shown in Figure 4-25 (taken after the protective dome removal). It must be pointed out that the cylinder clearly creaked during the hydraulic test (after the protective domes removal), starting from 280 bar.

Figure 4-23: Cylinder 10 – Unglued fibers after the first fatigue test

Figure 4-24: Cylinder 10 – Strongly discolored area after drop test

Figure 4-25: Cylinder 10 – Broken fibers on the valve dome

Also in this case, the discolored area of the capped dome confirmed to be the most severe damage. Failure occurred in that area after 975 cycles of the second fatigue test (Figure 4-26).

Figure 4-26: Cylinder 10 – Failure location after second fatigue test

4.11 CYLINDER 11

Cylinder 11 failed during the second hydraulic test. Visual inspection before this test showed a strongly discolored area in the capped side dome, at 180°, caused by the drop test performed at 45° angle. A second discolored area, due to a rebound impact, was observed on the valve side dome. Pictures of the damaged areas are reported in Figure 4-27 and Figure 4-28.

Figure 4-27: Cylinder 11 – Damaged area capped side

Figure 4-28: Cylinder 11 – Damaged area valve side

Failure occurred in correspondence of the discolored area on the capped dome, at 250 bar, as shown in Figure 4-29.

Figure 4-29: Cylinder 11 – Failure location after second hydraulic test

4.12 CYLINDER 12

Cylinder 12 failed during the second hydraulic test. Visual inspection before this test showed two main damages: some unglued fibers (Figure 4-30), observed after the first fatigue test, and a strongly discolored area (Figure 4-31) in the capped side dome, at 180°, caused by the drop test performed at 45° angle.

Figure 4-30: Cylinder 12 – Unglued fibers

Figure 4-31: Cylinder 12 – Damaged area valve side

Failure occurred in correspondence of the discolored area on the capped dome, at 170 bar, as shown in Figure 4-32.

Figure 4-32: Cylinder 12 – Failure location after second hydraulic test

5 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.

In 11 cases out of 12, with the only exception of cylinder 7, a relation has been identified between the impact zone of the drop test without protective domes and the failure zone.

The 45° angle drop test revealed to be the most severe one: none of the cylinders subjected to this type of test was able to pass the following hydraulic test. In terms of severity, the horizontal drop test follows the 45° one: only one cylinder, out of the three tested with horizontal drop, managed to pass the hydraulic test.

The less severe drop test is the vertical one. In this case, all of the three tested cylinders passed the subsequent hydraulic test; two of them failed during the last (second) fatigue test and one cylinder (number 2) managed to complete the whole test program, although showing the same kind of damages (discolored area on the domes) that led to failure in all of the other cases.

As far as cylinder 7 in concerned, the failure cannot be related to any kind of damage observed after the drop test. Failure occurred during the first fatigue test, when the protective domes were still on. This case suggests the opportunity to remove the protective domes from the very beginning, in order to be able to perform a more accurate visual inspection.

On the basis of the observed results, it is possible to state that the mechanism that leads to the failure of the cylinders is related to the breaking of the fibers in the dome areas, due to the impact caused by the drop test. The fibers breaking is put in evidence by discoloured (turned white) areas. The protective domes removal is a key element in order to be able to perform a correct visual inspection of the domes and to detect possible damages.

The whole experimental activity and the relevant main results are resumed in Table 5.1 and Table 5.2, respectively for cylinders 1-6 and cylinders 7-12.

Table 5.1: Experimental activities and results for cylinders 1-6

Cylinder ID	1	2	3	4	5	6
SN	1007600053	927900020	1002600016	1002600059	0911900022	1002600039
Preliminary Visual Inspection	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
Hydraulic Test @ 300 bar	Performed	Performed	Performed	Performed	Performed	Performed
Fatigue Test (20,000 cycles)	Performed	Performed	Performed	Performed	NA	Performed
Protective Domes Removal	Performed	Performed	Performed	Performed	Performed	Performed
Drop Test from 1.8 m Hight	Horizontal	Vertical (capped & valve sides)	45° angle (capped side)	45° angle (valve side)	Horizontal	Vertical (capped & valve sides)
Hydraulic Test @ 300 bar	**Failure at 167.4 bar**	Performed	**Failure at 228.8 bar**	**Failure at 210.0 bar**	Performed	Performed Creaking from 250 bar
Fatigue Test (20,000 cycles)	NA	Performed	NA	NA	**Failure after 375 cycles**	**Failure after 390 cycles**

Table 5.2: Experimental activities and results for cylinders 7-12

Cylinder ID	7	8	9	10	11	12
SN	0908400029	1002200057	0904700059	0927400061	0927400070	0911900045
Preliminary Visual Inspection	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
Hydraulic Test @ 300 bar	Performed	Performed	Performed	Performed	Performed	Performed
Fatigue Test (20,000 cycles)	**Failure after 12,935 cycles**	Performed	Performed	Performed	Performed	Performed
Protective Domes Removal	NA	Performed	Performed	Performed	Performed	Performed
Drop Test from 1.8 m Hight	NA	45° angle (valve side)	Horizontal	Vertical (capped & valve sides)	45° angle (capped side)	45° angle (valve side)
Hydraulic Test @ 300 bar	NA	**Failure at 171.0 bar**	**Failure at 240.0 bar**	Performed Creaking from 280 bar	**Failure at 250.0 bar**	**Failure at 170.0 bar**
Fatigue Test (20,000 cycles)	NA	NA	NA	**Failure after 975 cycles**	NA	NA

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