CONFIDENTIAL, NOT TO BE USED FOR DISSEMINATION

Test procedures on prototypes and experimental support tests

Project:	GASVESSEL
Project No.:	723030
Deliverable No.:	D4.1
Deliverable Full Name:	Test procedures on prototypes and experimental support tests with strain gauges to validation of the software simulations models (FEM analysis), safety factor validations tests
WP n.	4
Document Version:	RV2
Document Preparation Date:	2019-10-18
Responsibility:	PARTNER No. 7 - BM Plus

Type of Deliverable		
R	Document, Report	X
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patent fillings, videos, etc.	
OTHER		
ETHICS	Ethics requirements	
ORDP	Open Research Data Pilot	

Dissemination Level		
PU	Public	
CO	Confidential, only for Members of the Consortium (including the EU Commission Services)	X

Version Management

Software used		Microsoft Word
Company Internal Doc. n.		BMP. Gasvessel. D4.1
Author(s)		G. Monteverdi
Reviewed by		P. Maschio
Approved by		F. Bozzi
Authorized by		Coordinator
Revision No.	**Date**	**Modification description**
RV 1	2019-11-06	Issued for internal quality check
RV 2	2019-11-27	Issued for uploading on EU participant portal
RV 3		

EC Grant Agreement	No.723030
Project Acronym	GASVESSEL
Project Title	Compressed Natural Gas Transport System
Instrument	HORIZON 2020
Programme	Smart, green and integrated Transport
Start Date of Project	2017-06-01
Duration	48 months
Organisation Name of Lead Contractor for this Deliverable	Partner 7 BM Plus Srl

Financial/Administrative Coordinator	
Project Coordinator Name	Mr. Loris COK
Project Coordinator Organization Name	NAVALPROGETTI Srl
Address	Via dei Papaveri, 21 34151 TRIESTE (Italy)
Phone Numbers	0039 040 212918,
Email	loris.cok@navalprogetti.net; gasvessel@navalprogetti.net;
Project web-sites & other Access Points	www.gassvessel.eu

The GASVESSEL Project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement no. 723030

CONTENTS

List of Figures

List of Tables

Glossary, abbreviations and acronyms

EU	The European Commission or in general Europe
INEA	Innovation and Networks Executive Agency of European Commission
PO	Project Officer assigned by INEA to GASVESSEL Project
Partner	Company member of the GASVESSEL Project Consortium
Project	The GASVESSEL no. 723030 Project
CNG	Compressed Natural Gas
GA	Grant Agreement
CA	Consortium Agreement
KM	Knowledge Management
PMS	Project Management System
PM	Project Management
TM	Team Management
PA	Project Administration
P&C	Planning and Controls
PR	Project Reporting
DC	Document Control
HSEQ	Health, Safety, Environment and Quality controls and assurance
PRM	Procurement Management
MM	Materials Management
WP	Work Package
EPQ	Extended Project Qualification
LMS	Learning Management System
NP	Navalprogetti Srl – Trieste – Italy – The Coordinator – Partner -Lead Beneficiary of WP1 and WP5
DOW	Dow Deutschland Anlaghengesellschaft mbH - Partner
DOWA	DowAksa Deutschland GMBH - Partner
PNO	PNO INNOVATION – Belgium – Partner – Lead Beneficiary WP9
VTG	VNIPITTRANSGAZ – Kyiv – Ukraine – Partner – Lead Beneficiary WP6
SINTEF	SINTEF OCEAN AS – Trondheim – Norway – Partner – Lead Beneficiary WP7
BMP	BM Plus Srl – Buttrio – Italy – Partner – Lead Beneficiary WP4
CNGV	CNGV d.o.o. – Izola – Slovenia – Partner – Lead Beneficiary WP3
CEN	CENERGY Srl – Trieste – Italy - Partner
HLL	Hanseatic Lloyd Schiffahrt GMBH & Co – Bremen – Germany - Partner
CHC	Cyprus Hydrocarbon Company – Nicosia – Cyprus – Partner – Lead Beneficiary of WP2
EST	ESTECO S.p.A. – Trieste – Italy - Partner
ABS	American Bureau of Shipping (Hellenic) – Athens – Greece – Partner – Lead Beneficiary WP8

O&G	Oil and Gas
WP1	Project Management
WP2	Scenario analyses
WP3	Prototyping activities, design of pressure cylinders and prototyping pilot line
WP4	Prototyping of pressure cylinders. Procurement/construction/arrangement of prototyping pilot line
WP5	Ship Design
WP6	Offshore & Onshore gas loading/unloading systems
WP7	Costs and Benefits Analysis
WP8	Class Design Review – Safety Assessments
WP9	Dissemination and Exploitation
QA	Quality Assurance
QC	Quality Control
CBA	Costs Benefits Analysis
Work Plan	Planning of Activities in Attachment 1 of Project Management Plan D1.2
WBS	Work Breakdown Structure
DMS	Document Management System
SME	Small Medium Enterprise
AIP	Approval in Principle

1. Introduction

1.1 Executive Summary

This deliverable contains the guidance notes intended to be used for developing in detail testing procedures and plan of the CNG Cylinders, including sequence of operations, in order to achieve from Partner 13 – ABS the “Product Design Approval”.

1.2 Purpose and Scope

Scope of the document is to be the starting point for the execution of testing activities developed in accordance with the schedule here below, with the statements of the Approval in Principle (AIP) released by ABS and with the applicable rules and regulations.

As Partner ABS needs to review the testing plan in advance, in order to provide any comments or concerns, the full details of the testing plan, that will describe the tests, methodology and standards to be applied, is to be prepared, at the latest, within the end of month 31 (December 2019) and submitted to ABS.

Testing plan to have the form of a set of “Test Memoranda”, one for each planned test, reporting all the technical data needed to be recorded and registered during test operations. Technical data, so gathered, will make up the basis of the “Quality Manual” to be followed and applied in the future industrial production of CNG Cylinders.

Deliverable D4.1 by Partner 7 - BM Plus

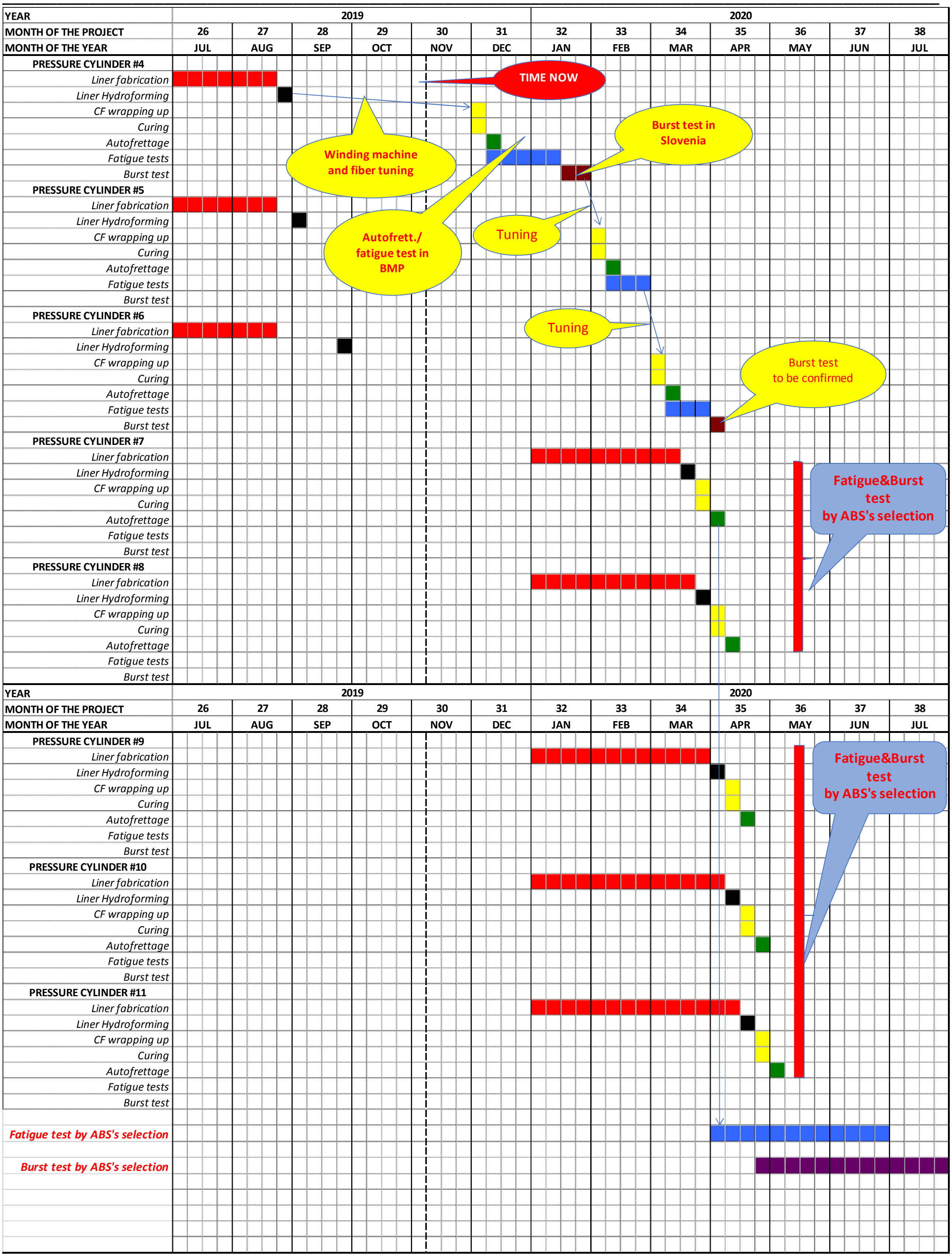


Table 1: Test Schedule

Typical example for Test Memoranda

H2020 – 723030 GASVESSEL
CNG Cylinders Prototyping

TEST MEMORANDUM

OPERATION: *Hydroforming* *(example)*
LINER NO. …………………LINER DIMENSIONS before hydroforming …………………….mm
DATE: ……………………… HOUR START………………………. HOUR FINISH……………………
WEATHER CONDITIONS: …………………°C, …………RH%

OPERATION	COMMENTS	REMARKS
Visual inspection of liner before hydroforming		
Checking mould and system for proper working conditions		
Introducing liner into the mould and filling it with water	………………m3	
Waiting a while for the natural release of air bubbles possibly trapped into the filling water	……………..minutes	
First level of pressurization	Pressure …………bar Radial deformation ……………mm	
Second level of pressurization	Pressure …………bar Radial deformation ……………mm	
Third level of pressurization	Pressure …………bar Radial deformation ……………mm	
Etc.		
Etc.		
Final level of pressurization	Pressure …………bar Radial deformation ……………mm	
Check for liner leakages		
Emptying and extract liner from mould		
Visual check of liner welds and for circularity		
Liner dimensions after hydroforming	…………………..mm	
Report the level of hardening of the base material obtained with hydroforming		

Attendees signature:

CNGV BM Plus ABS

_____________ ____________ ______________

DATE OF RESOLUTION OF REMARKS: ……………………………

SIGNATURES……..

Page 1 of ….

Typical example for Test Memoranda

H2020 – 723030 GASVESSEL
CNG Cylinders Prototyping

TEST MEMORANDUM

OPERATION: *Winding* *(example)*
LINER/CYLINDER NO. …………………
DATE: ……………………… HOUR START……………………… HOUR FINISH……………………
WEATHER CONDITIONS: …………………°C, …………RH%
TYPE OF GLASS FIBRE USED (data sheet attached) …………………………………………….
TYPE OF CARBON FIBRE USED (data sheet attached)………………………………………….
TYPE BASE RESIN USED (data sheet attached)………………………………………………….
TYPE OF HARDENER USED (data sheet attached)……………………………………………….
TYPE OF CATALYST USED (data sheet attached)……………………………………………….

OPERATION	COMMENTS	REMARKS
Resin mixture	Base resin…………%	
	Hardener………….%	
	Catalyst…………..%	
	Mixture temperature………°C	
	Mixture pot-life………….Hours	
Main Carriage translation speed	…………..m/sec	
Liner rotation on mandrels	…………..rpm	
Angle of passes applied (glass)	………….degree	
	………….degree	
	………….degree	
	………….degree	
Angle of passes applied (carbon)	………….degree	
	………….degree	
	………….degree	
	………….degree	
	………….degree	
Check of impregnation grade of filaments		
Pull on roving	……………N	
Final thickness of glass fibre achieved	…………..mm	
Final thickness of carbon fibre achieved	…………..mm	

Page 1 of ….

Attendees signature:

CNGV	BM Plus	ABS
_____________	____________	______________

DATE OF RESOLUTION OF REMARKS: ……………………………

SIGNATURES………..

Page 2 of ….

Similarly, a Test Memorandum is prepared for each cylinder and each single testing operation relevant to curing, autofrattage, fatigue and burst, providing evidence of data to be recorded, registered and filed with reference to the rules and regulations applied for testing.

2. Testing Methodology and Procedures

Testing methodology and procedures applied to produce documents and relevant results in accordance with ABS CNG guide Chapter 5 Section 10/11, also copied here below for prompt reference:

11 CNG Cargo Tank Prototype Testing

Prototype testing is required for all new cargo tank designs. The intent of this testing program is to validate the design experimentally. The test program is to be submitted for review to determine that it covers, as a minimum, the following for the cargo tank:

- Static Strength Performance
- Fatigue Performance
- Burst Performance

The prototype qualification program is to include, but is not limited to, the following.

11.1

A minimum of four (4) cargo cylinder/tanks are to be prototype tested. These cargo cylinder/tanks are to be tested for a combination of loads to prove fatigue and burst performance as indicated in the following table:

Test Cargo Cylinder/Tank No.	*Type of Test*	*Test Temperature*	*Artificial Surface Flaws*	*Number of Cycles*	*Pressure*	*Success Criteria*
1 [1]	Fatigue	Operating	None (As fabricated)	Minimum 10 times design cycles	Operating	10 times design life cycle and no failure
2	Burst [3]	Operating	None (As fabricated)	None	Failure	Test pressure to exceed code predicted burst pressure and ductile failure mode
3 [2]	Fatigue	Operating	Yes	3 times design life	Operating	Cracks should not exceed critical sizes
	Burst [3]				Failure	Exceed design pressure and ductile failure mode
4 [2]	Fatigue	Operating	Yes	3 times design life	Operating	Cracks should not exceed critical sizes
	Burst [3]	JT [4]			Failure	Exceed design pressure and ductile failure mode

Notes:

1 To be used for residual mechanical properties evaluation.

2 Burst test is to follow after fatigue test.

3 Prototype testing is to establish ductile mode of failure (fractographic evidence) in the burst test without any major fragmentations (physical events). See 5-4/1.1.2(c)

4 JT Temperature shall be in accordance with theoretical gas dynamic or experimental study.

A batch of 8 (eight) CNG Cylinders will be prepared (see schedule on page 8) among which ABS will random choose the 4 (four) to undergo full testing.

3. Activities Description

3.1 Pilot line description (see annexed layout)

Pre-industrialization testing of CNG cylinders prototypes is possible by setting up a dedicated pilot line.

The pilot line includes hydroforming equipment, winding machine, curing equipment, autofrattage equipment, fatigue and burst test equipment.

The pilot line was designed and installed in BM Plus premises, as Lead beneficiary of work package number 4 (WP4)

The overall description of the pilot line, here following, its operability and significant working data described will allow the preparation of the Test Memorandum for each single phase of the Testing Plan.

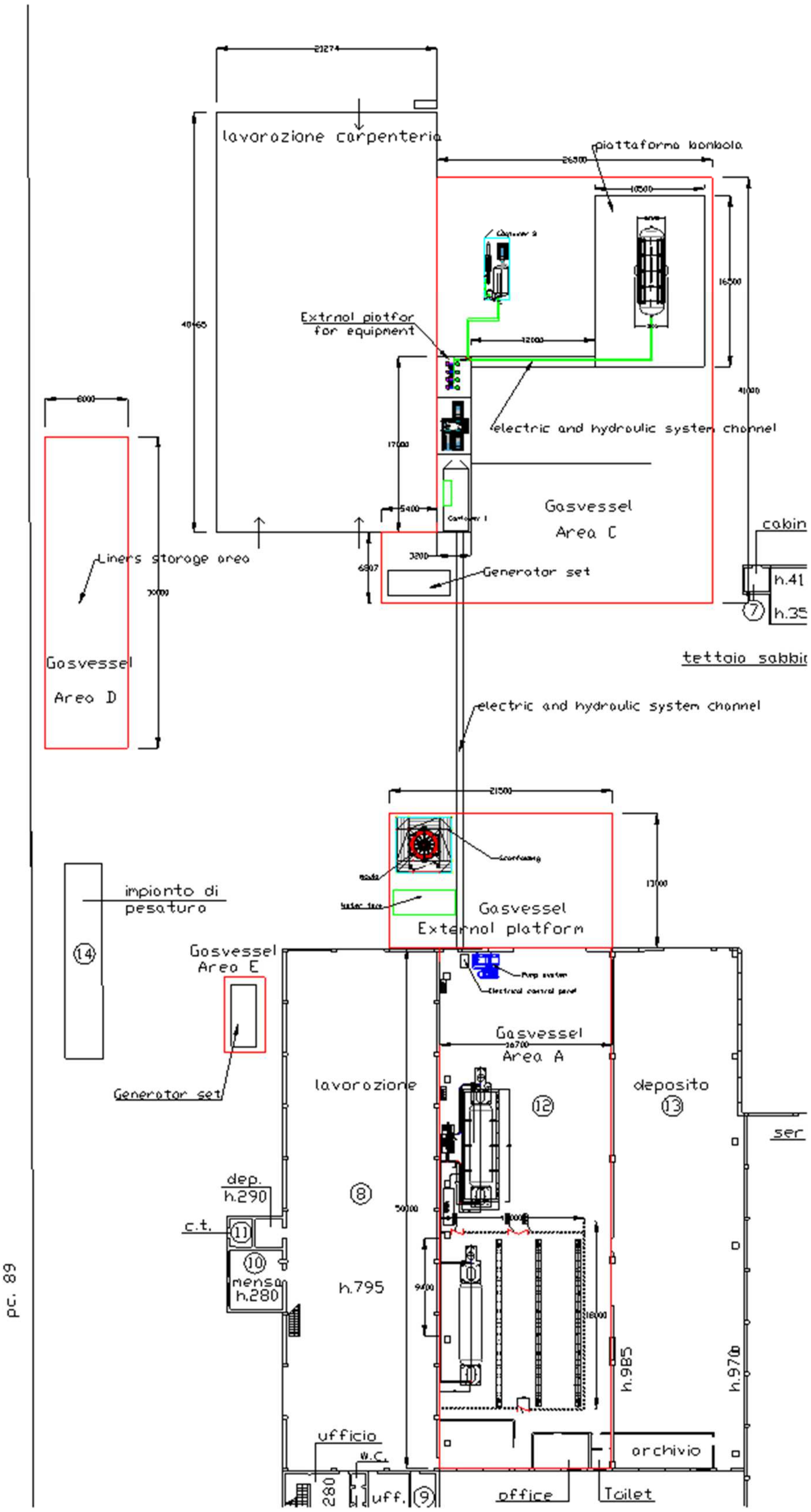


Figure 1 Pilot line general plan with the relevant internal and external areas

3.2 Hydroforming

3.2.1 Hydroforming equipment

The Hydroforming system consists of the following elements:

a) Mould, positioned on an external platform, able to contain the liner in order to reach the final shape. The mould is vertical ideal for the natural filling of the liner with water; Dimensions H = 10,0 m - diameter =2,8 m - weight= 30 t – sheet thickness = 35 mm.
The mould is designed to withstand a pressure of about 100 bar. In the upper part it has a removable cover connected to the fixed part through a double flange.
Along the mantle 18 holes are made to allow the laser sensor reading of the deformation of the liner during the hydroforming process; see Figure 3 and Figure 4 (left).

b) Water tank with a capacity greater than the volume of the deformed liner. Dimensions 5.9 m x 2.3m x 3.6m. Also positioned on an external platform; see Figure 4 (right).

c) Pump system suitable for filling and emptying the low pressure liner and high pressure pump up to 100 bar for hydroforming; see Figure 5 (left).

d) Electrical control panel of the system with buttons and touch screen monitor with manual controls and automatic programs for the hydroforming cycle; see Figure 5 (right).

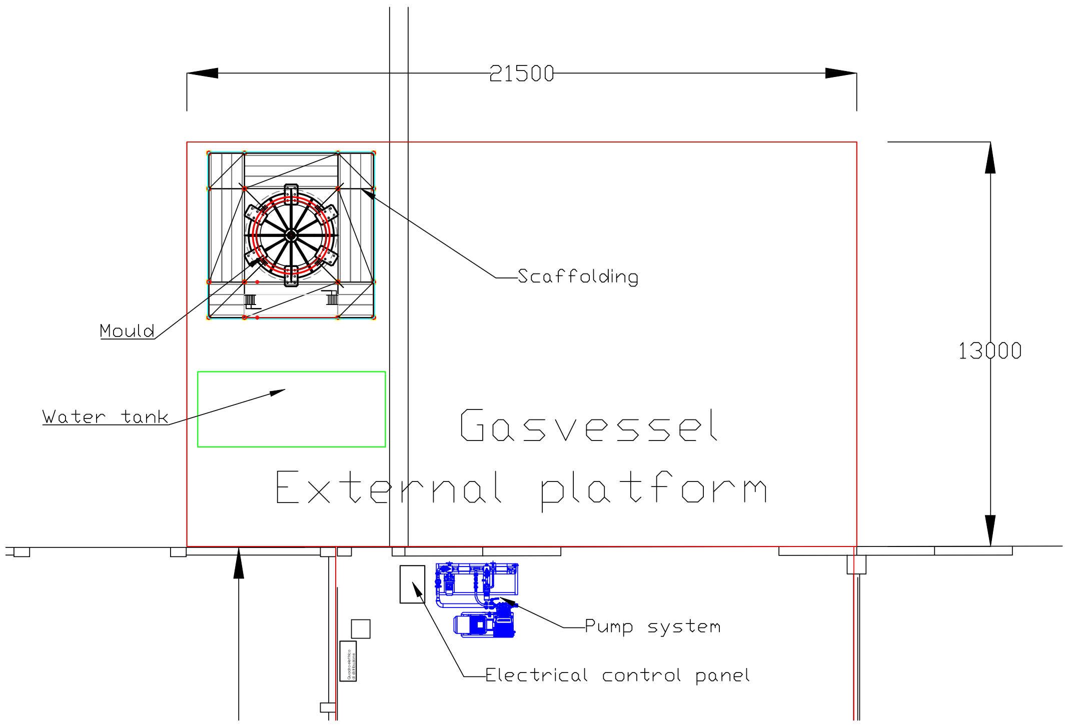


Figure 2

Figure 3 Hydroforming mould (right) and its installation (left)

Figure 4 Sensor on hydroforming mould (left); Water tank (right)

Figure 5 Pump system (left); Electrical control panel (right)

The Hydroforming process is performed to modify the mechanical characteristics of the liner material through plastic deformation. The process uses pressurized water to deform the mantle until the liner size reaches the size of the inner part of the mould. The liner is inserted into the mould with a crane. The mould is then closed with a dome that is locked with closed screws with controlled tightening (bolts pretension: 640 kN - 6144 N* m). The liner is connected to the pumping system ready to undergo the hydroforming process. In figs 07, 08, 09 and 10 some loading phases are shown, closing the mold with the cover, unloading the liner from the mold.

The hydroforming process can be performed either manually or following an automatic cycle as described below.

Figure 6 Liner ready for insertion into the mould

Figure 7 Liner inserted in the mould (left); Mould closure with dome (right)

Figure 8 Liner hydroformed

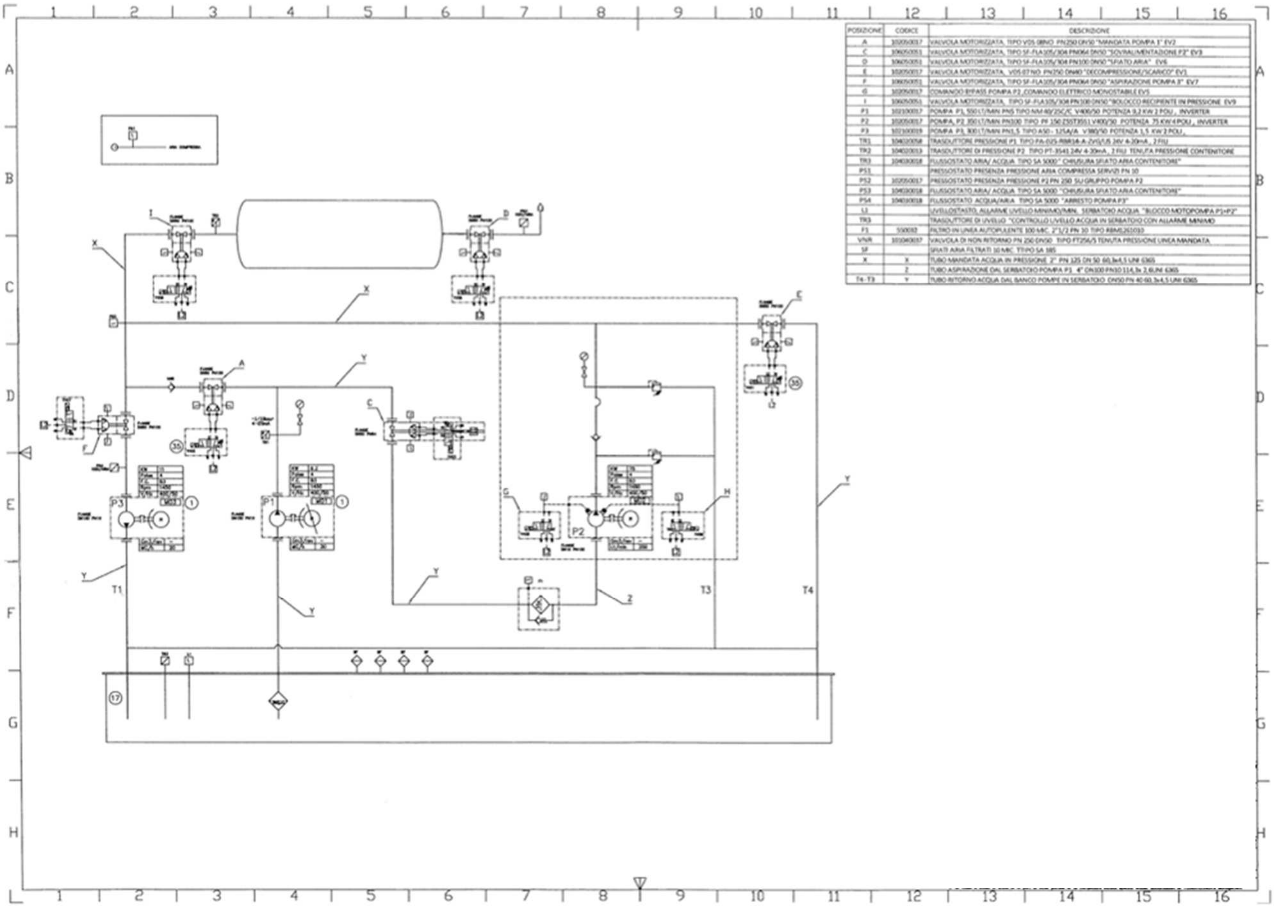


Figure 9 Hydraulic diagram

3.2.2 Description of manual controls

The monitor on the electrical panel shows the circuit of the system with well identified valves, motors and sensors, in particular (see Figure 10):

- The labels that identify the solenoid valves are blue when the electric control is active;
- The labels that identify the limit switches of the solenoid valves are: green when the open status is active and yellow when the closed status is active;
- The labels that identify the pressure switches are green when the signal is active;
- The pushbuttons for manual control of valves "C" "D" "F" are of the open-close type being the valves of bistable type; after the command they maintain the last position assumed; Leaving the manual mode these valves remain in the last commanded position;
- The buttons for manual control of valves "A" "I" "E" are of the ON-OFF type. Each time the button is pressed the valve status changes
  Leaving the manual mode these valves return in the closed position);
- The buttons for manual control of the "G" "L" valves are ON. The valve control is activated by pressing the button and deactivated when the button is released.
  Leaving the manual mode these valves return in the closed position;

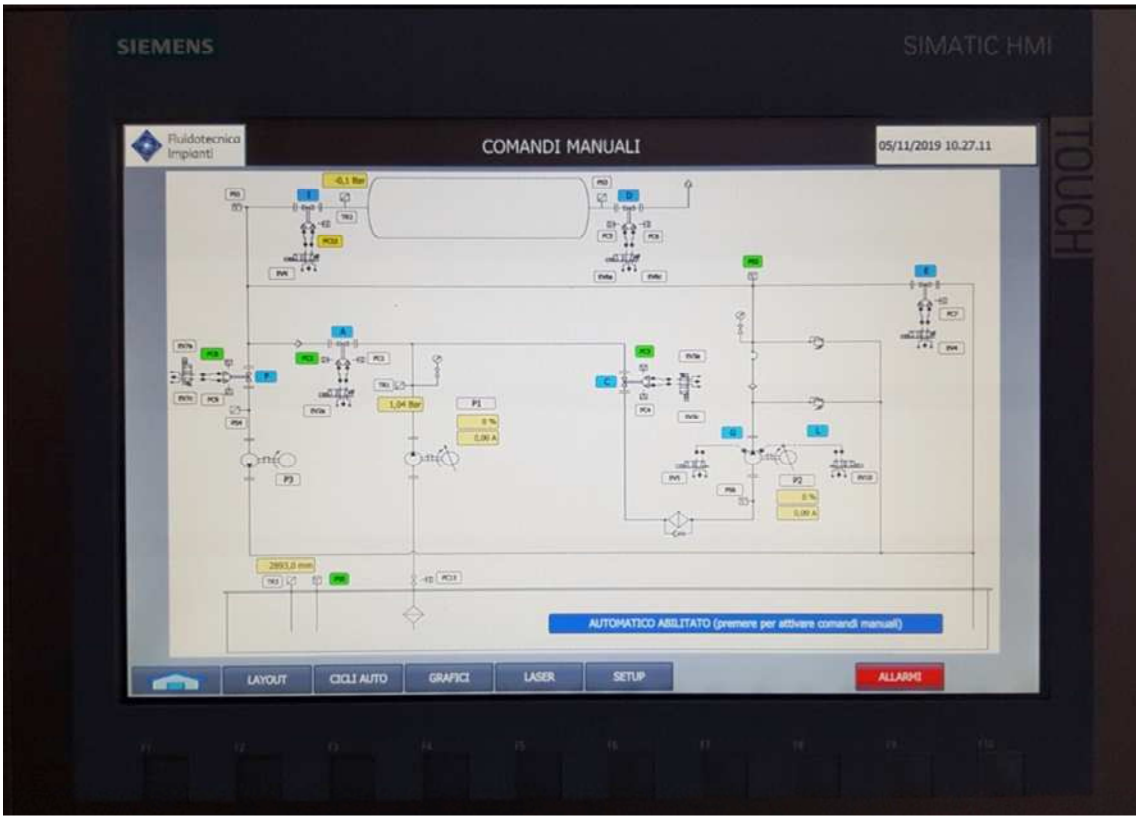


Figure 10 Monitor on the electrical panel – Manual control

Before proceeding with the start of the automatic pressurization and liner emptying cycle, in general setup (see Figure 11) sensors, speed regulators of the pumps and initial, intermediate and final pressure values must be calibrated:

- sensor calibration TR1 (bar) Work value min = 0,0 max = +25,0
- sensor calibration TR2 (bar) Work value min = 0,0 max = +250,0
- sensor calibration TR3 (mm) Work value min = 0,0 max = +6000,0
- Pump speed P1 in filling mode (%) Work value 100%;
- Pressurization start pressure P2 (bar) Work value 3,0 bar;
- P1 pump speed in pressurization (%) Work value 70%;
- Pump speed P2 in initial pressurization (%) Work value 50%;
- Pump speed P2 in final pressurization (%) Work value 40%;
- Intermediate test pressure (bar) Work value 20 bar;
- Final test pressure (bar) Work value 70 bar;
- Increasing pressure Steps by operator (bar) Work value 5,0 bar.

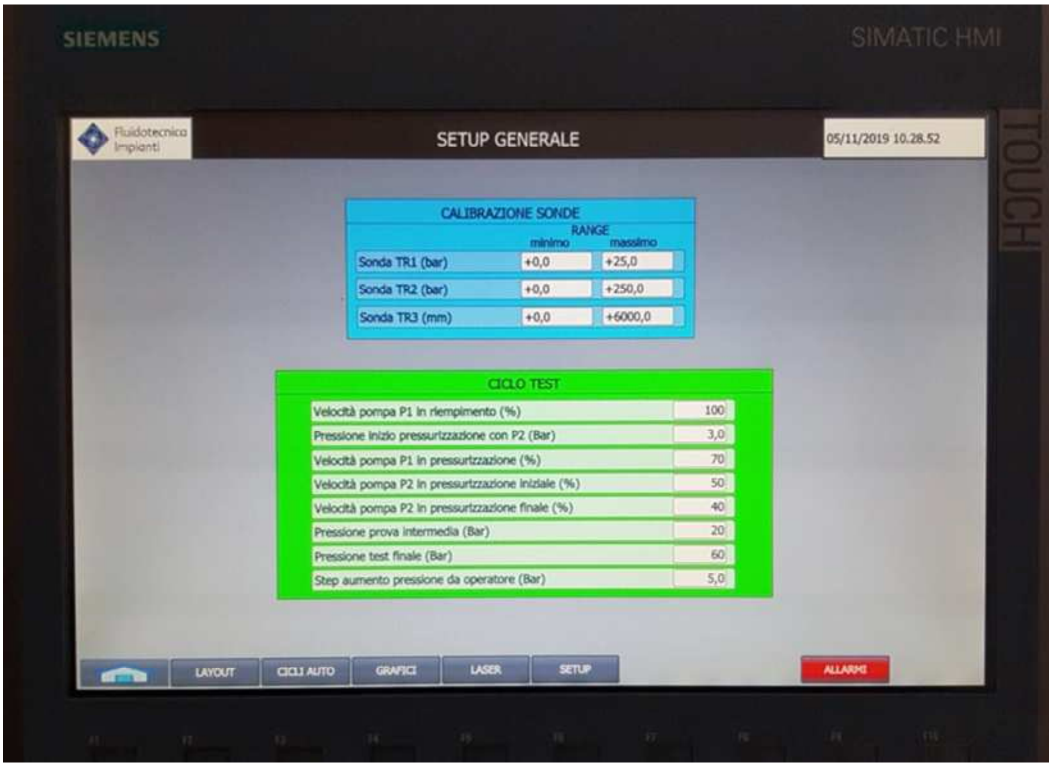


Figure 11 General setup

3.2.3 Description of automatic cycle

From the manual controls window, the automatic cycle is enabled by pressing the appropriate key on the touch screen; see Figure 12.

During the automatic cycle a green window is displayed indicating the sequential step of the program and a brief description.

The sequence of the pressurization cycle is as follows:

1. Check start conditions. All pumps must be stopped;
2. Valve closures "E" and "F" to close the water discharge ways;
3. Check valves "E" and "F" closed;
4. Closing valve "C" for high pressure circuit separation;
5. Check Valve "C" closed;
6. Opening valves "A" "I" and "D" for filling circuit opening and air vent.
   If the tank has already been filled, the "D" valve is not opened to avoid unnecessary water spills;
7. Check valves "A" and "I" open;
8. Start pump P1 at filling speed;
9. Filling verification occurred with water presence on PS3;
10. Valve closure "D". Laser sensors offset reset and Data Log start;
11. Waiting for reaching the TR1 pressure value for pressurization start with P2;
12. Valve opening "C" for preparing high pressure circuit;
13. Check valve "C" open;
14. "A" valve closing for pump P2 supply with P1 pump;
15. Check valve "A" closed;
16. Pump speed change P1 at set speed set for P2 supply;
17. Starting pump P2 at the initial pressurization speed set;
18. Closure of the "G" valve for pressure;
19. Waiting for reaching intermediate pressure set on TR2 for cycle pause. Valve opening "G" for putting P2 pump in stand-by;
20. Waiting for change of pressure set by the operator. Closing of the "G" valve for pressure increase;
21. Waiting for reaching new set of pressure on TR2. This pressurization phase is done with the P2 pump at the final pressurization speed. If the end test pressure value is reached, the sequence jumps to step 23;
22. Waiting for change of pressure set by operator. After the pressure change by the operator the sequence returns to step 21;
23. "I" valve closure for tank maintenance;
24. Pump P2 stop;
25. Waiting P2 pump stopped;
26. End of cycle. P1 pump stop and data log stop.

If the stop button is pressed during the cycle, the valve "G" is automatically opened, the pumps P1 and P2 are switched off and the valves "A" "I" "E" are closed.

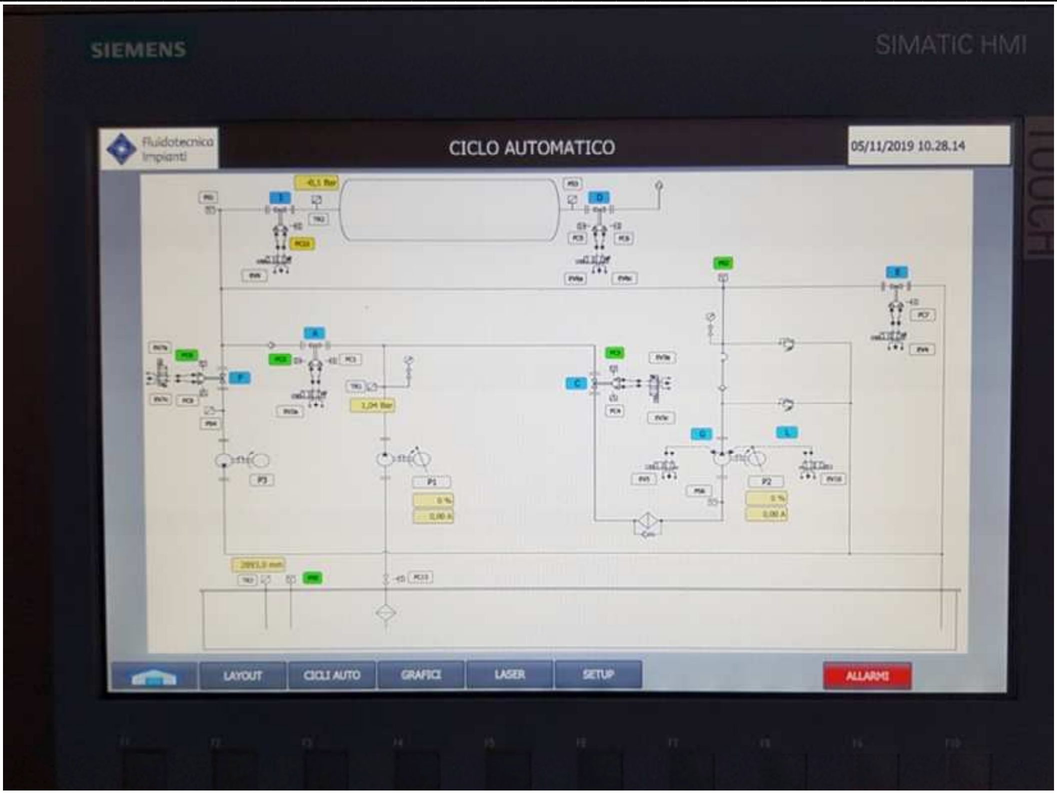


Figure 12 Monitor on the electrical panel – Automatic control

The sequence of the water emptying cycle is as follows:

1. Check start conditions. All pumps must be stopped;
2. Valve opening "I";
3. Check valve "I" open;
4. Valve opening "E" for pressure relief inside the tank;
5. Check valve "E" open;
6. Check low pressure inside the tank;
7. Valve opening "D" to allow air to enter the tank;
8. Check valve "D" open;
9. Valve closure "E";
10. Check valve "E" closed;
11. "F" valve opening for preparation of exhaust circuit with P3 pump;
12. Check valve "F" open;
13. P3 emptying pump run;
14. Waiting for empty tank with air presence on PS4;
15. Pump stop P3;
16. End of cycle;

If the stop button is pressed during the cycle, the P3 and P2 pumps are automatically switched off and the "A" "I" "E" valves are closed.

3.2.4 Acceptable results

Pressure to be reached at the end of hydroforming: 70 bar

Pressure to be kept checking liner weathertightness: 2 min.

At the end of the hydroforming operation the operator must record the number of the liner hydroformed and the pressure successfully achieved.

When the hydroformed liner is taken out from the mould, check for circularity and perform visual check of welds.

Report and register all findings including water quantity used and electric power adsorbed during operations.

3.2.5 Cases where pressure is not reached, or the liner begins to leak

In case required levels of pressure are not reached check the whole system, find reasons of misfunctioning, repair as required and repeat the hydroforming operation

If the liner starts to leak the test must be interrupted. The liner must be taken out from mould and checked for rupture. If feasible perform repairs and repeat hydroforming. Otherwise liner to be discarded.

It shall be noted that hydroforming process can restart from any stage where it has been previously stopped for whatsoever reason.

3.3 Winding

The Winding machine consists of the following elements (see also attached photos):

Figure 13 Overall view of the winding machine

- Main carriage
- Creels
- Impregnation tanks and equipment
- Resin mixer and dispenser
- Fibre deposition arm
- Mandrel support
- Electric motors and controls

3.3.1 Winding machine description

The winding machine to produce large cylinders consists, essentially, of the following:

a) 1 (one) spindle of rotation of the liner, (Axis ω).

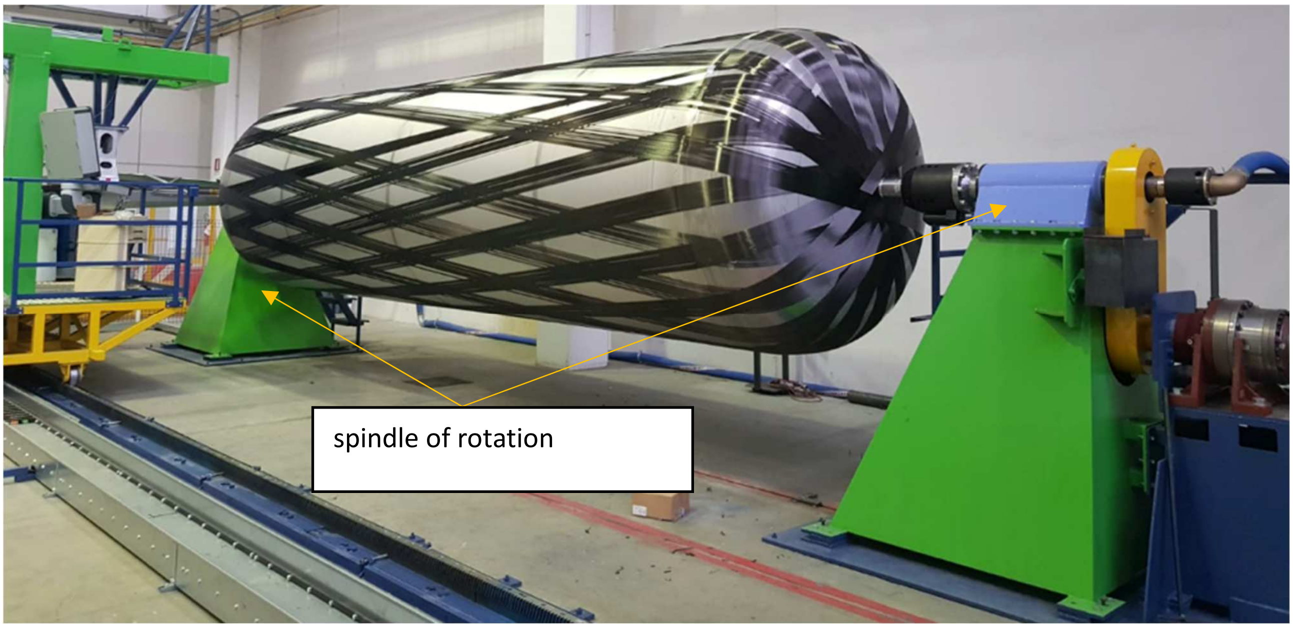


Figure 14 Spindle of rotation

b) 1 (one) main carriage moving parallel to the cylinder rotation axis, (X axis).

Figure 15 Main carriage

c) 1 (one) second trolley positioned on the main carriage with movement perpendicular both to the cylinder rotation axis (Axis ω) and to the X axis (Y Axis).

d) 1 (one) rotating head positioned on the carriage of the Y axis for fiber deposition, (Axis ϕ).

All axis movements are mechanically and electronically interpolating.

Both the motors and the drives are managed by a Siemens 640 CNC.

The winding software is first processed by a dedicated CADWIND program that processes the ISO program part to be downloaded to the CNC at the same time.

Each axis has a mechanical proximity sensor (multiple switch) and at least two cams.

See also sensor list and attached lay-out

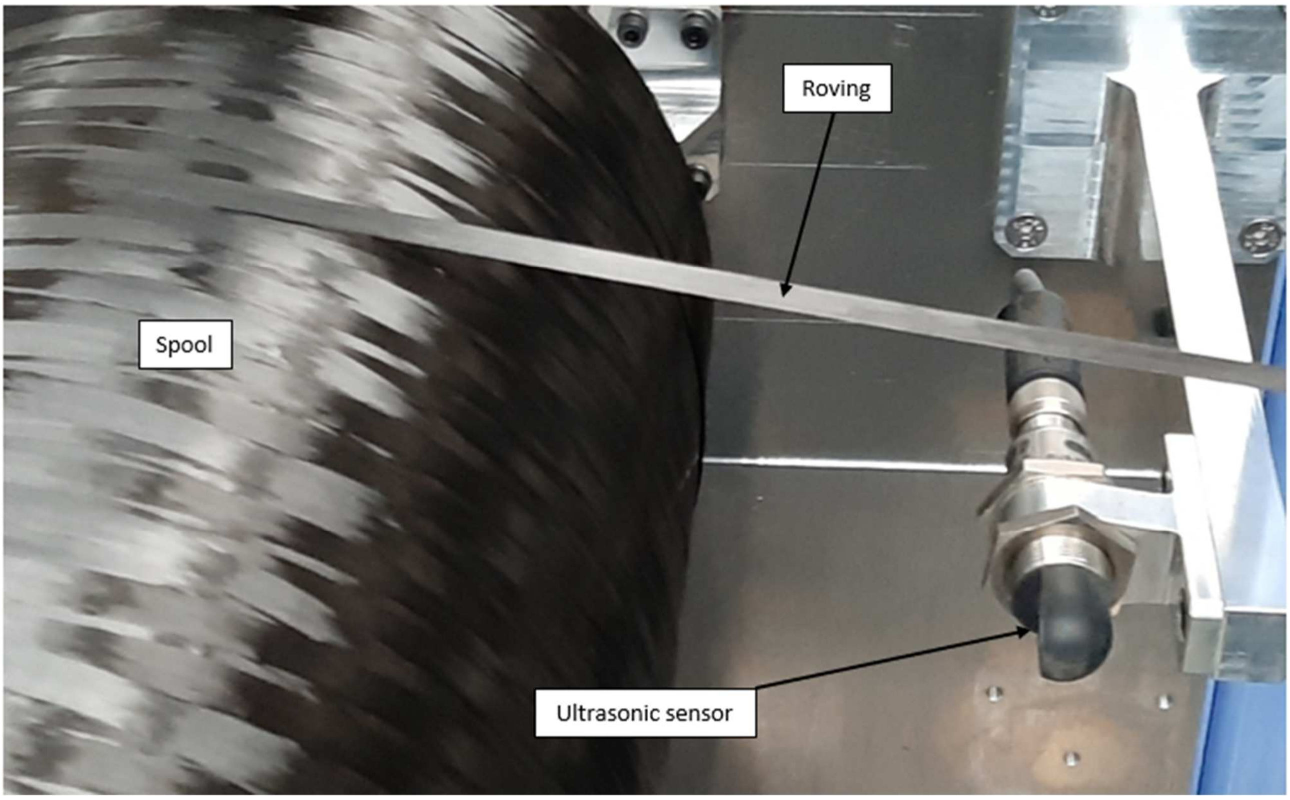
Accessories description

Creels (see photo)

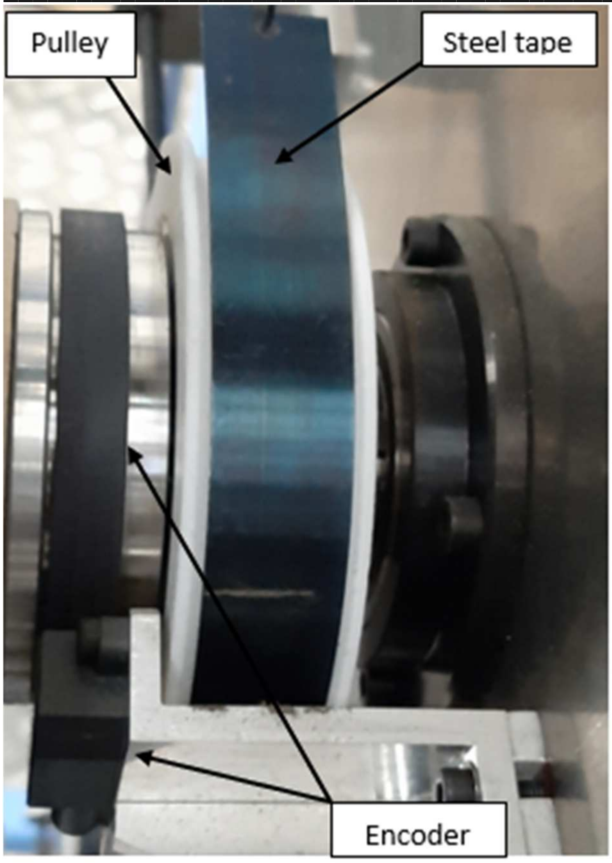
On the main carriage (Axis X) two creels are rigidly fixed, with 50 spools each, able to house the spools of the fibers (rovings) with external unwinding and to control their pulling during the various winding phases. An asynchronous motor (see photo), controlled by an inverter, acts on the screw by means of a jack and a series of mechanical transmissions. On the axis of the screw is also keyed an encoder that controls the number of revolutions of the screw. The control of the pull is carried out by screwing or unscrewing a screw that simultaneously puts 50 pre-set springs into tension. These act on the same number of friction belts that allow to brake all the coils simultaneously. The control system essentially works by controlling the number of revolutions of the screw through the encoder keyed directly on it and the motor through an inverter.

Functional principle of control of the pull

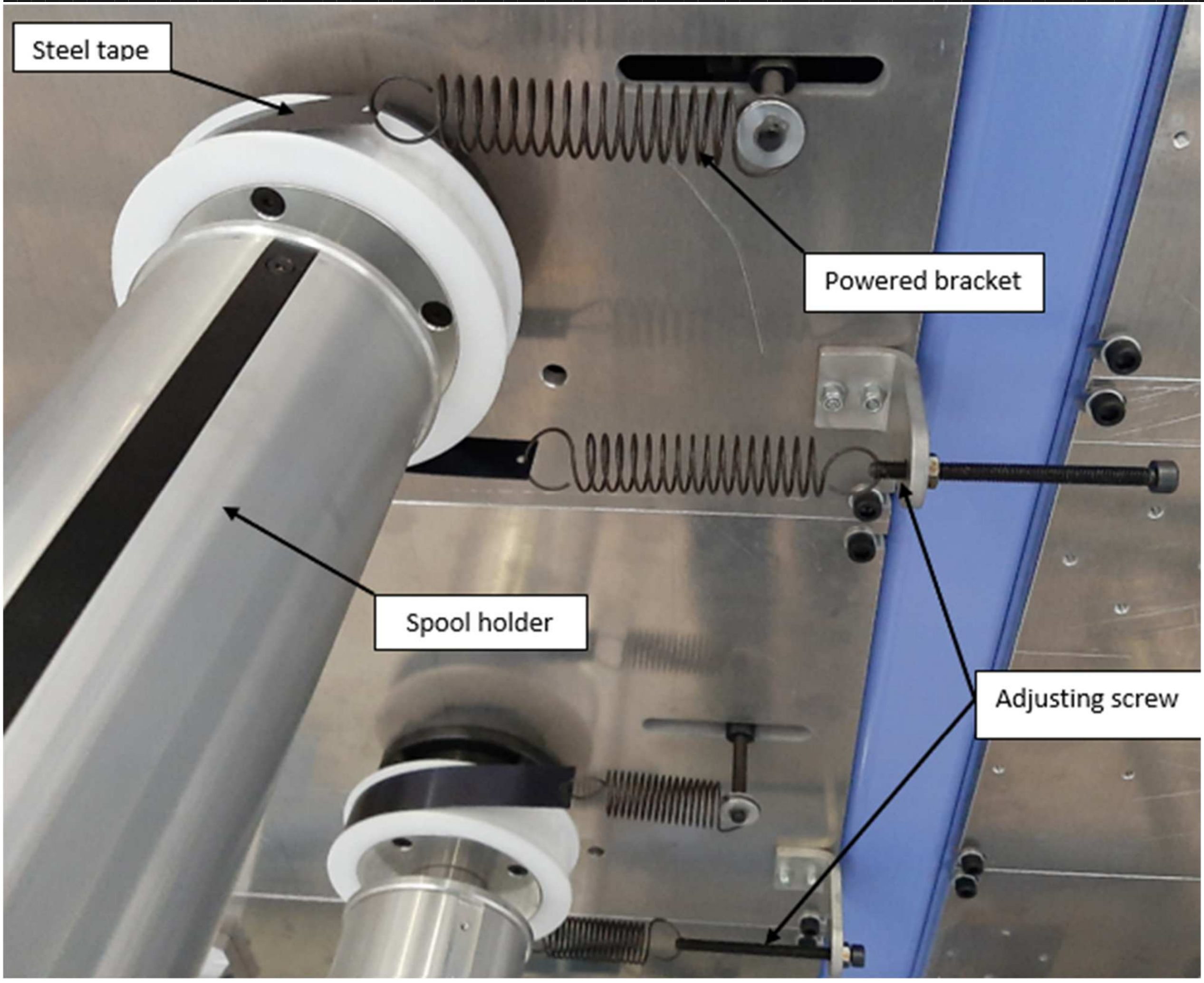
A pulley with a smooth groove is mounted on the shaft of the spool holder. On a pulley a steel tape supported by an automatic system rests on a given arc to vary the braking torque as a function of the reduction in the diameter of the spool in order to keep the roving pulling constant. An ultrasonic sensor continuously measures the spool diameter. See the photos below.



If the pull has to be kept constant, while the radius of the driving torque is reduced, we must act in the same way on the braking torque applied on the pulley, so to keep the roving pull constant we must reduce the friction torque on the pulley and therefore reduce the tension on the spring. This reduction in friction torque is linear with the reduction of the radius of the spool. It will be necessary to act on the motor that reduces the tension on the various steel tape continuously and according to a linear function. See the photos below with the highlighted details of the pull control.



Once the spring tensions are fixed (at the same time with a mechanical transmission system) the spool will be subjectto a braking torque proportional only to the pull of the spring (the friction drum does not change in diameter and it is assumed that the friction coefficient remains constant)



Consequently, if the spool decreases its radius by 1mm also the elongation length of the spring must be reduced by 1 mm. This measurement is made by the ultrasonic sensor (see photo) which continuously measures the radius of the spool.

Both the encoder and the motor are inserted directly on the axis of the screw. By controlling the number of revolutions of the same and by inverter on the motor we can control the position of the screw and the spring pull.

Impregnation system and tank (See the photos below)

Figure 16 Impregnation tank

On the main carriage there are also two impregnation tanks for the rovings, that come from the two creels.

50 rovings are impregnated on each tank at the same time.

The tanks are essentially made up of a cylindrical roller which is inserted inside an open-top basin. The tank is used to contain the resin and the roller catches the resin in the lower part of the tank. In direct contact with the lower walls of the tanks, two resistors are positioned to keep the resin at an almost constant temperature. A thermocouple inserted inside the tank and in direct contact with the resin continuously detects the temperature of the resin. An on / off adjustment system activates the heating elements, independently, when the resin goes below a set minimum and disconnects when a higher value is reached, which is also set. The rovings, by means of combs placed before and after the impregnation rollers, are channelled parallel to touch the upper surface of the rollers. The rotation of the rollers brings the resin into contact with the individual rovings, impregnating them. The two tanks are side by side and both impregnation rollers are connected, via suitable joints, to a single rotation motor equipped with an encoder (Z axis)

The peripheral speed of the rollers is proportional according to a constant at the speed of the winding rovings and can be regulated by a potentiometer.

The instantaneous winding speed of the fibres (in m / sec.) Is obviously given by the product of the spool diameter (in m) for π all divided by the number of revolutions (per sec.) of the spool, This is possible through two encoders, one in axis with the motor and the second in axis with the coil that carries out the roving which is positioned in the centre of the impregnation roller. (this roving makes a medium path between the two roving at the ends of the roller)

This spool is the same one that carries the diameter control system through the ultrasonic sensor and that allows, at the same time, to keep the roving pull constant.

The direction of rotation of the tank roller (Z axis) is contrary to the direction of rotation of the spindle (Axis ω).

The impregnation roller collects the resin and pushes it towards the rovings with speed against each other, in this way the two speeds are added increasing and improving the impregnation. Normally the rollers rotate in the direction of the fibre sliding bringing much less resin. During the tests the ideal peripheral speed of the impregnation rollers will be checked with respect to the speed of the rovings, to obtain the best resin supply. Once this parameter has been set, the ratio of the two speeds will remain constant even as the speed of winding of the roving varies. Finally the effect of the viscosity of the resin, against the current with the development of the roving, helps to keep the wires always in tension even when there are slightly different speeds between one roving and the other contributing to a better general constancy of the tensions on all the layer.

Device for measuring the pull on the rovings

At the exit from the resin tanks it is possible to install a device consisting essentially of three rollers and a load cell allows the tension of the rovings to be read. This device is used when setting up the machine to decide how to adjust the brake on the spool to obtain the most homogeneous and well impregnated composite possible.

Dosing and mixing pump.

The components of the resin (base resin, hardener, and catalyst) are automatically mixed by a pneumatically operated pump.

This device is placed next to the support of the two impregnation tanks and directly fishes all the components from containers placed next to this equipment. All these components are secured and secured on the main trolley (Axis X)

Two heaters, one for the base resin and one for the hardener, preheat the two components.

One or more solenoid valves operate three pistons that pump the various components into a mixer and then into the impregnation tanks. The pump already has the electrical control panel for pumping and mixing. An ultrasonic sensor measures the level inside the tank and controls the pump. The operation of the mixing pump is on / off type. When the level of the resin reaches a minimum, pre-set value, it opens the general solenoid valve which brings the supply air to the pump which starts feeding new resin into the tanks. When the level reaches a maximum, which is also pre-set, the general air supply solenoid valve is closed and the pump stops.

Control desks

There are two control desks.

One is on the ground and a second one is fixed on one of the columns of the frame that supports the axis of movement Y on board the main carriage.

Both control desks have the same controls and a screen for interacting with the numerical control.

From the desks it must be possible to carry out all the controls and control all the winding machine's movement functions.

When the operator interacts with the on-board desk the ground one is blocked and vice versa by means of a selector or code.

All the movements performed by the operator when it is present on the main carriage must be performed in "execution 1, 2 or 3, described below, and all the movements of the various axes are only available in these modes.

Start of a new wrapping and connecting procedure of the roving on the liner nozzle

3.3.2 Operating mode 1

The operator gives the positioning command for the beginning of the cycle either from the console on the ground or from the one positioned on the main carriage. (when a console is selected, the other one is automatically inhibited except for any safety and emergency functions)

The machine moves only if:

All the safeties are respected which means that at the same time the following conditions are present:

a) closed fence gates on the ground.

b) gates of the enclosure of the main carriage closed (operator possibly on the machine but in safety)

c) absence of alarms from the PLC or from the CNC

d) positive consent by the laser sensor "no human presence inside the enclosure"

Under these conditions, the operator, both on the main carriage and on the ground, can select the "fiber coupling cycle" mode, by means of a code to be entered from the console or by means of a selector (to be agreed together which is safer and more convenient) and the machine start moving following the following pattern:

e) the machine automatically sets itself in slow operating mode (the speeds must still be decided, at the moment it is thought to move the main carriage to a maximum speed of 100 mm per sec. with an acceleration ramp of 20 mm / sec2) This speed can be changed by both consoles, but only with a further decrease in speed even up to the stop. All other speeds of the individual axes are set accordingly, and each axis goes to the starting position (each axis goes to its corresponding origin "0"

f) the machine stops, and no movement is possible except the filling of the impregnation tanks with the resin and all the manual operations such as the arrangement of the reels on the creels, the positioning of the roving on the impregnation rollers, etc.

g) the operator controls the automatic filling of the resin tanks (see procedure for mixing and supplying resin in the tanks)

h) the operator can safely get out of the car carriage

i) the operator or operators arrange the roving through the various combs up to the spout of the winding head placed in position "0" in correspondence with the nozzle of the neutral support

j) the operator(s) wrap all the roving around the nozzle and manually lock them with the appropriate equipment

k) the operator (s) returns to their respective safe positions and selects the slow winding mode

l) the machine begins to wind slowly until the operator decides to enter production mode

m) If malfunctions or alarms occur during winding in mode 1 the machine must stop and maintain the mutual position of the axes (all motors are interfaced to absolute encoders) and restart from the program line of the part program corresponding to the stop.

Winding machine operating procedures

Winding machine operating mode in "production"

3.3.3 Operating mode 2

At the discretion of the operator the machine continues in mode 1 (slow at the discretion of the operator who in this mode can only decrease the speed)

The machine stops automatically if alarms occur.

When the operator decides to enter mode 2 it performs the following alternative operations:

First alternative

a) stops the machine that keeps all the positions relative to the winding and the operator descends from the main carriage and exits the fixed fence in safety conditions.

b) the operator closes all the security doors and, in this way, restores all the safety devices

c) the operator from the ground desk decides to switch to mode 2 by selecting from the panel or by means of a special key (this must also be agreed) and the machine resumes winding from the previous stop position with the slow speed provided by mode 1.

d) the operator can decide to increase the winding speed up to 110% of what the part program allows by acting on the potentiometer that at this point can adjust the speed also in increase

e) If malfunctions or alarms occur during the winding in mode 2 the machine must stop and keep the mutual position of the axes (all the motors are interfaced to absolute encoders) and restart from the program line of the part program corresponding to the stop.

Second alternative

f) The operator can carry out the same operations remaining on the main carriage with all operating safety conditions.

Winding machine operating mode in "part program modification"

3.3.2 Operating mode 3

At the discretion of the operator, both in mode 1 and in mode 2 the machine can be stopped at any time, without losing the mutual position of the axes, to modify the winding program if necessary, by selecting mode 3.

In this mode, with all the safeties active, the operator can get off the main carriage or get on it, modify part program lines or perform other manual operations that do not compromise the safety or correct operation of the machine.

After possibly carrying out one or more of these activities with the machine stopped the operator can resume from the stop position without jeopardizing the rest of the various winding phases and eventually enter mode 1 or 2.

Parameters of the rovings pull and calibration

The pull on each individual roving must be adjusted between 10 and 20 N. acting on the adjustment screw (see photo)

This pull can be calibrated as previously described using the device for measuring the pull on the rovings.

The force is read directly on the display of the load cells of the device. See photo

Parameters of impregnation of rovings.

As already described in the impregnation system, the speed of the impregnation roller is automatically adjusted by the device. Consequently, also the degree of impregnation is automatically maintained according to the winding speed of the rovings.

The degree of impregnation (speed of the impregnation roller) was decided by specific impregnation tests.

The final degree of impregnation can be checked subsequently on composite samples taken after fatigue or burst tests.

The resin mixing device with the hardener has a predetermined ratio determined by the stroke of the adduction pistons of the base resin and the hardener and is fixed at a ratio of 100 (base epoxy resin) to 83 (of hardener), while the catalyst it can be adjusted between a minimum of 0.5% to a maximum of 2% with respect to the total weight of the resin + hardener. This parameter is entered by the operator on the mixer console. This parameter has already been determined with a pot life test and obtained through experimental graphs and is a fixed parameter of 1.5%.

The heating temperature of the resin must be 40 ° C and is already pre-set in the resin mixer.

Likewise, the heating plates of the impregnation tanks, are already set at a temperature of 40 ° C and automatically kept at this constant value.

Resin to use

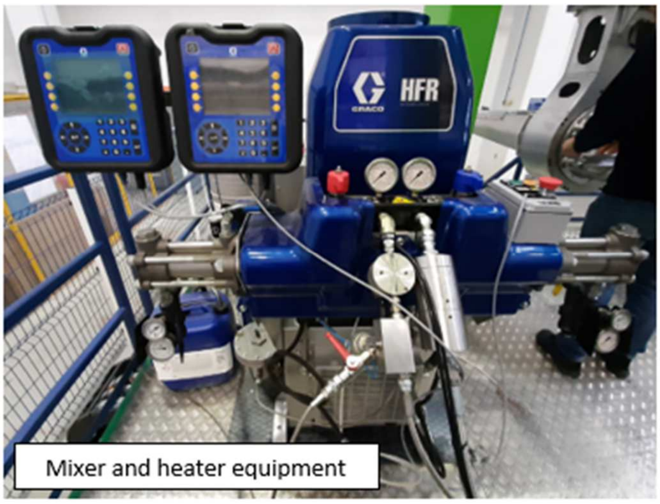
Voraforce TW 100 (Epoxy resin) 100 parts by weight

Voraforce TW 150 (Hardener) 83 parts by weight

Voraforce TC 3000 (catalyst) 1,5 parts by weight

Resin manufacturer: Dow

See below the photos of the mixer and dispenser of epoxy resin



Mixer and heater equipment

Adduction pumps of the resin and hardener

Resin-catalyst mixer

3.3.2 Winding specification

N° Winding	Type	Winding Angle	Friction	Pattern Number	Number of Cycles	Deg. Of Covering	Effective Deg. Of Covering	Turning Zone front to	Turning zone back from	Starting Frame	Starting Position [°]	Dwell front [°]	Dwell back [°]	Number of Rovings	Roving width	Fiber Volume content	TEX value	Fiber density	Resin density	PartProgram Name
Start	Combination	"89.2->9.4"		NaN	1	NaN	NaN	NaN	NaN	"48->46"	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
0 Fiber Glass	Helical	9,4	NaN	"-3/1"	34	101	101,11	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER9_4 Sub:LAYER9_4
1	Helical	9,4	NaN	"-3/1"	34	101	101,11	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER9_4 Sub:LAYER9_4
2	Helical	9,4	NaN	"-3/1"	34	101	101,11	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER9_4 Sub:LAYER9_4
3	Helical	9,4	NaN	"-3/1"	34	101	101,11	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER9_4 Sub:LAYER9_4
4	Helical	9,4	NaN	"-3/1"	34	101	101,11	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER9_4 Sub:LAYER9_4
5	Helical	9,4	NaN	"-3/1"	34	101	101,11	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER9_4 Sub:LAYER9_4
6	Helical	9,4	NaN	"-3/1"	34	101	101,11	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER9_4 Sub:LAYER9_4
	Combination	"9.4->12"	0,001	NaN	1	NaN	NaN	NaN	NaN	"46->46"	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	Main:MAINTRANSITION9_4TO12 Sub
7	Helical	11,75	NaN	"-8/3"	35	101	104,98	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER12 Sub:LAYER12
8	Helical	11,75	NaN	"-8/3"	35	101	104,98	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER12 Sub:LAYER12
9	Helical	11,75	NaN	"-8/3"	35	101	104,98	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER12 Sub:LAYER12
10	Helical	11,75	NaN	"-8/3"	35	101	104,98	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER12 Sub:LAYER12
11	Helical	11,75	NaN	"-8/3"	35	101	104,98	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER12 Sub:LAYER12
12	Helical	11,75	NaN	"-8/3"	35	101	104,98	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER12 Sub:LAYER12
	Combination	"12->19"	0,001	NaN	1	NaN	NaN	NaN	NaN	"46->46"	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	Main:MAINTRANSITION12TO16
13	Helical	19,5	NaN	"-9/4"	34	101	103,77	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER16 Sub:LAYER16
14	Helical	19,5	NaN	"-9/4"	34	101	103,77	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER16 Sub:LAYER16
15	Helical	19,5	NaN	"-9/4"	34	101	103,77	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER16 Sub:LAYER16
16	Helical	19,5	NaN	"-9/4"	34	101	103,77	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER16 Sub:LAYER16
17	Helical	19,5	NaN	"-9/4"	34	101	103,77	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER16 Sub:LAYER16
18	Helical	19,5	NaN	"-9/4"	34	101	103,77	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER16 Sub:LAYER16
	Combination	"19->25"	0,002	NaN	1	NaN	NaN	NaN	NaN	"46->46"	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	Main:MAINTRANSITION16TO24
19	Helical	25,4	NaN	"4/3"	33	101	106,01	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER24 Sub:LAYER24
20	Helical	25,4	NaN	"4/3"	33	101	106,01	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER24 Sub:LAYER24
21	Helical	25,4	NaN	"4/3"	33	101	106,01	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER24 Sub:LAYER24
22	Helical	25,4	NaN	"4/3"	33	101	106,01	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER24 Sub:LAYER24
23	Helical	25,4	NaN	"4/3"	33	101	106,01	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER24 Sub:LAYER24
24	Helical	25,4	NaN	"4/3"	33	101	106,01	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER24 Sub:LAYER24
	Combination	"25-37"	0,0032	NaN	1	NaN	NaN	NaN	NaN	"46->46"	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	Main:MAINTRANSITION24TO36
25	Helical	37	NaN	"13/3"	30	101	108,83	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER36 Sub:LAYER36
26	Helical	37	NaN	"13/3"	30	101	108,83	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER36 Sub:LAYER36
27	Helical	37	NaN	"13/3"	30	101	108,83	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER36 Sub:LAYER36
28	Helical	37	NaN	"13/3"	30	101	108,83	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER36 Sub:LAYER36
	Combination	"36->89.2"	0,0524	NaN	1	NaN	NaN	NaN	NaN	"46->46"	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	Main:MAINTRANSITION36TO89_2 Sub:TRANSITION36TO89_2
from 29	Circunferential ?	90				101										58	1600	1,785	1,14	
to 52	Circunferential ?	90				101										58	1600	1,785	1,14	
	Combination	"89.2->45"	0,0524	NaN	1	NaN	NaN	NaN	NaN	"46->46"	0	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	Main:MAINTRANSITION89_2TO45 Sub:TRANSITION89_2TO45
53	Helical	45	NaN	"4/3"	25	101	103,75	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER45 Sub:LAYER45
54	Helical	45	NaN	"4/3"	25	101	103,75	NaN	NaN	46	0	0	0	100	2	58	1600	1,785	1,14	Main:MAINLAYER45 Sub:LAYER45

Table 2 Winding specification

The sequence processed for the windings of the various layers with indication of the winding angles, number of layers and winding step is reposted below. The winding program also indicates the% overlap of the windings, the percentages of resin, the TEX title of the carbon fiber and the specific weight of the fiber and all the parameters related to the angle changes. Each pattern was reported as part program in ISO language and stored in the Winding Machine CNC.

3.4 Curing

The curing plant is essentially a large oven to obtain an accurate catalysis of the epoxy resin. As shown in the overall picture, the upper lid is removable and allows the cylinder to enter once all the windings have been completed.

The cylinder is inserted in a horizontal position inside the oven, between two rotating supports (spindles) that allow the two nozzles of the cylinder to be rigidly locked.

The two rotating supports also allow the passage of air inside the cylinder through special rotating joints. A fan connected to an electric heating coil sends hot air inside the cylinder through a closed circuit. (see photo of the hot air supply pipes) An adjustable temperature regulation system is controlled by two thermocouples and by appropriate hardware and software. High power IR lamps are placed on the oven walls to allow heat the cylinder even from the external.

A series of laser sensors positioned outside the oven walls allow to read the surface temperatures of the composite over the entire cylindrical area and on both ogives. Three+ three lamps are positioned on both ogives in order to uniformly cover the curvatures and homogeneously irradiate the surfaces of the ogives. Also in the cylindrical area there are three other lamps that fully cover the surface. Each lamp is controlled independently by the laser sensors from the same hardware and software described below in order to reach and maintain the required temperatures. The cylinder, during the curing phase, is set in rotation very slowly to allow the IR lamps to heat the entire surface uniformly. The operating instructions for the curing system are shown here below. The system is therefore able to heat the cylinder simultaneously both from the inside and from the outside, obtaining an optimal heat distribution for curing.

The curing process is divided into two phases:

first phase in which the internal and external temperature must not exceed 45° C +/- 5° C for 16 hours and a **second phase** in which the temperature is progressively brought to 120 ° C and maintained at this temperature +/- 5° C . Post-curing at 120° C should last for at least 8 hours.

The curing temperatures and times are recorded by the operator periodically every hour. In the event of a malfunction, an alarm system alerts the operator on duty.

Curing equipment description

Electrical cabinet

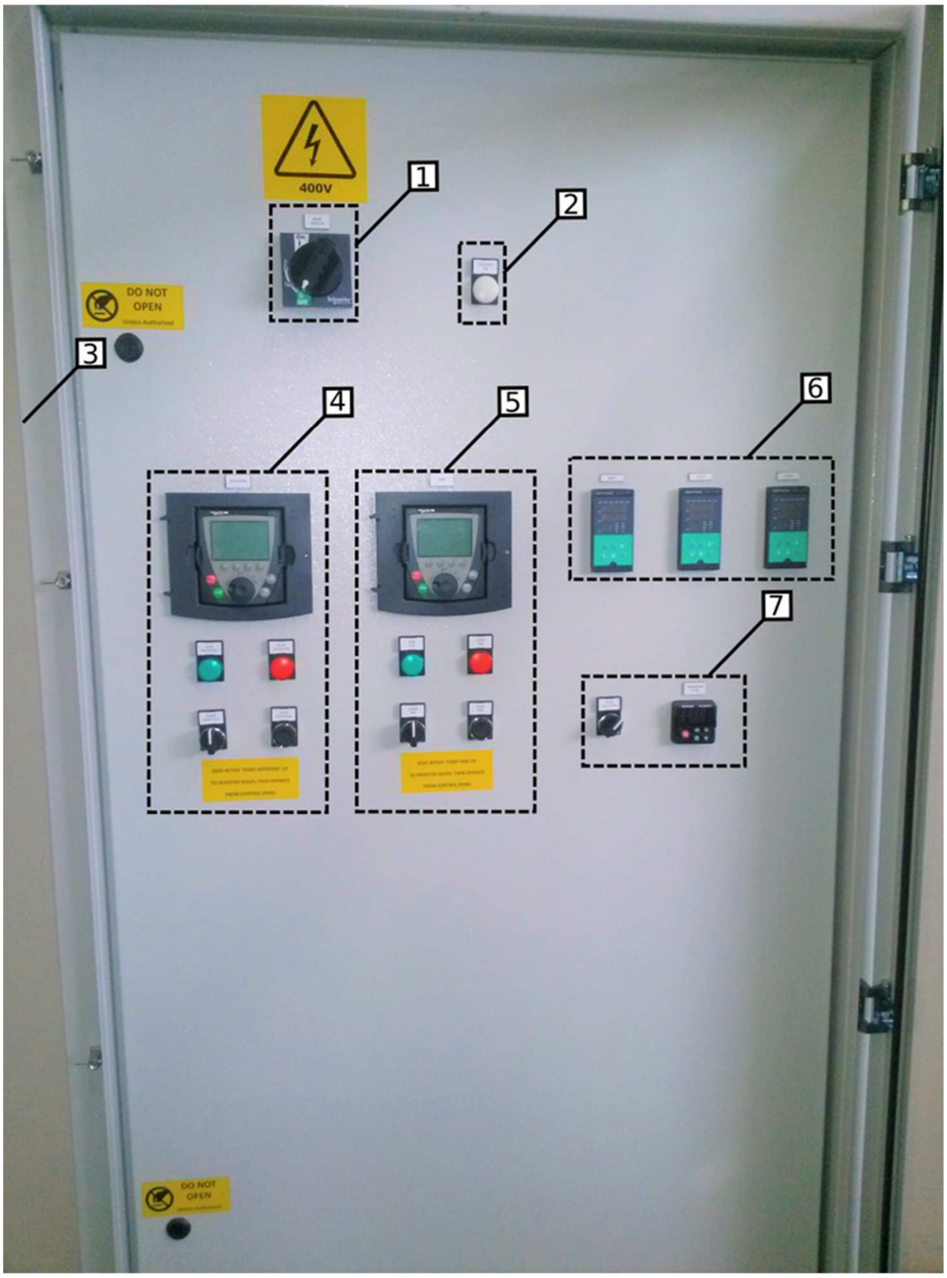


Figure 17Curing electrical cabinet

1. Main power switch
2. LED Power On
3. Emergency push button
4. Mandrel Control Panel
5. Centrifugal Fan Control Panel
6. IR Lamps control Panels
7. Electric coil Control Panels

Detail of le panel n° 4 and 5

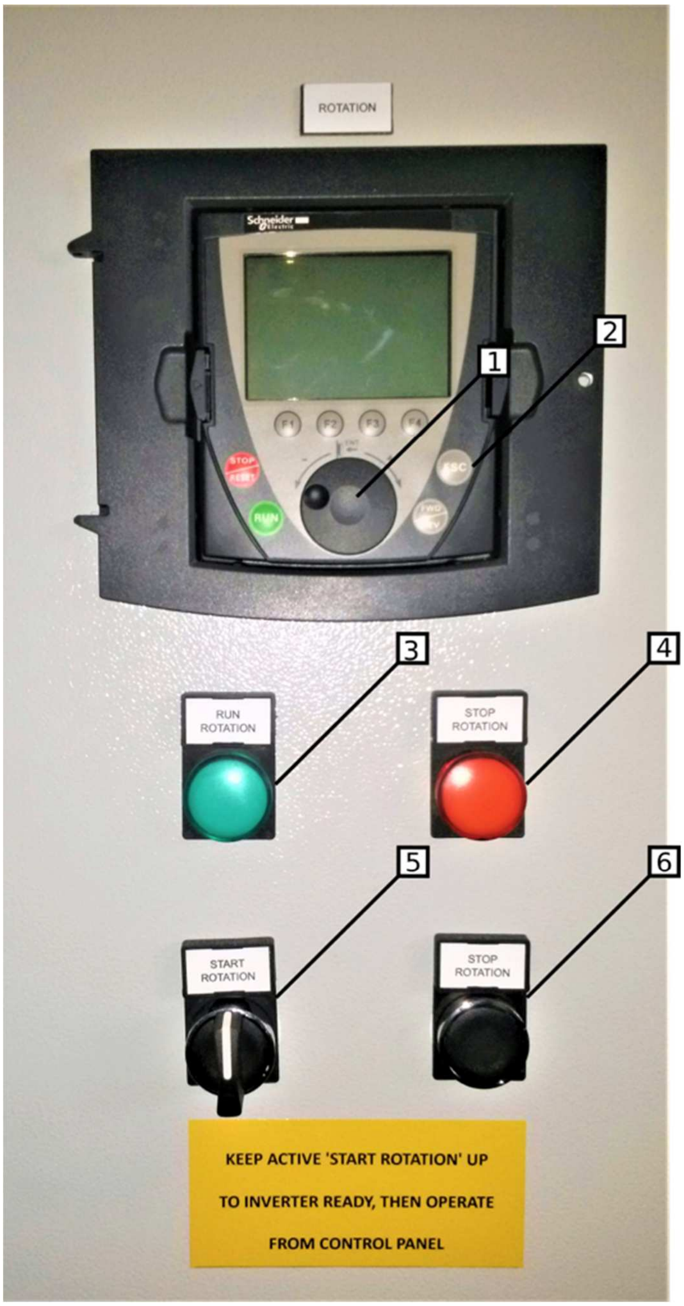
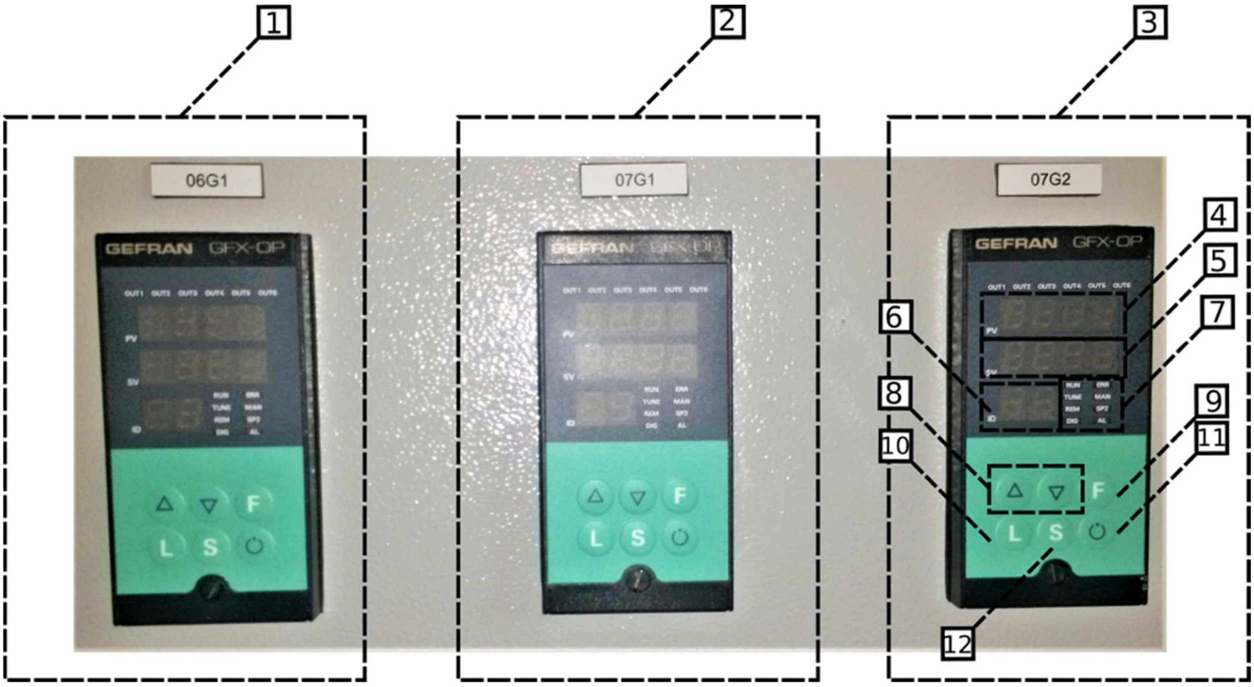


Figure 18 Detail of le panel n° 4 and 5

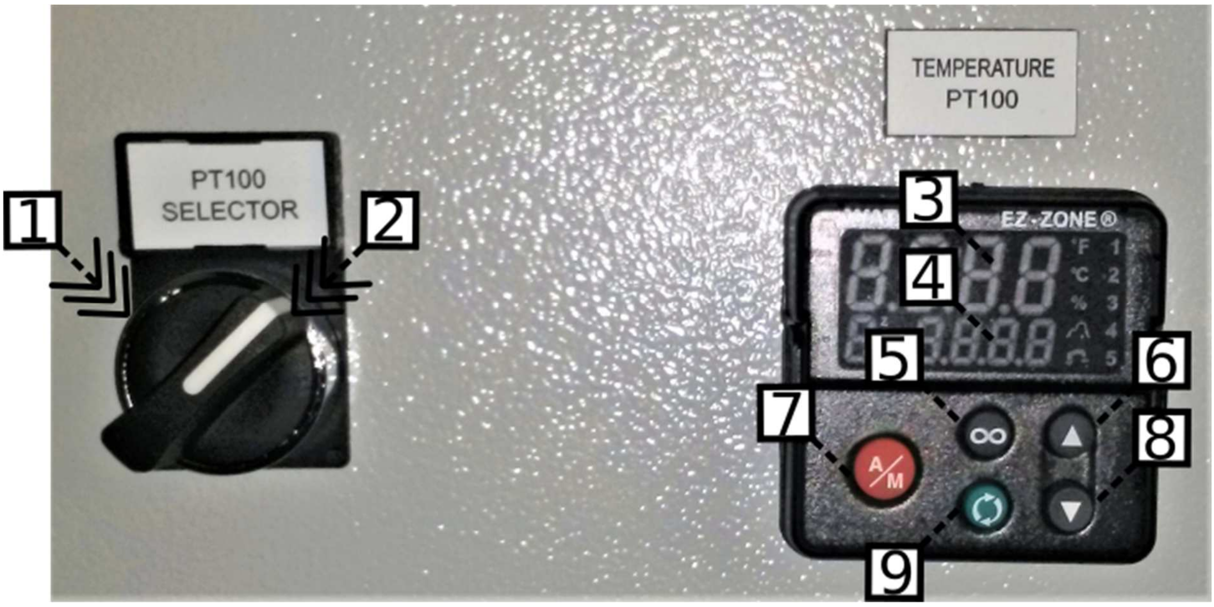
1. Rotation wheel selector and central Enter push button
2. Go back button
3. LED indicator Active Control
4. LED indicator STOP rotation
5. Rotational switch, anticlockwise turn power on, clockwise turn starts rotation
6. Stop Push Button

Detail of le panel n°. 6



1. Central Lamps operator panel
2. Left IR Lamps operator panel
3. Right IR Lamps operator panel
4. Current Temperature value
5. Temperature Setpoint Value
6. Lamp address (Shows current lamp under control)
7. Actual status of the IR Lamps controller
8. Up un Down buttons
9. Button for settings
10. Load Button
11. Turn IR Lamp On/Off Button
12. Store Button

Detail of le panel n°. 7



1. Temperature sensor at the input of the resistance
2. Temperature sensor at the exit of the resistance
3. Temperature value measured
4. Temperature set point in automatic, Power [%] in manual or display OFF in off mode.
5. Confirm button
6. Up button
7. Auto/Manual button
8. Down button
9. Menu selector button

WARNINGS

The fan must always run before using the air electric heating coil and the thermocouple adjustment system intervenes.

The spindle rotation must be activated first, before to use the IR lamp control.

VENTILATION AND INSTRUCTIONS FOR CHECKING HEATING

The fan must first be turned on. On the fan control panel, turn 5 counterclockwise. Using 1 select the fan speed (-50 hz).

Once the fan is on, select the desired sensor (usually 1) on the resistance control panel. Press 9 to select the control type (Auto) using the up (6) and down (8) buttons. To confirm press the button 5 marked with the infinite symbol.

To switch off, first select the switch-off mode by pressing 9 and using the up (6) and down (8) buttons. To confirm press button 5.

Press the stop button 6 on the fan rotation panel to stop the fan.

INSTRUCTIONS FOR CHECKING THE SPINDLE AND IR LAMPS

Activate spindle rotation. On the spindle rotational control panel, turn 5 counter clockwise. Using 1 select the spindle speed (5.71 hz).

On the IR lamp control panels, select the lamp with address 11 using the up and down button (8). Then press (11) to turn on the lamps. Repeat the same for address 12 and 13 on panels 07G1 and 07G2. On 06G1 turn on the lamps with address 11,12,13,14.

To turn off the lamps

On the IR lamp control panels, select the lamp with address 11 using the up and down button (8). Then press (11) to turn off the lamps. Repeat the same for address 12 and 13 on panels 07G1 and 07G2. On the 06G1 turn off the lamps with the address 11,12,13,14.

Disabling spindle rotation

Press the stop button (6) on the spindle rotation panel to stop the spindle.

Warning

Remember to put the spindle in the proper position to remove the cylinder.

3.5 Autofrattage

Autofrettage is a metal cold forming technique or a pressure application procedure, used in manufacturing composite containers with metal liners, which strains the liner past its yield point sufficiently to cause permanent plastic deformation, which results in the liner having residual compressive stresses and the fibres having residual tensile stresses at zero internal pressure.

The autofrettage system consists of a hydraulic pump capable of reaching 350 bar and a pressure multiplier able to increase the water pressure up to a pressure of about 1000 bar.

The photo shows the pressure multiplier placed on the floor inside the container that is used to transport the plant to the site destined for the burst test. On the side is visible the pump with the hydraulic control unit and the water tank necessary to fill the cylinder to reach the desired pressures. The electrical panel is also inserted in the container to power and control the pump during the test.

The system allows performing autofrettage, hydraulic testing and subsequently also the burst test.

Specifications for the autofrettage test.

The finished cylinder is placed on the support in a slightly inclined position to allow the water to completely fill the internal volume of the cylinder and to let out all the air. A siphon placed in the highest dome allows all the residual air to escape.

The autofrettage pressure must however be greater than the test pressure which is set at 450 bar. To determine the ideal autofrettage pressure, 24 strain gauges were glued onto the surface of the liner of the first cylinder that will be tested (see photo here below). 12 strain gauges are aligned with the circumferential principality tension and another 12 are in the axial direction.

Furthermore, in correspondence of the strain gauges glued on the liner, another 24 strain gauges will be glued onto the outer surface of the composite winding.

During the autofrettage phases, to determine which will be the ideal pressure to be adopted on the other cylinders, the elongations related to the various strain gauges will be determined with a special 48-channel strain gauge control unit, determining and recording, at the same time, the extensions of all the strain gauges at each step of increase of the pressure.

A table for detecting the elongations according to the applied pressures has been prepared and available.

The simultaneous detection of pressures is performed and memorized by means of the precision pressure switch housed near the water supply circuit that pressurizes the cylinder.

It should be noted that, after reaching the pressures above 450 bar, the cylinder is discharged (the pressure is restored to 0 bar) and the permanent deformations reached and the consequent compression that the composite exerts on the walls of the liner are determined. From this test it is possible to determine the ideal autofrettage pressure for which the steel liner is subjected during the loading and unloading phases to an average stress as close as possible or equal to 0. Finally, from the comparison of the FEM analysis already performed, with the experimental data of the elongations it is possible to compare the theoretical stress values with the experimental ones and validate the theoretical calculation part by finite element analysis. This is a fundamental point of the project that allows to validate the whole theory underlying the patent.

3.6 Fatigue test and equipment

Two finished cylinders shall be pressure cycled at ambient temperature to failure, or a minimum number of 10 000 cycles that is. Pressure cycling shall be performed in accordance with the following procedure:

a) the cylinder must be filled with water and we must be sure that all the air has been expelled during filling. For this reason, the cylinder is placed on a special tilting cradle that allows the slightly tilted tank to be positioned upward. Filling is performed by pumping water from the lower part of the cylinder. On the other side of the cylinder, in upper position, there is a special siphon that will be positioned in the highest part of the ogive in order to intercept all the air inside the cylinder and make it come out. The cylinder is connected, by a special hydraulic circuit, to a pressure booster system that allows to increase the hydraulic pressure up to the foreseen test pressure.

The hydraulic system.

Three pressure boosters are used simultaneously, which allow for a water flow of about 450 liters per minute. In this way it is possible to reduce the test time to about 15-20 days.

b) the maximum pressure of each cycle must be equal to or greater than the maximum pressure developed by the cylinder during filling at the maximum temperature foreseen. In our case the maximum gas pressure will be 375 Bar.

c) the minimum pressure for each cycle can be equal to 10% of the maximum pressure, in our case 37 bar.

d) enter the minimum pressure in the electronic control system of the test

e) enter the maximum pressure in the electronic control system

The control unit allows us to set the two minimum and maximum pressures and the number of cycles to be reached on the display.

f) enter the minimum number of cycles in the electronic control system.

g) push the start button.

If during the test the cylinder cracks (at these pressures the burst of the cylinder never occurs as the composite works down below its breaking limit) and starts to lose, automatically the pressure starts to go down, the control pressure switch of the pressure sends a signal to the control unit that automatically stops the test. The display shows the maximum number of cycles reached at the test pressure.

See the photos below of the ambient cycling test equipment.


3.7 Hydraulic test and burst equipment

The system to apply the autofrattage, as mentioned above, will be able to reach the pressure of 1000 bar, for this reason it will also be used for the hydraulic test and for the burst test.

The hydraulic test will be performed after the autofrettage, to check if the internal liner works in the elastic field.

To check if the liner subjected to a pressure of 450 bar (test pressure) does not undergo permanent plastic deformations, the amount of water in the tank (level) will be measured before and after being put under pressure at the end of the test at a pressure of 0 bar.

The test is valid only if the water level in the tank does not change within a margin of +/- 1%

The system is installed in a container and can be transported to the place where the burst test will take place. (see photos below)

The burst test serves to verify that the safety coefficient adopted for the realization of the cylinders is respected. The test consists in reaching the burst pressure using the equipment already described for the hydraulic test and for the autofrettage.

The safety coefficient adopted is equal to 2.25 the operating pressure of the cylinder. This coefficient is required by the reference standard ANSI NGV2 for carbon fiber reinforced composite type 3 cylinders. Since the operating pressure is 300 bar, the minimum burst pressure must be higher than 675 bar.

The burst test will be performed inside a quarry far from the inhabited center which has already been identified and booked for the test so the test will take place in granted safety conditions. The cylinder will be carried along with all the equipment for the explosion (containers with pressure booster, hydraulic pump with control unit and water tank) inside the quarry.

The cylinder will be placed on the ground on cradles. At the appropriate distance, protected by a quarry existing stone wall, the equipment inside the container will be fitted. All pressurization operations will be carried out under the stone wall protection. Water supply pipes, shut-off valves and hoses have already been prepared and are certified up to a pressure of 1000 bar. The hydraulic system is managed by an electric control unit which is connected to a pressure switch for recording the pressures reached. The first cylinder on which the burst test will be made is the same one that is already covered with strain gauges to be able to simultaneously record the deformations reached. The pressure will be increased according to the specifications of the ANSI NGV2 standard at a rate of less than 200 psi / sec. (<13.7 bar / sec)

4. Safety precautions

During the execution of the testing plan the maximum attention shall be paid to the safety of the researchers, operators, surveyors and equipment.

The Testing Plan shall be attended by the people strictly necessary for the execution of the tests. No admittance to stranger persons.

As a minimum, the safety precautions stated in the deliverable D10.2 shall be strictly adhered to.