POLITECNICO DI MILANO

Faculty of Industrial and Telecommunication Engineering

Master's Degree in Mechanical Engineering

Design of a High-Pressure and High-Diameter Composite Pipeline

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A chi ha creduto in me
Alla mia Famiglia
Ai miei Amici
...a Me

SOMMARIO

Nel settore Oil&Gas le condutture usate per il trasporto di petrolio e gas, usualmente costruite in acciaio, rappresentano una criticità. I motivi sono diversi: nel primo tratto, in prossimità dei pozzi di estrazione, ci sono enormi problemi di corrosione dovuti alla presenza di acidi e solfuri, nel resto delle condutture, la manutenzione e la gestione sono sempre complesse e frequenti.
L'utilizzo di materiali compositi a matrice polimerica, per loro natura leggeri e resistenti alla corrosione, potrebbe portare dei notevoli benefici.
Non esiste però un approccio progettuale che sia consolidato, in accordo alle normative esistenti, e che permetta di utilizzare i materiali compositi per queste applicazioni.
Lo scopo di questa tesi consiste nel provare a progettare una conduttura per applicazioni Oil&Gas con materiali compositi, basati su resine epossidiche e fibre EC-R, cercando di razionalizzare tutto il processo progettuale e fornire al progettista degli strumenti che siano di ausilio al suo lavoro.
In particolare, sono stati implementati degli strumenti di calcolo integrati fra loro che permettono:

- La previsione delle caratteristiche della lamina attraverso modelli analitici – *APT, Analytic Prevision Tool*
- La simulazione dello stato di sforzo della condotta sottoposta a pressione interna – *HST, Hydrostatic Simulation Tool*

Considerando il processo produttivo di Filament-Winding, questi programmi consentono l'ottimizzazione dell'angolo di avvolgimento delle fibre, θ°, e della frazione di fibra, V_f.
Progettando in accordo con i criteri della normativa BS EN ISO 14692, analizzata nelle sue due edizioni, i processi di qualifica e linee guida vengono analizzati e confrontati con l'ausilio di programmi integrati:
QT2002, Qualification Tool 2002 e *QT2016, Qualification Tool 2016.*
Si è concluso che la seconda edizione pone maggiore attenzione ai carichi assiali, che risultano essere la prima causa di rotture, e obbliga quindi il progettista ad utilizzare un angolo di avvolgimento che aumenti le capacità della pipeline di sostenere carichi assiali, anche non previsti. Dalle simulazioni effettuate, si evince inoltre che il futuro processo normativo comporterà un aumento di spessore intorno al 17%.

ABSTRACT

In the Oil&Gas sector, the pipelines used to transport oil and gas, traditionally built out of steel, feature some critical issues. The reasons are many and varied: along the initial stretch, in close proximity to the extraction wells, acids and sulphurs cause widespread problems of corrosion and along the rest of the pipeline maintenance and management of the infrastructure is always complex as it is frequent.
The adoption of composite materials with a polymer matrix, by their very own nature light and corrosion resistant, could provide notable benefits.
However, to this date, a consolidated design approach, congruent with existing regulations, which uses composite materials does not exist.
The objective of this thesis is to design a pipeline for Oil&Gas applications using composite materials, based upon EC-R fibre and epoxy resins, trying to rationalize the whole design process and to supply the designer with the tools necessary for his work.
Furthermore, various software's were implemented which allowed us to:

- Forecast the characteristics of the foil via analytical models - *APT, Analytic Prevision Tool*
- Simulate the state of stress of the pipeline under internal pressure – *HST, Hydrostatic Simulation Tool*

Adopting the productive process of filament winding, these software's allow for the optimization of the fibre winding angle, θ°, and of the fibre fraction, V_f.
Designing the pipeline in accordance to the criteria outlined in the BS EN ISO 14692, analysed in both of its editions, the processes of appraisal and guide line are analysed and confronted via the following software's:
QT2002, Qualification Tool 2002 and *QT2016, Qualification Tool 2016*.
It was concluded that the second edition gives greater attention to axial loads, which turn out to be the principal cause of breakage, forcing the designer to use a winding angle which enhances the pipeline's capacity to bare axial loads, even if these are not contemplated. From the undergone simulations, it is possible to foresee that future regulations will require about 17% increase in thickness.

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A3 - Attachments

Introduction and Scope

The history of the oil industry begins on the day 27 august 1859 when in Titusville, a village of carpenters in Pennsylvania, Oil sprang from the first oil well drilled by E. L. Drake.
Before then, the oil used was only what skimmed from water wells or diffused from the surface terrain.

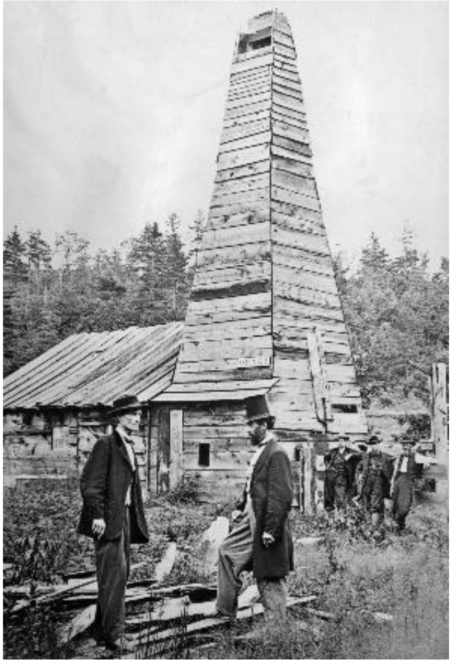


Figure A - The first oil well drilled by E.L.Drake in 1859

The need of the petroleum and natural gases has increased exponentially until now and the continue request of energy led off the expansion on the mainland of new, and numerous, extraction sites.
New resources mining sites have been developed off-shore, by means of oil stations.
The process of petroleum and natural gasses is performed by means of steel pipelines. The resources are extracted from the sea floor and taken on the surface by means of risers, a very long steel pipeline which connects to the oil station tube system, that allows the processing and the transportation of the oil and gas on-shore.
The processing of the fossil resources represents a very aggressive environment for the material which are commonly adopted, especially at the first stages of the extraction, when the liquid oils still have a high content of sulphuric acid and hydrogen sulphide.

The steel has been upgraded in its alloys to withstand the increasing condition of corrosion, high temperature and structural loading which involve the extraction from wells.
Nonetheless, large maintenance programs and frequent substitution of the whole plants are necessary, even in the off-shore oil stations, where the procedures collide with the sea power.

Nowadays, one of the main research topics of this industry sector is to find a solution which can limit the maintenance costs of the plants.

Composite materials seem to be the right answer to this hard issue.
Composites, a compound made of a polymer resin matrix reinforced with high resistance fibre, have the benefit to be chemically resistant to acids and hydrogen, which instead are steel oxidant and embrittlement agents.
Furthermore, the composites have also a good structural resistance and its low specific weight shall represent an evolution with respect to steels in the pipeline for petroleum and natural gas processes, especially, offshore.

Finally, these properties shall allow a significant reduction of maintenance actions and shall increase the service lifetime over than 20 years, delaying the operation of complete substitution and with significant benefits in costs.

Figure B - Statoil's Oseberg offshore oil and gas field platform in the North sea

The objective of this work is to investigate the composite adoption as the new material for the pipelines production for the Oil & Gas industries. In particular, in those pipelines placed off-shore and on-shore where the crude oil is transported up to the processing sites, and so, upstream of the purification.

The investigation is made through the design of a pipeline system for natural gas processing, whose characteristics well simulate the operating condition, and so the requirements. The case of study places over the threshold of the current manufacturing experience in terms of pressure and diameter, representing a challenging design case for the pipe and even more for the pressure vessel.

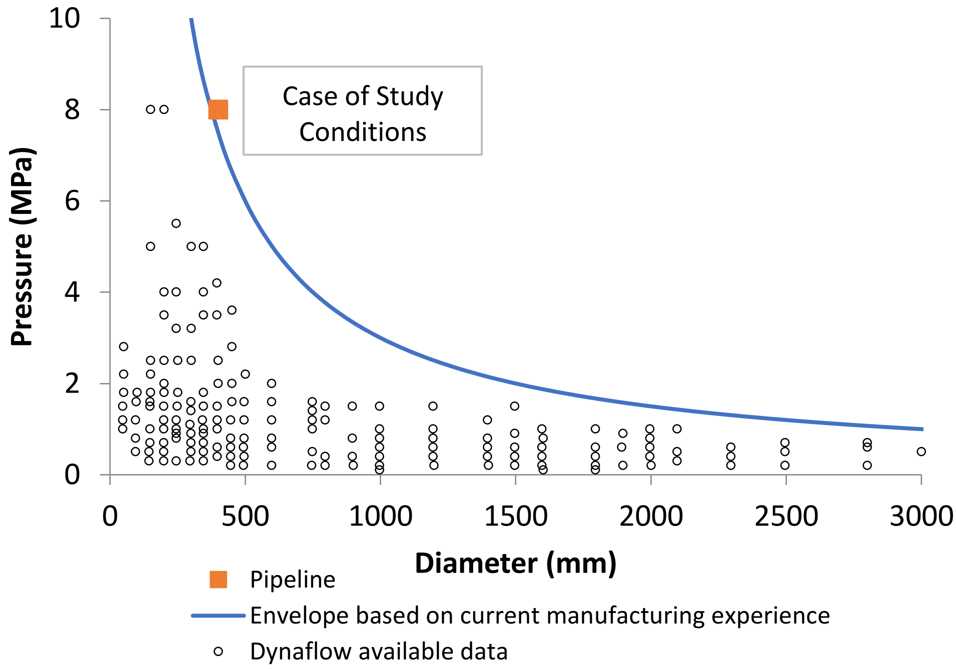


Figure C - Current manufacturing experience in pipeline systems[1]

[1] Curtesy of Dynaflow

Several regulatory authorities have developed international standards which cover the composite pipeline sector. Despite this, there is no a standard procedure for the design of pipeline and, furthermore, the most of standards just define some mandatory tests to be passed without providing a practical guideline for the design.
This thesis work proposes a method for the design of a plain pipeline in according with the qualification process concerning the ISO 14692, and develops computed tools which could be a valuable help to the designer.

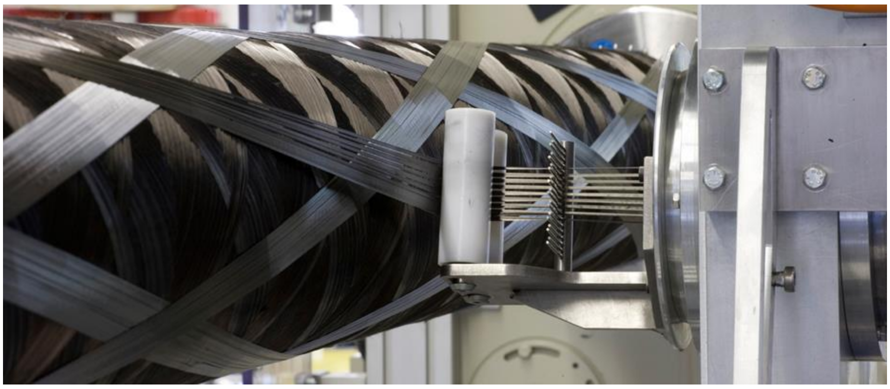
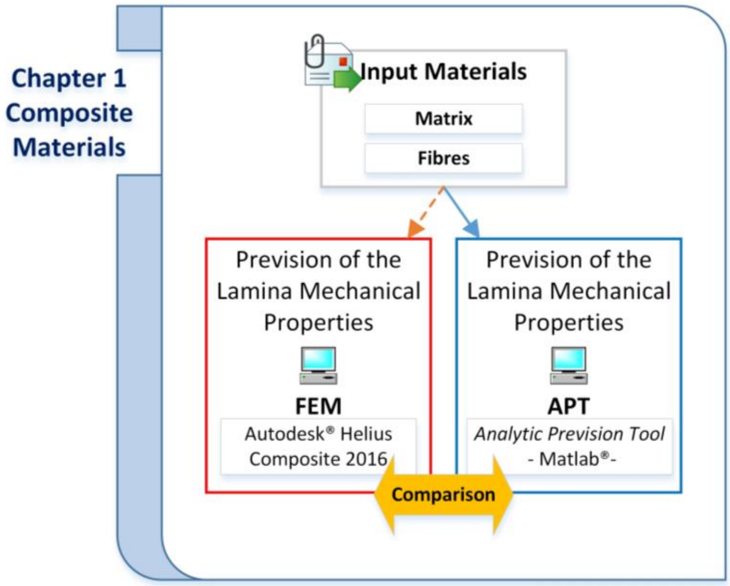


Figure D - Filament-winding of a composite plain pipe with different winding angles [35]

The **Chapter 1** concerns the composite material properties. They depend on the matrix polymer properties and on the reinforcing fibre characteristics. Several types of polymers and fibre exist, and the first step of the investigation is to identify the better components for the composites.
Among the many, the most performing materials concerning chemical, temperature, and structural resistance, result to be epoxy resins for the matrix and E-CR glass rovings for the fibres.

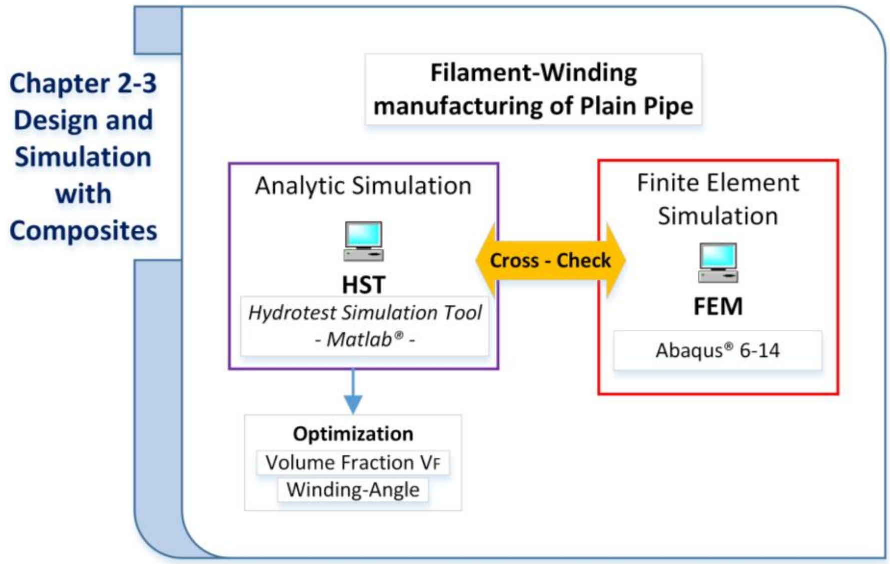


After defining the components, it is important to determine the properties of the composite as function of the properties and fractions of the components. Several models exist for the prevision of the lamina properties, mechanical and elastic.
So, the second step concerns the investigation of these models, as they are analytic or finite element based. The characteristics of the composite lamina, a single thin portion of the final composite, are the core of the design with composites, because these reassume the strengths and

the stress-strain relationships. The prevision of these properties provides the base for the design process regarding the composite in its final shape and structure.
The analytical models identified for the prevision of the lamina property have been automated in a Matlab® tool called APT, Analytic Prevision Tool.
The resulting properties, function of volume fraction, are compared to the ones obtained from the finite element approach based on Autodesk® Helius Composite 2016, aiming to identify where the two models match and differ.

The **Chapter 2** concerns the pipeline manufacturing and the analysis of the parameters involved in the production processes. The lead technology in pipe production for conduits and structural applications is the rotor-moulding, or filament winding process.
The process basically consists in the deposition of resin-impregnated fibres on the surface of a cylindrical rotating mandrel. The disposition is guided by a translating carriage, whose movement, together with the rotating speed of mandrel, defines the final pattern of the fibre.
Because of the mechanical behaviour of composite varies based on the pattern of the deposed fibre, the whole theoretical process and equations which describe the elastic behaviour of the final composite are taken into account and implemented in a script.
Furthermore, the failure criteria for composites are investigated in order to provide a design tool for the failure assessment of the pipeline, which represents the topic of **Chapter 3**.

The whole information obtained is processed, automated, and conveyed into a Matlab® R2015b script which simulates, starting from the case of study request, the hydrostatic loading of the plain pipe. The Hydrostatic Simulation Tool, HST, links to the APT, retrieves the lamina properties, and performs the simulation of the hydrostatic conditions applied to the composite plain pipe.
The main output of the hydrostatic simulation is the minimum reinforced pipe wall thickness necessary to withstand the inner pressure, as design requirement.

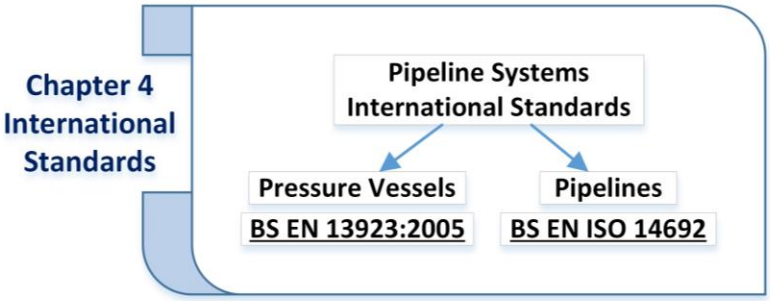


This simulator is cross-checked with a finite element model developed with Abaqus® 6-14.
At present, there are no experimental tests to validate the HST, so the only way to control the analytical simulation is by means of an independent numerical simulation.

By means of the HST, moreover, it is possible a wide investigation of the relationships between the manufacturing parameters such as the winding-angle and the volume fraction, and the wall thickness, with the aim to optimize the performance of the composite.

Afterward this deep discussion concerning the materials and the structural design with composites of a plain pipe, is important to consider the (mandatory) international regulations which govern the manufacture, purchase, installation, use, and safety of the pipeline system for the oil and gas industries.

The investigation proceeds in the **Chapter 4** with the study of the standard concerning the composite pipeline system, i.e. the pipes and the pressure vessel, in order to identify the most suitable standard for the qualification of the pipeline system.

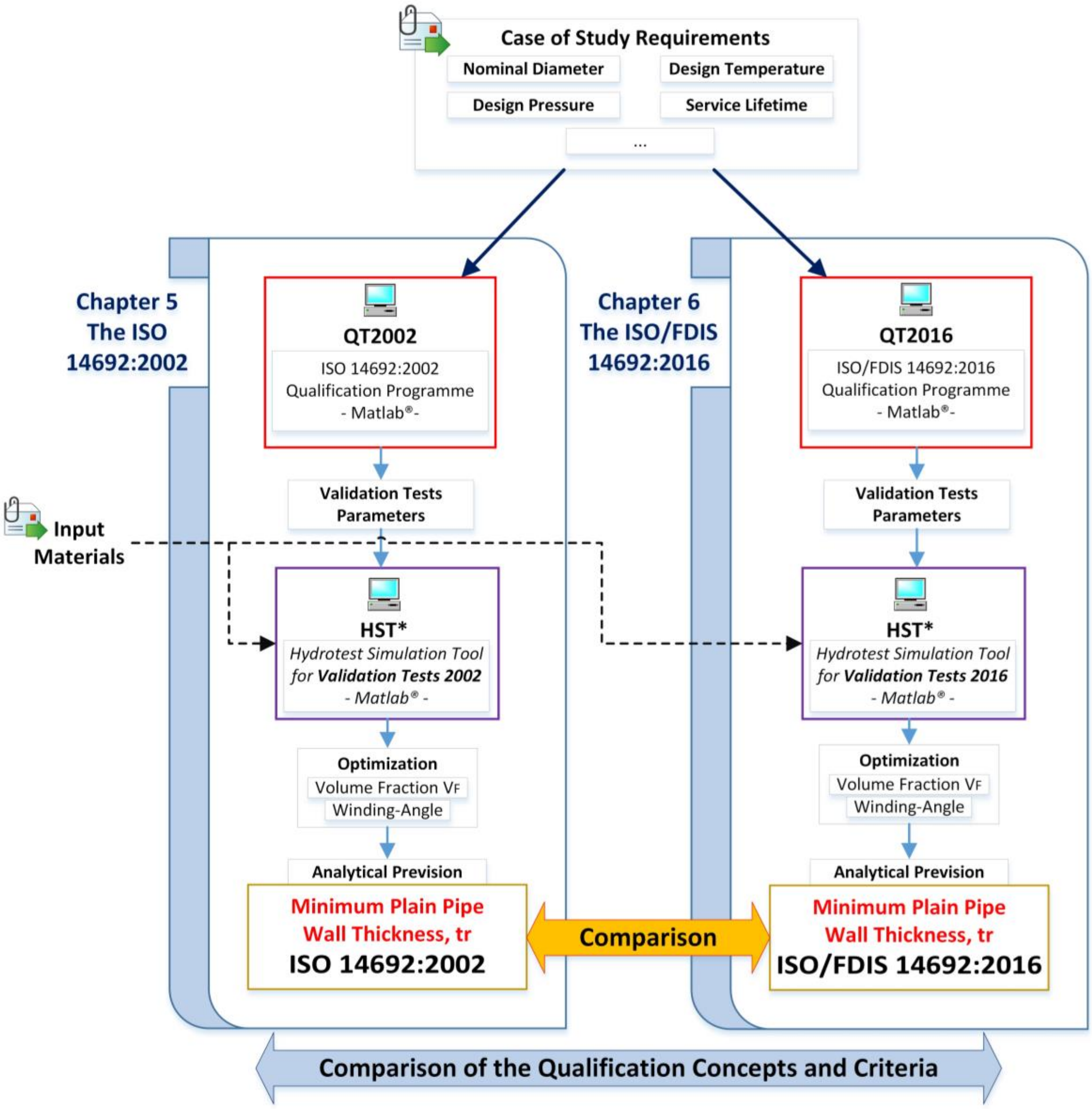


After a huge research, it has been chosen the British Standard BSI EN 13923:2005 - "Filament-wound FRP pressure vessels – Materials, design, manufacturing and testing" for the pressure vessel qualification; and the British Standard BS EN ISO 14692:2002 – "Petroleum and natural gas industries - Glass-reinforced plastics (GRP) piping" for the pipeline.
The characteristics of the case of study well match with the target of application of these standards.

The **Chapter 5** of this work proceeds with the analysis of the qualification programme of the BS EN ISO 14692:2002 concerning the pipelines.
The qualification programme concerning the regulation of all the components of a pipeline, such the plain pipe, reducers, tee connections, flanges and joints is fully analysed.
The steps of the programme are identified and a review of the standard, concerning the main, structural, qualification is proposed.
Based on the qualification programme to satisfy and on the validation tests to withstand, the design path in accordance to the qualification process is defined.
This design procedure is reassumed into developed flowcharts, provided into appendix, and describes the right process to follow for the determination of the pipe reinforced wall thickness, t_r, in accordance with the BS EN ISO 14692:2002.
The design process concerning the factors, coefficients, and parameters calculation is automatized by means of the Qualification Tool, QT2002, based on Matlab®.

The design procedure for the definition of the plain pipe wall thickness is fully simulated by a combined use of QT2002, HST and APT which allow the simulation of the validation tests and declare the minimum wall pipe thickness for the case of study.
Because the BS EN ISO 14692:2002 standard is the current legislation, this study gives some important information to the designer, which, by means of the developed tool, is able to give an

engineering estimation of all the design process variables concerning the case of study, but even concerning the general response of a plain pipe subjected to inner pressure with respect to the manufacture, design and qualification parameters.



From another point of view, it is known that the current standard is under revision and that publication of the 2nd edition of the BS EN ISO 14692:2017 is scheduled by August 2017.

For this reason, it was decided to analyse, in **Chapter 6**, the 2nd edition of the standard in its Final Draft version.

The BS EN ISO/FDIS 14692:2016 is the preliminary version of the standard, not yet published, approved by the international committee ISO TC 67/SC 6.

As in the case of the 1st version, the whole qualification procedure concerning the pipeline elements is analysed. The validation tests, which constraint the design process of the plain pipe, are identified and examined.

The design procedure is therefore reassumed into flowcharts, provided into appendix, and the calculation of factors, coefficients, and parameters, in particular regarding the validation tests, are

automated inside the QT2016[2], the Qualification Tool concerning the 2nd edition of the ISO standard.
After that, the simulation of the design process concerning the plain pipe of the case of study is performed. The validation tests, 3 in this case, are simulated by means of the combination of the QT2016, APT and HST, specifically modified.
The output of this process is the plain pipe reinforced wall thickness value, and, more generally, its dependences with respect to the design, manufacture, and standard parameters.

Basing on these last and the previous corresponding outputs concerning the 1st edition of the standard, the **Chapter 7** conclusive discussion gives an overview concerning all the factors impacting the design of a composite pipeline:

- Matrix and fibre properties
- Filament-winding parameters - volume fraction and winding angle
- The design according to ISO 14692:2002
- The design according to ISO/FDIS 14692:2016

Finally, a critical comparison between the two standard versions is presented, concerning the concepts, the design changes and, last but not least, the value of the wall thicknesses evaluated following both the qualification process.

The overall structure of the thesis work is shown in Figure F which follows.

[2] As in the case of the QT2002, even the QT2016 is Matlab® developed

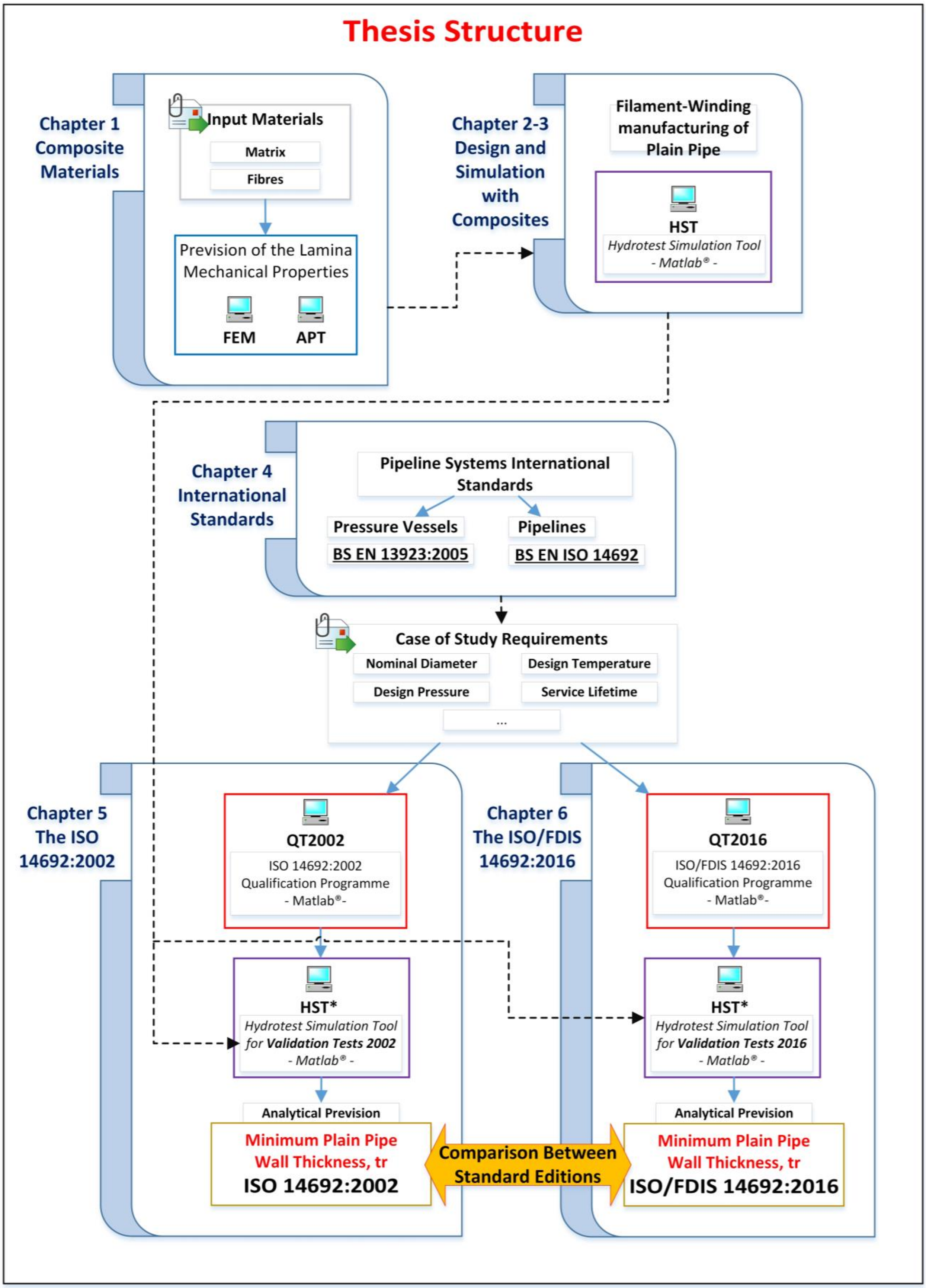


Figure E - Structure of thesis work

1. Composite Materials

This paragraph describes the characteristics of the composite materials: the fibre and matrix basic component types, and the available methods for the prediction of the lamina characteristics.
The analytical models, based on the literature, for the prevision of the lamina properties are widely described and discussed.
These analytical models are then reassumed, and the calculations automated, into the **Analytical Prevision Tool, APT.** This is a Matlab® developed script which allow an easy and fast tool to investigate the trends of the lamina properties with the variation of the volume fraction.
Furthermore, the prevision of the lamina properties starting from the matrix and the fibre is performed by mean of Autodesk® Helius Composite 2016: a finite element based software for composite design which includes a tool, FEM based, for the prevision of the lamina properties.
The two models are then compared: since the prevision of the mechanical and the elastic properties in composites is very complex, the objective is to highlight when and how much the two models, the analytical and the FEM based, are similar or differ.
The APT developed in this paragraph and the FEM prevision tool for the lamina properties are adopted as input for the HST[3], QT2002[4] and QT2016; Matlab® developed tools described in the next paragraphs.

1. Composites, Materials, and Applications.

Composites are materials constituted by two or more components with sufficient difference in mechanical behaviours. [1] [3]

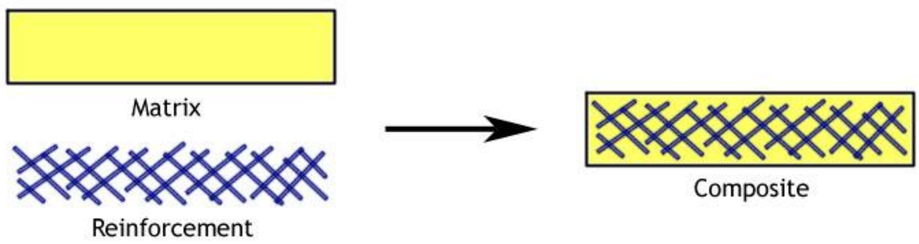


Figure 1 - Basic composite structure

Common polymer-based composite materials include at least two parts, the reinforcing fibres, and the resin. The continuous phase is called matrix and gives cohesion to the composite.
The filler is distributed through the matrix as particles, long-fibre or fabrics acting as a reinforcement.

The new material, physically made by the combination of the matrix and the reinforcement fibre in a defined volume fraction "V_f," has structural properties not which differ from each single component.

[3] Hydrostatic Simulation Tool
[4] Qualification Tool

Thus, composites are being increasingly developed for a multitude of tasks and are designed to replace materials, such as metals and their alloys, to offer low weight, stiffness & strength, low coefficient of thermal expansion, fatigue resistance and resistance to corrosion.

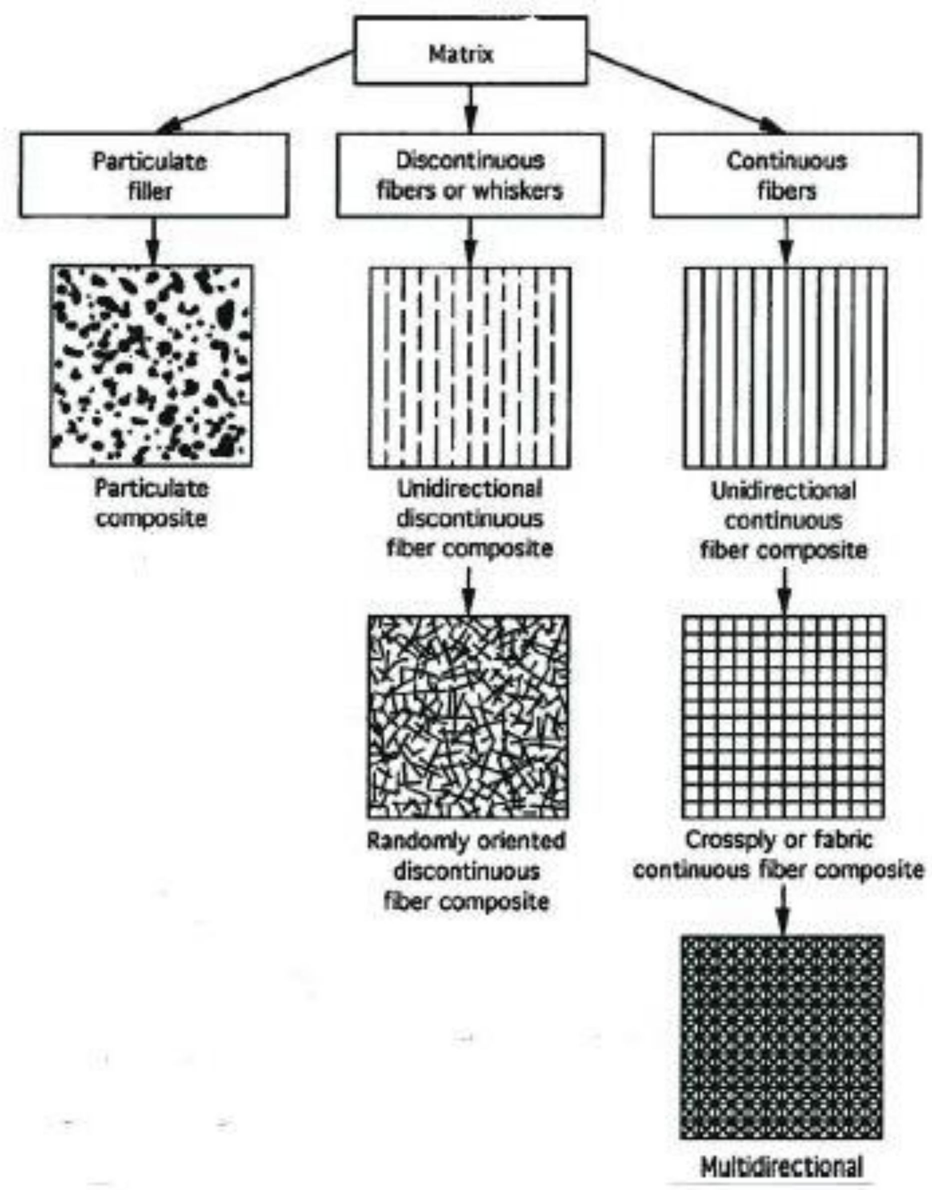


Figure 2 - Different typologies of composites [11]

Actual applications include aviation and space industries, where the high mechanical strengths, reached with a low weight, increase aircraft and helicopter payloads and flight time. [5]
Tail, wings, seals and other mechanical components adopt composites as primary material. For instance, Boing 787 Dreamliner makes a greater use of composites up to 50% of total material weight. [6]

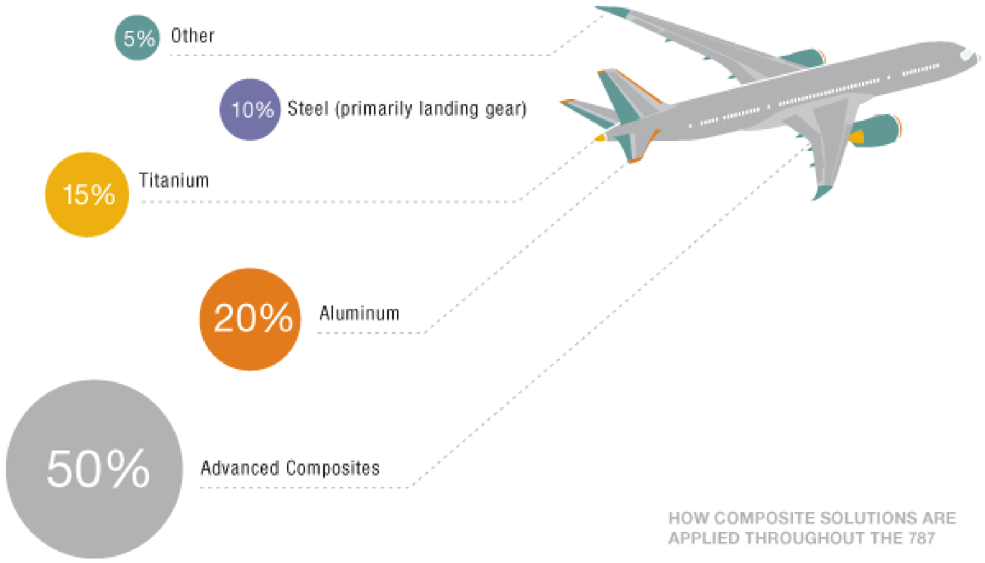


Figure 3 - The use of composite in Boing 787 [6]

Since 60', Nasa has widely studied applications of Composite Overwrapped Pressure Vessels (COPVs) which are currently adopted to contain high-pressure fluids in propulsion, science experiments and life support applications with significant weight advantage over all metal vessels. [4]

Figure 4 - Example of composite overwrapped pressure vessels [4]

Finally, in the Oil & Gas industries, the use of composite pipes and vessels allows an important reduction in maintenance, thanks to the higher resistance to corrosion compared to metal alloys.
The actual mild steels adopted in piping suffer to corrosion and, so, are designed oversize.
Replacement of overall piping system occurs every few years with high costs related with installation operation which often happen off-shore.

Figure 5 - Piping composite installation - curtesy of no-fiber glass system

Composite materials such as glass fibre reinforced composites (GFRP) can well resist to acid corrosion of contained fluid, reaching 25 years of life operation with a very low maintenance.
With this aim, the high potentials of these materials are being fully investigated nowadays.

For the purposes of this project, the most important features of the composite to select is high resistance to corrosion, combined with high mechanical strength.

2. Composite Materials

A brief description of main types of matrix and fibres is reported.

2.1. Matrix

The most common continuous phase used are polymers, especially adopted for fibre reinforced plastics (FRP), such as fiberglass reinforced (GFRP), carbon reinforced (CFRP) and aramid composite material (AFRP).
The final features of the composite depend mainly on the choice of the resin concerning the ductile behaviour, resistance to corrosion and fire-UV resistance properties.
The polymers can be Thermosets or Thermoplastics.

2.1.1. Thermoplastic

Thermoplastic resins for composites have been developed subsequently to the thermoset ones.
The only 10% of total long fibre reinforced composites adopt thermoplastic as matrix resin.
The main reason of this choice lays in the substantial variation of the overall fabrication cycle and machinery compared to thermoset composites.
Indeed, thermoplastics offer high toughness, high temperature resistance, recyclability in addition to the possibility of an easy repair but at very high money costs.
The costs related to the raw material and production make this technology competitive only in aviation and space industry, i.e. small-scale production sectors, where the necessities are high reliability and performances. [1]

Thermoplastics composites are not being considered further within this project.
Thus, composite is going to be intended only with thermoset matrix.

2.1.2. Thermoset

Thermoset polymer resins are the most used into composite filled with continuous reinforcing fibre (long fibre composites).
These polymers are all characterized by low coefficient of viscosity at ambient temperature allowing a good impregnation of fibre during fabrication processes.
Furthermore, the thermoset-based composites offer also a good resistance to chemical degradation after the polymerization (the process by means resin hardening occurs).
This is a chemical process and consists in an increase of the temperature, which is not an easy parameter to control uniformly in every part of component.

The not perfectly homogenous temperature, especially where the geometry has huge variations in thickness, leads to a wide variation in hardness[5], undermining the reliability of the component and the reproducibility of overall fabrication process.
Other general drawbacks are the relative low operating temperature allowed (but strictly depending on the type of used thermoset), sensibility to humidity, difficulties in the repair processes and impossibility to recycle the material after use.

2.1.2.1. Phenolic Resins

These have been the first resins used in aeronautic.
Phenolic resins have a good temperature resistance and can operate up to 200°C with a low toxic smog emission. The chemical resistance to solvents and ambient humidity are good, but resistance to oxidation is relatively low compared to other thermosets.
Phenolic resins used in composite materials are often based upon substances obtained by chemical reaction with formaldehyde in basic ambient called “Resols”[6].
The curing reaction of these “single-stage resins” can occur by a simple variation of PH and yields water as secondary product which must be isolated before the complete hardening.
The fracture behaviour is mostly brittle because of high density.

2.1.2.2. Epoxy Resins

Epoxies are high performance resins and have a higher cost compared to phenolic and polyester which reach 2 - 5 [Euro/kg]. [1]
The adhesive properties are good and allow perfect bonding with fibre.
The resistance to chemical corrosion is good as well and humidity absorption is very low.
These characteristics lead to a wide range of applications, especially where both mechanical and chemical performances requirements are high.
The maximum operative temperature reaches 180°C for some formulations.

The principal reagent consists of organic fluid with low molecular weight filled by epoxy groups.
The organic substance has a high viscosity, depending on polymerization grade.
Then, the activation reagent added to the mixture, which usually consists of amine, triggers the curing reaction.
The occurring polymerization does not have any secondary products and it is and exothermic reaction which can be lead even at ambient temperature depending on the desired final properties and on the technological necessities.

The chemical structure of the resin can slightly vary by changing starting epoxy groups in type and percentage. It influences reticulation density and so the mechanical properties which can be well fitted with the purpose of the composite.

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[5] Hardness inhomogeneities occur due to different curing temperature reached.
[6] Resoli [1].

2.1.2.3. Vinyl-Ester (Polyester) Resins

Polyester resins are characterized by low cost (about 1,5 – 3 Euro/kg), high reactiveness and wide versatility depending on chemical structure variations.

The mixture is based upon a polyunsaturated fatty acid solved into a monomer solution.
The family of polyunsaturated resins is composed by high density linear polymers and are produced by polycondensation: the elimination of water molecules between a glycol (ethylene, propylene, or diethylene) and an acid.
Finally, the monomer solution bonds with polymer produced by polycondensation, creating a resin with low viscosity which eases the impregnation process of the fibres during the fabrication of the composite.

The use of these resins presents some problems concerning their high thermal expansion coefficient which causes high residual stresses. In addition, the considerable water absorption capacity from ambient humidity leads to adhesion failure and to remarkable internal stresses due to swelling. Therefore, the overall mechanical resistance and adhesion with fibre result mediocre.
The maximum operation temperature does not exceed 130°C.

Despite all these problems, the chemical structure of polyester resins can be modified by substituting acid and glycol used in production of the polymer, changing moderately the mechanical and chemical properties.

Vinyl-ester resins have been developed for applications in high chemical aggressive environments at high temperatures. These resins represent a compromise between common polyester and high-performance epoxy ones at a relatively low cost.
Polymerization happens in presence of styrene and low quantities of peroxides similarly for common polyester resin. Anyway, the slight differences in terminal bonding groups cause an attenuation of the hydrophilic properties of vinyl-ester resins and lead to a less humidity ambient absorption.
Even the curing density results reduced. Thus, the mechanical and facture behaviours of materials are tougher compared with the common polyester or phenolic resins.

A brief comparison between thermoset resins above described is now presented.

Both Young’s modulus and yield strength may vary widely depending on the chemical composition of the resin. As previously discussed, vinyl-ester resins appear extremely different with respect to polyesters from which derive.

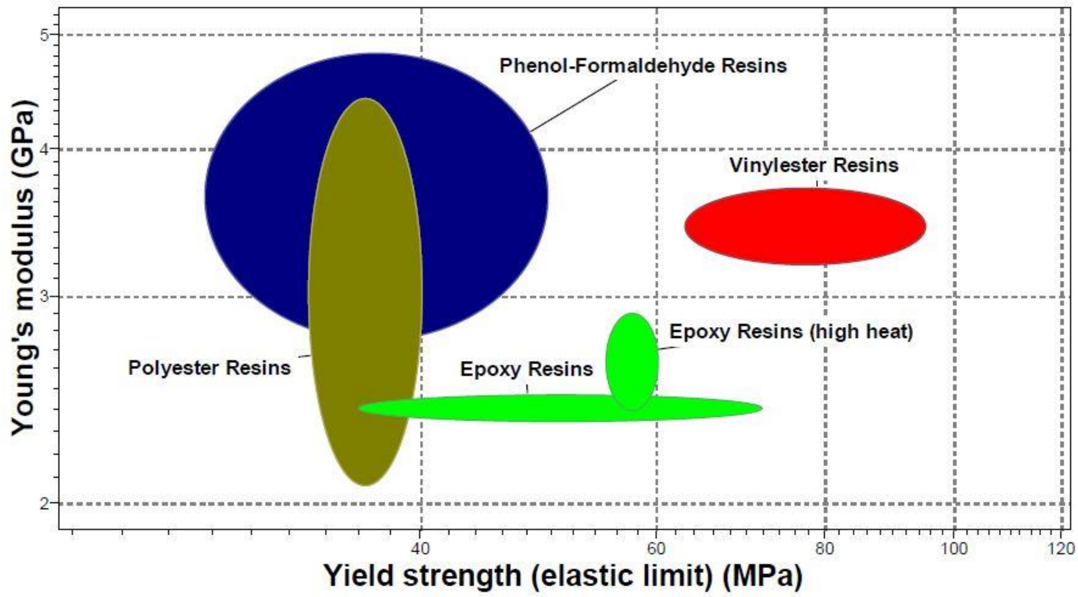

Figure 6 - Resin characteristics [7]

Medium market prices show how epoxy resins can be more affordable respect to the vinyl-ester, especially for large scale projects, by offering high performances at 1/3 of the raw material cost.

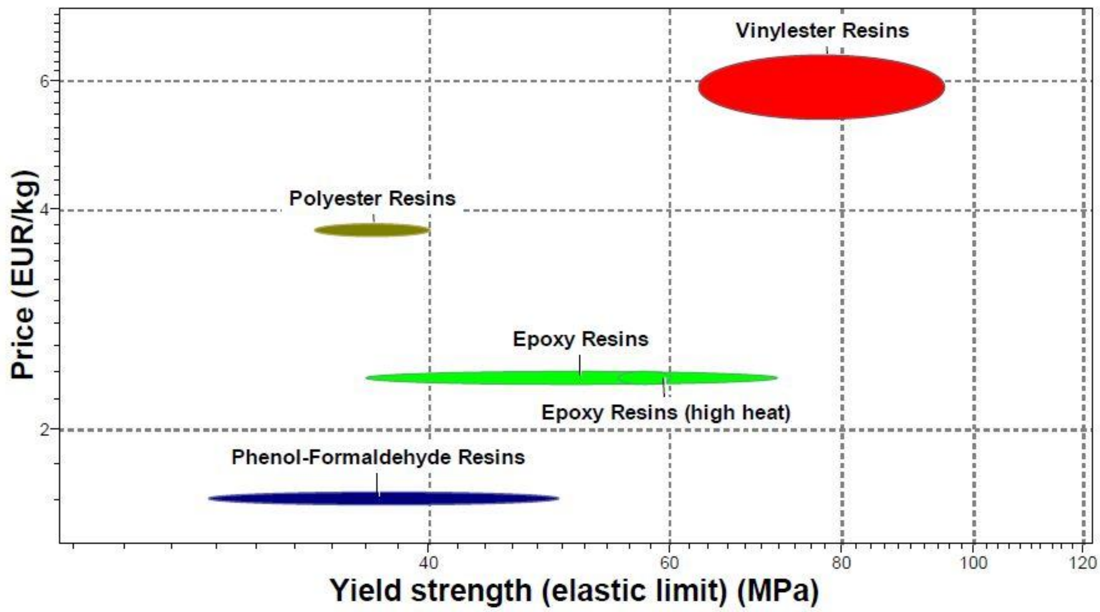

Figure 7 - Resin characteristics [7]

2.2. Reinforcing Fibres

Reinforcing components of composites are fibres which can be long or short (continuous or discontinuous).
The main aim of fibres is to increase the mechanical properties of composite. Concerning the unidirectional long fibre reinforced composites, the mechanical behaviour of these materials becomes anisotropic because of the oriented disposition of fibres.
The most used fibres are Glass Fibre (GFRP), Carbon Fibre (CFRP) and Aramid Fibre (AFRP).

All the continuous fibres are traded as yarns (single wire) or rovings (multiple wires between 20 – 200) and are used in filament-winding processes.
As well as in the form of yarns or rovings, reinforcing fibres are used even in fabric forms.
Handmade composites often adopt fabrics, which give almost isotropic in plane mechanical properties. For instance, $[0/90/+45/-45]_n$ are widely used.

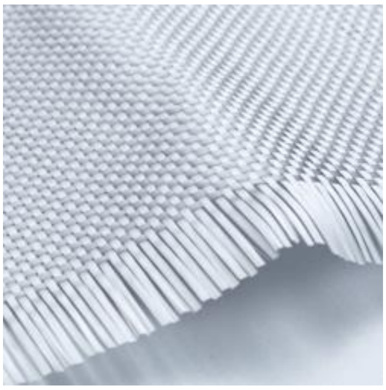

Figure 8 - Fabrics of glass fibres [32]

Figure 9 - Yarn of glass fibres [33]

2.2.1. Glass Fibre

Glass fibres are commonly used for composite both as long or short.
These fibres are characterized and widely used by the low cost in addition to a high tensile stress and by a generally good chemical resistance.
The principal disadvantages are related to the low Young's modulus ($E_{glass} \approx 70\ [GPa]$) and to the low abrasion resistance during manipulation. Moreover, glass fibres suffer from humidity absorption. This goes to undermine the adhesion between matrix and fibres and can also induce matrix failure in mechanical stressed composites.

The filaments which make up the fibres are characterized by their chemical composition and weight per length.
The glass is composed mainly by silica (SiO_2) in a tetrahedral arrangement.
The addiction of aluminium oxides and other metal oxides modifies the mechanical and chemical properties as shown below.

Component		**Mass Fraction %**		
		GLASS - C	**GLASS - E**	**GLASS - S, R**
		High Chemical Resistance	**General purposes**	**High Mechanical Properties**
Silicon oxide	SiO_2	65	54.3	64.2
Aluminium oxide	Al_2O_3	4	15.2	24.8
Iron oxide	FeO	-	-	0.21
Calcium oxide	CaO	14	17.2	0.01
Magnesium oxide	MgO	5	4.7	10.27
Sodium oxide	NaO	-	0.6	0.27
Boron oxide	B_2O_3	6	8	0.01
Varies		6	-	0.23
Total		100	100	100

Table 1 - Types of glass fibres [1] [8]

Other types of glass fibres include Type D for electric insulation, Type A for thermal insulation and Type E-CR for use in acid environments.

The international standard ISO 2974 designates the [TEX] as the weight per length unit for all fibre for composite purposes. It corresponds to 1 g per km (10^{-6} [kg/m]).

International Standards ISO 1139 and ISO 2078 define technical designation of the glass fibres. The provided information includes:

1) A letter that identify the type of glass used (C, E, E-CR…)
2) A letter that indicate Type of fibre: C if continuous, D if discontinuous
3) A number which define nominal diameter of single filament or fibre expressed in [μm]
4) A number which defines [TEX] of filament or fibre.

and optionally:

5) The direction and value of torsion of the fibres
6) A number which indicates the number of filaments per fibre
7) The manufacturer code

For example: E-CR9 34 Z 40: continuous filament in glass type E-CR with 9 [μm] diameter of fibres and 34 [TEX]. Z indicates positive torsion with 40 rounds per metre.

Below, the mechanical properties of standard E-CR grade glass fibres.

E_f	G_f	ν_f	S_f	S_f^c
80-81 [GPa]	35 [GPa]	0.20	3100-3800 [MPa]	3100-3800 [MPa]

Table 2 - EC-R glass fibre properties

The cost of the Glass fibre may vary between 7 to 10 [Euro/kg]. [1]

2.2.2. Carbon Fibre

Carbon fibres are used in fabrication of high performance composites. Carbons are characterized by high Young's modulus and high resistance.
Principal disadvantages in the use of these fibres are the elevated cost and the brittle fracture behaviour. Even though the tensile strength values result very high, the subsidence is brittle with a very low energy absorption.
Graphite has hexagonal lattice structure with carbon atoms organized essentially in planes, bonded each other by mean of Van der Waals interactions. Therefore, the mechanical behaviour of fibre is essentially anisotropic, with the transversal modulus and the resistance very lower than the in-plane ones.

Carbon fibres are expensive and may cost 180-250 [Euro/kg]. [1]

2.2.3. Aramid Fibre (Kevlar®)

Aramid fibres are characterized by the high toughness and the high resistance to manipulation.
The elastic modulus, the resistance and costs place essentially between carbon fibre and glass fibre values.
Aramid fibres were introduced by DuPont in 1971 under the patent name Kevlar®.
Aramids suffer from low compression resistance and from the high resistance reduction due to exposition to UV light. Radiations induce a reduction from 20% to 50% of mechanical properties, while the colour of fibres goes from yellow to brown.
The use of these fibres is not diffused as glass and carbon.
The cost of aramid fibre is considerably high with respect to glass fibre, but less than carbon one and places around 110 [euro/kg]
The comparative table below shows typical properties of fibres:

Property	Unit	Carbon	Glass	Aramid
Axial modulus	GPa	230	85	124
Transverse modulus	GPa	22	85	8
Axial Poisson's ratio	-	0.30	0.20	0.36
Transverse Poisson's ratio	-	0.35	0.20	0.37
Axial shear modulus	GPa	22	35.42	3
Axial coefficient of thermal expansion	µm/m/C°	-1.3	5	-5.0
Transverse coefficient of thermal expansion	µm/m/C°	7.0	5	4.1
Axial tensile strength	MPa	2067	1550	1379
Axial compressive strength	MPa	1999	1550	276
Transverse tensile strength	MPa	77	1550	7
Transverse compressive strength	MPa	42	1550	7
Shear strength	MPa	36	35	21

Table 3 - Comparative reinforcing fibre properties table [1]

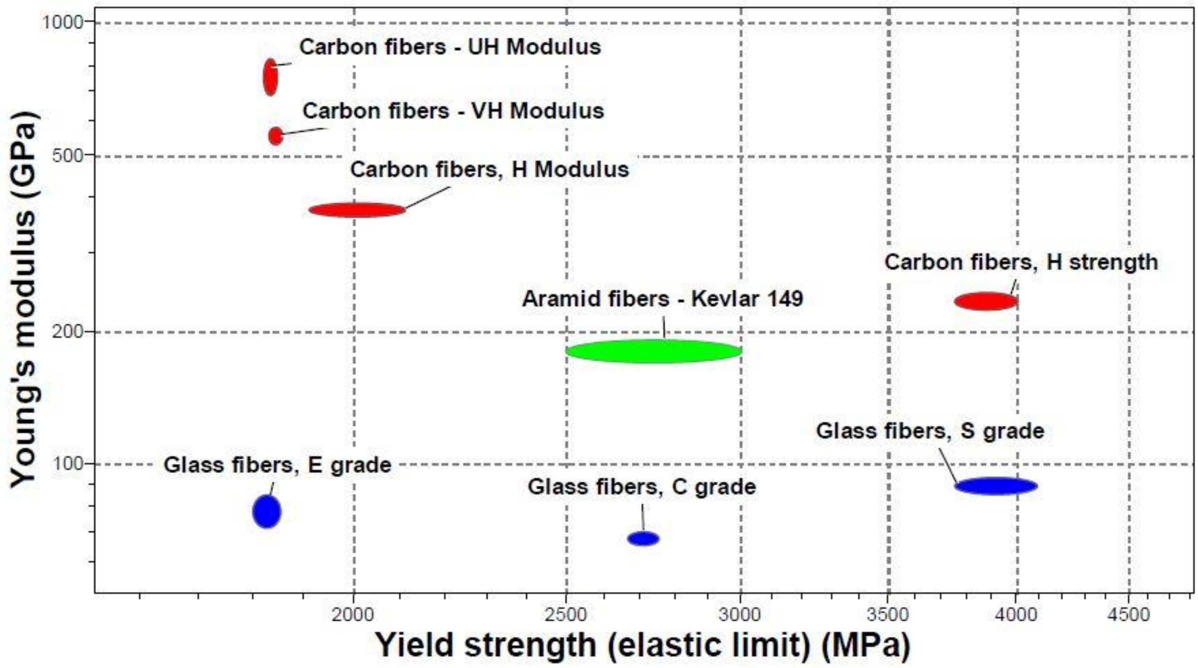

Figure 10 - Reinforcing fibre characteristics

2.3. Mechanical Modelling of Composites

Composite artefacts are composed by a multitude of individual plies (laminas) which are oriented in different directions depending on required characteristics of the final structure.
Even if the mechanical behaviour of the matrix is isotropic, the presence of oriented fibres makes the composite properties anisotropic. Unidirectional long-fibre reinforced laminas have high resistance strength value along fibre direction while this value drops dramatically along other directions.
Therefore, to avoid this drawback, composites are built by overlying more laminas in different fibre directions, giving rise to a new material characterized by an almost isotropic behaviour.

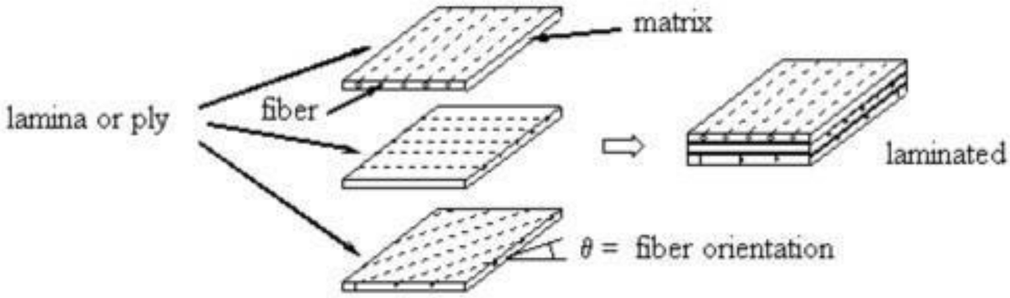

Figure 11 - Structure of composite materials [10]

The laminate is the overlay of laminas which are bonded together to form a unique cohesive material.

The lamina, constituted by matrix and a unidirectional long-fibre reinforcement, is considered as the base element of composite materials.
Generally, the matrix is well approximated as a homogenous and isotropic material.
Likewise assumes that the lamina is homogenous[7], even if the local deformations and stress varies between matrix and fibre section as reported in figure (12).
Consequently, this assumption considers the average stresses through the thickness and the unit volume deformation of ply instead of space-dependant ones.

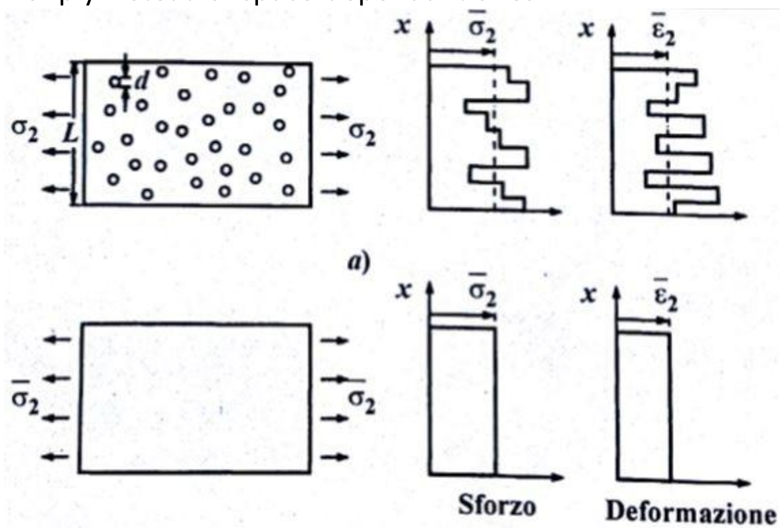

Figure 12 – Average and point to point tresses and deformations d=discontinuity dimension, L=characteristic dimension of lamina [9]

[7] The lamina is treated as a homogeneous material with isotropic behaviour.

Plotting the stress-strain curves of matrix and reinforcement, the curve of lamina will lay intermediate in respect to the curves of matrix and fibre, depending on volume fraction.

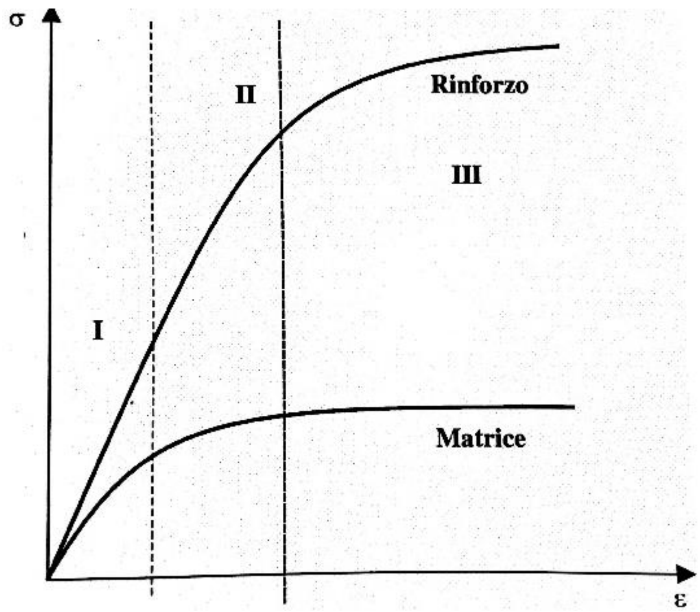

Figure 13 - Stress trends of matrix and reinforcement fibre [9]

Furthermore, the graph can be divided in three zones:
I: matrix and fibre have linear elastic behaviour
II: matrix has non-linear behaviour while fibre is still linear
III: both matrix and fibre have non-linear behaviour

The long-term design with composites considers the mechanical behaviour of zone I, so with the ply homogeneous, anisotropic, and with linear elastic mechanical behaviour.

2.4. Elastic Properties of Anisotropic Materials

The mechanical behaviour of a perfect elastic material is defined by its stiffness matrix [S]. [9]
Stiffness matrix derives from Hooke's law which links stresses to strains through the elastic constant E (Young's modulus).
Regarding isotropic full-elastic materials, Hooke's law is: $\varepsilon = \sigma/E$
And its matrix representation is: $\varepsilon = [C_{ij}]\,\sigma$

$$\begin{vmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{vmatrix} = \begin{bmatrix} 1/E & -\nu/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & 1/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & -\nu/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{vmatrix}$$

where the shear modulus G is: $G = \frac{E}{2(1+\nu)}$

As already said, composites are anisotropic materials due to the presence of oriented fibres.
For the lamina, the Hooke's law coefficient modifies in a general complete symmetric compliance matrix [C_{ij}], where Young's, shear and Poisson's moduli are directions-dependant.

$$[C_{ij}] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix}$$

So, complete anisotropic materials have 21 independent constants, that decrease to 9 if the material has symmetric properties on 3 orthogonal planes.

This is the case of the orthotropic material:

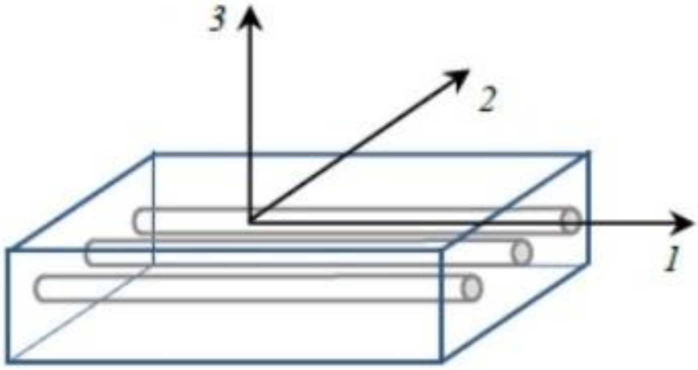

Figure 14 - Reference system of unidirectional lamina of composite

$$\begin{vmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{vmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & -\nu_{31}/E_3 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{32}/E_3 & 0 & 0 & 0 \\ -\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{23} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{31} \end{bmatrix} \begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{vmatrix}$$

where

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2};\ \frac{\nu_{31}}{E_3} = \frac{\nu_{13}}{E_1};\ \frac{\nu_{23}}{E_2} = \frac{\nu_{32}}{E_3}$$

Each single ply of a composite, filled by unidirectional long fibres, can be treated as orthotropic. Furthermore, by considering negligible the stress along direction 3, i.e. σ_3, and ε_3 as uninteresting, the Hooke's law can be more simplified:

$$\begin{vmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{vmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & 0 \\ 0 & 0 & 1/G_{12} \end{bmatrix} \begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{vmatrix}$$

And for symmetry:

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}$$

By inverting the compliance matrix, one can get stress as a function of strain along the principal material direction. This turns out to be:

$$\begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{vmatrix} = \begin{bmatrix} \frac{E_1}{(1-\nu_{12}\nu_{21})} & \frac{\nu_{21}E_2}{(1-\nu_{12}\nu_{21})} & 0 \\ \frac{\nu_{12}E_1}{(1-\nu_{12}\nu_{21})} & \frac{E_2}{(1-\nu_{12}\nu_{21})} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{vmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{vmatrix}$$

$$[Q] = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} = \begin{bmatrix} \frac{E_1}{(1-\nu_{12}\nu_{21})} & \frac{\nu_{21}E_2}{(1-\nu_{12}\nu_{21})} & 0 \\ \frac{\nu_{12}E_1}{(1-\nu_{12}\nu_{21})} & \frac{E_2}{(1-\nu_{12}\nu_{21})} & 0 \\ 0 & 0 & G_{12} \end{bmatrix}$$

where the [Q] is referred to as the reduced stiffness matrix.

Finally, the independent elastic constants result to be four: E_1 E_2 G_{12} ν_{12}

The elastic constant of the lamina can be evaluated through laboratory tests or pre-evaluated by knowing the characteristics of matrix and fibre mixture in addition to the volume fraction content of fibre, V_f, by mean of micromechanics and semi-empirical theories. [9]

2.4.1. Volume Fraction V_f

All the theoretical calculations for the prediction of the mechanical properties of the lamina are based on the fibre volume fraction.
Experimentally, it is easy to determine the fibre weight fraction W_f, from which the fibre volume fraction V_f and the matrix volume fraction V_m can be calculated:

$$V_f = \frac{W_f/\rho_f}{\left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_m}{\rho_m}\right)}$$

where:
$V_m = 1 - V_f$
W_f is the fibre weight fraction
W_m is the matrix weight fraction
ρ_f is the fibre density
ρ_m is the matrix density

In terms of volume fractions, the lamina density ρ_l can be written following the rule of mixture, and so:

$$\rho_l = \rho_f V_f + \rho_m V_m$$

2.4.2. Mass Fraction W_f

In terms of individual constituent, is possible to convert the volume fraction V_f into the mass fraction W_f and vice versa. The mass fraction is a more suitable parameter to use in the fabrication process because it can be determined knowing the weights of matrix and fibre consumed moment by moment, during the filament-winding. The evaluation follows the equations below:

$$W_f = \frac{weight_{fibre}}{weight_{fibre} + weight_{matrix}}$$

Mass fraction can be also evaluated starting from the Volume Fraction using the following equation:

$$W_f = \frac{\rho_f / \rho_m}{\rho_f / \rho_m \cdot V_f + (1 - V_f)} V_f$$

2.5. Analytical Prevision of Lamina Properties

Several analytical and semi-empirical models exist for the prevision of the both elastic and mechanical properties which characterise a composite lamina.
Tables 4-5-6 show the nomenclature of needed properties for the design of a composite artefact.

Elastic Lamina Properties	Symbol	Unit
Longitudinal elastic modulus	E_1	[MPa]
Transverse elastic modulus	E_2	[MPa]
Shear modulus	G_{12}	[MPa]
Major Poisson's ratio	ν_{12}	-
Density	ρ_l	[kg/m^3]

Table 4 - Lamina elastic properties nomenclature

Mechanical Lamina Properties	Symbol	Unit
Ultimate longitudinal tensile strength	S_1	[MPa]
Ultimate transverse tensile strength	S_2	[MPa]
Ultimate longitudinal compressive strength	S_1^c	[MPa]
Ultimate transverse compressive strength	S_2^c	[MPa]
Ultimate in-plane shear strength	S_{12}	[MPa]

Table 5 - Lamina mechanical properties

Strain Lamina Properties	Symbol	Unit
Longitudinal strain to tensile failure	$(\varepsilon_1)_{ult}$	[με]
Transverse strain to tensile failure	$(\varepsilon_2)_{ult}$	[με]
Longitudinal strain to compression failure	$(\varepsilon_1)_{ult}^c$	[με]
Transverse strain to compression failure	$(\varepsilon_2)_{ult}^c$	[με]
In-plane Shear Strain to failure	$(\gamma_{12})_{ult}$	[με]

Table 6 - Lamina strain properties

Strain to failure parameters are evaluated starting from the elastic and strength parameters by mean of the simplified Hooke's law already treated and related to orthotropic materials.

The prediction theories are based on the characteristics of the matrix and the fibre in addition to the volume of fibre V_f.
The nomenclatures of such input properties are shown in Table 7-8.

Elastic Properties	Matrix	Fibre	Unit
Elastic modulus	E_m	E_f	[MPa]
Shear modulus	G_m	G_f	[MPa]
Poisson's ratio	ν_m	ν_f	-
Density	ρ_m	ρ_f	[Kg/m^3]

Table 7 - Elastic properties of matrix and fibre

Mechanic Properties	Matrix	Fibre	Unit
Tensile strength	S_m	S_f	[MPa]
Compressive strength	S_m^c	S_f^c	[MPa]
in-plane shear strength	$S12_m$	$S12_f$	[MPa]

Table 8 - Mechanical properties of matrix and fibre

The assumptions at the basis of most used prediction theories, and below reported, are:

- the matrix and the fibres have a linear elastic behaviour until failure
- the matrix and the fibres are homogeneous and singularly isotropic*
- the matrix and the fibres are and in perfect adhesion each other

The isotropic hypothesis, which is usually valid for matrixes, may fit well only for glass reinforcing fibres. Other fibres, such as the aramid and carbon, shall be modelled as orthotropic.
In this case, the relation must be modified properly, taking into account the longitudinal and transverse characteristic.

Furthermore, the values of $S12_m$ and $S12_f$ in-plane shear strengths are often calculated according with Von Mises's failure criteria for ductile material in the case of matrix, and so:

$$\mathrm{S}12_m = S1_m/\sqrt{3}$$

and according with Galileo-Rankine failure criteria for brittle material in the case of fibre, so:

$$S12_f = S1_f$$

[9].

2.5.1. Micromechanics of a Unidirectional Lamina for Elastic Properties Prevision

Several micromechanics theories allow the calculation of lamina properties and the most used are:
1) Micromechanics Theory
2) Halpin-Tsai Theory

Micromechanics theory bases on the assumption of perfect adhesion between matrix and fibres. Longitudinal and transversal responses of the lamina can be well represented by means of parallel and series mechanical models, as they are used for springs.

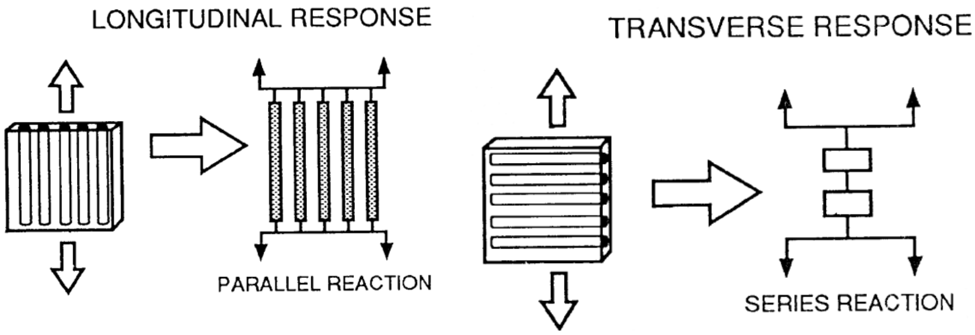

Figure 15 - Longitudinal and Transversal response models for the prevision of lamina properties

The longitudinal response is treated as all components react in parallel, while transversal response considers all reacting in series.
For a mechanical stress, for example, the assumption translates by considering all components subjected to the same strain.
So, in the case of Young's modulus, longitudinal lamina property is:

$$E_1 = V_f E_f + (1 - V_f) E_m$$

where the major contribute dominates above the minor one.

Otherwise, transversal response is analysed considering all components as subjected to the same stress. And so:

$$E_2 = \frac{E_f E_m}{(1 - V_f) E_f + V_f E_m}$$

where the minor value, instead, dominates above the major one.

So, the matrix mainly defines the transversal lamina Young's modulus, while the longitudinal is highly dependent on fibre.
Shear modulus is calculated as a transversal property, and so:

$$G_{12} = \frac{G_f G_m}{(1 - V_f) G_f + V_f G_m}$$

The principal limit of this model is the approximation of the state of stress and strain within the material which is considered as uniform.
In fact, the same results could be obtained by considering a composite lamina in which all the fibre are grouped in an array of volume $V_{tot} \cdot V_f$ and bonded parallel to a matrix array of $V_{tot} \cdot V_m$ volume as seen in Figure 16.

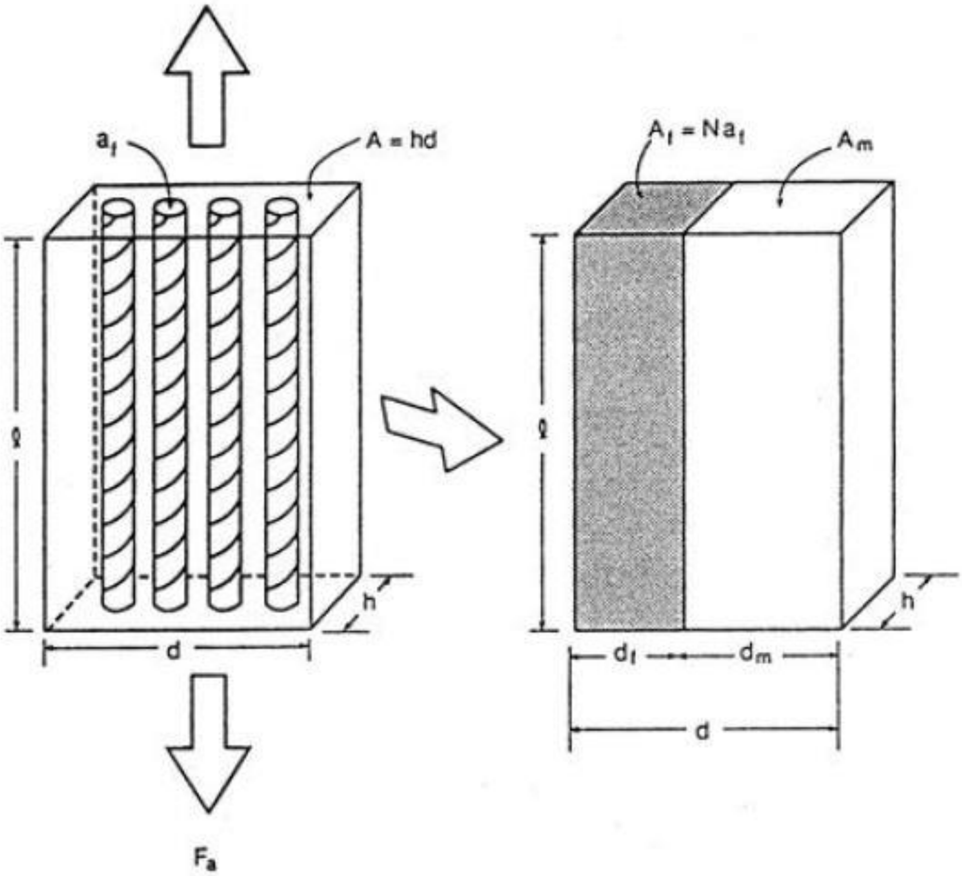

Figure 16 - Parallel model for longitudinal properties prevision [1]

Even if the prediction of longitudinal properties is in line with experimental results, this approximation causes an underestimation of the transversal properties of the lamina, such as the transversal Young's Modulus and shear modulus. [1]

This lack has guided the development of the semi-empirical model of Halpin-Tsai, which tries to fit better the real behaviour of the lamina.

2.5.1.1. Theory of Halpin-Tsai

This easier method to calculate the transversal properties of a composite lamina combines the two-previous, parallel and series models, by considering the matrix un-uniform distribution.

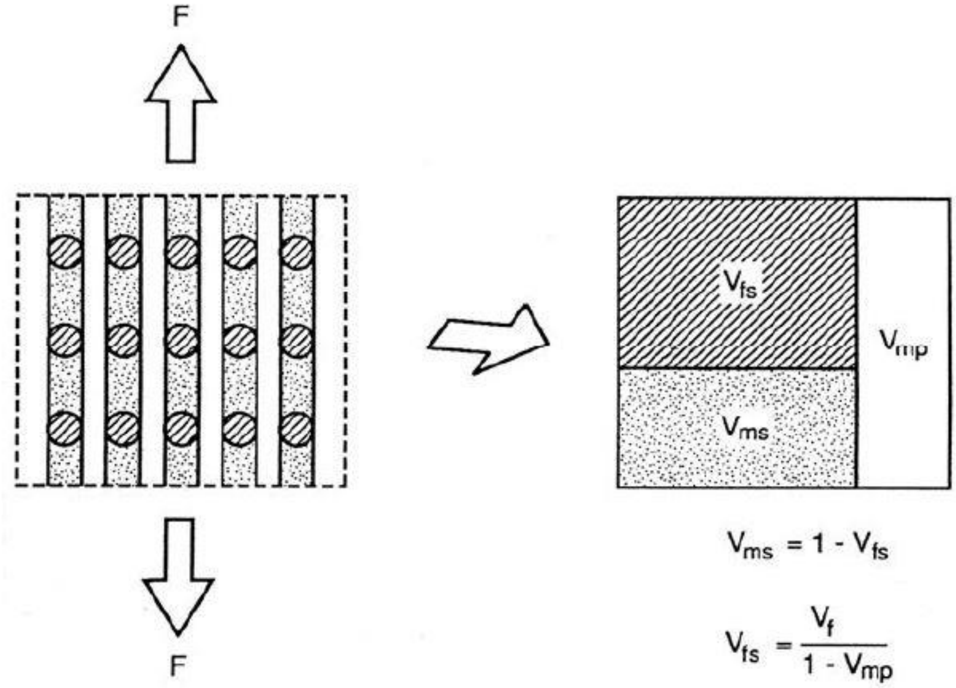

Figure 17 - Scheme of the partition between fibre and matrix in a series-parallel model. Indexes refer to fibre in series (f_s), matrix in series (m_s), and matrix in parallel (m_p)

Fibre and matrix between fibres along loading direction combine in series, while the remaining matrix which separates the columns of fibre, reacts in parallel with others two.

The volume fractions of each phase depend on the microstructure of the material in terms of diameter, distance between fibres and type of arrangement.
It is possible to separate these microstructural properties from the phase properties by means of a reinforcing factor coefficient ξ.
Transversal properties can be so calculated using the Halpin-Tsai equation:

$$E_2 = \frac{E_m \left[1 + \xi \left(\frac{E_f - E_m}{E_f + \xi E_m}\right) V_f\right]}{1 - \left(\frac{E_f - E_m}{E_f + \xi E_m}\right) V_f}$$

Consequently, even the shear modulus is calculated as:

$$G_{12} = \frac{G_m \left[1 + \xi \left(\frac{G_f - G_m}{G_f + \xi G_m}\right) V_f\right]}{1 - \left(\frac{G_f - G_m}{G_f + \xi G_m}\right) V_f}$$

where geometry of reinforcement has been isolated into reinforcement factor:

$$\xi = \frac{V_{mp}V_f}{1 - V_f - V_{mp}}$$

Reinforcing factor ξ is the scale parameter between parallel and series model, in fact:

$\xi = 0;\ E_2 = \frac{E_f E_m}{(1-V_f)E_f + V_f E_m}$

$\xi \to inf;\ E_2 = (1 - V_f)E_m + V_f E_f$

Intermediate values give intermediate previsions between these two limits.
The ξ parameter takes into account fibre geometry, packing geometry and loading conditions [27].

Major Poisson's ratio can be evaluated applying the rule of mixture as well as done for the lamina density prevision, so:

$$\nu_{12} = \nu_f V_f + \nu_m V_m$$

Summary is given in Table 9:

Property	**Symbol**	**Equation**	**Model**
Longitudinal elastic modulus	E_1	$E_1 = V_f E_f + (1 - V_f)E_m$	Mixture
Transverse elastic modulus	E_2	$E_2 = \frac{E_m\left[1 + \xi\left(\frac{E_f - E_m}{E_f + \xi E_m}\right)V_f\right]}{1 - \left(\frac{E_f - E_m}{E_f + \xi E_m}\right)V_f}$	Halpin-Tsai
In-plane Shear Modulus	G_{12}	$G_{12} = \frac{G_m\left[1 + \xi\left(\frac{G_f - G_m}{G_f + \xi G_m}\right)V_f\right]}{1 - \left(\frac{G_f - G_m}{G_f + \xi G_m}\right)V_f}$	Halpin-Tsai
Major Poisson's ratio	ν_{12}	$\nu_{12} = \nu_f V_f + \nu_m V_m$	Mixture
Density	ρ_l	$\rho_l = \rho_f V_f + \rho_m V_m$	Mixture

Table 9 - Summary of the prevision equations for elastic and rheological properties

2.5.2. Micromechanics of a Unidirectional Lamina for Mechanic Properties Prevision

A prevision of the mechanical performances of lamina can be made starting from elastic and mechanic properties of matrix and fibre.

The five ultimate strength parameters generally needed to know are:

- Longitudinal tensile strength
- Transverse tensile strength
- Longitudinal compressive strength
- Transverse compressive strength
- In-plane shear strength

"The strength parameters for a lamina are much harder to predict than the stiffness because the strengths are more sensitive to the material and geometric non-homogeneities, fibre-matrix interface, fabrication process, and environment. For example, a weak interface between the fibre and the matrix may result in the premature failure of the composite under a transverse tensile load, but may increase its longitudinal tensile strength.
For these reasons of sensitivity, some theoretical and empirical models are available for some of the strength parameters. Eventually the experimental evaluation of these strengths becomes important because it is direct and reliable" [27].

The next paragraphs describe the models used for the prevision of tensile and shear ultimate strengths.

2.5.2.1. Longitudinal Tensile Strength

A simple mechanics of material approach model is used for the evaluation of the longitudinal tensile strength of lamina under the further assumption that the failure strain of the matrix is higher than for the fibre. This is the case of the polymeric matrix composite where, in example, glass fibres fail at strains equal to 3-5%, but an epoxy fails at 9-10% strains. [27].

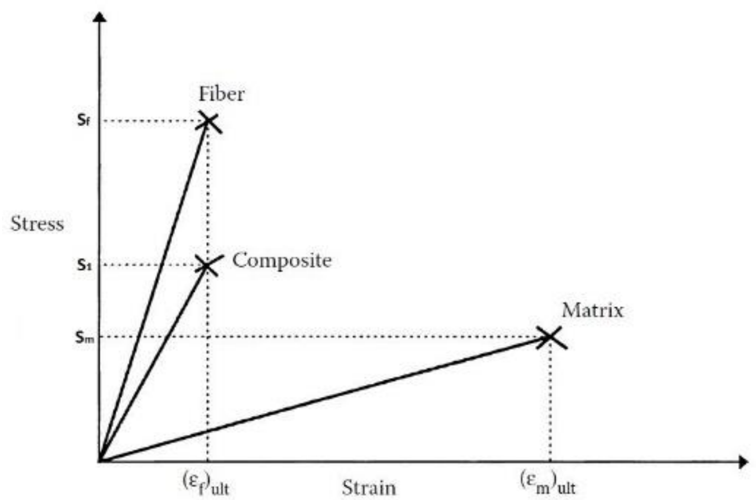

Figure 18 - Stress-strain curve for a unidirectional composite under uniaxial tensile load along the fibres

The ultimate failure strain of fibre and matrix are:

$$(\varepsilon_f)_{ult} = \frac{S_f}{E_f}$$

$$(\varepsilon_m)_{ult} = \frac{S_m}{E_m}$$

Because the fibres carry more load than matrix in polymeric matrix composites, it is assumed that, when the fibres fail, the whole composite fails.
The longitudinal tensile strength is given by:

$$S_1 = S_f V_f + (\varepsilon_f)_{ult} E_m \left(1 - V_f\right)$$

2.5.2.2. Longitudinal Compressive Strength

The longitudinal compressive strength of a composite is strictly related to the concept of peak instability load. A compressive load in fibre direction leads to fibre instabilities, which can be in phase or in opposition, as shown in Figure 19:

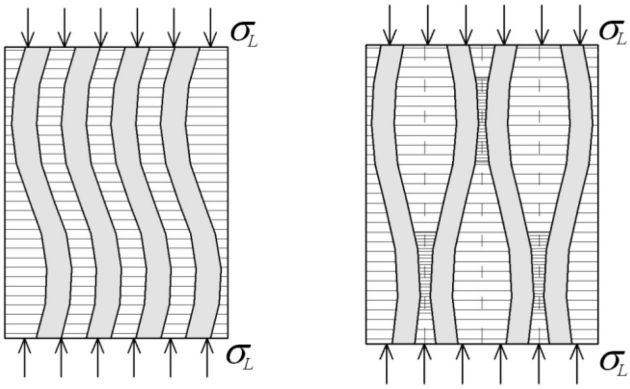

Figure 19 - Instabilities for a composite subject to a compressive longitudinal load: "In-Phase" and "In-Phase Opposition" instabilities [31]

- **In Phase Instability**

The deformation occurs keeping the fibre distance constant. This may happen when the composite has high values of volume fraction V_f. The matrix undergoes essentially to shear deformation.
Longitudinal compressive strength in this case may calculated by mean of the follow equation:

$$S_1^c = \frac{G_m}{1 - V_f}$$

- **Instability in Phase Opposition**

The deformation occurs so the fibres are in opposition among them. This happens when the composite has low values of volume fraction V_f and the stress state within the matrix is tensile and compressive depending on zones. [29]
The Rosen's equation may be a valid tool for the prediction of the longitudinal compressive strength for this case:

$$S_1^c = 2V_f \sqrt{\frac{V_f E_f E_m}{3(1 - V_f)}}$$

For composites with $V_f > 0.4$ the predicted mode of failure ought to be "In Phase", even if the theory just exposed predicts values.
Unfortunately, Rosen's equations give values extremely higher than experimental ones for a $V_f > 0.5$.

The model developed by Greszezuc, seems to better predict the failure due to longitudinal compressive loading which may occurs when the transverse deformation, caused by load, reaches the value of the transverse strain to tensile failure $(\varepsilon_2)_{ult}$.[29]

The model gives the follow equation:

$$|S_1^c| = \frac{(E_f V_f + E_m V_m)(1 - V_f^{1/3})(\varepsilon_m)_{ult}^c}{\nu_f V_f + \nu_m V_m}$$

where $(\varepsilon_m^c)_{ult}$ is the ultimate strain to compressive failure of matrix calculated as:

$$(\varepsilon_m)_{ult}^c = \frac{S_m^c}{E_m}$$

The structural interesting composites never collapse reaching the fibre longitudinal compressive strength. The above models link the collapse due to compressive loading to a fibre instability phenomena or to a transversal failure.

The prevision remains complex and an experimental campaign is mandatory for the design of composites subjected to compressive loadings.

2.5.2.3. Transverse Tensile Strength

When a transverse tensile load is applied to the lamina, fibres act as hard inclusions in the matrix. [25]. The radial stress near the fibre-matrix interface is tensile and is nearly 50% higher than the applied stress.
In addition, for a composite with high volume fraction V_f, there is an interaction of the stress fields from neighbouring fibres, as investigated by *Adams* and *Doner* [25].

The simplest model assumes that the fibre and the matrix are replaced by their respective "equivalent" volumes and are depicted as two structural elements (slabs) with strong bonding at their interface.

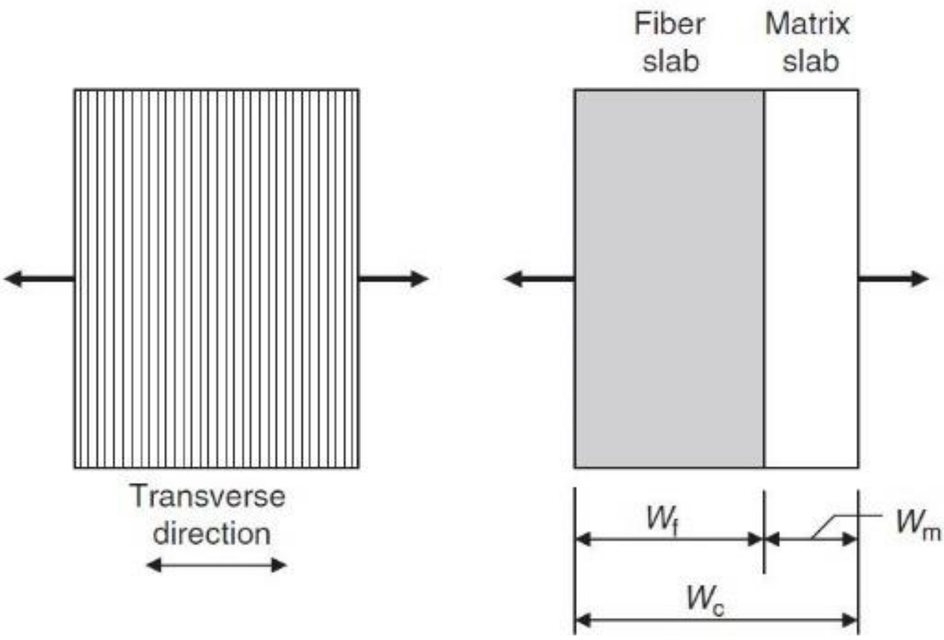

Figure 20 - Transverse loading of a unidirectional continuous fibres lamina and the equivalent slab model

Under the assumptions that: 1) the total deformation in the transverse direction W_c is the sum of the total deformations of the fibre and matrix slab, and 2) the tensile stress in the fibres and matrix are equal; a simple equation for predicting the transverse tensile strength of a unidirectional continuous fibre lamina is:

$$S_2 = \frac{S_m}{K_\sigma}$$

where

$$K_\sigma = \frac{1 - V_f(1 - (E_m/E_f))}{1 - \left(4V_f/\pi\right)^{0.5}(1 - (E_m/E_f))}$$

This model, developed by Greszezuk, assumes that the transverse tensile strength of the lamina is limited by the ultimate tensile stress of the matrix. K_σ represents the maximum stress concentration factor in the matrix in which fibre are arranged in a square array. The equation predicts that, for a given matrix, the transverse tensile strength decreases with the increasing of the fibre modulus as well as increasing fibre volume fraction [25] [29]. The values predicted in this way are found to be in reasonable agreement with those predicted by finite difference method for fibre volume fraction less than 60%. [25]

A critical comparison between analytical prediction value and the experimental evaluation of the transverse tensile strength for a lamina is reported in [27].
It shows how for a 70% fibre volume fraction epoxy/glass unidirectional lamina, the predicted and the experimentally evaluated values may be quite different.
The predicted value of S_2 is 20.56 [MPa] results to be about half respecting to the experimentally evaluated, which reach the value of 53.28 [MPa].
The overall trend of the transversal tensile strength as function of the volume fraction V_f is presented in the figure (21).

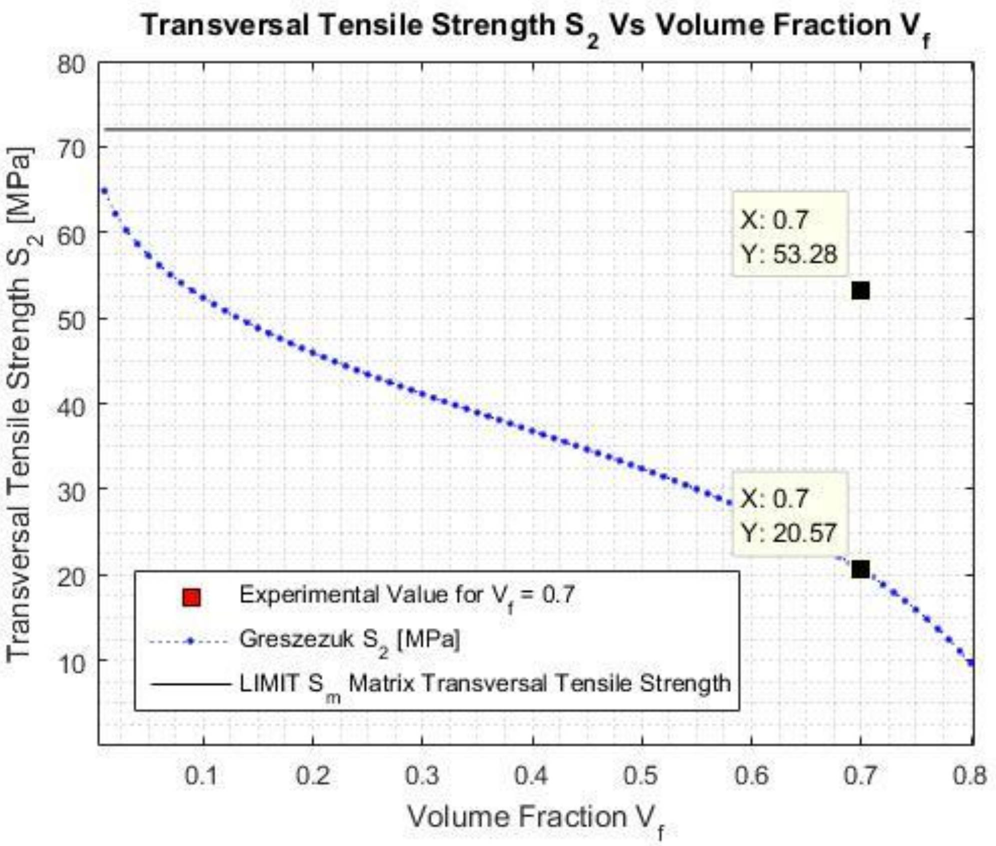

Figure 21 - Transversal tensile strength as function of the volume fraction in Greszezuk's model

"Predicting transverse tensile strength is quite complicated. Under a transverse tensile load, factors other than the individual properties of the fibre and matrix are important. These include the bond strength between the fibre and the matrix, the presence of voids, and the presence of the residual stresses due to thermal expansion mismatch between the fibre and the matrix.
Possible modes of failure under transverse tensile stress include matrix tensile failure accompanied by fibre matrix de-bonding and /or fibre splitting"[27].
Since the failure of a pipe due to internal pressure occurs due to weeping, the transverse tensile strength results to be a very important parameter which requires an accurate analytical, FEM and experimental evaluation.

2.5.2.4. Transversal Compressive Strength

"Composite laminates subjected to transverse compressive loads usually fail under matrix shear combined with the crushing of the fibres. It is difficult to give an accurate micromechanical prediction of the transverse compressive strength because, unlike the case of composites loaded longitudinally where the fibre and matrix behaviour follows very closely the iso-strain or iso-stress approximation until the initiation of failure, composites loaded transversely do not follow the iso-strain or iso-stress approach (Gonzales & Lorca, 2007).". Cit…[31] (Lupasteanu, et al., 2013)

The transverse compressive strength of a unidirectional lamina may be calculated by mean of the following empirical equation developed by Weeton (1986) and Sellbrink (1996):

$$S_2^c = S_m^c C_v \left[1 + \left(V_f - \sqrt{V_f}\right)\left(1 - \frac{E_m}{E_f}\right)\right]$$

Later, Autar Kaw, (2006) and Gibson, (2012) developed a theoretical approach but under the same hypothesis for the perfect bond, full elastic behaviour until fracture, uniformly distributed fibres, and no residual stresses. [31].

The transverse compressive strength may be predicted using the relation:

$$S_2^c = E_2 (\varepsilon_2)_{ult}^c$$

where

$$(\varepsilon_2)_{ult}^c = \left[\frac{d}{s}\frac{E_m}{E_f} + \left(1 - \frac{d}{s}\right)\right](\varepsilon_m)_{ult}^c$$

$$(\varepsilon_m)_{ult}^c = \frac{S_m}{E_m}$$

d and s are respectively the diameter of fibres and the distance between the centres of fibres, as shown in Figure 22:

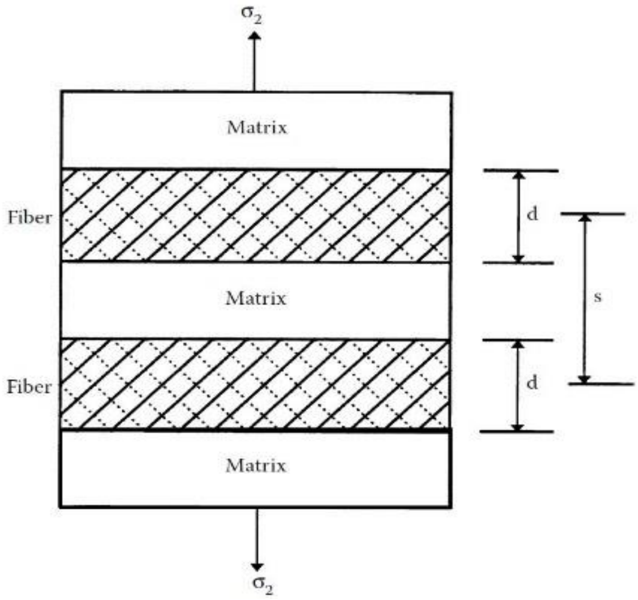

Figure 22 - Representative volume element to calculate transverse tensile strength of a unidirectional lamina.

The d/s ratio strictly depends from array packaging of fibre. This value can be calculated with the follow equation in the case of circular fibres arranged in square array:

$$\frac{d}{s} = \left(\frac{4V_f}{\pi}\right)^{0.5}$$

Or in the case of circular fibres arranged in hexagonal array packaging with the next:

$$\frac{d}{s} = \left(\frac{2\sqrt{3}V_f}{\pi}\right)^{0.5}$$

[27].

2.5.2.5. In-plane Shear Strength

The model for an analytical evaluation of the in-plane shear strength S_{12} is given by the following equation, which represents the case of lamina under shear stress as well as the last case analysed before in the case of transverse loading. [27]

$$S_{12} = G_{12}(\gamma_{12})_{ult}$$

where

$$(\gamma_{12})_{ult} = \left[\frac{d}{s}\frac{G_m}{G_f} + \left(1 - \frac{d}{s}\right)\right](\gamma_{12})_{m,ult}$$

With the ultimate strain to in-plane shear failure of matrix $(\gamma_{12})_{m,ult}$ calculated as:

$$(\gamma_{12})_{m,ult} = \frac{S12_m}{G_m}$$

and $S12_m$ the in-plane shear strength of matrix.

A value of $d/s = 0.9441$ is calculated for circular fibres arranged in square arrays for a volume fraction of 0.7.

A comparison from analytical model and experimental evaluation of the in-plane shear strength and reported in [27] shows how the prevision may be un-accurate.
The study shows that the predicted in-plane shear strength equal to 9.469 [MPa], results to be at least 10 times smaller than the experimental one which reaches the value of 87.57 [MPa].

"The prediction of the ultimate shear strength is complex. Similar parameters, such as weak interfaces, the presence of voids, and Poisson's ratio mismatch, make modelling quite complex." [27].

Even if the failure mode of the pipe does not take into account primarily the in-plane shear strength, as in the case of transversal strengths, its prevision shall be more accurate and based on finite elements models and experimental data.

2.5.2.6. Strains to Tensile Failure

Finally, knowing the yield stress of the lamina, the calculation of the strain to rupture can be performed by applying the Hooke's equation for both the cases of traction and compressive loads.

$$\begin{vmatrix}\varepsilon_{1,ult}\\ \varepsilon_{2,ult}\\ \gamma_{12,ult}\end{vmatrix} = \begin{bmatrix}1/E_1 & -\nu_{21}/E_2 & 0\\ -\nu_{12}/E_1 & 1/E_2 & 0\\ 0 & 0 & 1/G_{12}\end{bmatrix}\begin{vmatrix}S_1\\ S_2\\ S_{12}\end{vmatrix}$$

where for symmetry: $\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}$

Here is summary of equations adopted for the analytical prevision of mechanical strengths of a unidirectional lamina of composite.

Property	Symbol	Equation	Model
Ultimate longitudinal tensile strength	S_1	$S_1 = S_f V_f + (\varepsilon_f)_{ult} E_m (1 - V_f)$	Mixture (modified)
Ultimate transverse tensile strength	S_2	$S_2 = \frac{S_m}{K_\sigma};\ K_\sigma = \frac{1 - V_f(1-(E_m/E_f))}{1-(4V_f/\pi)^{0.5}(1-(E_m/E_f))}$	Greszezuk
Ultimate longitudinal compressive strength	S_1^c	$\lvert S_1^c \rvert = \frac{(E_f V_f + E_m V_m)(1 - V_f^{1/3})(\varepsilon_m^c)_{ult}}{\nu_f V_f + \nu_m V_m};\ (\varepsilon_m)_{ult}^c = \frac{S_m^c}{E_m}$	Greszezuk
Ultimate transverse compressive strength	S_2^c	$S_2^c = E_2(\varepsilon_2)_{ult}^c$ $(\varepsilon_2)_{ult}^c = \left[\frac{d}{s}\frac{E_m}{E_f} + \left(1 - \frac{d}{s}\right)\right](\varepsilon_m)_{ult}^c;$ $(\varepsilon_m)_{ult}^c = \frac{S_m}{E_m}$	Autar Kaw & Gibson
Ultimate in-plane shear strength	S_{12}	$S_{12} = G_{12}(\gamma_{12})_{ult}$ $(\gamma_{12})_{ult} = \left[\frac{d}{s}\frac{G_m}{G_f} + \left(1 - \frac{d}{s}\right)\right](\gamma_{12})_{m,ult}$ $(\gamma_{12})_{m,ult} = \frac{S12_m}{G_m}$	Autar Kaw

Table 10 - Summary of prevision equations for lamina mechanical properties

3. APT and FEM Lamina Properties Prevision Tools

The lamina properties evaluated by mean of the previous analytical models can be easily implemented as a Matlab® script, called **Analytical Prevision Tool (APT)**. Anyway, as already said, these equations work under several hypotheses, and sometimes are limited for a given range of volume fraction.

Furthermore, the matching with the experimentally evaluated values, may be often far and not realistic, as in the case of evaluation of the in-plane shear strength S_{12} and the transversal strength S_2.

The designed Matlab® ATP is flexible and can easy integrate different matrixes and fibres to produce several laminas. The designer should use this tool to compare different components and volume fractions, aiming to define the best coupling which hypothetically guarantees the target performances.

A different, parallel way, to estimate the characteristics of the lamina is by means of the Finite Element Modelling. A suitable software for the FEM prevision of the lamina properties is Autodesk® Helius Composite 2016. Helius is a standalone software and a black box[8]; contrary from the analytical, its use as a design tool is considered to be more suitable in an advanced phase, when the components, the matrix and fibre, have been already designed.
The Helius, in fact, cannot be automated in Matlab® and its uses requires more time.

Since it is not possible, especially in the preliminary design phase, to perform a comparison between the APT and the experimentally evaluated data, the FEM predicted properties are reported to provide a critical comparison to the APT evaluated.

The properties of the matrix and the fibre used for this simulation have been extrapolated from CES EduPack® 2016. Matrix and fibre have been chosen considering the performance of the materials described at the beginning of this chapter in relation to the requirements of high corrosion resistance and high strength at high temperature which represent the challenge of the project.

The components represent a starting point for structural consideration about the plain pipe resistance to inner pressure, and do not intend to represent the best components solution for the project.

[8] No information is provided about the parameters of the FEM simulation adopted by the software

The Matlab® ATP and the FEM base on the follow matrix and fibre:

Matrix Type	Epoxy		
Property	**Symbol**	**Value**	**Unit**
Elastic modulus	E_m	2470	[MPa]
Shear modulus	G_m	877	[MPa]
Poisson's ratio	ν_m	0.41	-
Density	ρ_m	1400	[Kg/m^3]
Tensile strength	S_m	71.7	[MPa]
Compressive strength	S_m^c	172	[MPa]
In-plane shear strength	$S12_m$	41.40	[MPa]

Table 11 - Matrix properties

Fibre Type	EC-R Glass		
Property	**Symbol**	**Value**	**Unit**
Elastic modulus	E_f	81000	[MPa]
Shear modulus	G_f	32926	[MPa]
Poisson's ratio	ν_f	0.23	-
Density	ρ_f	2500	[Kg/m^3]
Tensile strength	S_f	3450	[MPa]
Compressive strength	S_f^c	4500	[MPa]
In-plane shear strength	$S12_f$	3450	[MPa]

Table 12 - Glass fibre properties

The next paragraphs report the trends of elastic and mechanical lamina properties as a function of the volume fraction for both FEM and APT methods.
A comparison between the two methods and a critical discussion of the results follows.
Structure of the investigation is given in the following figure.

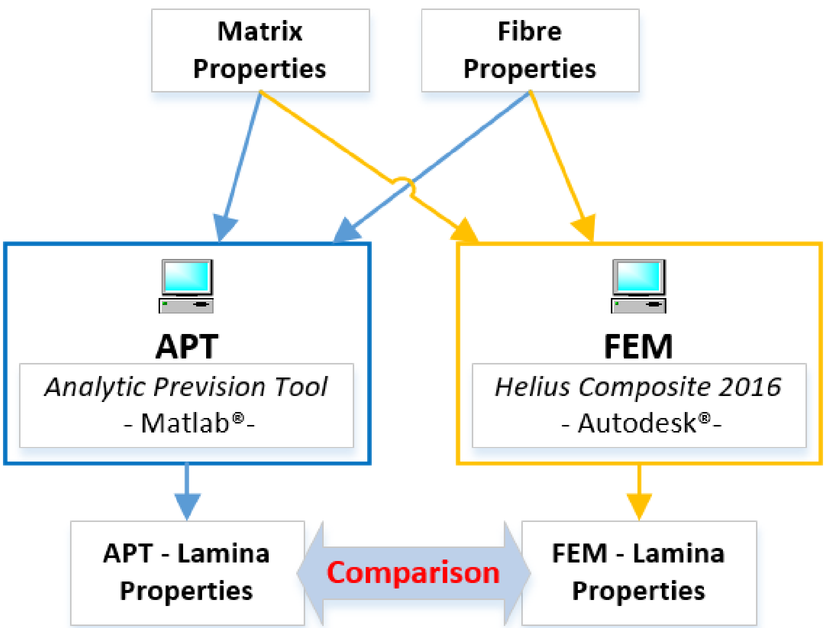

Figure 23 - Investigation procedure concerning the lamina properties evaluated with APT and FEM prevision.

3.1. APT - Analytical Prevision Tool data

The Matlab® APT calculates the 32x71 matrix[9] which reassumes, row by row, the lamina elastic and mechanical properties as function of the volume fraction V_f from 0.1 to 0.8 with step increments of 0.01.

Composite Type	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Fiber Vf	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.2
Thickness (mm)	0	0	0	0	0	0	0	0	0	0	0
E11 (MPa)	10323	11108.3	11893.6	12678.9	13464.2	14249.5	15034.8	15820.1	16605.4	17390.7	18176
E22 (MPa)	3112.57	3184.11	3257.14	3331.71	3407.87	3485.66	3565.15	3646.38	3729.41	3814.31	3901.14
E33 (MPa)	3112.57	3184.11	3257.14	3331.71	3407.87	3485.66	3565.15	3646.38	3729.41	3814.31	3901.14
G12 (MPa)	1061.62	1082.15	1103.11	1124.53	1146.42	1168.79	1191.67	1215.06	1238.98	1263.46	1288.51
G13 (MPa)	1061.62	1082.15	1103.11	1124.53	1146.42	1168.79	1191.67	1215.06	1238.98	1263.46	1288.51
NU12	0.3893	0.38753	0.38576	0.38399	0.38222	0.38045	0.37868	0.37691	0.37514	0.37337	0.3716
NU13	0.3893	0.38753	0.38576	0.38399	0.38222	0.38045	0.37868	0.37691	0.37514	0.37337	0.3716
+S1 (MPa)	439.683	473.131	506.579	540.027	573.475	606.923	640.371	673.819	707.267	740.715	774.163
+S2 (MPa)	51.9305	51.1389	50.3909	49.6804	49.0024	48.353	47.7286	47.1265	46.5442	45.9795	45.4307
-S1 (MPa)	989.439	1039.66	1088	1134.51	1179.28	1222.37	1263.82	1303.68	1342.01	1378.83	1414.19
-S2 (MPa)	141.764	141.278	140.86	140.494	140.172	139.885	139.625	139.387	139.165	138.955	138.753
S12 (MPa)	32.6783	32.4451	32.231	32.033	31.8482	31.6747	31.5105	31.3542	31.2044	31.0601	30.9201
+e1 (mm/mm)	0.04063	0.04081	0.04096	0.04109	0.0412	0.0413	0.04139	0.04147	0.04154	0.04161	0.04166
+e2 (mm/mm)	0.0001	0.00045	0.00096	0.00144	0.0019	0.00233	0.00274	0.00313	0.0035	0.00385	0.00418
-e1 (mm/mm)	0.0905	0.08866	0.08691	0.08523	0.08361	0.08205	0.08054	0.07909	0.07767	0.0763	0.07497
-e2 (mm/mm)	0.00823	0.0081	0.00796	0.00781	0.00765	0.0075	0.00733	0.00717	0.007	0.00683	0.00665
e12 (mm/mm)	0.03078	0.02998	0.02922	0.02849	0.02778	0.0271	0.02644	0.0258	0.02519	0.02458	0.024
Density (kg/m3)	1510	1521	1532	1543	1554	1565	1576	1587	1598	1609	1620

Table 13 – APT lamina properties as function of volume fraction V_f

Outranged values of the volume fraction are not taken into account: values smaller than 0.1 represent matrix based composite not suitable for the high strength purposes, while values higher than 0.8 cannot be manufactured.
As described later, the most suitable range of volume fraction is between 0.3 and 0.6 volume fraction.

The trends of the elastic and mechanical characteristic are reported in Figures 24-26.

[9] The total number of lamina parameters is 32. It includes also the thermal and the moisture properties which are not object of this job and are not reported. The whole of the Matlab® scripts have been developed considering a future implementation.

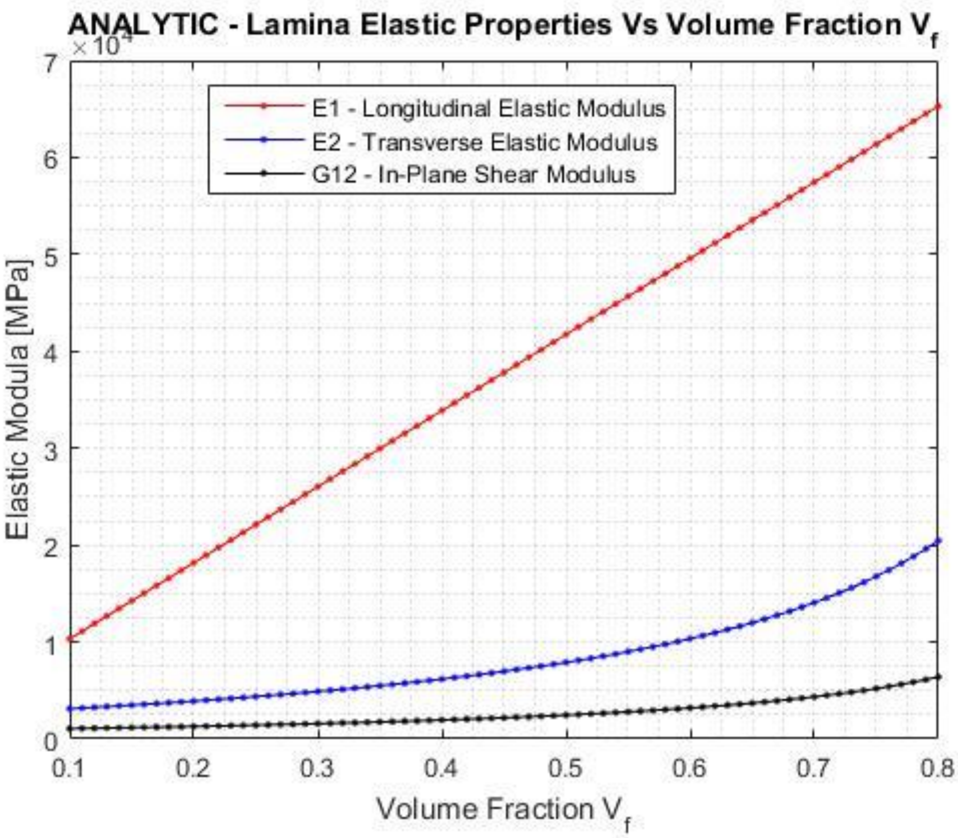

Figure 24 - APT elastic properties prediction

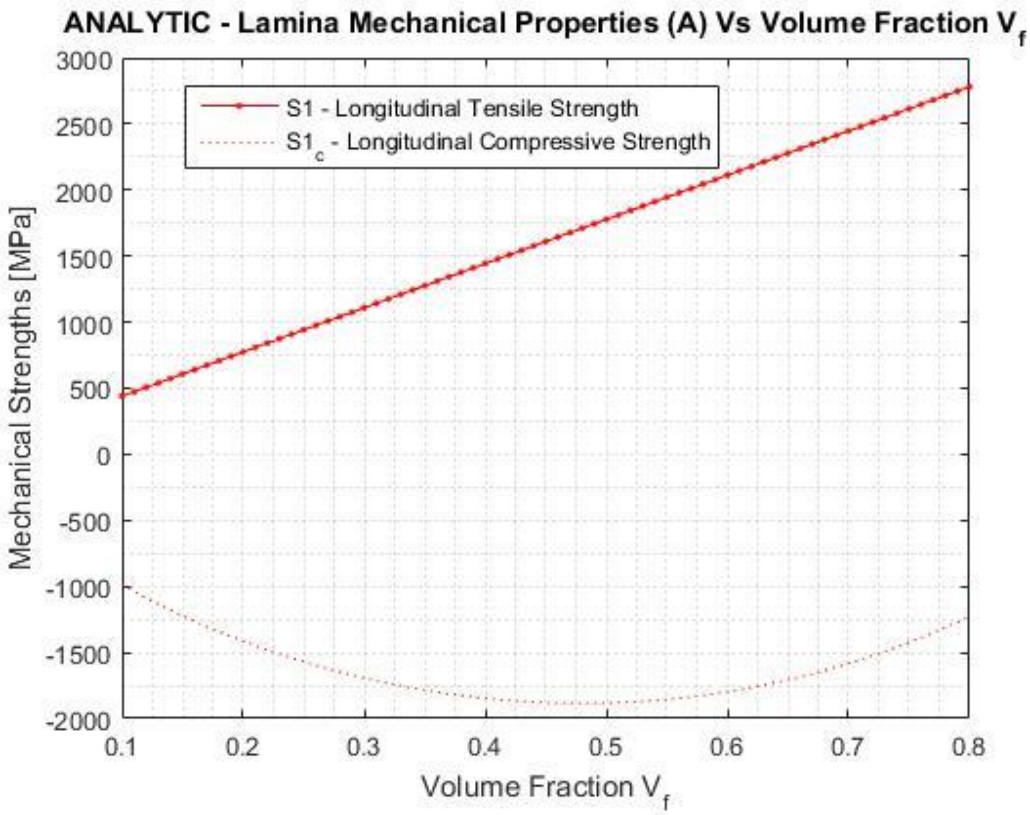

Figure 25 - APT mechanical properties A prediction

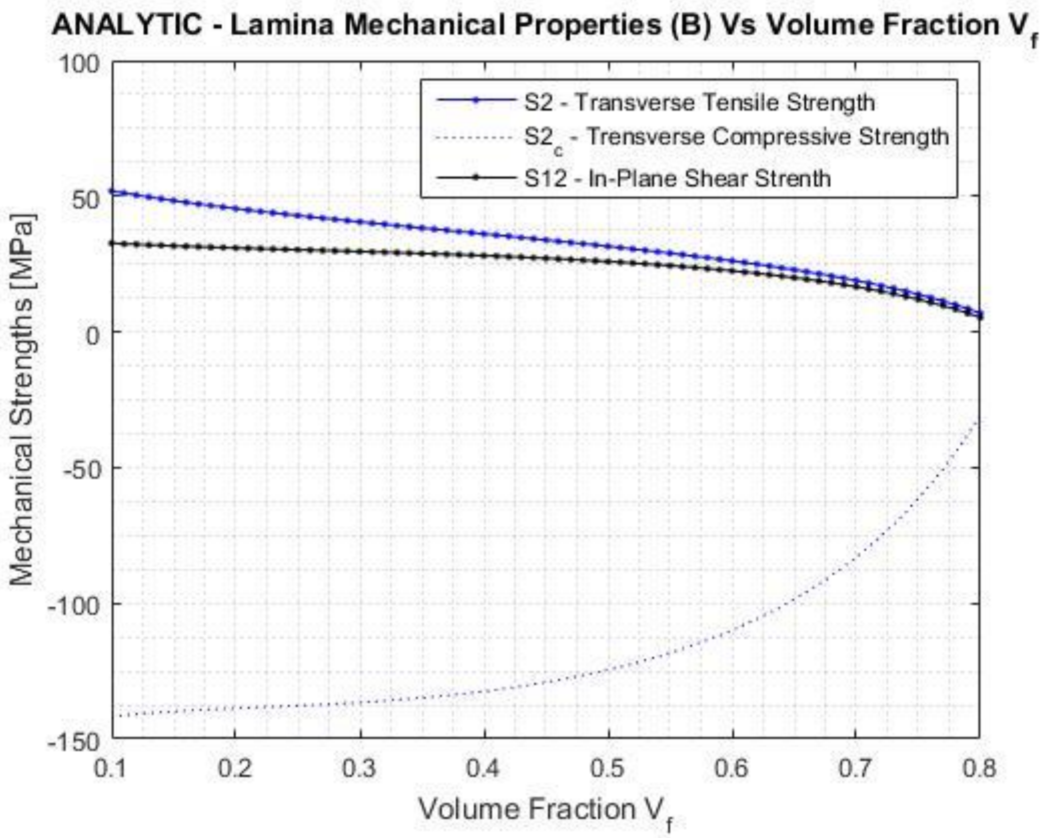

Figure 26 - APT mechanical properties B prediction

3.2. Finite Element Prevision – Autodesk Helius Composite 2016

Autodesk Helius Composite 2016 software provides a prevision of the elastic and mechanical prevision based on a finite element model which is automatic and not user-editable.

Taking into account the same matrix and fibre described in the previous paragraph, the output of Helius software is a 32x71 matrix which contains the series of laminas as a function of the volume fraction from 0.1 to 0.8 with step increments of 0.01.

Table 14 reports a part of the 32x71 matrix which contains all the lamina properties.

Composite Type	unidir.	unidir.	unidir.	unidir.	unidir.	unidir.	unidir.	unidir.	unidir.	unidir.	unidir.
Fiber Vf	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20
Thickness (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E11 (MPa)	10323.0	11108.3	11893.6	12678.9	13464.2	14249.5	15034.8	15820.1	16605.4	17390.7	18176.0
E22 (MPa)	3562.08	3640.65	3719.02	3797.43	3876.07	3955.09	4034.65	4114.87	4195.88	4277.78	4360.69
E33 (MPa)	3562.08	3640.65	3719.02	3797.43	3876.07	3955.09	4034.65	4114.87	4195.88	4277.78	4360.69
G12 (MPa)	1061.62	1082.14	1103.11	1124.53	1146.42	1168.79	1191.66	1215.05	1238.97	1263.45	1288.50
G13 (MPa)	1061.62	1082.14	1103.11	1124.53	1146.42	1168.79	1191.66	1215.05	1238.97	1263.45	1288.50
NU12	0.39	0.39	0.39	0.38	0.38	0.38	0.38	0.38	0.38	0.37	0.37
NU13	0.39	0.39	0.39	0.38	0.38	0.38	0.38	0.38	0.38	0.37	0.37
+S1 (MPa)	345.00	379.50	414.00	448.50	483.00	517.50	552.00	586.50	621.00	655.50	690.00
+S2 (MPa)	56.67	56.29	55.96	55.67	55.42	55.20	55.02	54.86	54.72	54.61	54.52
-S1 (MPa)	-450.00	-495.00	-540.00	-585.00	-630.00	-675.00	-720.00	-765.00	-810.00	-855.00	-900.00
-S2 (MPa)	-135.94	-135.04	-134.25	-133.55	-132.95	-132.43	-131.98	-131.59	-131.27	-131.00	-130.78
S12 (MPa)	32.69	32.47	32.28	32.11	31.96	31.84	31.73	31.64	31.56	31.49	31.44
+e1 (mm/mm)	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
+e2 (mm/mm)	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
-e1 (mm/mm)	-0.04	-0.04	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
-e2 (mm/mm)	-0.04	-0.04	-0.04	-0.04	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
e12 (mm/mm)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02
Density (Kg/m3)	1510	1521	1532	1543	1554	1565	1576	1587	1598	1609	1620

Table 14 – FEM lamina properties as function of the volume fraction

The trends based on Helius are reported in Figures 27-28-29 as a function of the volume fraction.

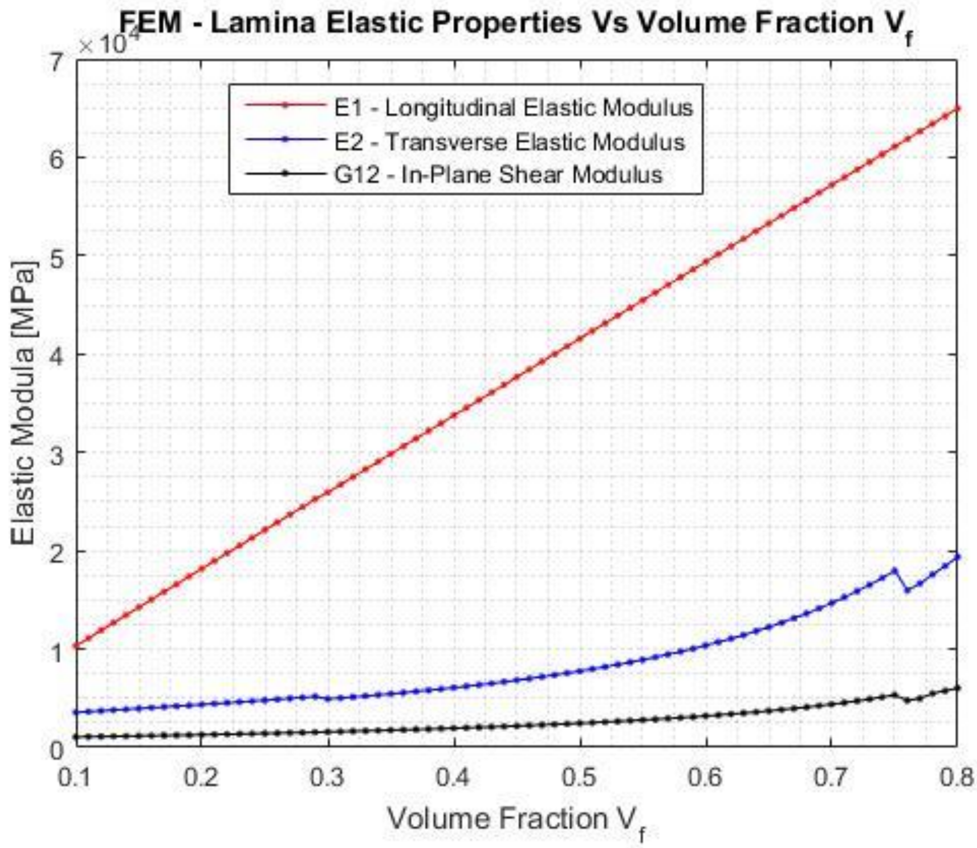

Figure 27 - FEM elastic properties prediction

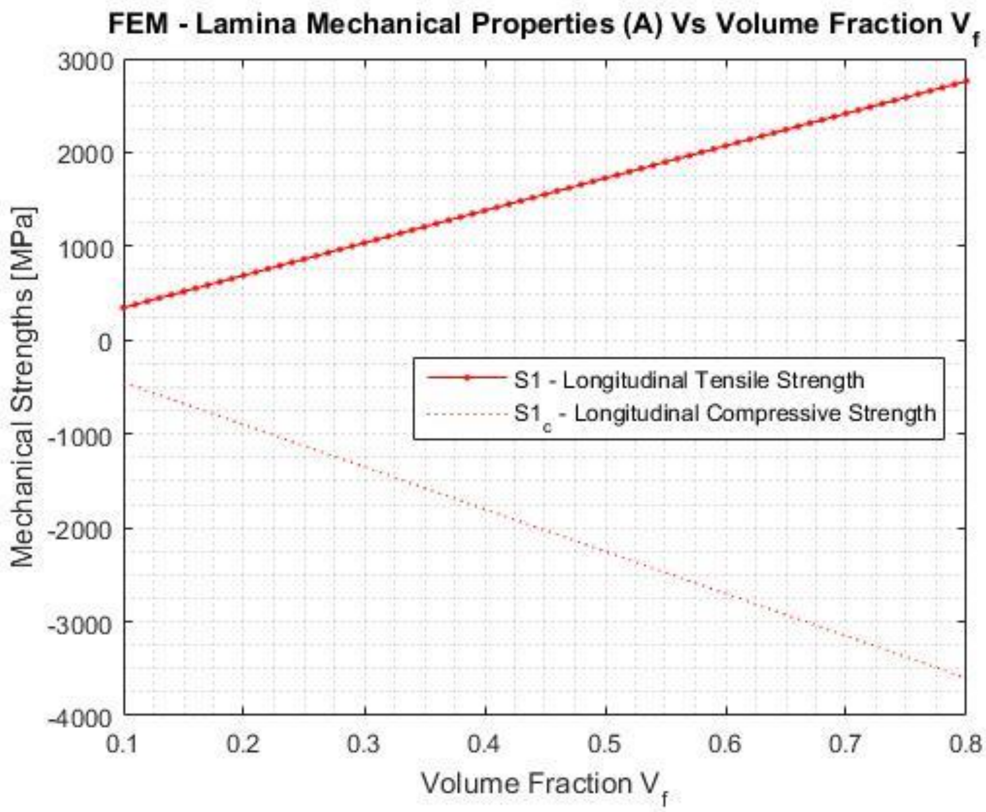

Figure 28 - FEM mechanical properties A

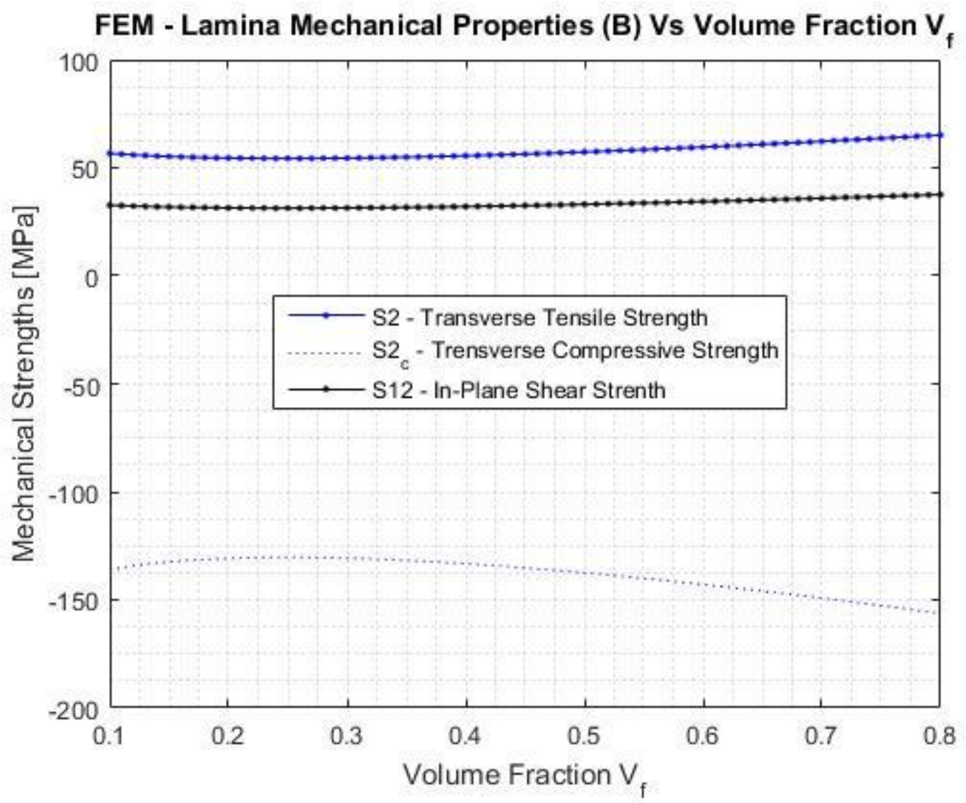

Figure 29 - FEM mechanical properties B

Because the software is closed, is not possible to determine the cause of the drops concerning the transversal elastic modulus and the in-plane shear modulus at 0.75 volume fraction in Figure 26.

3.3. APT – FEM data Comparison

Since the source matrix and fibre are the same, it is interesting to compare the properties evaluated by the analytical prediction equations and the finite element model, to investigate where the properties equal and differ.

The Figures 30-31-32 report the difference between the finite element model and the analytical one, complaining to the equation:

$$\Delta = FEM(x) - APT(x)$$

where
x represent a generic lamina property

When the area is positive, it means that finite model property is higher than the analytical predicted one; on the contrary, if the area is negative, it means that the analytical prevision is higher than the FEM evaluated.

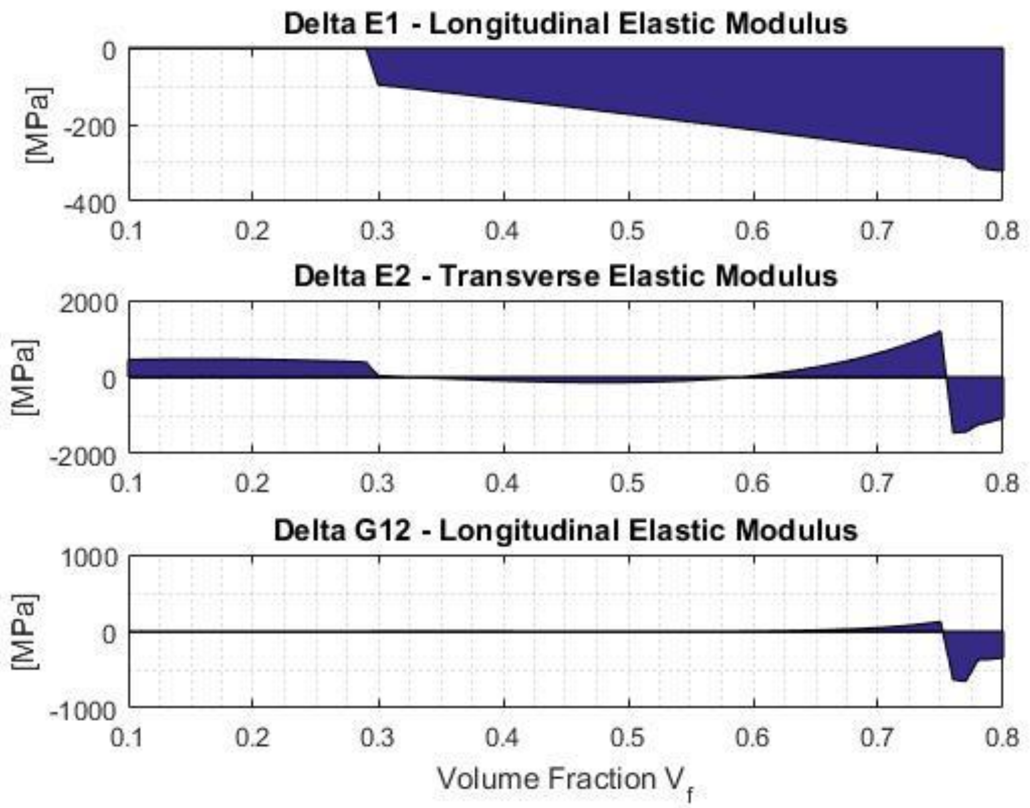

Figure 30 - Elastic properties comparison

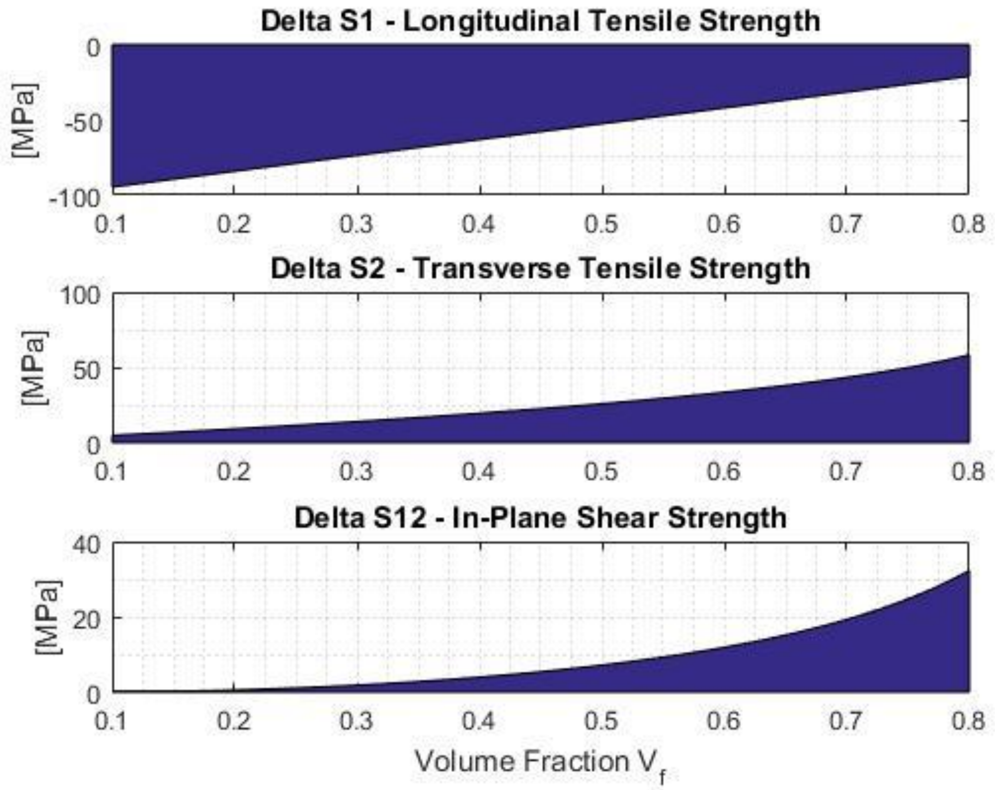

Figure 31 - Mechanical properties A comparison

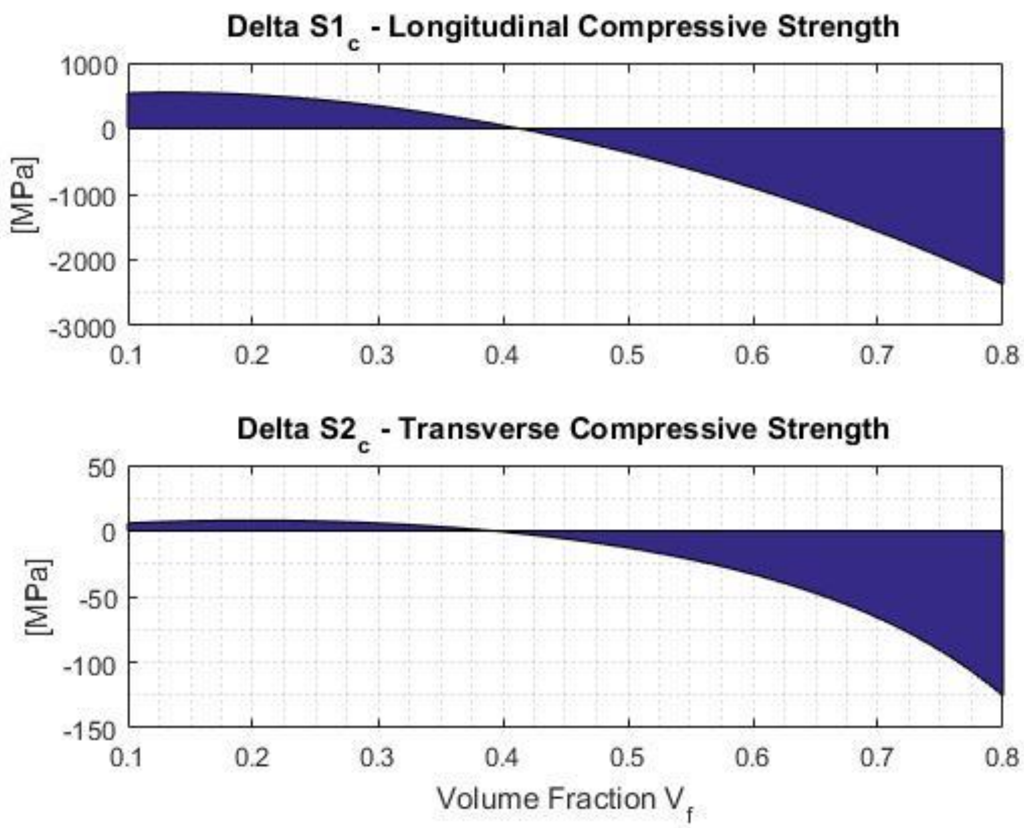

Figure 32 - Mechanical properties B comparison

The Figures 33-34-35 give a more significant report of the differences between the two models by explaining the variation as percentages.
The percentages are calculated in accordance with the equation:

$$\Delta = \frac{FEM(x) - APT(x)}{|FEM(x)|} \cdot 100$$

These last graphs well explain how the properties change between the two models.

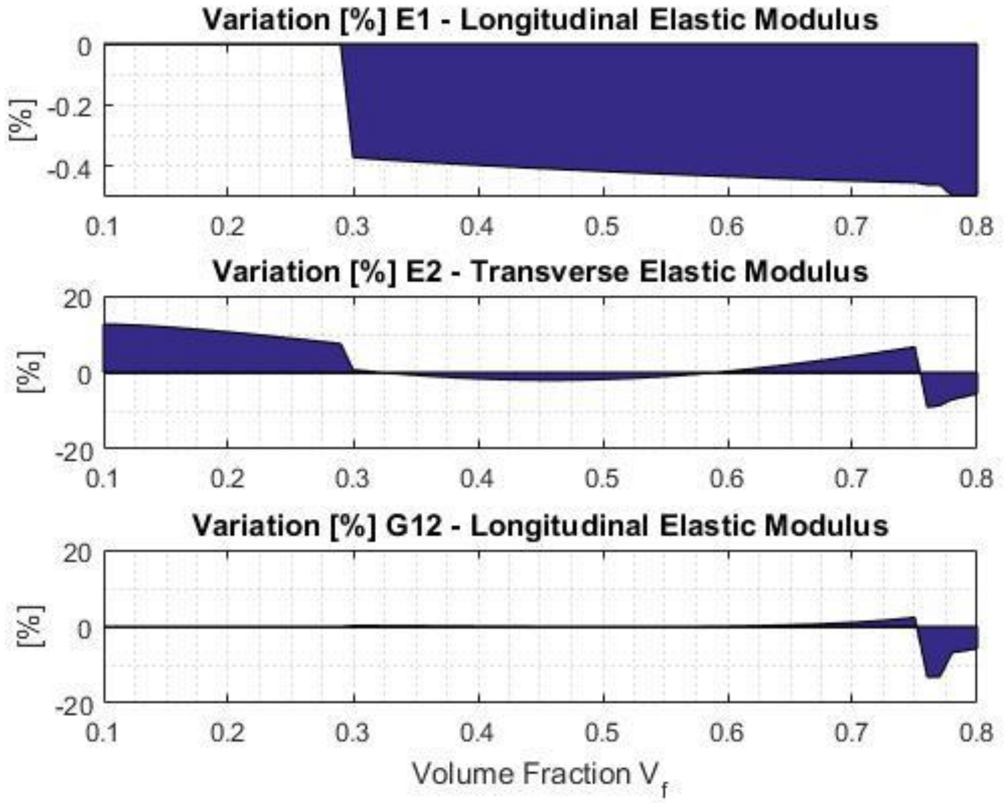

Figure 33 - Elastic properties percentage variation

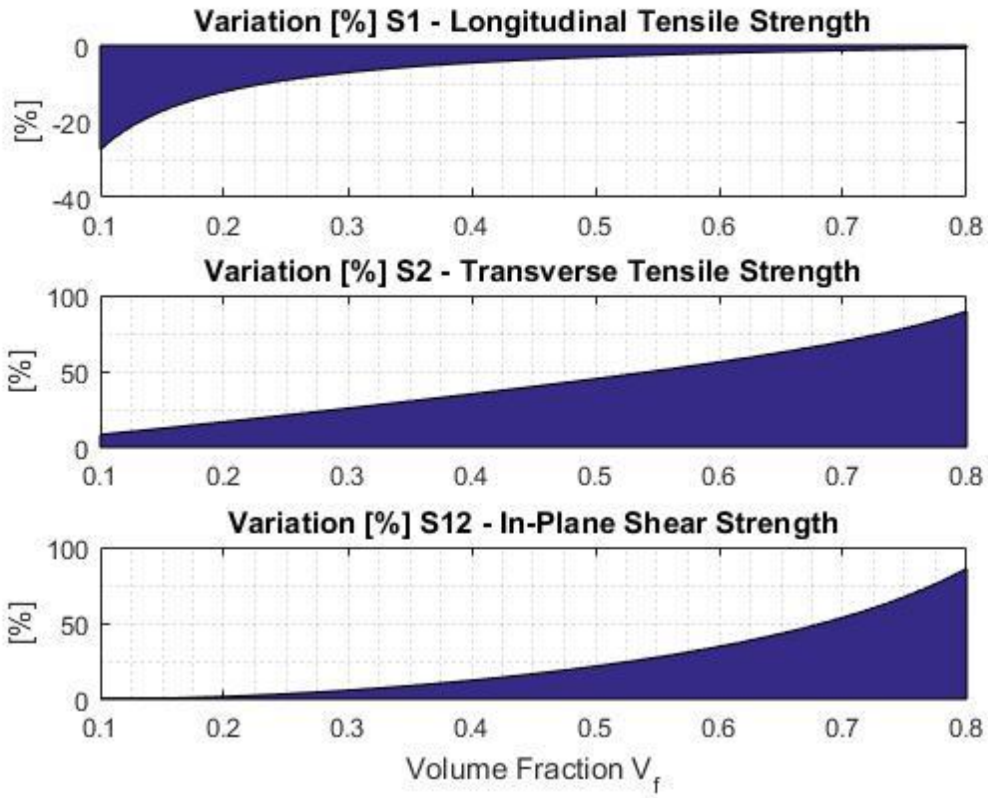

Figure 34 - Mechanical properties percentage variation

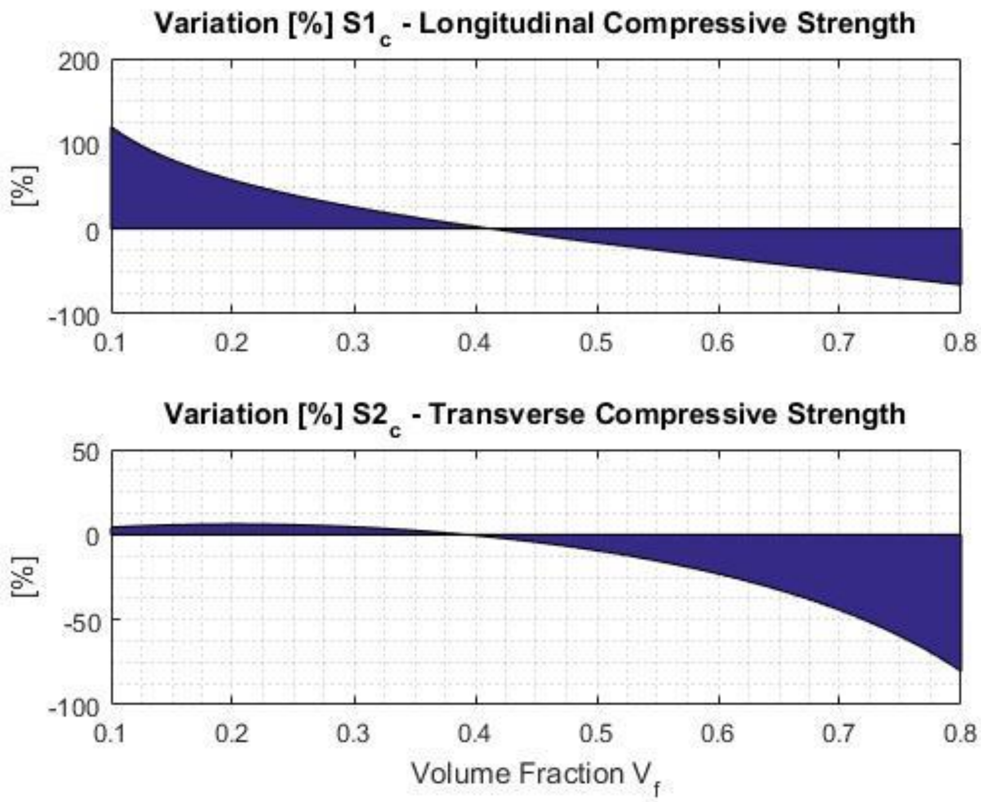

Figure 35 - Mechanical properties B percentage variation

The **elastic properties** result to be almost equally evaluated by the two models, especially in the range from 0.3 to 0.6 of the volume fraction, which is the most used range in composite material production, and completely covered by the filament-winding production technology.

On the contrary, the mechanical properties vary significantly: Helius finite element model gives a lower value of the **longitudinal tensile strength**, up to 10 % in the range 0.3 - 0.6 volume fraction.

The **transverse tensile strength**, which linearly governs the failure of pipes under hydrostatic pressure, varies significantly.
The analytical model provides values lower than Helius up to 40 % in the range 0.3 - 0.6 volume fraction and this translates in an important difference in the pipe wall thickness prevision.
A comparison in the Figure 36 explains how the wall thickness varies as function of the volume fraction for a pipe of 400 [mm] diameter, at 12 [MPa] internal pressure, and $\pm 55°$[deg] winding angle.

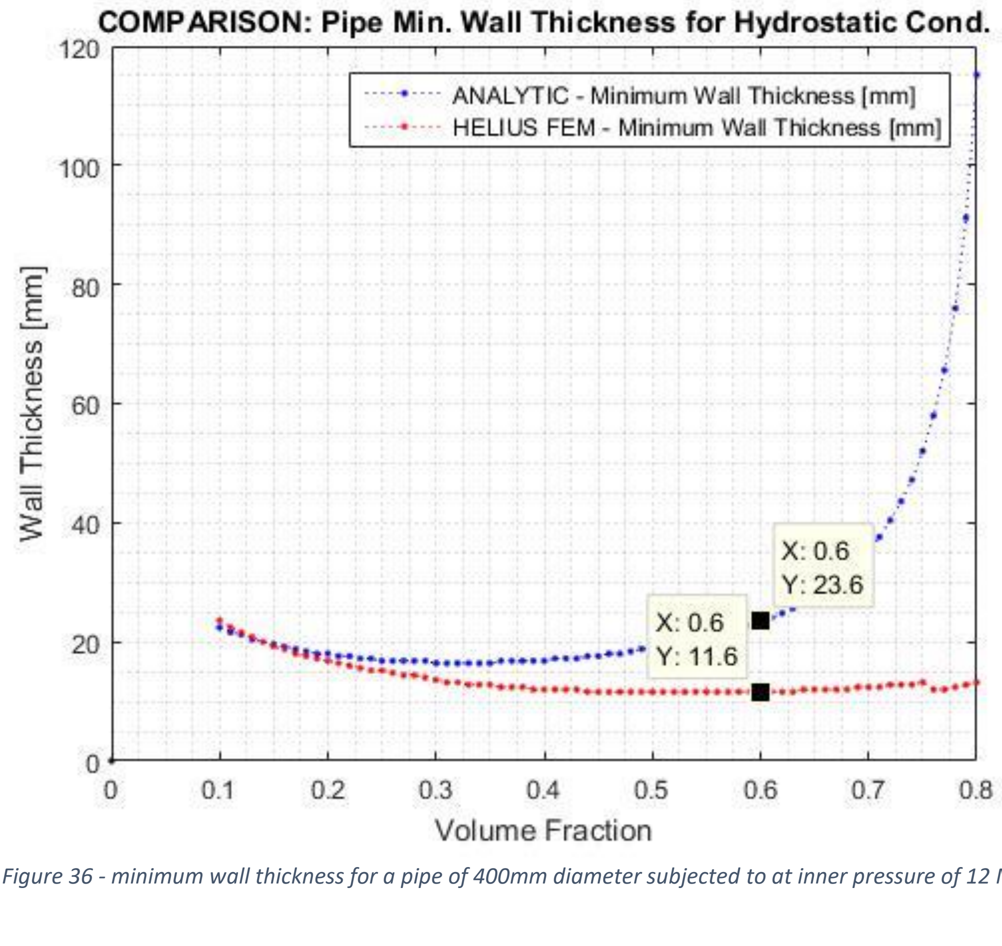

Figure 36 - minimum wall thickness for a pipe of 400mm diameter subjected to at inner pressure of 12 MPa.

Considering a volume fraction of 0.6, the prevision value of the minimum wall thickness for a pipe of 400 [mm] diameter, loaded with an inner pressure of 12 [MPa] goes from 11.6 [mm] for the finite element model, to 23.6 [mm] for the analytical one[10].

[10] Prevision of the pipe wall thickness is made basing on the Hydrotest Simulation Matlab® Script – HST developed and numerically cross-checked. Further information in Hydrotest simulation paragraph.

As for the transverse tensile strength, the same happens for the **in-plane shear strength**, whose variation reaches 40 % within the 0-3 - 0.6 range.
Finally, **the compression strengths**, both the longitudinal and the transversal, vary up to 50 %.

In conclusion, the variation of the strengths is wide and, as confirmed in Figure 36, and this provokes an important disparity in the prevision of the wall thickness for a pipe under hydrostatic pressure conditions. The “Gap” between analytical model and the “black box” Helius Composite 2016 finite elements mode increases with the volume fraction.

The value which more influences all the failure criteria is the transversal tensile strength, followed by the in-plane shear strength.
The wide variation of the compressive strengths becomes significant only onto the Tsai-Wu failure criterion, which results to be, anyway, the most severe among the applied criteria.
The discrepancies between the analytical and the finite element models, in addition to the unsatisfying matching of the analytical prevision equations with respect to the experimental evaluated values[11], lead to the conclusion that the experimental evaluation of the lamina property is the ONLY reliable source for the design of composites.

The power of the prevision models, described above, is to be a fast way to compare components and laminas. The choice of the component which best fits to the purposes of the composite, or to the induced stress state, can be well accomplished by these models. Furthermore, the use of the analytical model can be made automatic, providing a very useful tool to the designer for the choice of the matrix, fibre, and lamina.
After that, a preliminary – coarse - sizing can be made basing on the analytical and finite element values, while the ultimate design step must be done using ONLY the experimentally evaluated characteristics.

[11] As described, in particular for the transverse tensile strength and the in-plane shear strength

2. Pipe Production Processes

Since the principal topic of this work concerns the design of a plain pipe and a pipe system, it is important to describe the manufacturing processes which are adopted nowadays in pipe system fabrication.
The analysis of the common phases in composite production is described at the beginning of this chapter, and then focused on filament-winding process, which represent the lead technology in pipe production.

The filament-winding technology is fully explained in all its parameters which impact the final properties of pipe manufactured, mainly concerning the winding-angle[12].

1. Composite Production Phases

Although several composite fabrication processes exist, all of them have some production phases in common because of the nature of the raw materials.
The main phases are the *fibre impregnation*, *fibre disposition,* and the *hardening process*.
The production of structural composite usually needs a complex spatial disposition of fibre in order to offer an effective response to the loads.

These fibres must be impregnated with the resin before the deposition.
After winding, the resin filled fibres hardens. The process may be carried out in autoclave depending on temperature needed for the curing operation.
During this time is important to keep in shape the composite avoiding any viscoelastic movement. This can be achieved, often, by means of a rigid mould.

The production of revolution solid shaped composites is obtained by means of a fibres continuous deposition process which leads to a composite made up of several unidirectional layers; the process takes the name of *filament-winding*.

[12] The volume fraction V_f is another degree of freedom of the process and it depends on fabrication parameters. Nevertheless, for a design purposes, the volume fraction is considered to be a pre-determined property of the composite, defined into the material definition, instead of being a filament winding parameter.

2. Filament Winding

The filament-winding fabrication technology is broadly adopted in the production of axial-symmetric composites.

Figure 37 - Filament winding of a composite pipe with $\pm 55°$[deg] winding-angle [35]

Composite pipes, pipe elbows and vessels are made by means of this process.
The characterizing phase of this process is the disposition of unidirectional layers of pre-impregnated fibres on a mandrel which rotates along its axis.

The most used resins are thermoset, usually polyesters and epoxies with a good impregnation grade. Concerning reinforcements, the filament-winding is a process which uses single-end rovings in continuous form. The single-end rovings adopted are composed by several single filaments braided together, and are the preferred for their high strand integrity. [30]

A variation of the process, called *tape winding*, makes possible the use of thermoplastics by means of the deposition of pre-impregnated tapes instead of rovings.

After the winding, the filament-wound mandrel is subjected to curing and post curing operations. During this time, the resin filled fibres hardens, and the mandrel is continuously rotated to maintain uniformity of resin content around the circumference.
The hardening is carried out into autoclave when the polymerization process needs high temperature, as in case of high performance composites.

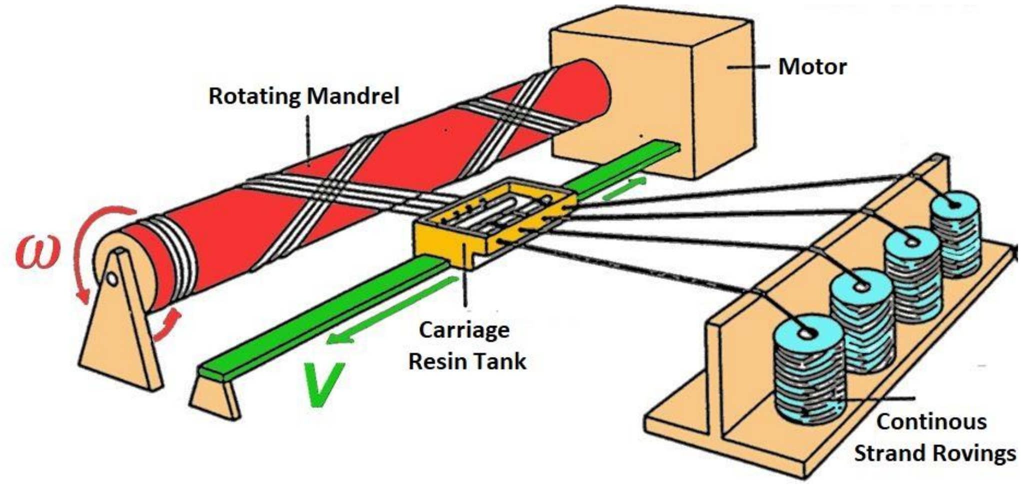

Figure 38 – 2 degrees of freedom filament winding machine [1]

The filament-winding machine, in its easiest version, consists of a rotating shaft and a translating carriage.
After the mandrel is fixed to the machine, it rotates along the shaft while the fibres are being deposited on its surface. The fibres impregnate with resin by means of a tank carried by the carriage and then, guided upon the rotating mandrel.
The carriage can move alternatively along an axis parallel to the rotating shaft and it determines the disposition of the fibres.
The deposition angle, called **winding-angle**[13] or **helical-angle**[14], is defined by acting on the angular rotating speed of mandrel ω and the carriage translation speed v.
Qualitatively, $\frac{\omega}{v} \gg 1$ corresponds to an almost circumferential disposition of fibres, while $\frac{\omega}{v} \ll 1$ corresponds to an almost longitudinal one. The limits of technical feasibility allow the fibre disposition with a winding-angle between 20° and 87° degree. [1]
The alternate deposition of fibres leads to a pattern which can be analytically managed using theories exposed in the following chapter to predict its response to loading. Figure 39 shows the carriage movement and the final pattern.

[13] Called in [1].
[14] Called in [28].

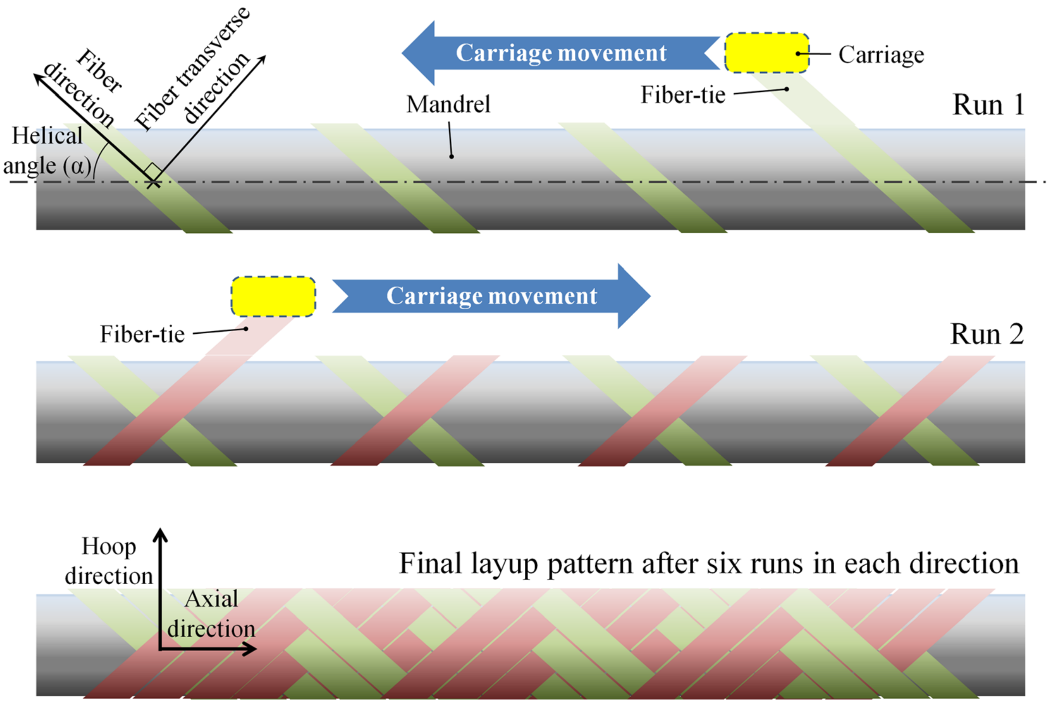

Figure 39 - Schematic diagram of helical filament winding and coordinate system [28]

The achieved accuracy of the process reported for conventional helical winding on a cylindrical mandrel machine is about 0.75 [mm], which represents the gap between the theoretical position of a fibre and its real deposition point. [36]

From a strength analysis point of view, low values of winding-angle give to a pipe-shaped composite high resistance with respect to load in axial direction, such axial tension and bending. High values of the winding-angle give instead high resistance in hoop direction.

The mandrel gives the shape to the composite: with the axis of the mandrel coincident to the axis of rotating shaft is made possible the fabrication of composite pipes, vessels, and fuselages.
This is the case of the 2 degrees of freedom filament winding machine as shown in Figure 38.

Often, is not possible to remove the mandrel from the composite after the filament winding process. it means that the remaining mandrel becomes a part of the final product itself.
In this case, the design requires that the layers set down the mandrel surface overcome alone the structural demand of the composite.
The internal mandrel may be made of a different (but compatible) polymer and may have the declared function to be a barrier from the fluids hold inside the final product. The presence of this barrier can chemically isolate reinforced wall from the liquids, increasing its long-time performances.
Alternatively, some mandrels are designed to be fused or disassembled at the end of the process.

The carriage held a series of crossheads which guide the deposition of fibre.
The impregnation is made by means of a bowl full of polymer in which the dry fibres are immersed into the resin.
This process can happen both offside or onside the carriage, depending on the size of bowl itself.

Complex shapes, as in the case of vessels closures, or, generally, to improve the control of the process, require more complex machines with degrees of freedom up to 5.

With this technology is possible to make up not-symmetric composites, as in the case of pipe elbows where the two axes are not coincident.

Figure 40 - Elbow manufacturing process [34]

The main difference consists on the deposition system which evolves, from a simple fixed crosshead on the carriage, to a 3 independent moving axes head, able to handle the direction of the fibres even when the surface curves along the translation axis.
This version of machine can be even adopted for the production of not axial symmetric composites, with a very complex, but always convex, shapes.

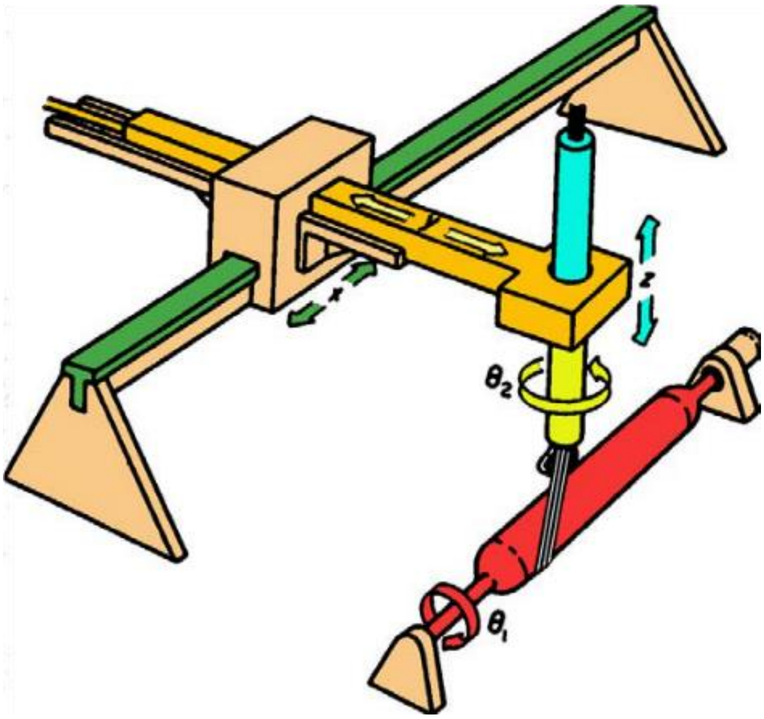

Figure 41 - 5 degrees of freedom filament-winding machine [1]

Furthermore, a traction force is imposed by means of brakes to the fibres under deposition. This force, called *Backtension,* is directed along the fibres and develops a load perpendicular to the surface which compacts the set down fibres to the mandrel, dramatically increasing the friction forces and denying any relative movement.

Figure 42 - Deposition head of a 5 degrees of freedom filament-winding machine [34]

The presence of this force limits the deposition direction range on the given surface.
The deposed fibre by filament-winding may, preferably, be laid along geodetic curves to the surface: this allow to maintain the backtension given during the deposition, developing normal forces to the surface and avoiding sliding forces which would make the fibres instable.
An example of geodetic curves of a series of revolution solids is reported in Figure 43.

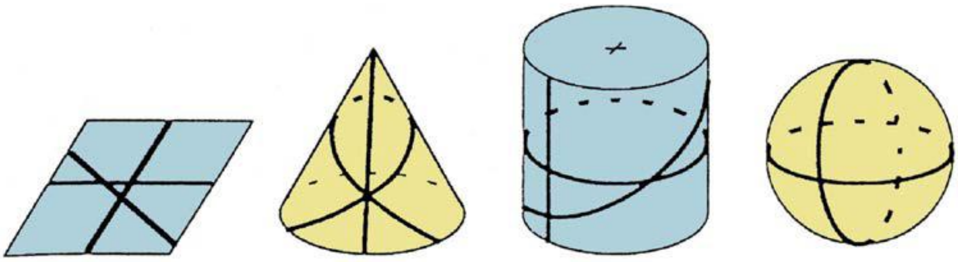

Figure 43 - Example of geodetic curves [1]

In Figure 44, example of geodetic curves in a cylindrical vessel.

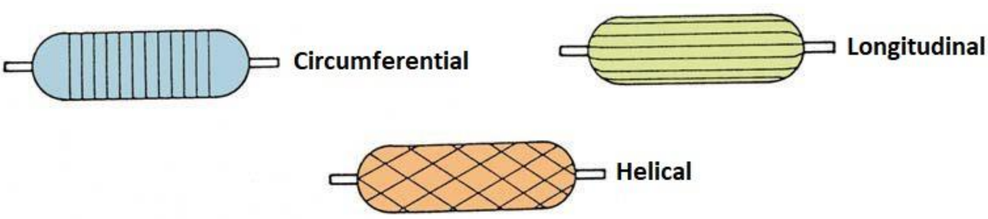

Figure 44 - Example of fibre deposition for a pressure vessel [1]

The helical disposition is adopted also in plain pipe manufacturing.

Since the sum of all the on-plane forces acting on a fibre goes to zero, the backtension within the fibres along all the thickness of the composite produces a radial pressure directed inside the composite according to the Mariotte's equation:

$$P_{bt} = \frac{2\, S_p \;\; \sigma_{bt,tang}}{D}$$

where S_p represents the thickness of the composite wall, D the relative diameter and $\sigma_{bt,tang}$ represents the tangential component of the backtension force in respect to the revolution axis of the solid. a representation of a shaped surface is shown in Figure 45, the pressure P_{bt} is directed in $-\vec{N}$ direction.

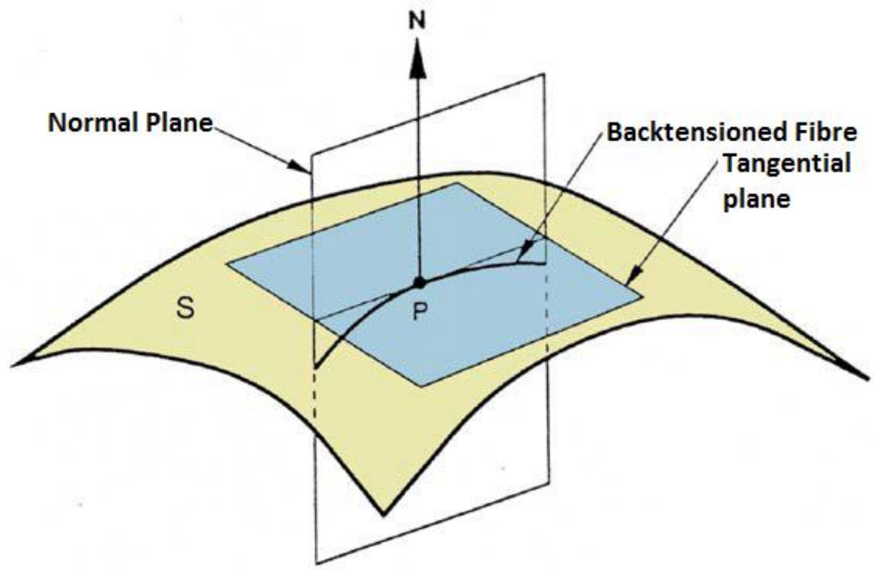

Figure 45 - Portion of curved surface of a mandrel on which back-tensioned fibre is being laid [1]

When design purposes impose a not-geodetic deposition it makes necessary to control the stability of the winding process.
The fibres may tend to slide transversally looking for a more stable laying line.
These kinds of transversal movements would cause a local reduction of thickness in those points where the curvature reaches the highest values, generating structure vulnerability.

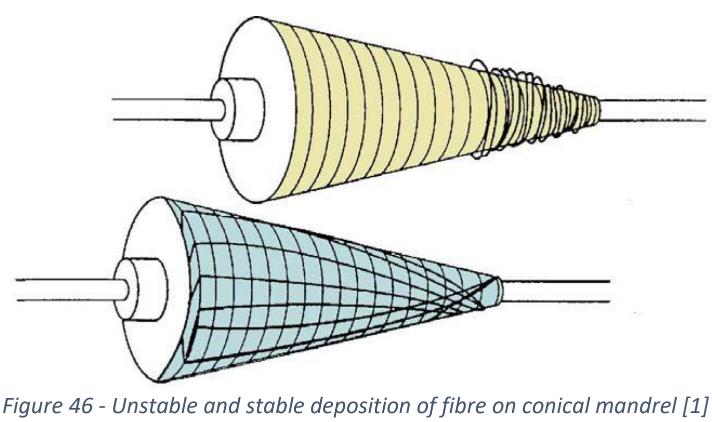

Figure 46 - Unstable and stable deposition of fibre on conical mandrel [1]

This can be avoided by balancing transversal sliding forces with an appropriate friction force on the surface.
The stability of a winded filament depends only from the angle α° between the principal normal of the curves, $\vec{n}$, and the normal $\vec{N}$ to the surface in the point considered.
The stability of the fibre is achieved if:

$$\tan\alpha \leq \mu$$

where μ is the friction coefficient between the fibre and the surface.

Important parameters that influence the friction coefficient are the viscosity of the matrix and the surface quality of the fibres itself. [1].
Finally, the last mentionable parameter to discuss is the single ply thickness. The **single ply thickness**, **SPT**, of a filament-wound laminate defines the numbers of layers needed to reach the designed wall thickness of a axial-symmetric composite.
This parameter may influence the resistance of manufactured pipe to fatigue and depends on several factors:

- The single fibre diameter
- The single-end roving adopted
- The *Back-Tension* applied during the manufacturing, if present
- The viscosity of matrix
- The volume fibre fraction V_f

The value of 0.2 [mm] is a suitable value for the production of glass-fibre reinforced plain pipes subjected to inner pressure[15].

2.1. Advantages and Disadvantages of Filament-Winding Process

The most important advantage of the filament winding process is the cost, which results much lower than other technologies, such hand-lay-up, pre-plied, and tape-laying manufacturing. [29]

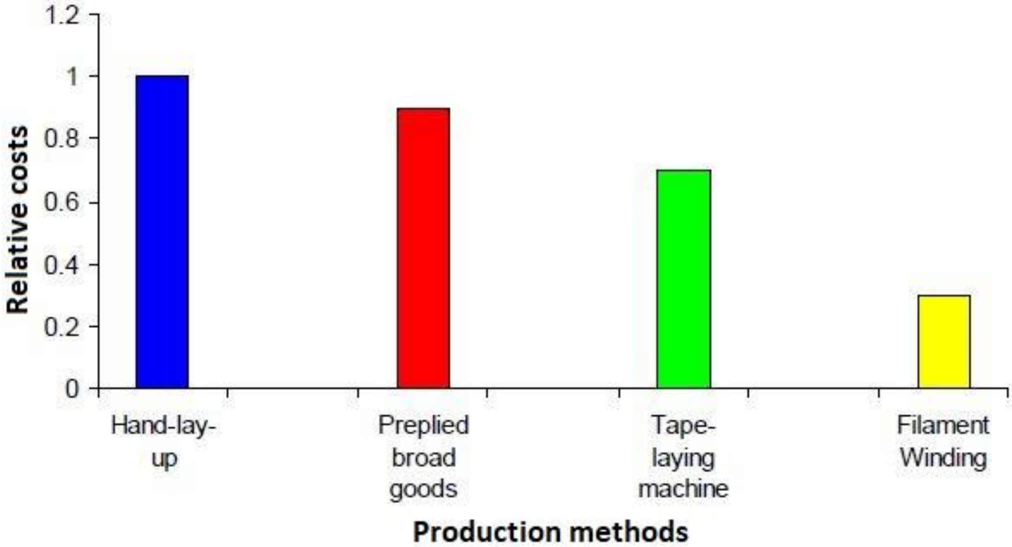

Figure 47 - Relative production costs for different methods of fabrication [29]

[15] This value is highly dependent from project specification. 0.2 [mm] has been chosen reasonably as a default value. Different value may be adopted.

The reduction of costs is because the high deposition speed of fibre.

The advantages of filament winding manufacturing can be summarized as follow:

- High repetitive deposition pattern
- Possibility to use continuous fibres
- Easy deposition of fibre in a wide range direction
- The curing process may not be carried out in autoclave[16]
- Possibility to obtain high volume fraction V_f
- Reduction of cost deriving from the use of not pre-impregnated fibre[17]

Anyway, the process suffers of some drawbacks:

- The manufactured shapes are limited to axial-symmetric or similar
- No concave shape can be manufactured
- The winding-angle variation is difficult and cannot be changed suddenly
- The mandrel may be removable and its cost is relevant

[16] Depending on resin matrix adopted

[17] The use of pre-impregnated fibre is possible and offers an excellent process control concerning the quality of the composite artefact, the volume fraction, and the homogeneity of deposed tape width.

3. Demand Requests

The composite pipes manufacture is the widest filament-winding production sector.
Typical current and potential GRP piping applications concerns the fluid and gas transport and distribution of fuels, oil, gas, chemically aggressive gas, acids, hydrogen, water …

The layout of pipe systems may depend on installation site and purposes.
i.e. the pipe systems for long distance transportation of fluid are very long and may be buried.
On the contrary, pipes for fluid processing are complex supported short sections plus joints, elbows and valves. In both the cases the pipes first and most general purpose is to process a defined quantity of fluid per unit time.

The basic demand parameters needed for a structural design of a composite pipe are:

- The fluid type
- The design pressure
- The nominal diameter
- The maximum operating temperature
- The service lifetime

The filament-winding process parameter which mainly influences the resistance of a pipe to an internal pressure concerns the fibre disposition and is:

- The winding angle $\theta°$

The fluid type, which shall be gas or liquid, impacts on the weight of the installed pipeline; the design pressure is the main cause of stress within the wall pipe.
The operating temperature and the service lifetime modify the performances of the composite and its degradation.
Finally, the winding angle modifies the response of the composite to the load and it could be optimized during the design.

Taking into account the filament-winding process, the chosen materials and the design constraints, it is possible to determine the reinforced wall thickness t_r basing on stress analysis and failure criteria.

3. Design and Simulation with Composites

Since the objective is the design of a plain pipe subjected, mainly, to high inner pressure, the topic of this chapter is the structural design with composites.
The **first topic** of this chapter, looking at the Figure 48, concerns the **composite design** and describes the macro-mechanic of lamina, laminate, and the failure criteria in composite.
The analytical equations needed to describe the stress state within the pipe wall are reported, such as a description of the failure criteria to assess the resistance of the laminate.

The **second topic** concerns the development of a Matlab® tool which simulates the hydrostatic condition of a pipe subjected to inner pressure.
Starting from given manufacturing parameters and requests, the minimum reinforced wall thickness needed to withstand the pressure in accordance with the stress state and composite failure criteria is analytically evaluated.

This **Hydrostatic Simulation Tool, HST**, could be a powerful tool for the designer, who becomes able to give an estimation of the wall thickness needed to withstand the inner pressure as function of manufacturing parameters, and so, to optimize the production.
The script is finally applied to the case of study, and the results are discussed.
A report concerning the validation of the script by mean of numerical simulation performed in Abaqus® closes the chapter.

1. Composite Design

The design with composite material differs from the common design for steel. Even if the failure analysis is similar to the one adopted in steel design[18], the procedure for the determination of state of stress, starting from applied loads, is more complex and articulated.
The aim of this paragraph is to provide the basic information needed to understand the analytical procedure to determine when and how the failure of a composite laminate subjected to general loads occurs.
The Matlab® simulation tools which will be reported later, bases on the following concepts and equations.

A summary of the overall design procedure for composite materials is reassumed in Figure 48.

The first step is the **micromechanics of a lamina**.
It allows to analytically predict the characteristic of a composite layer starting from the single properties of the matrix and the fibre. The prevision theories, such micromechanics and Halpin-Tsai, needs to know the volume fraction V_f of the manufacturing process to compute the lamina values.

[18] Using proper failure criteria which compare strength to state of stress

Both these methods allow the prediction of the elastic and strength properties of the lamina, including the maximum stresses and strains tolerable by each single ply and needed for the application of the failure criteria. This step has been fully threated in the first chapter.

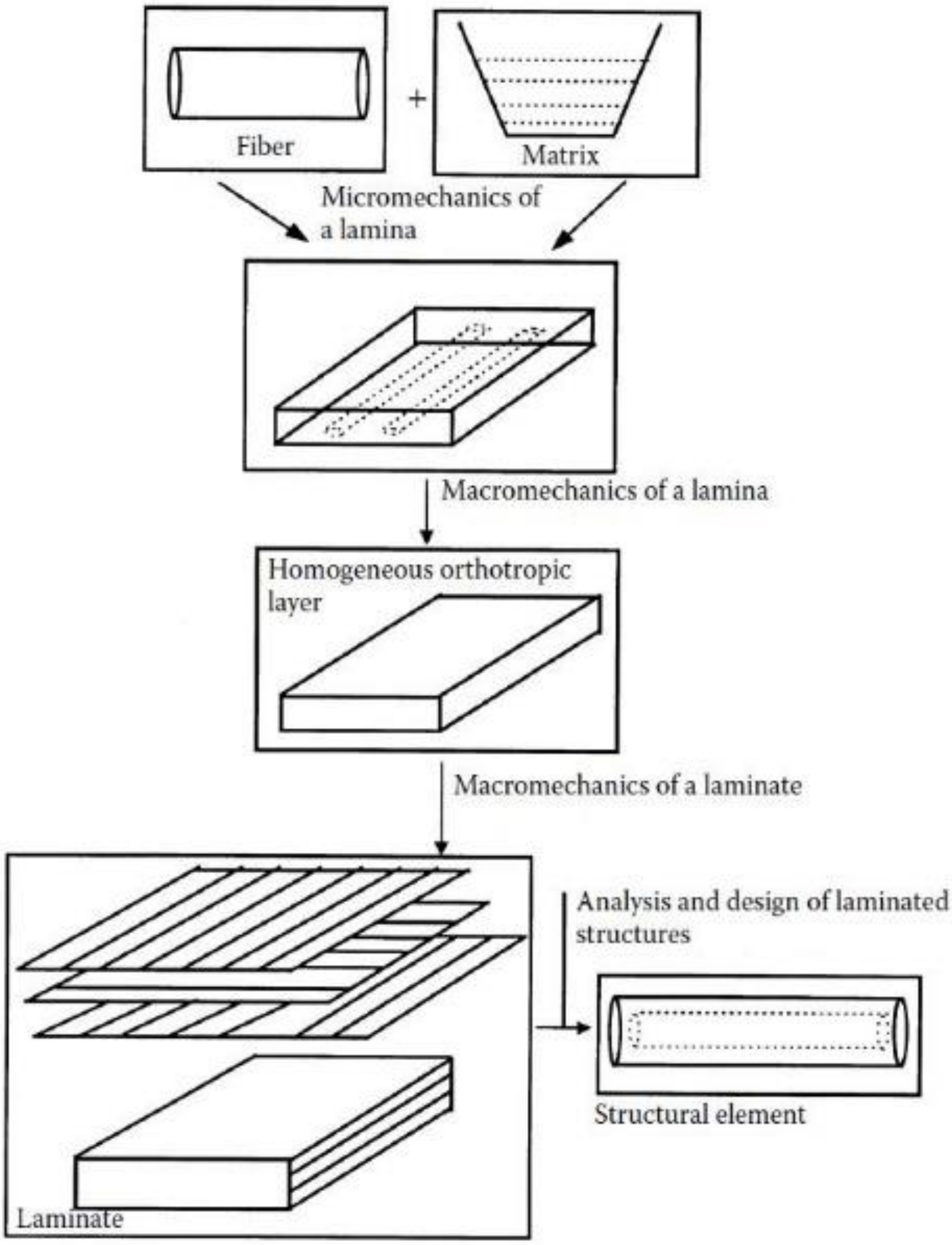

Figure 48 - Summary of design procedures in composites

The **macromechanics of a lamina** gives a mathematical arrangement and the equations needed to describe the mechanical behaviour of the single ply subjected to a general state of stress.
The composite mechanical behaviour, generally completely anisotropic and expressed by a full complete [6x6] Hooke's matrix, can be simplified in the case of a single ply up to a case of a homogeneous orthotropic layer.
The orthotropic hypothesis allows to decrease the elastic parameter from a starting number of 36 to only 4, which are: the longitudinal elastic modulus E_1, the transverse elastic modulus E_2, the major Poisson's modulus ν_{12}, and the in-plane shear modulus G_{12}.

These parameters are among the many can be predicted from micromechanics theories and/or derived by mean of experimental tests.

Several layers compose a composite, so it's necessary to investigate the overall mechanical behaviour of a laminate.
The **macromechanics of a laminate** gives the mathematical arrangement which describe the mechanical behaviour of a composite subjected to a generic state of stress. The constitutive equations for a laminate are recapped into the $ABBD$[19] 6x6 matrix [1].
The computation of $ABBD$ matrix needs the mechanical behaviour of lamina, the lamination sequence of laminate, the thickness and the orientation of each layer of composite.
By mean of $ABBD$ matrix is possible to describe the overall mechanical behaviour of the composite, i.e. the pipe wall.
Adopting this method, the final state of strain of the composite, expressed in Global Reference System (GRS_{xy}), can be computed knowing the loads applied at boundaries of the laminate.

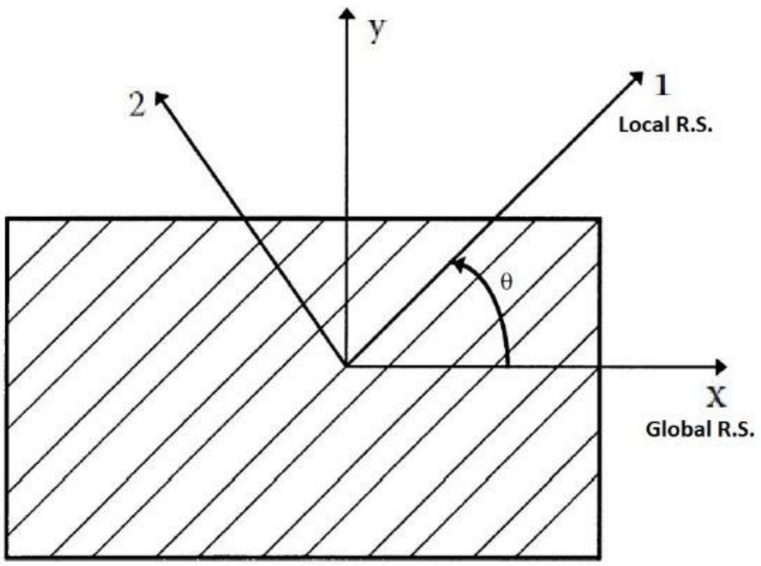

Figure 49 - Global and Local reference systems in composites

Consequently, the analytical evaluation of the strain tensors in the local reference system (LRS_{12}) can be done knowing the orientation of each ply, its thickness, and its position within the laminate.
Then, the Hooke's equations for orthotropic material link the strain tensor to the stress tensor in the LRS_{12} of a ply.
The assessment of each ply is made by means of failure criteria which compare the stresses and strains capacities of the lamina to the stress and strain tensor resulting,
The most used are *Tsai-Hill criterion*, *Tsai-Wu criterion*, *Maximum Stress criterion* and *Maximum Strain criterion*. The assessment occurs when all the failure criteria are verified.

The **design of a laminate based, composite, structure** is made by iterating this procedure until all the assessment is reached for all the laminas within the composite.

[19] The ABBD-matrix characterizes the mechanical behaviour of the laminate [1]

1.1. Mechanical Behaviour of Lamina Loaded in all Directions

Even in the easiest composite structure, such as unidirectional long-fibre lamina subjected to a uniaxial load, the symmetry axis of the material may not be coincident to the direction of load system.

It is so necessary to have a system of equations able to transform stress and strain as a function of the angle of rotation $\theta°$ between fibre and load direction.

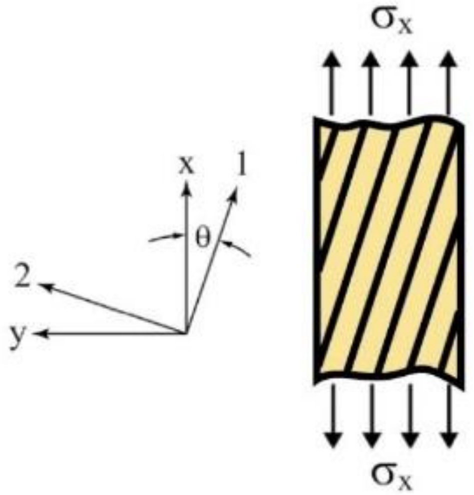

Figure 50 - Definition of the rotation angle of the reference axis of material with respect to the loading direction

The stresses and strains can be transformed into coordinates that do coincide with the principal material direction. This can be accomplished using the free-body diagram in Figure 51 and writing equations in matrix form.

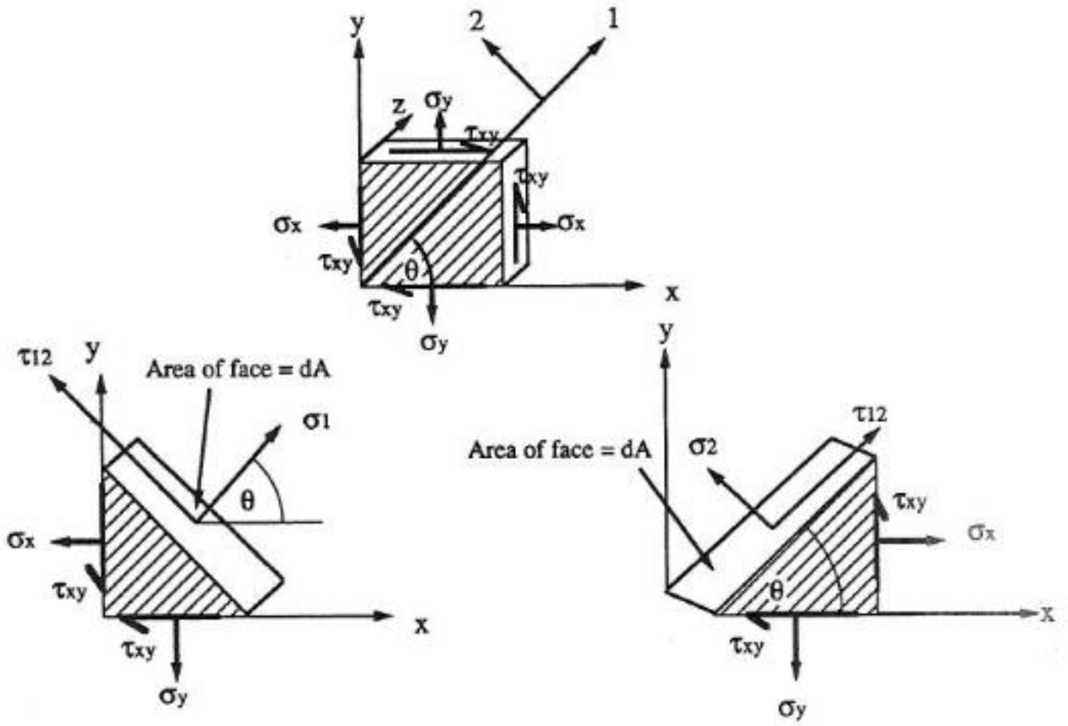

Figure 51 - Coordinate transformation from global to local reference system

$$\begin{vmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{vmatrix} = \begin{bmatrix} cos^2\theta & sin^2\theta & 2sin\theta cos\theta \\ sin^2\theta & cos^2\theta & -2sin\theta cos\theta \\ -sin\theta cos\theta & sin\theta cos\theta & (cos^2\theta - sin^2\theta)\end{bmatrix}\begin{vmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{vmatrix}$$

The 3x3 matrix is called the transformation matrix and is denoted by [T].

The same matrix is used to transform strains.
If a change of coordinates from the 1-2 coordinate system to the x-y coordinate system needs to be performed, the inverse of [T] must be found. This is given by:

$$[T]^{-1} = \begin{bmatrix} cos^2\theta & sin^2\theta & -2sin\theta cos\theta \\ sin^2\theta & cos^2\theta & 2sin\theta cos\theta \\ sin\theta cos\theta & -sin\theta cos\theta & (cos^2\theta - sin^2\theta)\end{bmatrix}$$

Thus:

$$\begin{vmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{vmatrix} = [T]\begin{vmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{vmatrix} \quad \text{and} \quad \begin{vmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{vmatrix} = [T]^{-1}\begin{vmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{vmatrix}$$

$$\begin{vmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{vmatrix} = [T]\begin{vmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{vmatrix} \quad \text{and} \quad \begin{vmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{vmatrix} = [T]^{-1}\begin{vmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{vmatrix}$$

Consequently, substituting in Hooke's equations:

$$\begin{vmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{vmatrix} = [T]^{-1}[Q]\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 2\end{bmatrix}[T]\begin{vmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{vmatrix}$$

Defining a new matrix called the lamina stiffness matrix or "Q-Bar" as:

$$[\bar{Q}] = [T]^{-1}[Q]\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 2\end{bmatrix}[T]$$

1.2. Macromechanics of Laminate

The following assumptions are made[20]:

(1) The laminate thickness is very small compared to its other dimensions.
(2) The lamina (layers) of the laminate are perfectly bonded
(3) Lines perpendicular to the surface of the laminate remain straight and perpendicular to the surface after deformation.
(4) The laminae and laminate are perfectly linear elastic
(5) The through-the-thickness stresses and strains are negligible

[20] These assumptions are valid as long as the laminate is not damaged and undergoes small deflections.

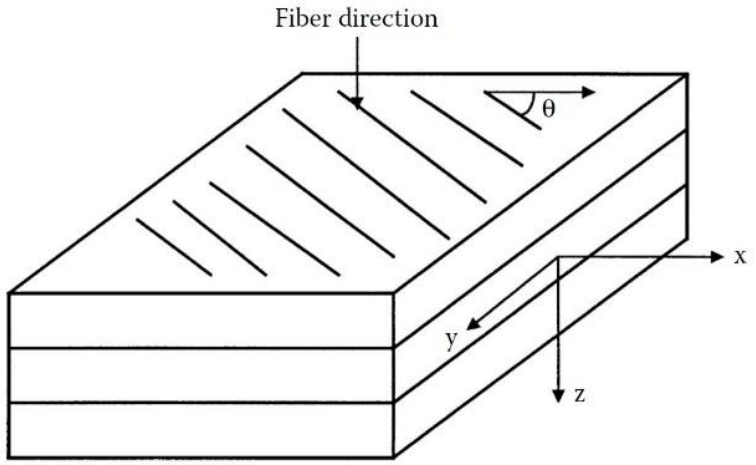

Figure 52 - Composite laminate and global reference system

The calculation of the stresses and strains within single lamina being part of a composite material passes through the concept of laminate already explained.
Knowing the elastic properties of each lamina in addition to its orientation and to the distance from the middle surface, it is possible to derive the constitutive equations for the laminate.
Constitutive equations allow the calculation of strains related to the overall laminate subjected to external forces.

In matrix form, these equations can easily be written as:

$$\begin{vmatrix} N_x \\ N_y \\ N_{xy} \\ M_\mathrm{x} \\ M_\mathrm{y} \\ M_\mathrm{xy} \end{vmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{21} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{vmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ K_\mathrm{x} \\ K_\mathrm{y} \\ K_\mathrm{xy} \end{vmatrix}$$

where:

N_x N_y N_{xy} represent the in-plane loadings applied on boundaries as shown in Figure 53

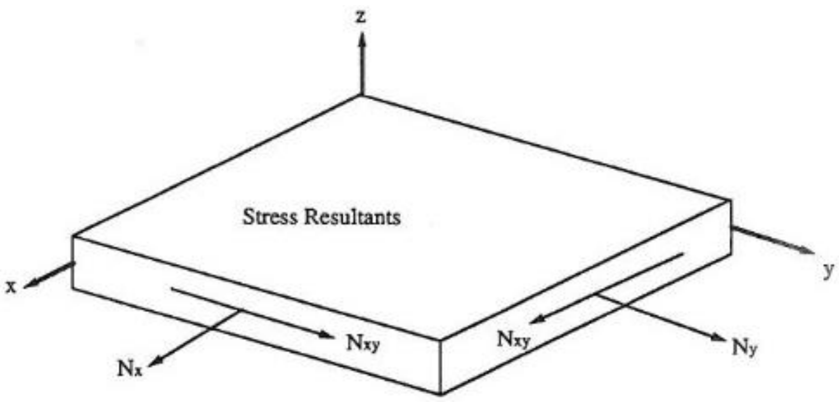

Figure 53 - Stress-resultants from in-plane loads

M_{x} M_{y} M_{xy} represent the boundary moments as shown in Figure 54

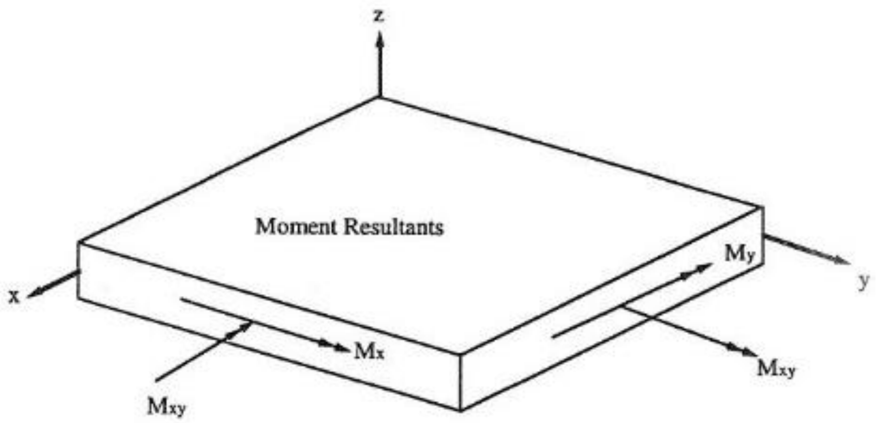

Figure 54 - Stress-resultants form boundary moments

ε_x^0 ε_y^0 γ_{xy}^0 represent the middle surfaces strains

K_{x} K_{y} K_{xy} represent the middle surfaces curvatures

and the coefficients A_{ij} B_{ij} D_{ij} are calculated as:

$$A_{ij} = \sum_{k=1}^{n} \left[\bar{Q}_{ij}\right]_k (h_k - h_{k-1})$$

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{n} \left[\bar{Q}_{ij}\right]_k (h_k^2 - h_{k-1}^2)$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n} \left[\bar{Q}_{ij}\right]_k (h_k^3 - h_{k-1}^3)$$

where h refers to the distance of the k lamina from the middle surface, as shown in Figure 55

Written in contracted form the equation becomes:

$$\begin{vmatrix} N \\ M \end{vmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{vmatrix} \varepsilon^0 \\ K \end{vmatrix}$$

This can be partially inverted to give:

$$\begin{vmatrix} \varepsilon^0 \\ K \end{vmatrix} = \begin{bmatrix} A^* & B^* \\ C^* & D^* \end{bmatrix} \begin{vmatrix} N \\ M \end{vmatrix}$$

where

$$[A^*] = [A]^{-1}$$
$$[B^*] = -[A]^{-1}[B]$$
$$[C^*] = [B][A]^{-1}$$
$$[D^*] = [D] - [B][A]^{-1}[B]$$

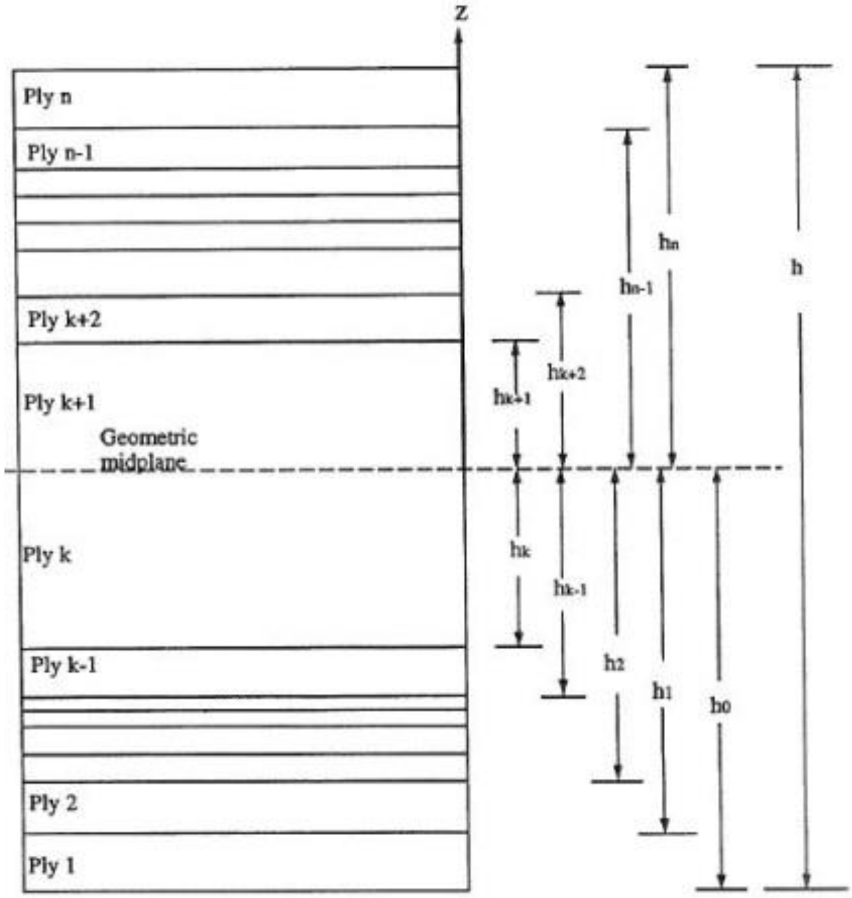

Figure 55 - Identification of single plies within a laminate
Note that ply k and ply k+1 are the same lamina, but are separated into two plies by the geometric plane

The fully inverted form is the most often used form of the laminate constitutive equations, because it allows the evaluation of the strain state of the overall laminate starting from the known loading conditions.

$$\begin{vmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ K_\mathrm{x} \\ K_\mathrm{y} \\ K_\mathrm{xy} \end{vmatrix} = \begin{bmatrix} A_{11}' & A_{12}' & A_{16}' & B_{11}' & B_{12}' & B_{16}' \\ A_{21}' & A_{22}' & A_{26}' & B_{21}' & B_{22}' & B_{26}' \\ A_{16}' & A_{26}' & A_{66}' & B_{16}' & B_{26}' & B_{66}' \\ C_{11}' & C_{12}' & C_{16}' & D_{11}' & D_{12}' & D_{16}' \\ C_{21}' & C_{22}' & C_{26}' & D_{21}' & D_{22}' & D_{26}' \\ C_{16}' & C_{26}' & C_{66}' & D_{16}' & D_{26}' & D_{66}' \end{bmatrix} \begin{vmatrix} N_x \\ N_y \\ N_{xy} \\ M_\mathrm{x} \\ M_\mathrm{y} \\ M_\mathrm{xy} \end{vmatrix}$$

where:

$$[A'] = [A^*] - [B^*][D^*]^{-1}[C^*]$$
$$[B'] = [B^*][D^*]^{-1}$$
$$[C'] = -[D^*]^{-1}[B^*]$$
$$[D'] = [D^*]^{-1}$$

In the case of in-plane loading conditions without moments, the curvature terms simplify, the middle surface strains $\varepsilon_x^0\ \varepsilon_y^0\ \gamma_{xy}^0$ can be substituted by the laminate strains $\varepsilon_x \varepsilon_y\ \gamma_{xy}$ as these are constant along all the thickness of the laminate, and the matrix becomes:

$$\begin{vmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{vmatrix} = \begin{bmatrix} A_{11}' & A_{12}' & A_{16}' \\ A_{21}' & A_{22}' & A_{26}' \\ A_{16}' & A_{26}' & A_{66}' \end{bmatrix} \begin{vmatrix} N_x \\ N_y \\ N_{xy} \end{vmatrix}$$

[11] [13].

Hence the laminate strains in the case of in-plane stresses are equivalent to the lamina ones and just evaluated. It is now possible to perform the failure assessment by means of stresses and strains based criteria for each lamina.

1.3. Modes of Failure

Failure of composite laminates is a very complicated matter. Despite this, failure prediction models should be simplified, since accounting for all the different physical phenomena which occur in the failure process would be too complicated.
Failure may occur in several different ways depending on the state of stress and composite nature.
In the case of polymer-glass reinforced composites the modes of failure which most often occur are the follow.

- **Longitudinal tensile failure**

The longitudinal tensile failure of lamina occurs when the stress along the longitudinal direction to the fibre reaches the longitudinal tensile strength of lamina.

- **Transverse tensile failure**

The transverse tensile failure of the lamina, also called *weeping,* occurs when the stress along the transverse direction to the fibre reaches the transverse tensile strength of the lamina.
The composite may fail due to the failure of the matrix between the fibres or due to the breach of the matrix-fibre interface.
This mode of failure is the most common in the case of pipe under inner pressure loading. [15]

- **In-plane shear failure**

the in-plane shear failure occurs when the laminate is subjected to a shear stress higher than its in-plane shear strength.

1.4. Failure Criteria

The purpose of the failure criteria is to compare the stress or strain state of the on-axis lamina to its strength, in order to determine if the lamina is going to fail due to the applied loads.
The failure criteria define the allowable stress state, while the stiffness relationships above described allow the stress and strain state of the laminate to be determined, and so, the single lamina one.
A schematic representation of a generic failure criterion is reported in Figure 56

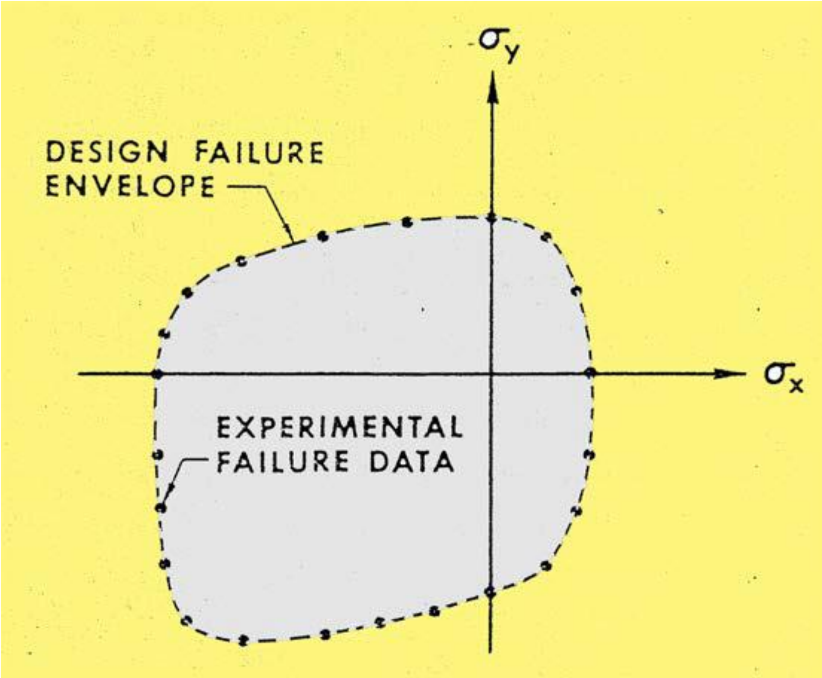

Figure 56 - Schematic representation of a failure criterion [1]

States of stress inside the failure envelope will not provoke failure.
Furthermore, a failure criterion is required to consider the effects of the multiaxial state of stress. Many failure criteria exist and the most used are the *Maximum Stress*, *Maximum Stress*, *Tsai-Hill* and *Tsai-Wu* theories. [13]

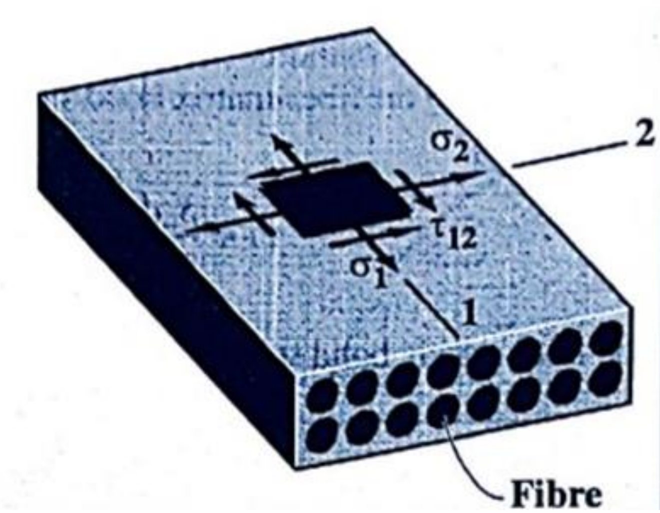

Figure 57 - State of stress of a single lamina [1]

1.4.1. Maximum Stress Criterion

The *Maximum stress criterion* and the *Maximum strain criterion* permit to determine in which way the composite will fail under specific state of stress.

In order to be assessed, the *Maximum stress* criterion defines that the stresses in each one of the material principal direction must be less than the respective strength, otherwise failure is assumed to occur.

The equations to verify are:

$$-S_1^c < \sigma_1 < S_1$$

$$-S_2^c < \sigma_2 < S_2$$

$$|\tau_{12}| < S_{12}$$

In the *Maximum Stress* criterion, each stress component is considered independently, resulting in three sub-criteria.
This allows to qualify the mode of failure of the composite.

1.4.2. Maximum Strain Criterion

This criterion derives directly from the analogue criterion defined for isotropic materials and considers as warning index the maximum strain.
To avoid failure, the below conditions must be verified:

$$-(\varepsilon_1)_{ult}^c < \varepsilon_1 < (\varepsilon_1)_{ult}$$

$$-(\varepsilon_2)_{ult}^c < \varepsilon_2 < (\varepsilon_2)_{ult}$$

$$|\gamma_{12}| < \gamma_{12,lim}$$

This criterion can be also expressed as function of stresses:

$$-S_1^c < \sigma_1 - \nu_{12}\sigma_2 < S_1$$

$$-S_2^c < \sigma_2 - \nu_{21}\sigma_1 < S_2$$

$$|\tau_{12}| < S_{12}$$

As for the previous criterion, it is possible to qualify the mode of failure of the composite by analysing the inequalities one by one.

1.4.3. Tsai-Hill Criterion

Hill has derived his criterion from the Von Mises criterion, based on distortion energy definition, to apply it to anisotropic materials.
At a later time, Tsai has extended Hill criterion to the case of orthotropic laminas.
The failure criterion is defined as a function of stresses and strengths, whose value must be less than 1 to avoid failure.

$$\frac{{\sigma_1}^2}{{S_1}^2} - \frac{\sigma_1\sigma_2}{{S_1}^2} + \frac{{\sigma_2}^2}{{S_2}^2} + \frac{{\tau_{12}}^2}{{S_{12}}^2} < 1$$

Considering that the lamina state of stress is always plane, thus $\sigma_3 = \tau_{31} = \tau_{32} = 0$.
The Figure 58 represents also the Tsai-Hill criterion, which appears to be symmetric with respect to the origin because it considers a symmetric behaviour of material.
In the case of non-symmetry of material behaviour, it is possible to consider, within Tsai-Hill criterion, the compression value of yield stress and state of stress in place of tensile ones. Consequently, the failure curve will not be symmetric to origin anymore.

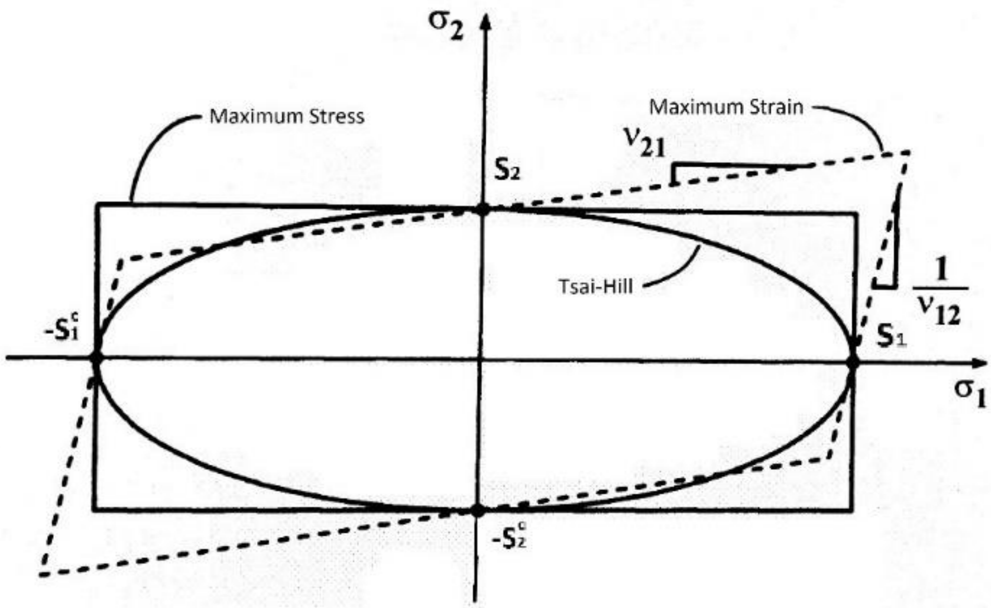

Figure 58 - A comparison between the Maximum stress, Maximum strain and Tsai-Hill criteria in case of in-plane state of stress

1.4.4. Tsai-Wu Criterion

Tsai-Wu criterion, also called *Tensor Polynomial Criterion*, is widely used, and can be written in its most general form as:

$F_{ij}\sigma_i\sigma_j + F_i\sigma_i < 1$ where: i,j = 1 to 6

In the case of plane stress and orthotropic material i,j = 1,2,6 ($\sigma_6 = \tau_{12}$) and $F_{16} = F_{26} = F_{66} = 0$
Thus, the expanded form becomes:

$$F_{11}{\sigma_1}^2 + F_{22}{\sigma_2}^2 + F_{66}{\tau_{12}}^2 + 2F_{12}\sigma_1\sigma_2 + F_1\sigma_1 + F_2\sigma_2 < 1$$

where 5 over 6 strength parameters can be obtained from simple mechanical test:

$$F_1 = \frac{1}{S_1} - \frac{1}{S_1^c}$$
$$F_2 = \frac{1}{S_2} - \frac{1}{S_2^c}$$
$$F_{11} = \frac{1}{S_1 S_1^c}$$

$$F_{22} = \frac{1}{S_2 S_2^c}$$
$$F_{66} = \frac{1}{{S_{12}}^2}$$

Hence, the sixth parameter F_{12} requires a combined stress or biaxial load case to be evaluated.
Another, more convenient, way to obtain this parameter is to impose that the criterion must represent a closed curve, avoiding infinite values of strengths.
The normalized interaction term is so defined as:

$${F_{12}}^* = \frac{F_{12}}{\sqrt{F_{11}F_{22}}} \qquad \text{and so:} \qquad F_{12} = {F_{12}}^* \sqrt{F_{11}F_{22}}$$

Normalized interaction term must be $-1 < {F_{12}}^* < 1$ in order, for the criterion, to represent an ellipse rather than parallel lines or a hyperbola.
In practice, it results very difficult to experimentally obtain F_{12}. Therefore, this coefficient is often arbitrary set to a fixed value such as -0.5 or 0. [11]

Combining all the equations, the criterion takes the form:

$$\frac{{\sigma_1}^2}{S_1 S_1^c} + \frac{{\sigma_2}^2}{S_2 S_2^c} + \frac{{\tau_{12}}^2}{{S_{12}}^2} + 2F_{12}\sigma_1\sigma_2 + \frac{\sigma_1}{S_1} - \frac{\sigma_1}{S_1^c} + \frac{\sigma_2}{S_2} - \frac{\sigma_2}{S_2^c} < 1$$

In the case of zero shear stress, the criterion can be plot as below:

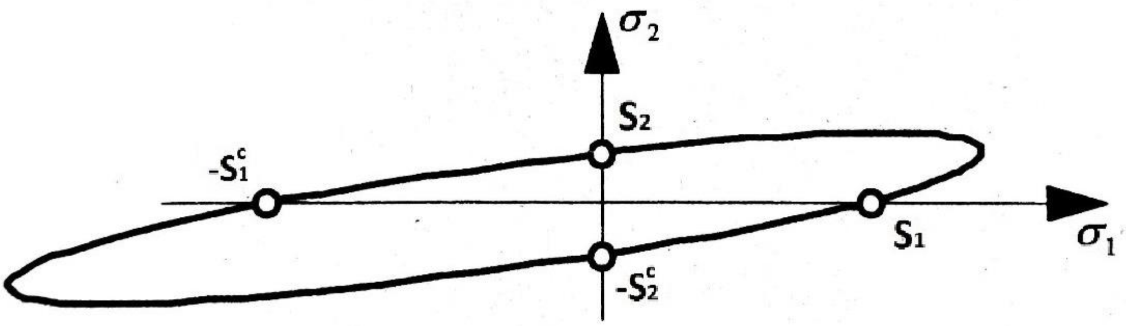

Figure 59 - Representation of Tsai-Wu criterion in principal stress directions [11]

2. Simulation of Hydrostatic Stress Condition of a Plain Pipe

After analysing the general design process concerning the composite material, the theories described above are applied for the creation of a computed tool specially developed for the design and verification of plain pipe under inner pressure.
Below, the descriptions of the:

- State of stress of a pipe under hydrostatic condition
- Structure of the HST – Hydrotest Simulation Tool
- Design with HST

2.1. State of stress of a pipe under hydrostatic condition

The stress state of the reinforced wall of a pipe under inner pressure far enough from the boundaries (that is of interest for this thesis) is generally triaxial.
The inner pressure may induce circumferential, radial, and axial stresses, whose values depend on the design constraints.
The determination of the stresses within the pipe wall bases on equilibrium equation. The pipe is modelled with closure ends and can be so treated as a pressure vessel.
The longitudinal stress is analysed by cutting the tube perpendicularly to its axis.
To maintain the half pipe portion in static equilibrium, axial stress within the wall must withstand the inner pressure. Indicating with x the axial direction:

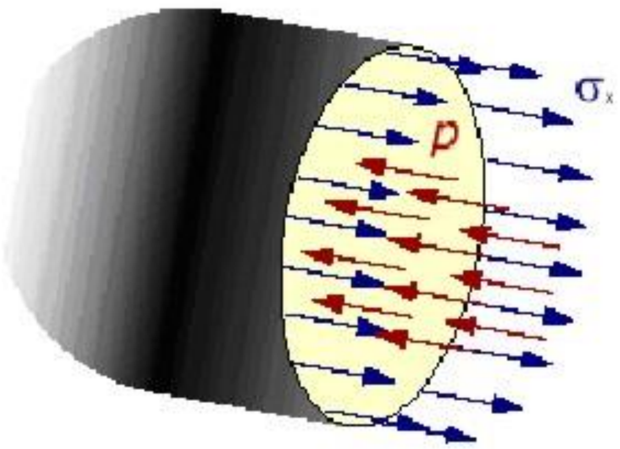

Figure 60 - Axial equilibrium of a pipe under inner pressure loading [28]

$$\sigma_x t_r \pi D = p\pi \frac{D^2}{4}$$

where p indicates the inner pressure, D the internal diameter of tube, and t_r the wall thickness.
The σ_{ap}, axial stress due to inner pressure p is equal to:

$$\boldsymbol{\sigma_{ap}} \equiv \sigma_x = \frac{pD}{4t_r}$$

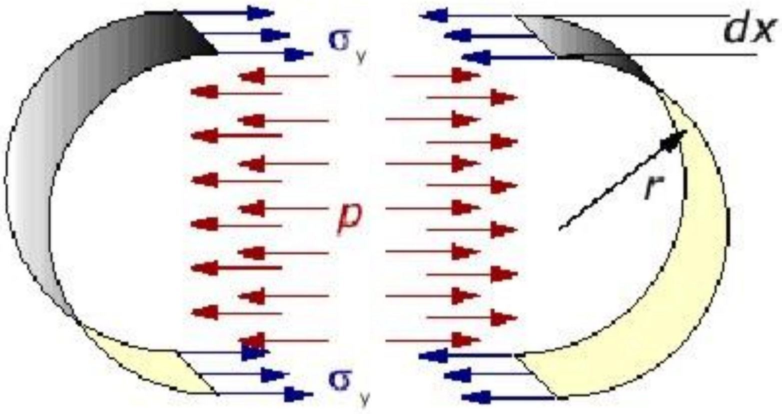

Figure 61 - Lateral equilibrium of a pipe under inner pressure loading [28]

Similarly, by cutting the pipe with a plane which passes through the pipe axis, as in the Figure 61 and imposing the static equilibrium, the following equation defines the stress in circumferential y direction:

$$2\sigma_y t_r \, dx = pD \, dx$$

The σ_{hp}, hoop stress due to inner pressure p is equal to:

$$\boldsymbol{\sigma_{hp}} \equiv \sigma_y = \frac{pD}{2t_r}$$

The Mariotte's equations, just obtained, allow an easy calculation of the average stresses within the pipe wall. The equations can be applied in the case of pressure vessels until the thickness to diameter ratio $\frac{t_r}{D}$ is less than 0.10.
When $\frac{t_r}{D}$ > 0.1, the stresses within the wall thickness vary, and the Mariotte's equations may no longer be a valid design model. A more complex calculation of the whole state of stress is therefore required.

Since the pipe systems may be locally supported, the state of stress may vary depending on the boundary constraints. The extreme conditions are two:

1) The pipe is long and has no top and bottom closures. The longitudinal displacement (contraction) is allowed. In this case, the inner pressure generates only the circumferential stress, while the axial is equal to zero.
   This condition rarely happens.

2) The pipe has closures and the axial displacement is allowed (unrestrained closures case). So, it can be treated as a common pressure vessel. The stresses come only due to internal pressure and are equal to σ_{hp} and σ_{ap}.

More generally, it is possible to define overall the state of stress of pipe wall introducing the ***R Loading Ratio***, defined as the ratio between the axial and hoop stress.

$$R = \sigma_h / \sigma_a$$

where σ_a and σ_h are the overall axial and hoop stresses acting on pipe due to pressure and to the constraints.
The *Loading Ratio* in the case of long unrestrained-ends pipe (1) is equal to 1:0, while in the case of pipe with unrestrained closures (2) is equal to 2:1 constrain.

The presence of axial constraints along the pipe may modify the *Loading Ratio* which places between the two extreme cases values.
If the pipe is subjected to a traction loading, like in the case of vertical installation, the *Loading Ratio* increases over the 2:1 value.

Facility pipe systems for high pressure and gas transportation, main object of this work, ought to have *Loading Ratios* up to 2:1 depending mainly on the axial containments. Other loadings which may induce stresses, like weight and support deflection, slightly influence the stress state of these thin wall kind of pipes.

2.2. HST – Hydrostatic Simulation Tool

The simulation tool, Matlab® developed, is based on the composite theories explained previously and allows the analytical evaluation of the minimum reinforced wall thickness for a pipe subjected to a hydrostatic loading, correspondent to a *loading ratio* $R = 2{:}\,1$.

For the definition of the composite material, the HST incorporates the APT threated into chapter 1, which allows the prevision of the lamina properties starting from a given matrix and fibre.

Figure (61) shows the operation diagram followed by the Matlab® software HST for the definition of the minimum pipe wall thickness.

The HST structure is iterative. Starting from a close-to-zero wall thickness, the script calculates the correspondent state of stress for the considered, temporary, wall thickness. Then, it applies the failure criteria; if even just one of the failure criteria is not verified, the software increments the thickness.

The process is repeated until the all the failure criteria verify the assessment.

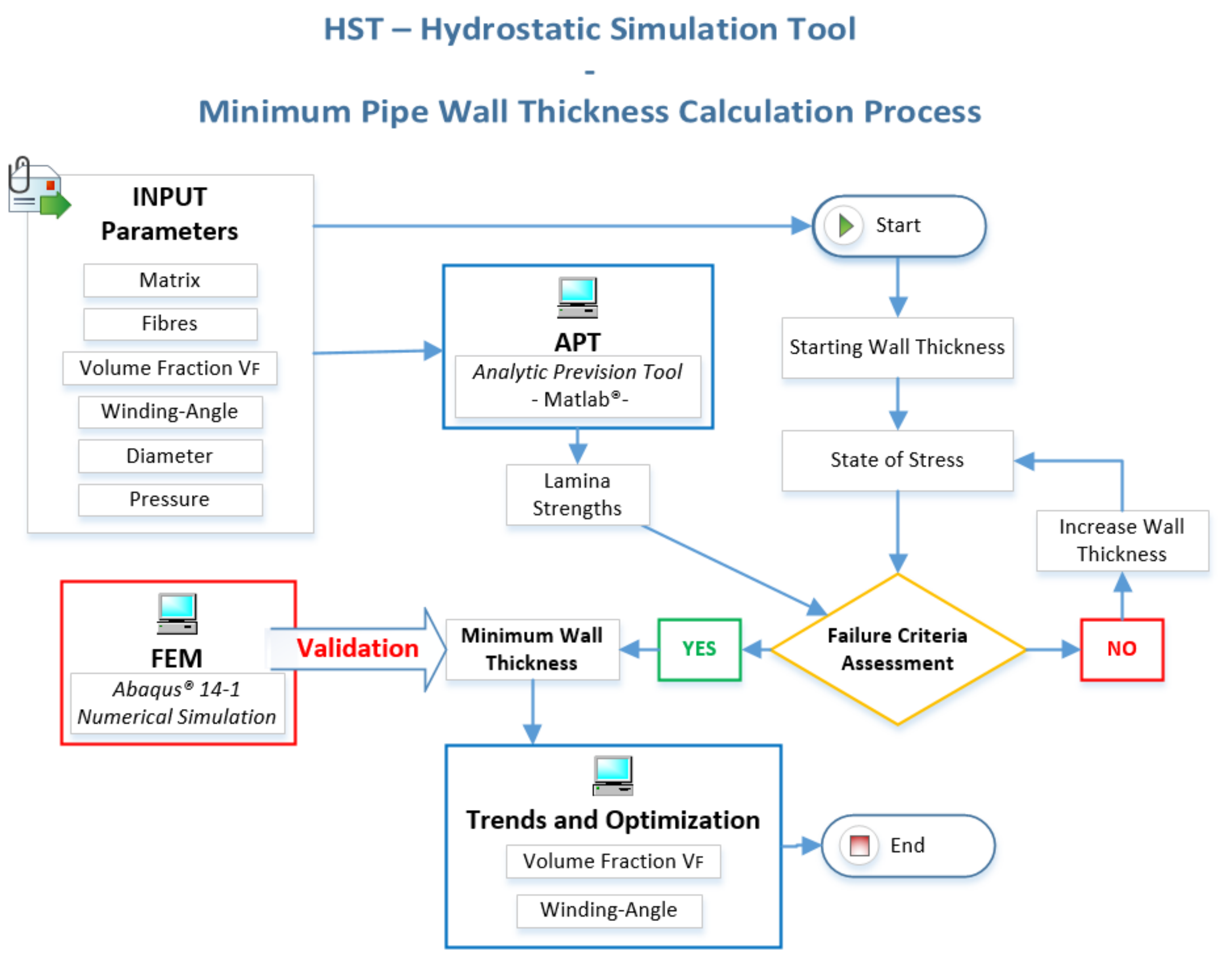

Figure 62 - Operation diagram of the HST

When the iterative process increases the thickness, it considers the pattern drawn of a filament-winding process by adding a couple of layers a time, which correspond to $\pm\theta°$ winding angled plies.
So, the full laminate is composed by couples of plies disposed at $\pm\theta°$ winding angle, whose value θ is constant.
Since the Single Ply Thickness (SPT) is a finite value, it means that the thickness has increments equals to $2 \cdot SPT$[21]. Especially, when the tested pressures and/or the diameters of pipes are low, the thickness may be sufficient to withstand to the increment imposed.

The inputs of the simulation are:

Demand HST Input Parameters	**Symbol**	**Unit**
Inner Diameter	ID_r	[mm]
Internal Pressure	P	[MPa]
Winding-angle	$\theta°$	[Deg°]
Material Parameters		
Volume Fraction	V_f	-

Table 15 - Input parameters of HST

[21] Filament-winding consists in a disposition of a couple of ply at a time. A ply cannot be singularly deposited.

The outputs of the HST are:

HST Outputs	Symbol	Unit
Minimum reinforced wall thickness	t_r	[mm]
n° of Layers	N	
Maximum stress criterion	index	-
Maximum strain criterion	index	-
Tsai – Hill criterion	index	-
Tsai – Wu criterion	index	-

Table 16 - Output values of HST

The program shall be used by the designer to investigate the effectiveness of the parameters occurring in the plain pipe design process, such as the winding angle and the volume fraction.

The matrix and fibres chosen are the same of the APT, which properties are reported in Table 11 and Table 11[22].

The hydrostatic simulation tool has been developed to be flexible and user friendly.
Three different modes of use have been developed:

1) **Punctual Simulation**

The HST determines the minimum reinforced wall thickness for given fixed values of the main four input parameters.
The program calculates the indexes for all the failure criteria considered in each iteration. These values are plotted as function of the layer number, and so as function of the thickness values considered during the simulation.
An example of these plots is given in Figure 63.

The failure indexes of Tsai-Hill and Tsai-Wu, as explained in failure criteria paragraph, declare that the lamina withstand the state of stress if the value is less than 1.

The maximum stress and maximum strain criteria are subdivided into the three sub-criteria. This allows to identify which is the last equation of the criterion to be validated, and so, to determine which is the failure mode of the composite when the stress state increases.
Maximum stress and strain failure indexes are considered binary: 0 if the criterion (sub-criterion) is not verified and 1 when the criterion becomes verified since the thickness increment.

[22] Each single property of matrix and fibre could be considered an input variable. For the purposes of this work, the matrix and fibre properties consider to be given and fixed.

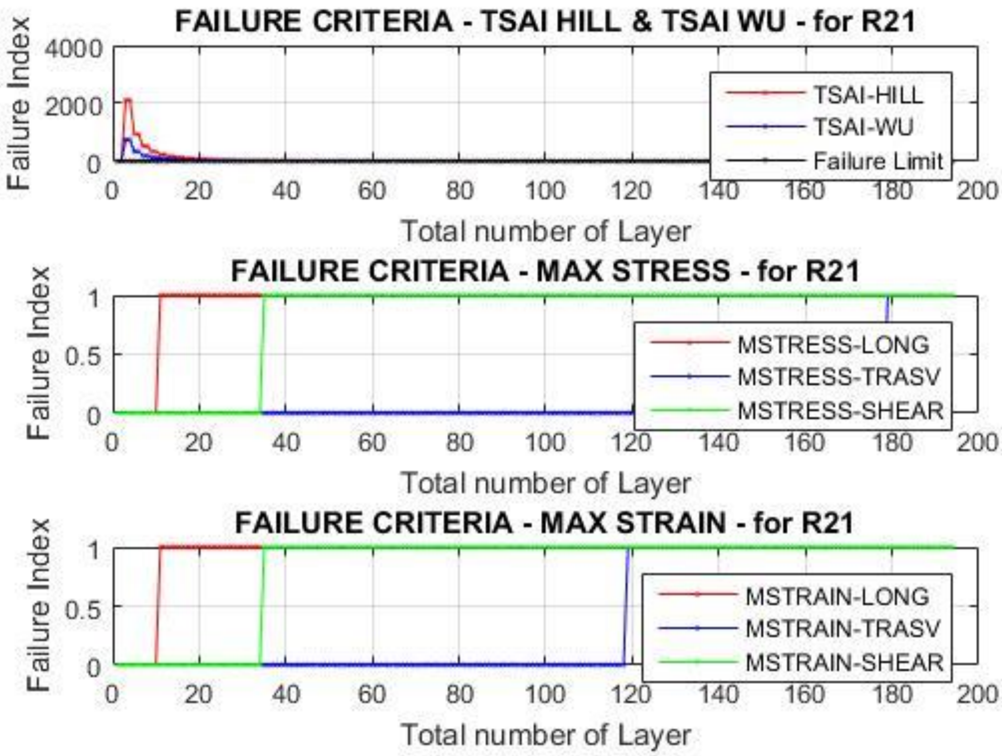

Figure 63 - Failure indexes plot for HST - Punctual Simulation – 400 [mm] diameter pipe at 12 [MPa].

Finally, the values of the all failure indexes are reported for the final wall thickness identified by the simulation. This allows to determine which is the last failure criterion to be verified.
An example of the values is reported in Table 17.

Failure Indexes		
MaxStress – Longitudinal	MaxStress – Transversal	MaxStress – in-plane Shear
MaxStrain – Longitudinal	MaxStrain – Transversal	MaxStrain – in-plane Shear
Tsai – Hill		
Tsai - Wu		

Table 17 - Summary of failure indexes

The plots in Figure 63 and the Table 18 reassume the punctual HST input and outputs, for the case of a plain pipe of 400 [mm] inner diameter, loaded at 20 [MPa], for a composite characterized by the given matrix and fibre, winding-angle $\pm 55°$ [deg] and volume fraction V_f=0.6 and stress ratio 2:1.

Input Parameters				**Failure Indexes**				**Outputs**		
ID_r	400	[mm]		1	1	1		Wall Thickness	38.8	[mm]
P	20	[MPa]		1	1	1		n° of Layers	194	-
$\theta°$	55°	[deg°]		TH 0.8965						
V_f	0.6	-		TW 0.9987						

Table 18 - Summary of punctual HST parameters, inputs and outputs.

The calculated values for this simulation show that the minimum reinforced wall thickness and the number of plies are respectively 38.8 mm and 194.
The more restrictive failure criterion is Tsai-Wu, which is the last to be validated, in fact the corresponding value of Tsai-Hill is the lowest among the considered criteria. This can be also evidenced by zooming the plot trends.

Finally, in the case of pipe subjected to inner pressure and in case of increment of the inner pressure, the failure shall occur due to the failure in the direction transversal to the fibre.
This conclusion comes graphically. In fact, looking at the maximum stress indexes, the last sub-criterion to be validated at 180 layers is the one in the transversal direction, blue line.
This is valid, and limited, to the considered composite material.

2) One-variable Simulation

The HST calculates the minimum reinforced wall thickness and all the outputs as in the case of the punctual simulation, where three input parameters are fixed and one varies within a given range.
The output wall thicknesses evaluated are represented as 2D plots.

3) Two-variables Simulation

The HST calculates the minimum reinforced wall thickness and all the outputs as in the case of the One-variable Simulation, where two input parameters are fixed and two other vary within a given range.
The output wall thicknesses evaluated are represented as a surface on a 3D plots.

2.2.1. HST - Limitations

The developed tool is limited to a structural quasi-static simulation, performed at standard laboratory temperature.
The **temperature effect** on material properties is not taken into account.
The model which describes the behaviour of the composite at high temperature is material specific and requires experimental testing to determine the slope of this dependency. Furthermore, the use of epoxies or general thermoset resins means that the mechanical performance of the composite slightly increases with the temperature. [1]
For these reasons, the simulation at ambient temperature would be considered more severe than at high temperature[23].
The HST is not **time dependant**.
The simulation is performed as quasi-static, no dynamic is considered, and no material degradation is taken into account.
The models which describe the dependency of the composite mechanical properties with respect to the time, due to degradation effects, are very complex. They require experimental testing to be well applied and are material specific.

[23] Temperature which not reaches the glass transition temperature T_g and remains much lower than it.

For these reasons, the time has not been considered in the simulation.
This represents a lack in the simulation process, a gap which can be fixed by means of experimental tests on the composite material, in the final stage of the design project.

The last limitation concerns the pattern variability. The pipe wall is intended to be produced by using the same winding angle for all the couple of layers which form the pipe, so the orientation pattern can be expressed as $[\theta°]_n$, where n represents the number of couple of layers.

This choice allows to limit the pattern optimization of pipe wall under loading, one of the topics of this work, to the optimization of a single parameter, the winding angle.
So, the degrees of freedom under studying result to be four: Diameter, Pressure, Volume Fraction and Winding Angle.

2.2.2. HST – Abaqus® Numerical Cross-Check

The HST, hydrostatic simulation tool, which simulates the response of a pipe under inner pressure, calculating the reinforced pipe wall thickness, has been cross-checked with a numerical simulation performed in Abaqus®.

The cross-check process is performed comparing the minimum wall reinforced thickness calculated by the HST to the one calculated by means of the numerical model.

This paragraph is dedicated to the description of the numerical model of the pipe. The used software is Abaqus® version 6.14. The model is created assuming the following hypothesis:

- The properties of the resin of the matrix and E-glass corrosion resistant (E-CR) fibres are the used for the APT simulation. The characteristics are reassumed in Table 11 and Table 12, and reported here.

Matrix Type	**Epoxy**		
Property	**Symbol**	**Value**	**Unit**
Elastic modulus	E_m	2470	[MPa]
Shear modulus	G_m	877	[MPa]
Poisson's ratio	ν_m	0.41	-
Density	ρ_m	1400	[Kg/m^3]
Tensile strength	S_m	71.7	[MPa]
Compressive strength	S_m^c	172	[MPa]
In-plane shear strength	$S12_m$	41.4	[MPa]

Table 11 - Matrix properties

Fibre Type	EC-R Glass		
Property	**Symbol**	**Value**	**Unit**
Elastic modulus	E_f	81000	[MPa]
Shear modulus	G_f	32926	[MPa]
Poisson's ratio	ν_f	0.23	-
Density	ρ_f	2500	[Kg/m^3]
Tensile strength	S_f	3450	[MPa]
Compressive strength	S_f^c	4500	[MPa]
In-plane shear strength	$S12_f$	3450	[MPa]

Table 12 - Glass fibre properties

- In order to generate the material properties of the lamina and thus the laminate, the APT, Analytical Prevision Tool, is used, considering as fiber content in volume 60%, which is a typical value reachable by filament-winding.
- Linear elastic mechanical behavior of the composite up to failure.
- The pattern deposition is $[\pm 55°]_n$. This inclination is optimized for the case of circumferential and axial stresses (ratio 2:1) which raise for pipes and pressure vessels. Ply thickness is set to 0.2 mm, that can be characteristic of the rotor-moulding manufacturing process. Figure (63) shows the stacking sequence.
- The finite elements selected for the model are shells. Figure 64 shows the geometry considered for the pipe, having inner diameter of 400 mm. Two semi-spherical heads are placed to simulate the axial blocks.

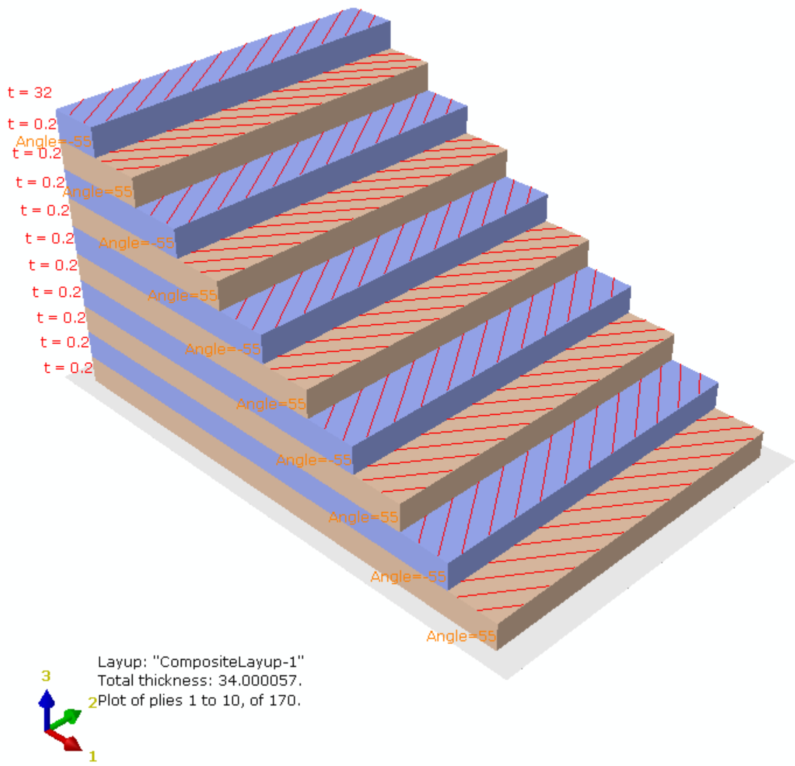

Figure 64 - The stacking sequence with the initial 10 layers (in grey the shell reference surface; ply-1 is the first inner layer)

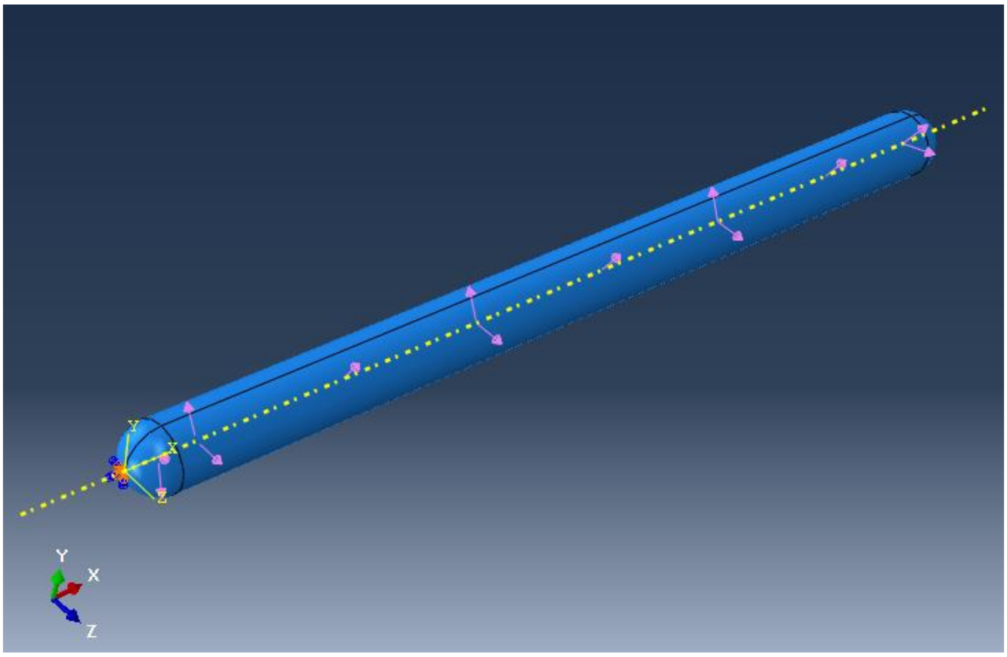

Figure 65 - The shell geometry

The parameters of simulations are:

Diameter	Pressure	Winding-angle	Volume fraction
400 [mm]	21[MPa]	$\pm 55°$	0.6

Table 19 - Simulation Data

The **Hydrotest Simulation Tool,** based on the analytical equations previously described, gives a minimum reinforced pipe wall thickness equal to **40.8** [mm].
The number of layers is 204 and the relative failure index values of Tsai-Hill and Tsai-Wu criteria are equal to 0.8939 and 0.9968. Therefore, as already mentioned, the most restrictive criterion is Tsai-Wu.

The failure indexes in the case of the numerical simulation are given as ranges because Abaqus® performs the assessment along all the wall pipe thickness. The most stressed ply results to be one at the external surface.

The numerical simulation of the pipe with the wall thickness of 40.8 [mm], the same value found by HST, gives a failure index value of Tsai-Hill that places between 0.9947 and 0.9954.
The Tsai-Wu failure index, otherwise, goes from 1.0245 to 1.0253. So, the pipe fails.
Because of Tsai-Wu criterion, it is necessary to increase the wall thickness.

A new **numerical simulation** is performed with the wall thickness value of **42.0** [mm], corresponding to 210 layers.
The Tsai-Hill failure index goes from 0.9660 to 0.9670.
The Tsai-Wu failure index places between 0.9952 and 0.9958.
The pipe withstands the pressure. the trends of the failure indexes are reported in figure (65).

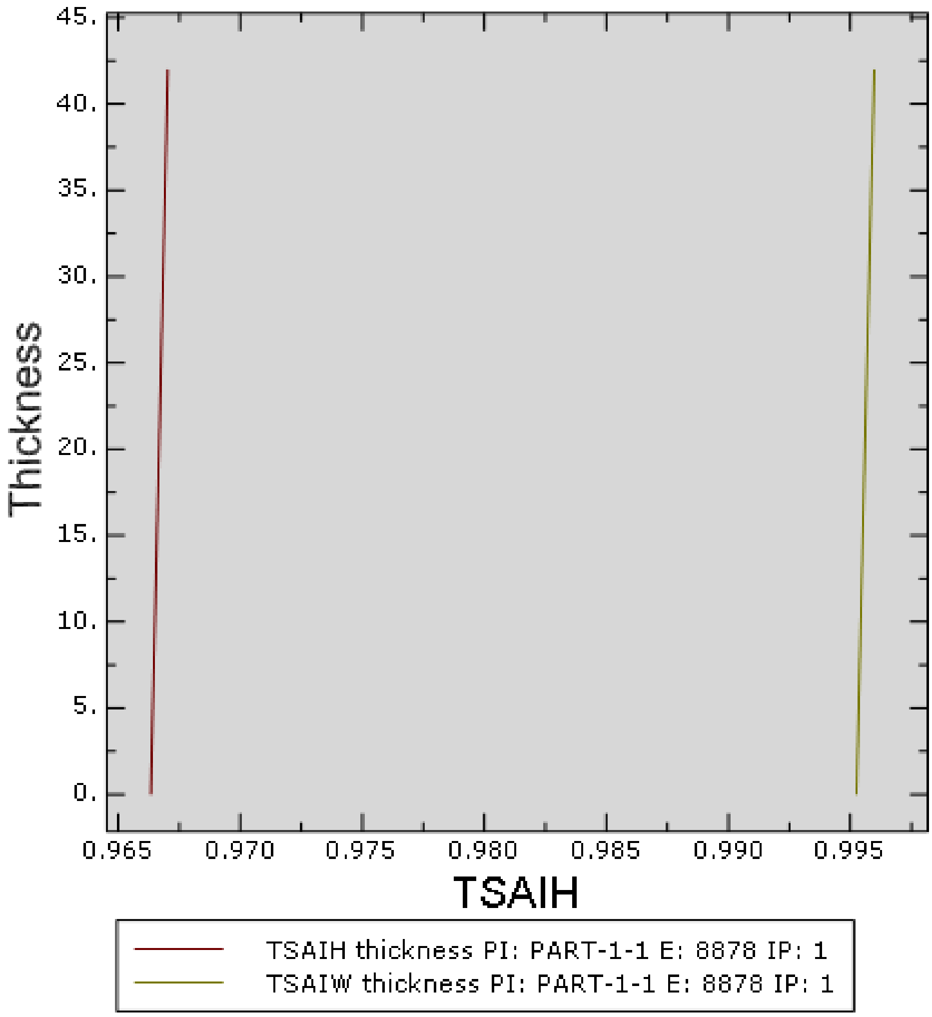

Figure 66 - Tsai-Hill and Tsai-Wu failure index value within the wall thickness

The analytical simulation performed by the Hydrotest Simulation Tool underestimates the value of the minimum pipe wall thickness, if compared to the Abaqus® numerical simulation, for a value of 1.2 [mm], on a total of 42 [mm].

The gap between the numerical and the analytical simulation is around 3 %.

The comparison has been performed using different materials and volume fractions, such even different pressures and diameters.
The gap between the two models raises up to the value of 5 % in the case of pipes with thin wall, which, anyway, are not the considered for this work.

For these reasons, the HST is considered to be a reliable simulation tool.

2.2.3. HST – Results and Considerations

As described in the introduction of this work, the objective of the job is to determine the feasibility of using composite materials in pipelines subjected to high internal pressure and having high diameters, specific for oil and gas industries.
From this point of view, the Hydrostatic Simulation Tool represents a powerful software which may provide several information about the trends concerning the dependences of the wall thickness with respect to the four input parameters: Pressure, Diameter, Volume Fraction and Winding Angle.
The tool shall provide the analytical calculated pipe wall thickness for the case of study, whose demand requests are summarized in Table 20.

Case of Study – Plain Pipe Demand Requirements		
Parameter	**Symbol**	**Unit**
Design Pressure	8	[MPa]
Nominal Diameter	400	[mm]
Design Temperature	80°	[C°]
Service lifetime	25	Years
Type of Fluid	Natural Gas	-
Special	Presence of Liner	

Table 20 - Case of Study design parameters

The only demand information which can be taken into account by the HST are the diameter and the design pressure[24].
The use of the Hydrostatic Simulation Tool allows the optimization of the other two parameters (volume fraction and winding angle) which do not appear in the demand requirements.

Table 21 represents the investigation process adopted and the performed simulations.

	HST CODE	INPUT				OUTPUT
		Pressure [MPa]	Diameter [mm]	Angle [Deg°]	Volume Fraction Vf 0-1	
ANALYTIC						NUMBER
	A0	12	400	55	0.6	Thickness
						PLOT 2D
	A1a	12	400	1:1:90	0.6	Thickness vs **Angle°**
	A1b	12	50:5:600	55	0.6	Thickness vs **Diameter**
	A1c	5:1:30	400	55	0.6	Thickness vs **Pressure**
	A1d	12	400	55	0.1:0.01:0.8	Thickness vs **Vf**
						PLOT 3D
	A2a	12	400	1:1:90	0.1:0.01:0.8	Thickness vs **Vf** vs **Angle°**
	A2b	12	50:5:600	55	0.1:0.01:0.8	Thickness vs **Vf** vs **Diameter**
	A2c	4:0.5:32	400	55	0.1:0.01:0.8	Thickness vs **Vf** vs **Pressure**
	A2d	4:0.5:32	50:5:600	55	0.6	Thickness vs **Pressure** vs **Diameter**

Table 21 - Summary of the hydrostatic simulation program

The pressure adopted in simulations is increased from the required 8 [MPa] to 12 [MPa]. This gives a proper safety coefficient to the design. Furthermore, as will be later explained, the standard

[24] See limitation of HST paragraph 2.2.2

concerning pipe impose an after-installation hydrotest which is carried out at a hydrotest pressure $P_{Hydrotest} = 1.5 \cdot P_{des}$, which in this case is equal to 12 [MPa].

The following sub-paragraphs report the design considerations which can be extrapolated from the simulation results.

2.2.3.1. A1: HST – One-Variable Simulation

The first performed simulations have been the One-variable ones, with the aim to define the dependence of the wall thickness from a single variable parameter at time.
The slopes are presented in dimensional and dimensional-less form.

2.2.3.1.1. Thickness vs Winding-Angle

The simulation parameters are reassumed in Table 22, dimensional and dimensional-less graphs follow.

CODE	Pressure	Diameter	Angle	Volume Fraction
A1a	12	400	1:1:90	0.6

Table 22 - A1a Simulation Data

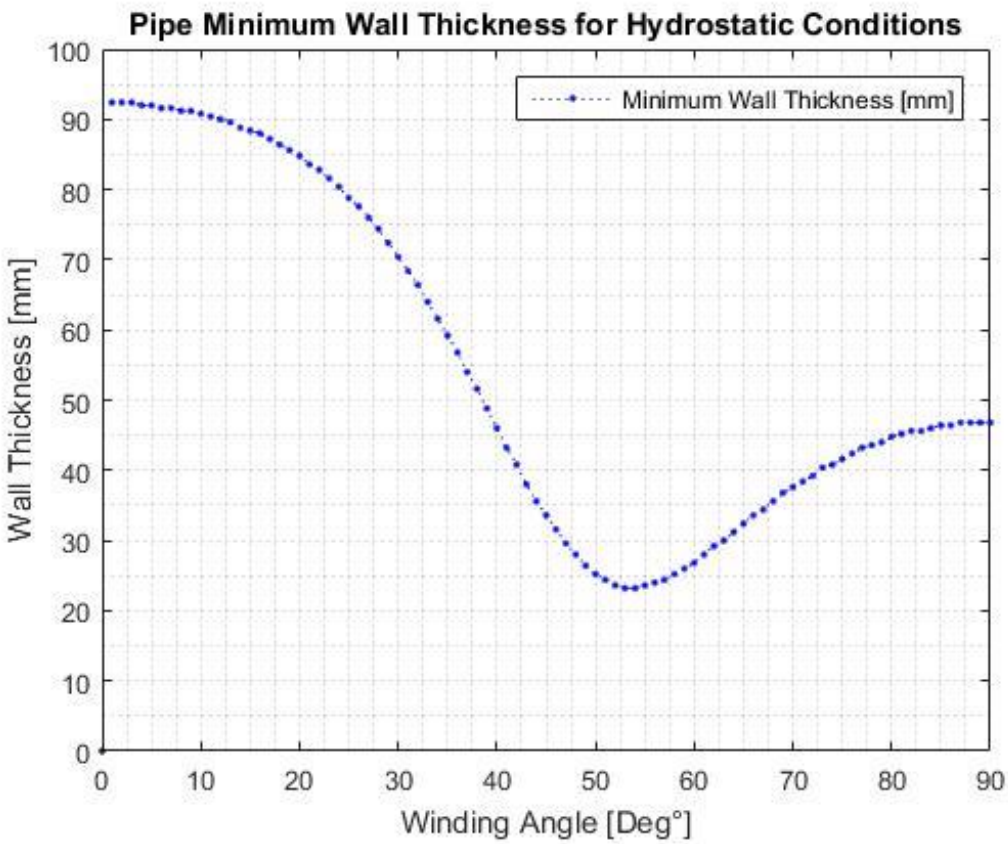

Figure 67 - Thickness vs Winding-Angle

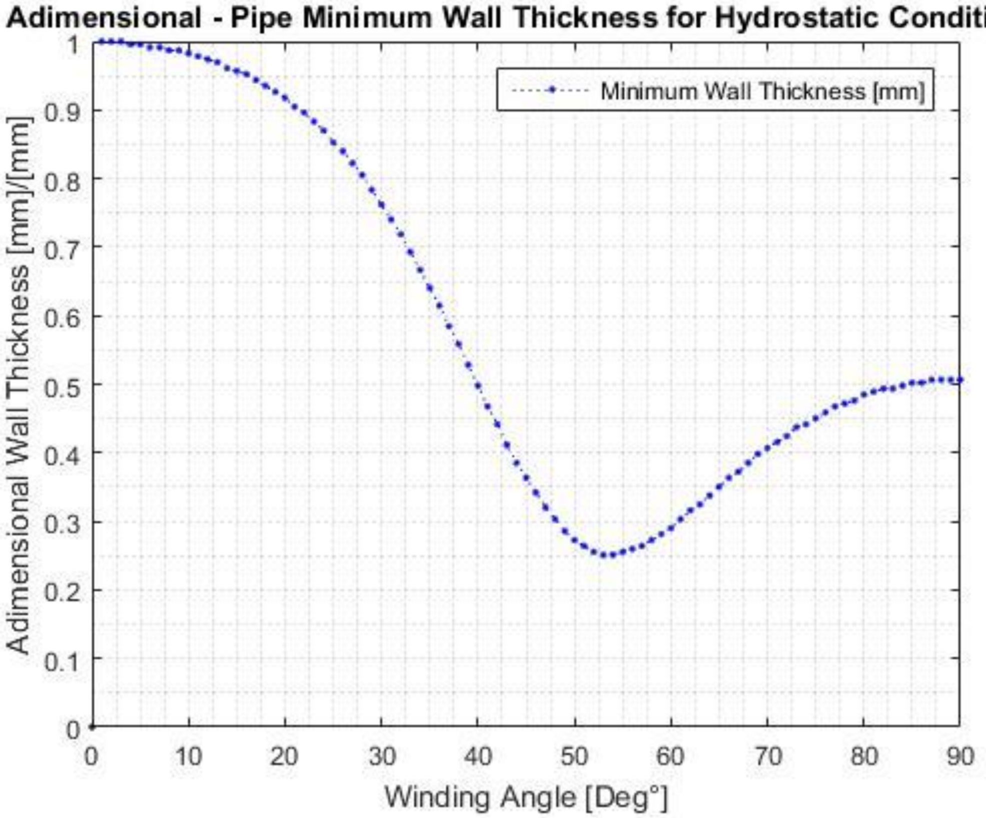

Figure 68 - Dimensional-less Thickness vs Winding-Angle

The typical pattern of a filament-winding manufacture in the case of a pipe that withstand mainly to an internal pressure is $[\pm\theta°]_{nS}$, where $\theta°$ is the winding angle and n is ¼ of the total number of layers.

The winding angle for a *Loading Ratio* $R = 2:1$, which minimizes the wall thickness, is $\pm 55°$ degrees.

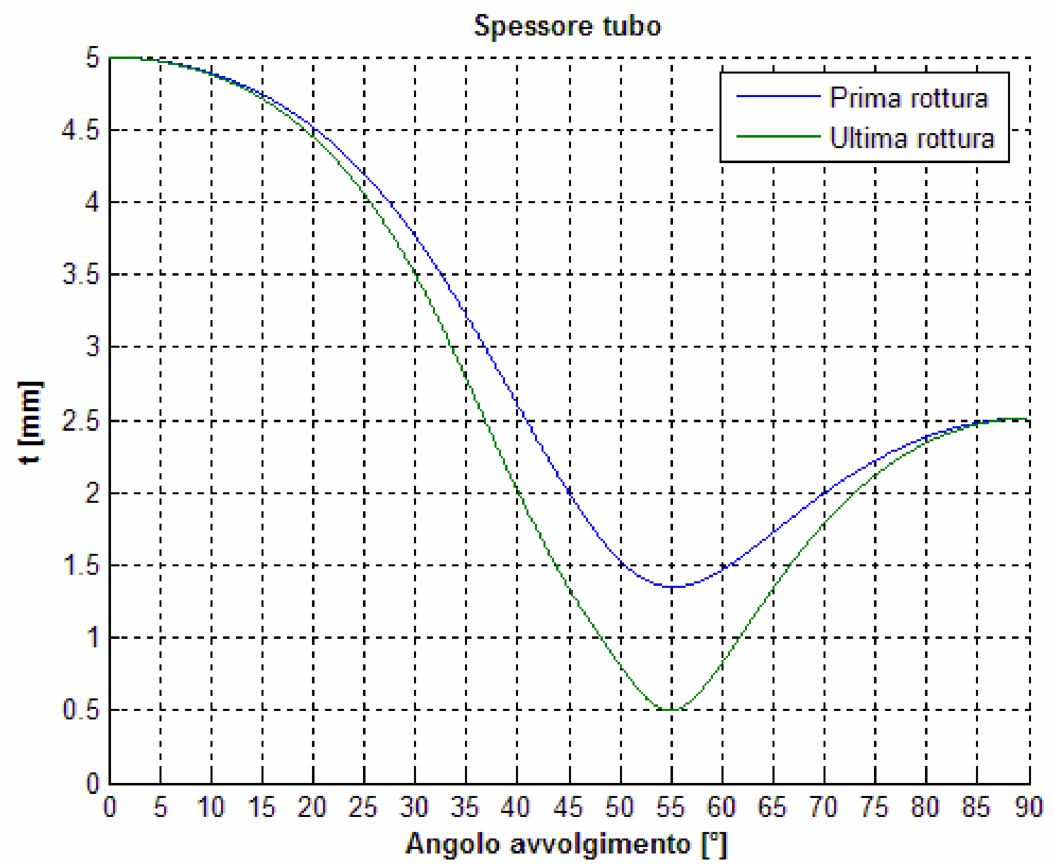

Figure 69 - Minimum pipe wall thickness for hydrostatic condition analytically evaluated by (Gentile, De Iorio, & Caprino) [28]

The same curve has been found by analytical simulations of a hydrostatic tests of a pipe under inner pressure reported in [28]. The slope is the same and the optimizing angle is confirmed to be $\pm 55°$ [deg].

2.2.3.1.2. Thickness vs Volume Fraction V_f

The simulation parameters are summarized in Table 23; dimensional and dimensional-less graphs follow.

CODE	Pressure	Diameter	Angle	Volume Fraction
A1b	12	400	55	0.1:0.01:0.8

Table 23 - A1b Simulation Data

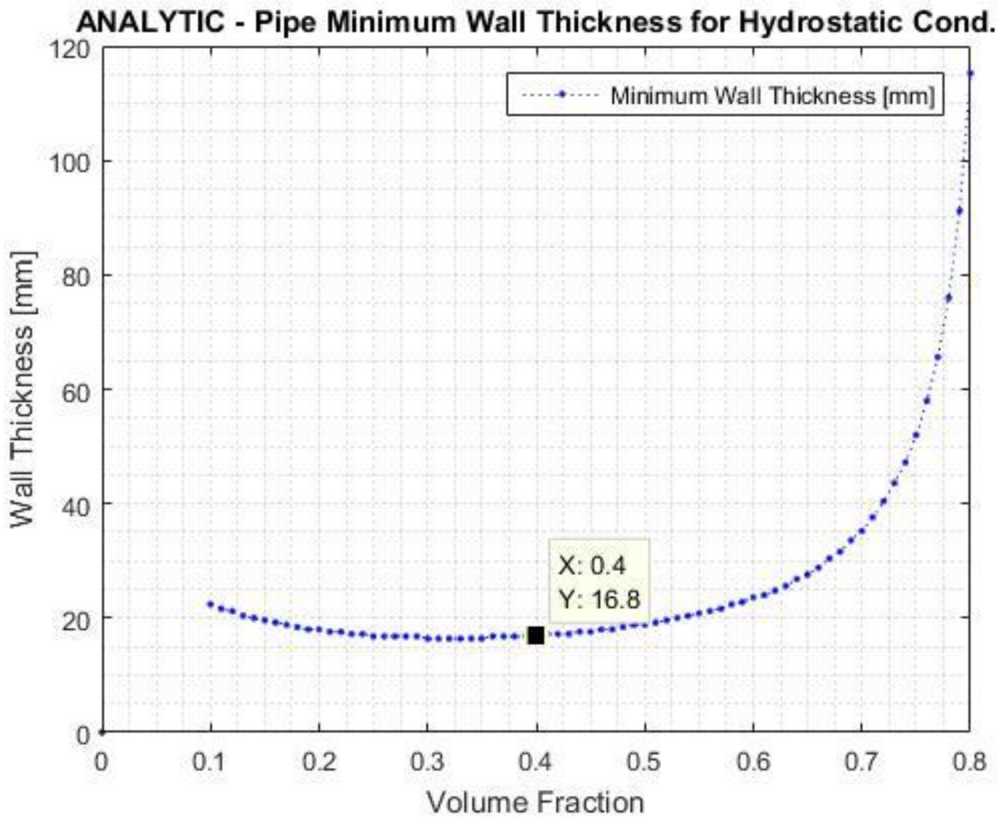

Figure 70 - A1b Thickness vs Volume fraction

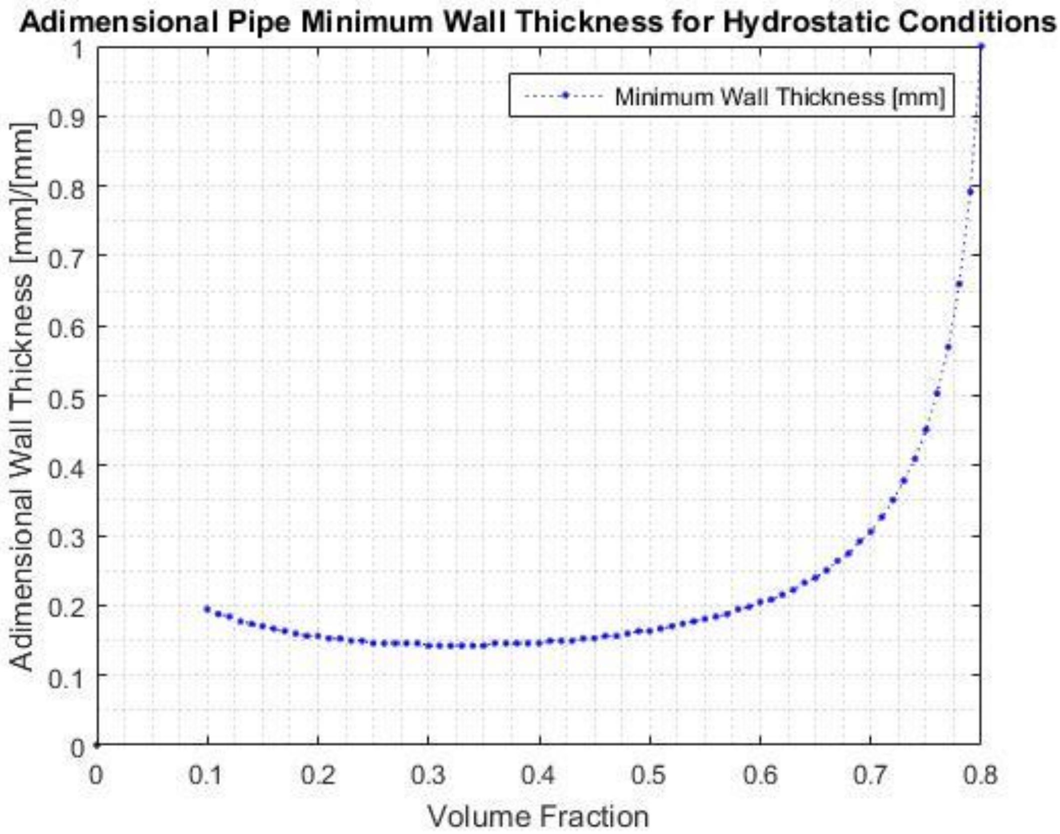

Figure 71 - A1b Dimensional-less Thickness vs Volume fraction

The optimizing value of fibre content, for the matrix and fibre taken into account, is 0.4. This value of volume fraction gives a minimum wall thickness value which is equal to 16.8 [mm] for the simulation parameters considered.

The dependence of the wall thickness as function of the volume fraction has been already analysed in chapter 1, 3.3 and shows:

- The high dependence of the pipe wall thickness from the analytical prevision of the transversal tensile strength, which governs the failure of the pipe
- The proved gap between the analytical data and the finite element evaluated concerning the transversal tensile strength
- The under-estimation of the prevision model concerning the transversal tensile strength with respect to experimentally evaluated data[25]

These lead to the conclusion that this optimizing value shall not be considered reliable.

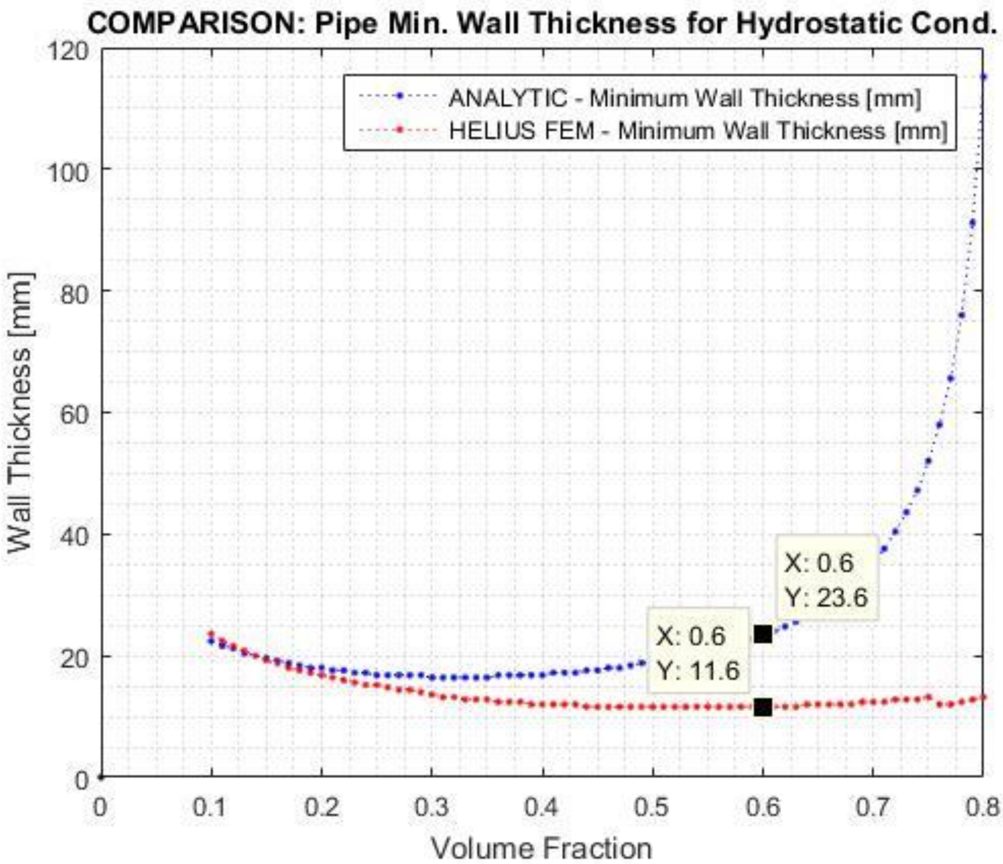

Figure 72 - Minimum wall thickness for a pipe of 400mm diameter subjected at inner pressure of 12 MPa.

The comparison of the wall thickness dependency from the volume fraction, based on the APT and FEM, confirms that in the case of FEM expected properties[26], the thickness decreases when the volume fraction increases.

[25] Ref. Chapter 1, Transversal tensile strength prevision model, 2.5.2.3

[26] FEM properties expect to be closer to the experimental evaluated.

For these reasons, the next simulations are performed using a fixed volume fraction equal to 0.6[27].

2.2.3.1.3. Thickness vs Diameter

The simulation parameters are summarized in Table 24; dimensional and dimensional-less graphs follow. The variation of the diameter is made to highlight the dependencies in case of the design of other size pipes.

CODE	Pressure	Diameter	Angle	Volume Fraction
A1c	12	50:5:600	55	0.6

Table 24 - A1c Simulation Data

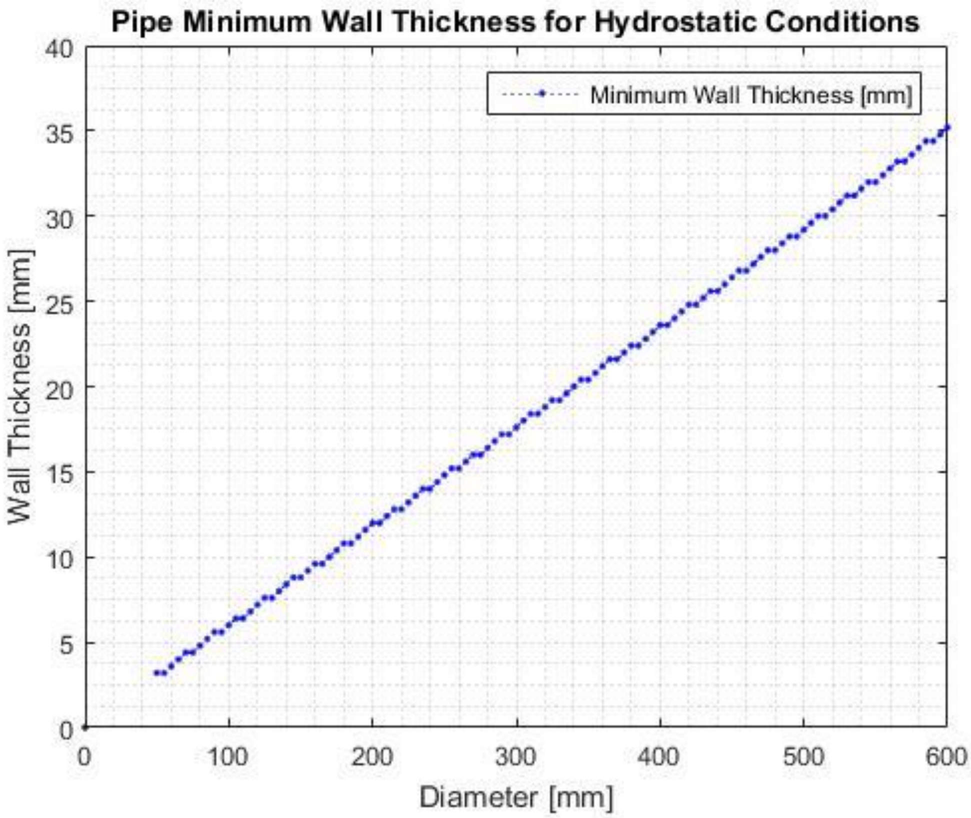

Figure 73 - A1c Thickness vs Diameter

[27] The volume fraction of 0.6 is considered high and conform to the filament winding common processes. A volume fraction of 0.4 in filament winding product is considered too low. [28]

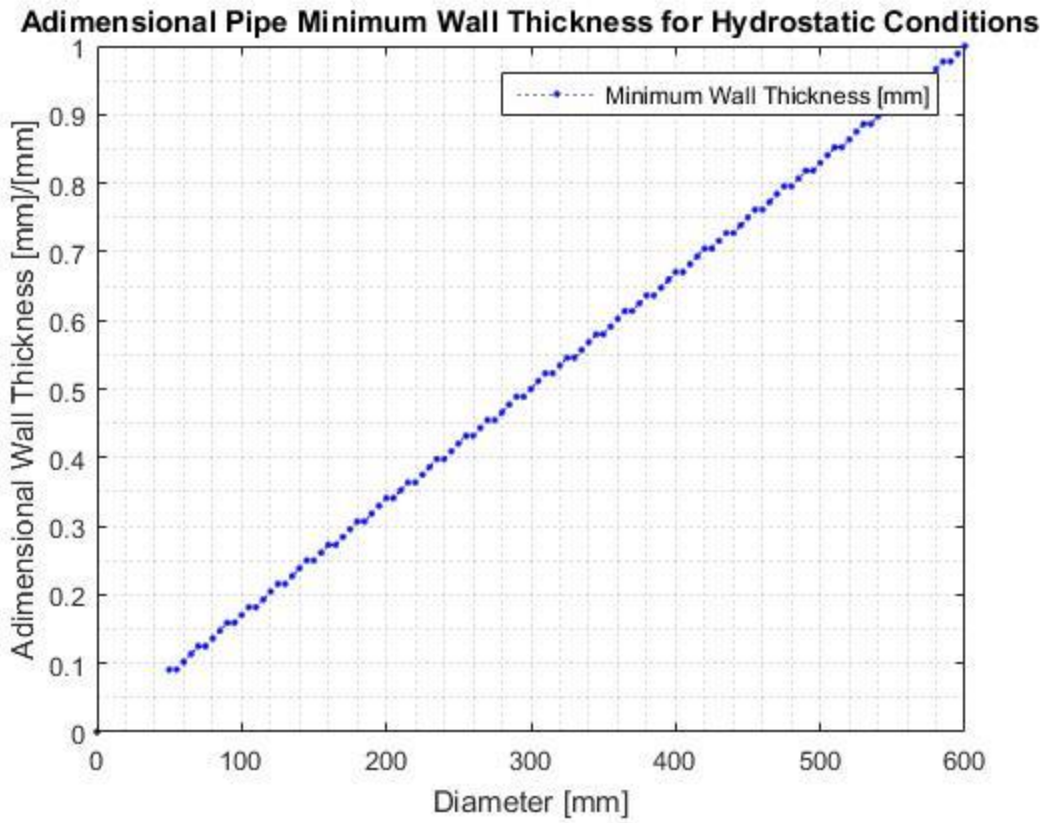

Figure 74 - A1c Dimensional-less Thickness vs Diameter

The graphs show a linear dependency of thickness with respect to the diameter. This because the stress state, defined by Mariotte's equations, increases linearly with the diameter of the pipe.

2.2.3.1.4. Thickness vs Pressure

The simulation parameters are reassumed in Table 25; dimensional and dimensional-less graphs follow.

CODE	Pressure	Diameter	Angle	Volume Fraction
A1d	5:1:30	400	55	0.6

Table 25 - A1d Simulation Data

The dependency of thickness with respect to the pressure is linear, since linear the increment of the stress state is linear in Mariotte's equations.

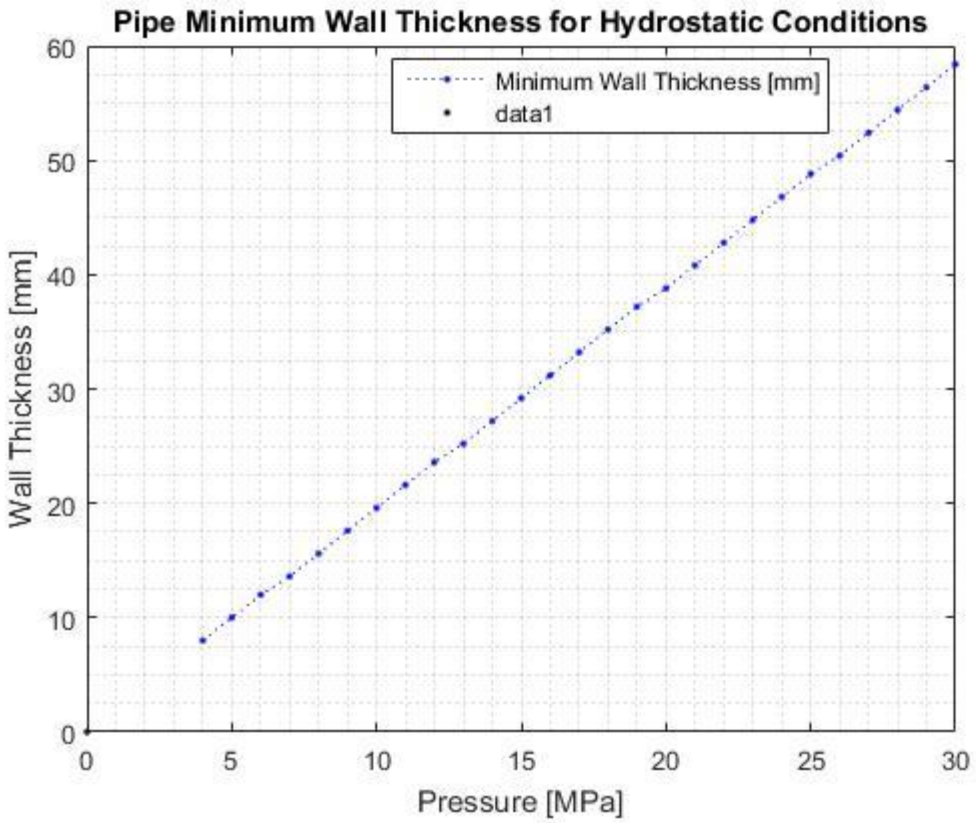

Figure 75 - A1d Thickness vs Pressure

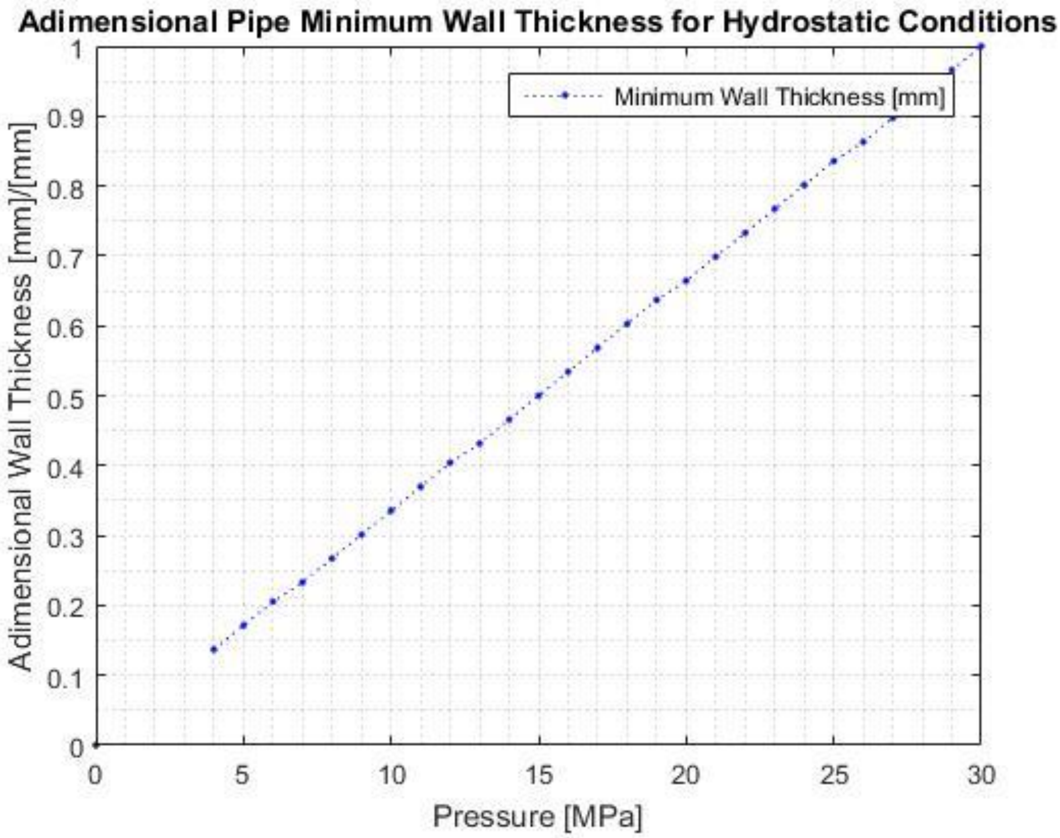

Figure 76 - A1d Dimensional-less Thickness vs Pressure

2.2.3.2. A2: HST – Two-Variable Simulation

Simulation with two variables gives as outputs a 3-dimension surface, in which each point corresponds to the wall thickness calculated for the considered conditions.
The following simulations well explain the trends and the dependencies singularly analysed in HST One-variable Simulations.
Furthermore, these graphs show the linear independency of the four parameters taken into account. In fact, the shapes of the curves are the same showed in one-variable simulations, repeated and scaled.

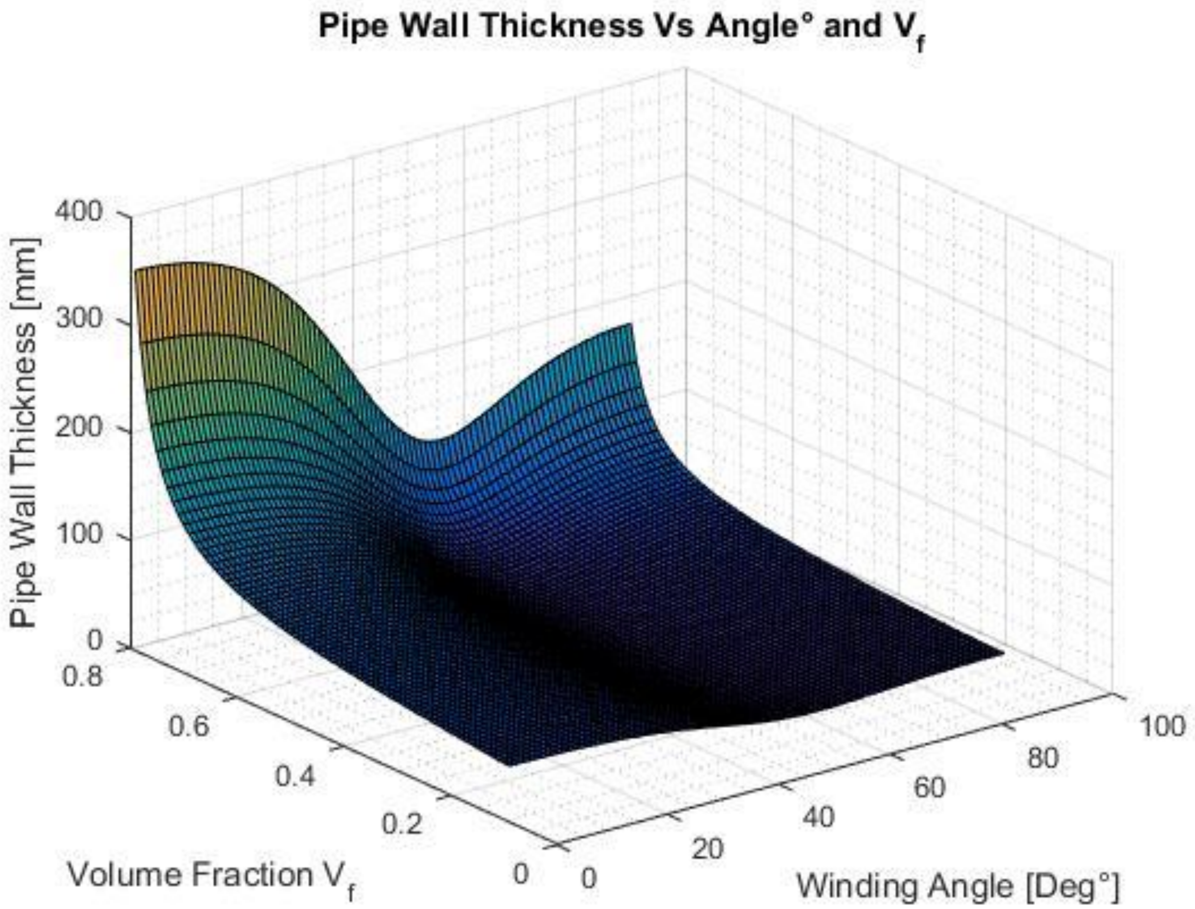

Figure 77 - A2a - Thickness vs Volume fraction and winding angle.

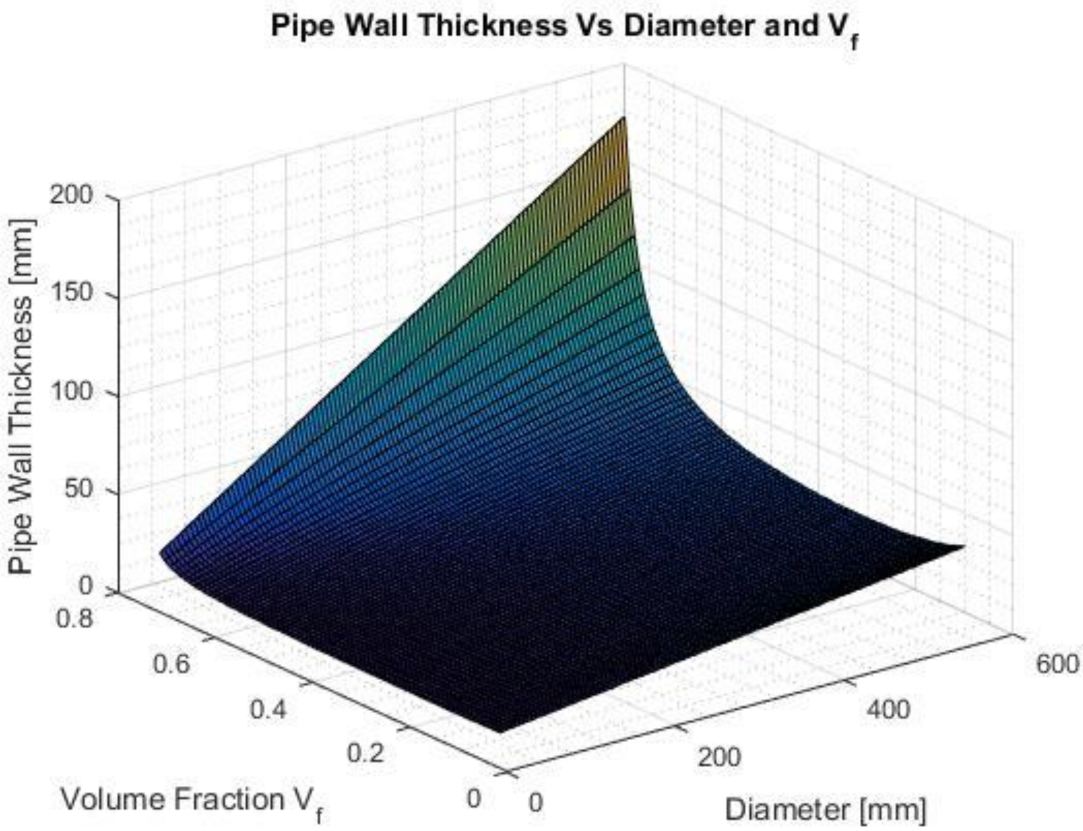

Figure 78 - Thickness vs Volume fraction and Diameter

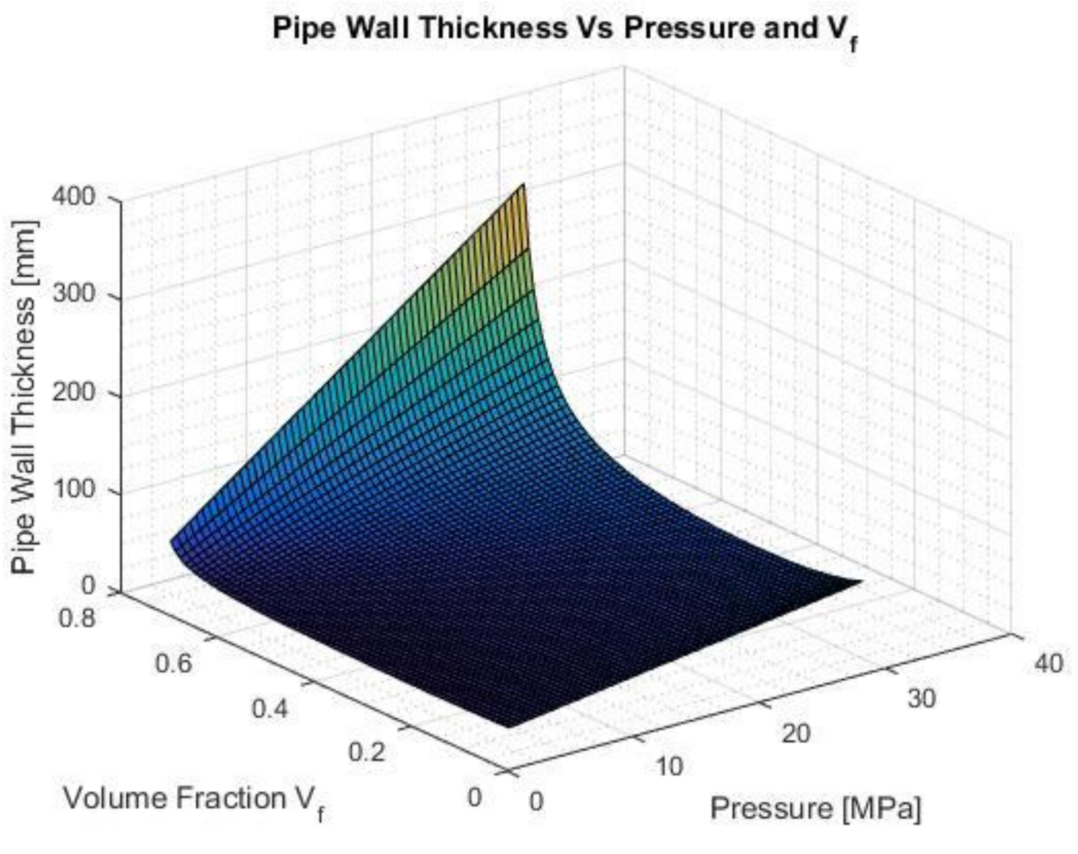

Figure 79 - Thickness vs Volume fraction and Pressure

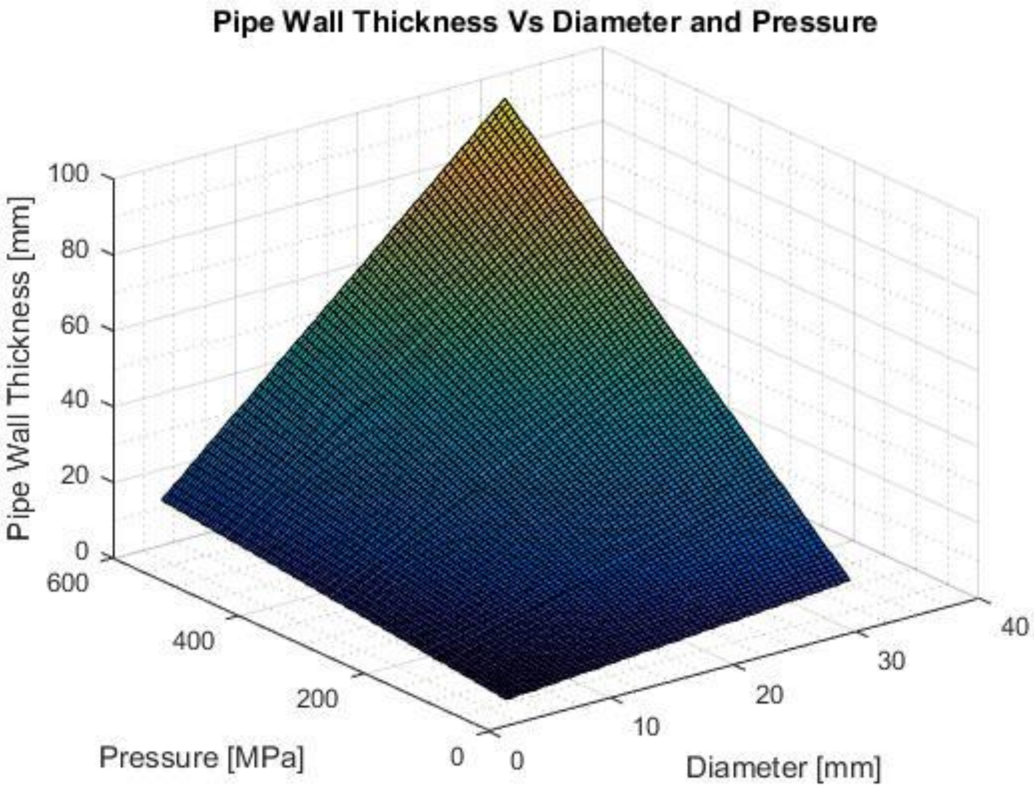

Figure 80 - Thickness vs Pressure and Diameter

2.2.3.3. A0: HST – Punctual Simulations

The simulations A1 and A2 show that:

- The optimizing winding-angle for a loading ratio R=2:1 is $\pm 55°$ [deg]
- The optimizing volume fractions are:
  - $V_f = 0.4$ using the Analytical Prediction Tool
  - $V_f = 0.6$ considering the FEM for the prediction of lamina properties

Two punctual simulations are performed.
The **first** is performed using the analytical prediction tool for the lamina properties, and the value of **0.4** and **0.6** volume fractions.
The **second** is performed using the FEM for the prediction of lamina properties and the value of **0.4** and **0.6** of volume fractions.
Then, the thicknesses are compared.

1) APT based HST simulations

Follows the two simulations using APT and the volume fraction values of 0.4 and 0.6.

1A - HST simulation based on Analytical Prevision Tool for Lamina Properties										
Input Parameters				**Failure Indexes**				**Outputs**		
ID_r	400	[mm]		1	1	1		Wall Thickness	**16.8**	[mm]
P	12	[MPa]		1	1	1		n° of Layers	84	-
$\theta°$	55°	[deg°]		TH 0.7811						
V_f	**0.4**	-		TW 0.9978						

Table 26 - Simulation data HST basing on APT (1)

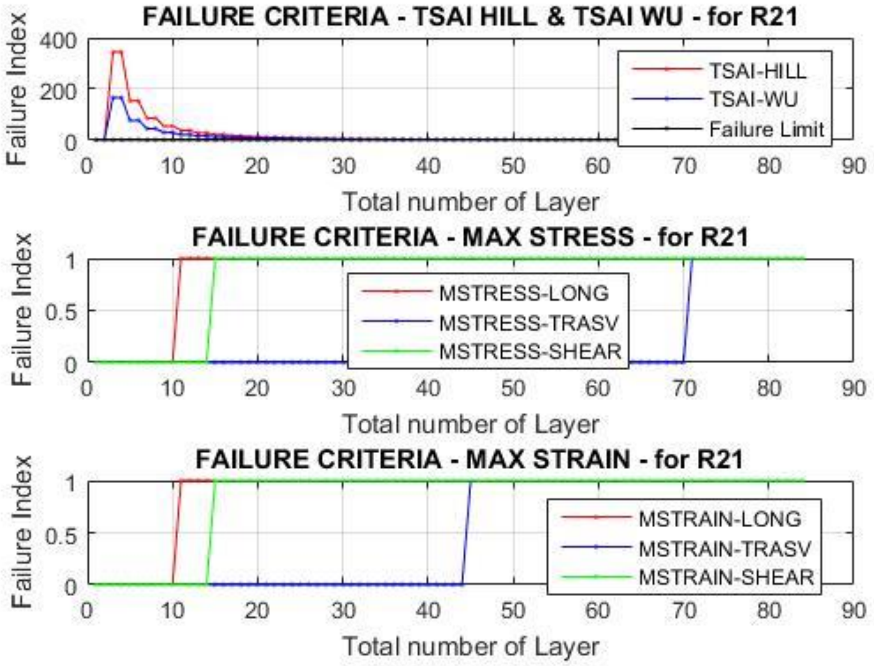

Figure 81 - Failure Indexes for APT based simulation (1)

1B - HST simulation based on Analytical Prevision Tool for Lamina Properties										
Input Parameters				**Failure Indexes**				**Outputs**		
ID_r	400	[mm]		1	1	1		Wall Thickness	**23.6**	[mm]
P	12	[MPa]		1	1	1		n° of Layers	118	-
$\theta°$	55°	[deg°]		TH 0.8724						
V_f	**0.6**	-		TW 0.9811						

Table 27 - Simulation data HST basing on APT (2)

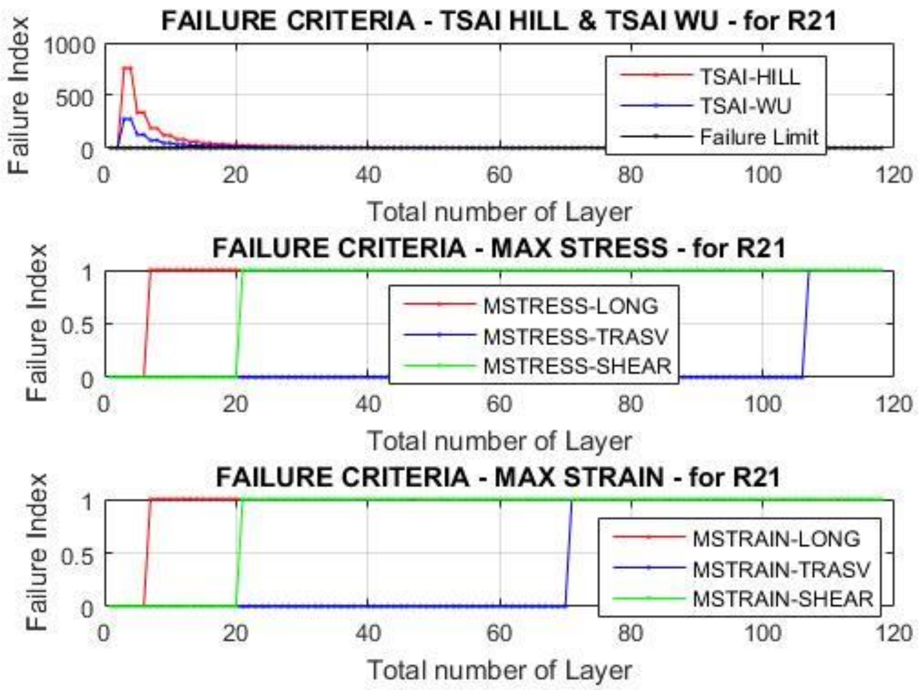

Table 28 - Failure Indexes for APT based simulation (2)

The expected pipe reinforced wall thicknesses calculated using the Analytical Prevision Tool are: 16.8 [mm] for a volume fraction of 0.4 and 23.6 [mm] for a volume fraction of 0.6.

2) FEM based HST simulations

Follow the two simulations based on FEM prediction of lamina properties and volume fraction values of 0.4 and 0.6.

2A - HST simulation based on FEM Prevision for Lamina Properties										
Input Parameters				**Failure Indexes**				**Outputs**		
ID_r	400	[mm]		1	1	1		Wall Thickness	**12**	[mm]
P	12	[MPa]		1	1	1		n° of Layers	60	-
$\theta°$	55°	[deg°]		TH 0.6743						
V_f	**0.4**	-		TW 0.9808						

Table 29 - Simulation data HST basing on FEM (1)

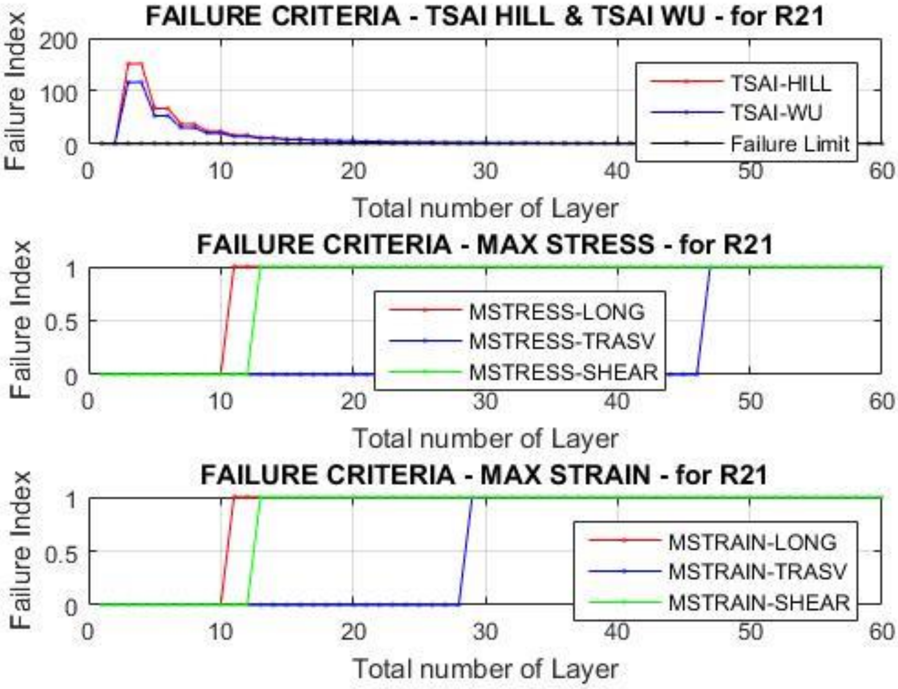

Figure 82 - Failure Indexes for FEM based simulation (1)

2B - HST simulation based on FEM Prevision for Lamina Properties										
Input Parameters				**Failure Indexes**				**Outputs**		
ID_r	400	[mm]		1	1	1		Wall Thickness	**11.6**	[mm]
P	12	[MPa]		1	1	1		n° of Layers	78	-
$\theta°$	55°	[deg°]		TH 0.7408						
V_f	**0.6**	-		TW 0.9729						

Table 30 - Simulation data HST basing on FEM (2)

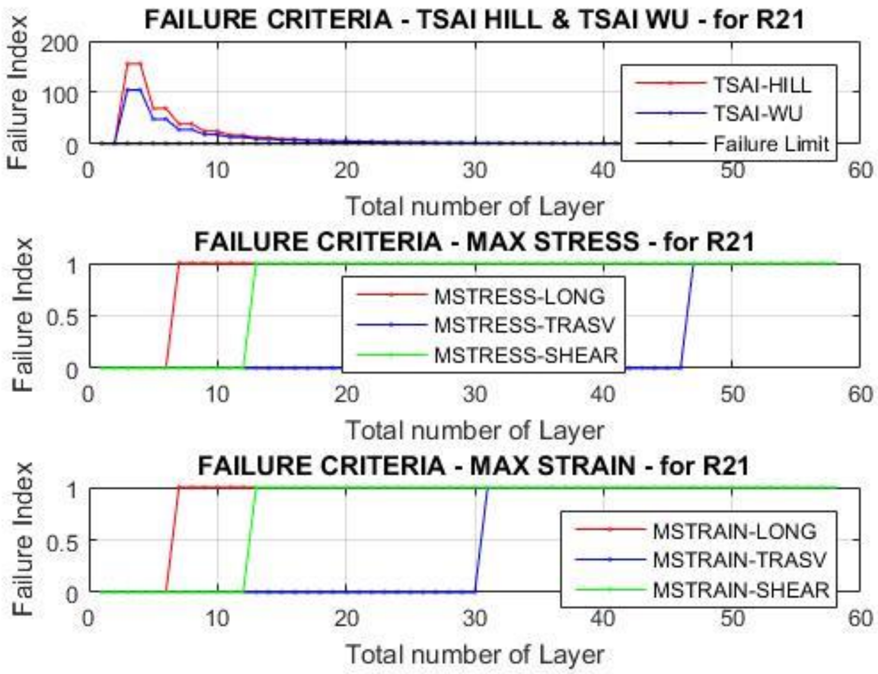

Figure 83 - Failure Indexes for FEM based simulation (2)

The expected pipe reinforced wall thicknesses calculated using the FEM for the prevision of properties are 12 [mm] for a volume fraction value of 0.4 and 11.6 [mm] for a volume fraction of 0.6.

2.3. HST – Design Conclusions

A summary of the results from the HST punctual simulation is given into the following table.

HST Summary – Pipe Wall Thickness			
		APT based	**FEM based**
Volume	**0.4**	16.8 [mm]	12 [mm]
Fraction	**0.6**	23.6 [mm]	11.6 [mm]

Table 31 - Summary of the HST punctual simulations

The expected wall thicknesses vary in a range from 11.6 to 23.6 [mm].
The analytical prediction tool for the lamina properties provides a weaker lamina if compared to the lamina properties predicted by Autodesk® Helius Composite 2016 Finite Element Model.

The HST results indicate that:

- **The optimal winding angle is $\pm 55°$ [deg].**

This value optimizes the resistance of the composite to a stress state condition given from the inner pressure. This value shall vary if other stress states are considered, but it is not dependant on the pressure, diameter, or volume fraction.

- **The optimal volume fraction is 0.6**.

The volume fraction influences the overall lamina properties, which impact on the resistance of the composite pipe.
The prevision of the transversal tensile strength by mean of analytical models, reassumed into APT, is proved to have a limited reliability. The analytical prevision models mismatch up to 100% with the experimentally evaluated values reported in the literature[28], and with the finite element based prevision tools. Furthermore, this value governs the failure of the pipe for the state of stress taken into account (R=2:1).
Even if the theoretical optimizing value, based on the analytical prevision model, ought to be considered 0.4, the value of 0.6 is chosen. This high value of volume fraction is usually reached in filament wounded composites and it is further in line with the trend given by the FEM based HST, where the thickness decreases with the increment of volume fraction. Figure 72.

Finally, the choice of 0.6, with the adoption of the analytical prevision tool for lamina properties, giving the higher values, represents also the safest design condition considering the inaccuracies of the analytical and finite element based methods for the prevision of the lamina mechanical characteristics.

Despite these considerations, the further simulation will use both the values, 0.4 and 0.6 in order to have a complete view of the cases of study.

[28] (Lupasteanu, Taranu, & Popoaei, 2013) – [31]

4. Pipeline Systems International Standards

The chapters 1, 2 and 3 treated the design with composites, and the design of the pipeline, from a strictly engineering point of view. Chapter 4 and the following Chapters 5 and 6 investigate the design from a regulatory point of view.

1. International Standards

Because of the necessity to regulate the manufacture, purchase, installation, use, safety of the composite piping systems worldwide, several standards have been published by the international regulation authorities. Some of these authorities are:

BSI – British Standard Institution
ISO – International Standards Organization
ASME – American Society of Mechanical Engineers
API – American Petroleum Industries
ASTM - American Society for Testing and Materials International
DNV.GL - Det Norske Veritas
AWWA – American Water Works Association

Each one of these societies has developed standards to regulate the use of the GRP pipeline system, considering specific ranges which concern the use, the size, the pressure, the material, the temperature[29].
The designer, in according to the customer, shall design the pipeline system in accordance to a proper international standard. The international standard includes a qualification programme, which lists all the needed requirements.
The requirements shall be in form of information, such traceability of materials, or in form of a validation procedures.
The validation procedures, often, are represented by a burst test or by survival tests which have to be carried out, in particular environment conditions, on the final pipeline components.
The overcoming of these tests defines the compatibility of the final product to be in accordance with the standard considered.

With the aim to define the most suitable standard concerning pipeline system international regulation, the available international standards are compared to the case of study demand characteristics, summarized in Table 32.

Since a pipeline system often includes pressure vessels, the regulations considered for the qualification are of two natures:

- International standards for composite pipelines.
- International standards for composite pressure vessels.

[29] These reported are the most important factor which limit the applicability of a standard to a specific pipeline system case. Other limits exist, specific for each standard.

The following paragraphs present the analysis of the qualification programme and the correspondent design in accordance with the standard chosen, concerning the pipeline.

Case of Study – Plain Pipe Demand Requirements		
Parameter	**Symbol**	**Unit**
Design Pressure	8	[MPa]
Nominal Diameter	400	[mm]
Design Temperature	80°	[C°]
Service Lifetime	25	Years
Type of Fluid	Natural Gas	-
Special	Presence of Liner	

Table 32 - Case of Study demand requirements

The analysis of the pressure vessel chosen standard is not part of this work.

1.1. The Choice of the International Standard for the GRP Pipeline Systems

The chosen standard for GRP pipeline systems is the **ISO 14692**.

The pipeline systems are usually composed by plain pipe, bends, reducers, tees, supports, flanged joints, and threaded joints.
The pipeline standards usually, cover these components.
For the pipe, it is found that the only design guide is ISO 14692. All others available standards are qualification standards only through prototype testing. Therefore, the procedure should be mainly based on ISO 14692 standard.
The EN ISO 14692:2002 standard (Petroleum and natural gas industries - Glass-reinforced plastics (GRP) piping) is a wide standard composed of 4 parts: Part 1: Vocabulary, symbols, applications and materials; Part 2: Qualification and manufacture; Part 3: System design; Part 4: Fabrication, installation and operation. This standard provides the design of piping systems and a series of verifications and tests aimed at qualifying the manufactured pipeline. For the qualification procedure, this standard recalls some ASTM standards for the testing of the pipe.

The main limitation for the application of EN ISO 14692:2002 standard and the following FDIS update is the exclusion of thermoplastic and elastomeric liners. This limitation is due to the fact that such materials may introduce significant changes in performance characteristics of the GRP piping. The use of a thermoplastic liner will result in change of the failure mode for pressure retention. Liners (if any) shall be made of thermoset resin matrix.

Other suitable standards for the qualification of pipes and pipeline systems are:

- API 15 HR:2016 “High pressure fiberglass line pipe” – 4th edition: Specification for high pressure fiberglass line pipe. This is the equivalent American standard with respect to ISO. This standard can be applied to the pressure, dimension, and temperature fixed inputs for the present project.
- ASTM 2996-15: Standard Specification for Filament-Wound “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe. This is a short specification with classification systems, methods of testing, requirements for materials, mechanical properties, dimensions, performance

and manufacturing. It does not provide any specific design method and fixes classes for filament-wound reinforced and tests to qualify the piping systems.

A comparison among these three standards (EN ISO 14692-3:2002, API 15 HR:2016, and ASTM 2996-15) is attached to this work as A3 sheet - ***PIPELINE STANDARD COMPARISON – 1,2***
These standards have not been chosen because of the lack concerning the design guide.

Other non-applicable standards that were also browsed are:
- ASME B31.1 "Power Piping": restricted to underground systems for combustible liquids, maximum pressure 150 [Psi];
- ASME B31.3 "Process pipes": process piping made of steel;
- ASME B31.8 "Gas transmission and Distribution Piping": not to be used for Off-shore lines;
- ASTM D3839 "Standard Guide for Underground Installation of "Fiberglass" (Glass-Fiber Reinforced Thermosetting-Resin) Pipe": this standard is dedicated to underground installation;
- ASTM F1173 "Standard Specification for Thermosetting Resin Fiberglass Pipe Systems to Be Used for Marine Applications": this is mainly a qualification standard
- AWWA C950 and AWWA M45 "Fiberglass Pressure Pipe": limited to potable water distribution;
- DNV-OS-F202 "Composite Risers": mainly related to the design of risers;
- DNV-RP-F119 "Thermoplastic composite Pipes": for flexible thermoplastic pipe;
- BS EN ISO 13628-2:2006 "Petroleum and natural gas industries — Design and operation of subsea production systems; Unbonded flexible pipe systems for subsea and marine applications": this standard is dedicated to flexible pipes;
- ISO 15840 "Ship and Marine technology standard specification for thermosetting resin fiberglass pipe and fitting to be used for marine applications": this standard is restricted to marine applications (engine rooms etc.);

Finally, other browsed documents that can be considered as "auxiliary" standards, and that will be used for the qualification of the materials and pipes are the following ASTM standards:
- ASTM D1598 "Standard test method for time-to-failure of plastic pipe under constant internal pressure";
- ASTM D1599 "Standard test method for resistance to short-time hydraulic pressure of plastic pipe, tubing, and fittings";
- ASTM D2105 "Standard test method for longitudinal tensile properties of "fiberglass" (glass-fiber-reinforced thermosetting-resin) pipe and tube;
- ASTM D2992 "Standard practice for obtaining hydrostatic or pressure design basis for fiberglass (GFR thermosetting resin) pipe and fittings";
- ASTM D2996 "Standard specification for filament-wound "fiberglass" (glass-fiber-reinforced thermosetting-resin) pipe";
- ASTM D3567 "Standard practice for determining dimensions of "fiberglass" (glass-fiber-reinforced thermosetting resin) pipe and fittings".

1.2. The Choice of the International Standard for Composite Pressure Vessels

The chosen standard for composite pressure vessel is the **BS EN 13923:2005**.

For the design of the pressure vessel, there is not an ISO standard, but we can take into account the standard BS EN 13923:2005 "Filament-wound FRP pressure vessels – Materials, design, manufacturing and testing". This standard is a unique document; it recalls and extends the validity of the standard BS EN 13121 "GRP tanks and vessels for use above ground". This second standard is composed of 4 parts, updated in different years: 1) Raw materials – Specification conditions and acceptance conditions (2003); 2) Composite materials – Chemical resistance (2003); 3) Design and workmanship (2016); 4) Delivery, installation and maintenance (2005).
The main difference between BS EN 13923 and BS EN 13121 is related to the pressure range. For the BS EN 13121, the maximum considered design pressure is only 1 [MPa]. On the other hand, for the BS EN 13923 the maximum design pressure is 20 [MPa], thus this standard is more focused on high pressure vessels.

Other selected standards for the qualification of the pressure vessel are:

- The Pressure Equipment Directive 2014/68/EU (PED) for the certification of pressure vessel. This is not a design standard, but needs to be considered for the certification of the vessel system. It is a European standard which aims to regulate fabrication, special requirements, conformity assessment and commerce of pressure vessels within the UE. Each new vessel made in UE or commercialized under UE jurisdiction must comply with this standard. It is a general standard valid not only for GRP vessels.
- ASME BPVC.X-2015 standard, which is the American equivalent standard for the design and qualification of GFR vessels. The standard classification divides vessels in 3 classes. For each class, a huge guide covers both specific design and testing procedures.

A comparison among these standards is attached to this work as A3 sheet - ***VESSELS STANDARD COMPARISON***

It should be mentioned that neither ANSI nor ASTM have equivalent standards.
Other non-applicable standards that were also browsed are:

- API 12P:2008 "Specification for Fiberglass Reinforced Plastic Tanks": this standard considers only unpressurized tanks made of only E-Glass type fibers;
- ISO/TR 13086-1:2011 "Gas cylinders — Guidance for design of composite cylinders": this is a partial design guide of gas cylinders; thus, it is referred to smaller vessels undergoing higher pressures.

2. The ISO 14692 – Glass-reinforced plastics (GRP) piping

The ISO 14692 is an international standard dealing with the qualification of pipes, fittings, and joints made in Glass-Reinforced Plastics (GRP) for certain applications.
The first version of the ISO 14692 in its first edition was published in 2002 for the use of GRP piping, explicitly in the oil and natural gas industries, and based on the document *Specifications and recommended practice for the use of GRP piping offshore* published by the United Kingdom Offshore Operators Association (UKOOA) in 1994.
The ISO 14692:2002 is the active standard.
The first edition of the standard is being withdrawn and replaced with a new edition – the second – the publication of which is scheduled for August 2017. *"This second edition cancels and replaces the first edition of which has been technically revised."* cit. [18].
Since the second edition of the standard has not been published yet, the whole considerations given according to this future standard basis on its Final Draft version approved in date December 2016 and corresponding to the document ISO/FDIS 14692:2016 redacted by the international commission ISO TC 67/SC 6.
Some differences may occur between the published ISO standards and their Final Draft version.
For this reason, this document is not intended to replace the future ISO 14692:2017 (2nd edition) standard, but gives only a summary, a guideline, of its preview.

Since the both standard editions are going to be fully developed in the following chapters, a brief description of the common concepts is being now reported. A critical comparison between the two is made in the conclusion chapter.

2.1. Structures of ISO 14692:2002 and ISO/FDIS 14692:2016

The main objective of the ISO 14692 is to provide the oil and gas industries, the system designers, end users, engineering companies, inspection companies, manufacturers, and installers with mutually agreed specifications and recommended practices for the design, purchase, manufacturing, qualification testing, handling, storage, installation, commissioning and operation of GRP piping systems.

The standard is not intended to be applied to drainage and sewerage applications, and it is not specifically intended for non-structural applications, such as open drain systems and other low-pressure piping applications.

ISO 14692 (all parts) covers all the main components that form a GRP pipeline and piping system (plain pipe, bends, reducers, tees, supports, flanged joints) with the exceptions of valves and instrumentation.

The standard is subdivided into four parts which follow, except the first part, the individual phases in the life cycle of a GRP piping system, i.e. from design through manufacture to operation.

- *Part 1: Vocabulary, symbols applications and materials.*
  In this part are defined terms, symbols, and the applications that ISO 14692 (all parts) is intended to cover. Limits on the material used in the construction of components are defined, together with the pressure terminologies used throughout ISO 14692 (all parts).

- *Part 2: Qualification and manufacture*
  Its objective is to enable the purchase of GRP components with known and consistent properties from any source. The qualification process, the manufacture and material requirements are reported. Main users of the document are envisaged to be the principal, and the manufacturer, certifying authorities, and government agencies.

- *Part 3: System design*
  This part gives guidelines for the design of GRP piping systems. The requirements and recommendations apply to layout dimension, hydraulic design, structural design, detailing, fire endurance, spread of fire, emissions, and control of electrostatic discharge.
  Its objective is to ensure that the piping systems meet the specified performance requirements when designed using the components qualified in ISO 14692-2.

- *Part 4: Fabrication, installation, and operation (1st ed.) – Fabrication, installation, inspection, and maintenance (2nd ed.)*
  The objective of this part is to ensure that installed piping systems will meet the specified performance requirements throughout their operational life.

Since the aim of this document is to investigate the qualification process according to the both ISO 14692 standard editions, the latest *Part 4: Fabrication, installation, and operation (1st ed.) – Fabrication, installation, inspection, and maintenance (2nd ed.)* will not be further developed.

3. Design in accordance with ISO 14692:2002 and ISO/FDIS 14692:2016

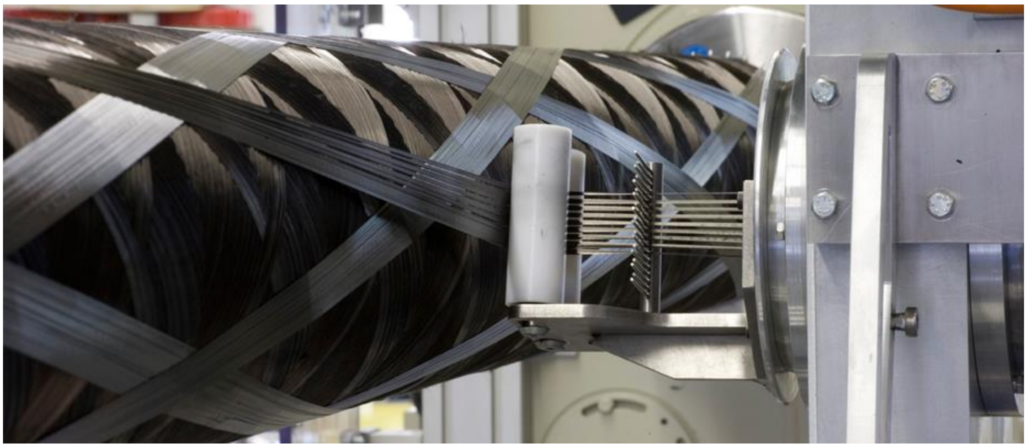

Figure 84 - Filament-winding of a composite plain pipe with different winding angles [35]

The chapters which follow, 5 and 6, are intended to be a review of the international standards, manly concerning the qualification processes, leading the design of a GRP piping system according to the ISO 14692 in its 1st and 2nd editions.

The main steps of the two qualification processes regarding ISO 14692 editions are given separately.

The description of the ISO 14692 standard starts from the qualification processes.
The knowledge of the qualification process makes possible the characterization of all the mandatory validation tests, starting from the design demands such as the design pressure, the structural dimensions, the operating temperature, the lifetime, and the external state of stress conditions due to environment.

Because of the design purposes of this work, the qualification paths concerning the two editions of the standard, have been summarized and automated in two Matlab® tools.
The **Qualification Tools**, respectively called **QT2002** and **QT2016**, recall the qualification procedures, together with the system demand requests[30], and allow the automatic calculation of the parameters regarding the mandatory tests. If the test satisfies the requirements, this assesses the suitability of the product in accordance with the standard.

The test parameters work then as the input for the analytical simulation of the validation tests, which allow to determinate the minimum reinforced wall thickness of the pipe in accordance with the qualification procedure of the ISO 14692.
The analytical simulation of the validation tests is based on the APT and HST[31], as well as on the matrix and fibre described in the Chapter 1 – Composite Materials.

[30] Reassumed in Table 20
[31] HST is used with appropriate redeployments to well adapt to the validation tests conditions

The combined use of these developed software, **QT**, **APT** and **HST**, permits the determination of the minimum pipe wall reinforced thickness, t_r [mm], which is considered to be in accordance with the qualification requirements[32].
The investigation procedure is shown in Figure 85[33].

The calculation of the expected minimum pipe wall reinforced thickness is performed for each one of the international standard edition (1st and 2nd).

A critical discussion, as well as the application of the qualification programmes to the case of study are given in paragraph 8 of chapter 5, concerning the ISO 14692 1st edition, and chapter 6 concerning the ISO/FDIS 14692 2nd edition.

Finally, the conclusive Chapter 7 provides also a critical comparison between the results from the both design processes.

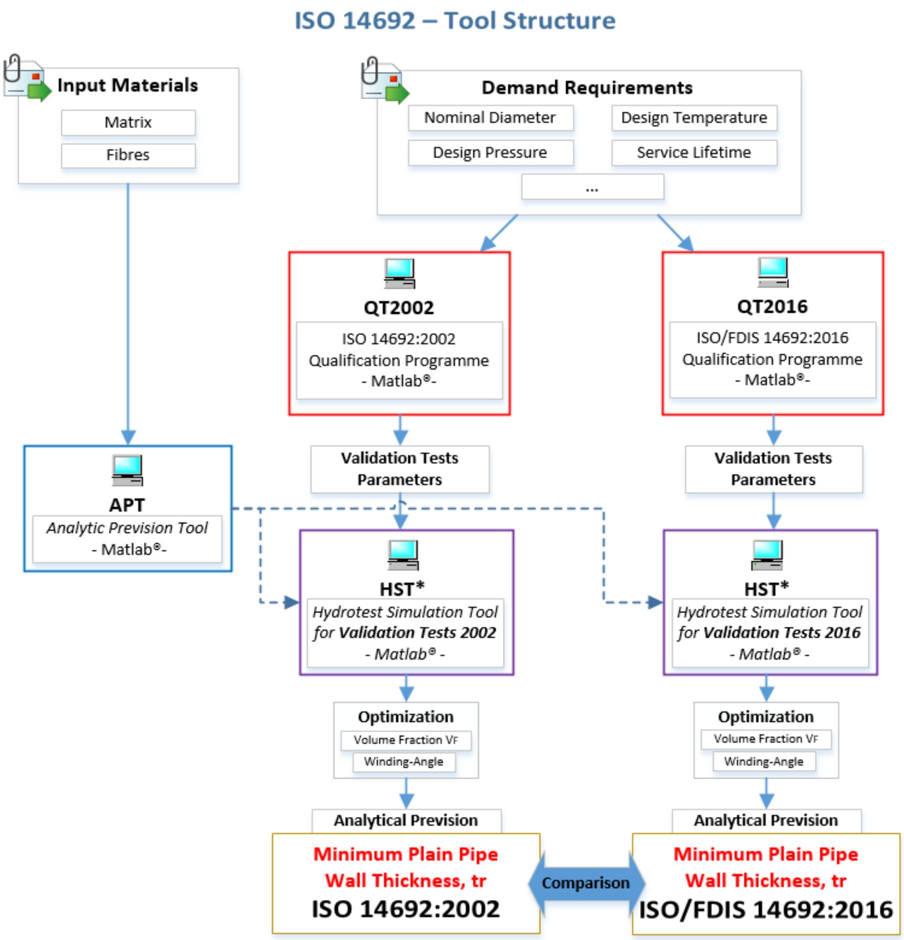

Figure 85 - Guideline of the design procedure adopted for the evaluation of the pipe wall thickness in accordance with ISO 14692 1st and 2nd edition.

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[32] By mean of the simulations of the validation tests it's intended to provide a prevision of the pipe wall thickness. The simulations DO NOT replace the experimental testing.
[33] The given flowchart is simplified. The QT, HST, and APT works together; the procedure IS NOT LINEAR. The process is iterative and calculate the final thickness by starting from a low value and checking all the requirements given from the qualification programme of each edition.

4. General Information and Limitations

Due to the complexity of the standards, some flowchart concerning the qualification processes are given to provide an easy tool to navigate within the qualification and design path.

Design guidelines are reported within the description of the qualification path, as well as all the procedures to evaluate the factors and coefficients needed for the qualification of the pipe.

Because both the ISO 14692 editions recall other international standards, mainly concerning the pressure tests, some brief summaries can be found into the appendix.

A review of the calculations needed, concerning the structural design of the plain pipe, is given within chapters 5 and 6.

The scope of this work is the design concerning the only mechanical performance of the pipe; fire and electrostatic performances are not considered.

The analysed qualification programme concerns the only plain pipe design. Other components such as tees, joints, elbows follow a qualification program which may include differences starting from the plain pipe one.

5. The ISO 14692:2002

This chapter presents the description of the qualification programme of a piping system in accordance with ISO 14692:2002.
This guide provides, at first, a brief introduction regarding the applicability range and the limitations of the standard.
The core discussion of this guide is carried out into the paragraph 4 and concerns the qualification programme. The qualification programme contains all the requirements, such experimental testing and calculation, which allow the design of the pipeline in accordance to the ISO standard.
The list of loads threated within the ISO standard constitutes the stress analysis described in paragraph 5.
The description of all the factor and coefficients used into the qualification programme and design are fully described into paragraph 6.
A summary of the testing after installation is finally given in paragraph 7.

1. Applications

The ISO 14692:2002 applies to GRP piping installation associated with oil and gas industry processing and utility service applications. The standard is primary intended for offshore application, but it may be also used as a guidance for high-criticality applications onshore.

Other applications may include:
1. onshore pipeline or piping systems transporting both oil and associated gas
2. pipeline and piping system for chemicals

Below, a brief list of typical current and potential applications of GRP piping where ISO 14692:2002 may be applied.

Fuel	Jet-A fuel	Hydrogen chlorite gas
Gas	Oil	Inert gas
HCl	Water (process, waste…)	…

Table 33 – Brief list of general application of ISO 14692:2002

2. Limitations

Parts 1 and 2 of the standard describe the requirements for the qualification and manufacture of GRP piping and fittings. Valves are excluded.

2.1. Materials

The main materials limitation concerns the resin and fibre types.
The manufacture of components shall be limited to thermosetting resins for rigid pipe systems. Typical resins are epoxy, polyester, vinyl ester, and phenolic. Thermoplastic resins are explicit excluded "because of the lack of experience in piping applications covered by this part of ISO 14692". Cit. [ISO 14692:2002-1, clause 6].
Thermosets glass transition temperature T_g shall be 30°C above the standard qualification temperature, which is 65°C. So, it must be greater than or equal to 95°C.
The maximum allowable operating temperature for GRP pipeline or piping system is determined by the resin type and the state of cure.
The following values are given for initial guidance only.

Resin Type	Maximum operating temperature
Epoxy	110° C
Vinyl ester	100° C
Polyester	70° C
Phenolic	150° C

Table 34 - Resin maximum operating temperature

The minimum operating recommended temperature for GRP regardless the resin type is -35°C, although lower temperature may be considered.

Temperature limits may be considerably different since the performance and properties of thermal, mechanical, and chemical resistance may vary significantly depending on the adopted resin and curing agent.
The previous guidelines are based on experience and on a generic resin compound.

The principal reinforcement material shall be glass fibre, whatever continuous or woven rovings.
The long-term behaviour, pressure retention, impact and fire performances of a glass fibre reinforced pipe are known. The use of other fibre such aramid or carbon are not explicitly excluded but the preferred fibre is glass due to the little information about the behaviours of the others.
Furthermore, the use of fibre other than glass is allowed as a local reinforcement in joints.

2.2. Mass Fraction W_f

The standard declares a range of acceptability of the product concerning the mass fraction of fibre, which in the case of the plain pipe, manufactured by filament-winding processes, ranges from 0.70 to 0.82.

2.3. Liner

ISO 14692:2002 is not applicable to the pipe systems which incorporate a thermoplastic or elastomeric liner because the presence of liner will result in a change of the mode of failure for pressure retention. [17].
"The failure for pipes with $\pm 55°$ degree angle of winding and without elastic liner is mostly by weeping. The reason is that the strain to failure of the glass is higher than the matrix material epoxy, vinyl ester, etc.". Cit. [15]. A liner in the pipe will increase the short-term pressure calculated i.e. by mean of ASTM D1599 test method.
The adoption of thermoset liner is not forbidden.

2.4. Wall thickness limitations 1 – Mariotte's Equation

As reported in 5.5 part 2, the limitations regarding the wall thickness are the following:

The structural calculation given into the standards are only valid for thickness-to-diameter ratios which are in accordance with equation:

$$\left(\frac{t_r}{D}\right) \leq 0.1$$

where

t_r is the average reinforced thickness of the wall, expressed in [mm], i.e. excluding liner and thickness for fire protection
D is the mean diameter, expressed in [mm], of the structural portion of the wall

The condition in equation (1) expresses the limitation of applicability of the Mariotte's equation for calculation of stresses within a pipe wall subjected to an internal pressure and defined as:

$$\sigma_{ap} = \frac{pD}{4t_r}$$

$$\sigma_{hp} = \frac{pD}{2t_r}$$

where
σ_{ap} is the axial stress (along pipe axis) expressed in [MPa] due to inner pressure p [MPa].
σ_{hp} is the hoop stress (perpendicular to the pipe axis) expressed in [MPa] due to inner pressure p [MPa].

When the thickness exceeds the condition, it is demonstrated that the stress state within the thickness should not be approximated, but properly analytically calculated in order to give a more accurate state of stress within the pipe thickness.

2.5. Wall thickness limitations 2 - Robustness

Furthermore, to provide sufficient robustness during handling and installation, the minimum total wall thickness t_{min}[mm], of all components shall be defined considering the follow limitation:

For $D_i \geq 100[mm]$: $t_{min} \geq 3[mm]$
For $D_i < 100[mm]$: $t_{min} \geq 0.025 * D_i\ [mm]$

where D_i is the internal diameter corresponding to the reinforced wall of the components, in [mm].
For more onerous applications, for example offshore, the minimum diameter should be increased to 5 [mm].

2.6. Winding angle

Pipeline systems are commonly manufactured as filament-wound products.
The optimized winding angle for the stress state induced by the inner pressure condition is $\pm 55°\ [deg]$ as previously demonstrated.
The standard does NOT give any mandatory range for the manufacture of the pipelines, anyway, the importance of this angle is remarked within all the standards.

The optimization of this manufacturing parameter is wide investigated within the case of study, the treatments of which follow the descriptions of both the editions of the ISO 14692.

3. Component Definitions

The ISO 14692:2002 divides products into several categories.
The Family Representative is mostly a plain pipe, with a specific diameter and wall thickness, of which such a full regression line according to ASTM D2992 can be determined. This is the family representative of the pipe. Similarity, a regression line shall be also determined for family representative of fittings, elbows, tees, and flanges.

The qualification test is a one-time test and a manufacturer has to provide the full withstand of the family representative product in order to accomplish the requirements of the standard.
The determination of the regression line according to ASTM D2992 B, of whose description may be found into appendix, is a process which takes, at least, more than 2 years, and is important to define the *Family Gradient* G.

Each family of production (pipes, fittings, elbows…) is subdivided into **product sectors**, depending on diameter ranges, and each product sector has a **product sector representative**, which is the component with the largest diameter into the sector.

"Sectors": Diameter ranges from D_{min} to D_{max} in [mm]						
25 to 250	250 to 400	400 to 600	600 to 800	800 to 1200	1200 to 2400	>2400

Table 35 - Overview of Sectors

"Sectors representative": Diameter D in [mm]						
250	400	600	800	1200	2400	>2400

Table 36 - Sector Representatives

Finally, the whole products which are not sector or family representative are considered **component variants** into the standards.

4. Qualification programme

"The qualification programme consists of standard methods for qualifying component performance with respect to static internal pressure, elevated temperature, chemical resistance, electrostatic and fire performance properties, with optional methods for qualifying potable water, impact, low temperature and limited cyclic pressure performance". Cit… [17].
The qualification of electrostatic performances and fire resistance are not taken into account in this review of the standard. The whole qualification programme is explained into part 2 of the standard.
Furthermore, the present shall be intended only as a guide and DOES NOT substitute the knowledge of the entire ISO 14692:2002 standards and of all the others mentioned within.

The assessment is made upon the concepts of **Qualified Pressure** and **Qualified Stress**.
The qualification program links the two parts and proceed from the qualified pressure assessment to the qualified stress one. The assessment is based on experimental testing of the components and the materials.

The experimental tests requirements define the constraints on which the **minimum reinforced wall thickness[34], t_r**, of the component[35] shall be chosen. The design process shall define a proper wall thickness which allows to pass all the experimental validation tests.
The nature of the tests to be achieved varies, depending on the component type, family representative, product sector representative.

Furthermore, the components that have been subjected to qualification testing shall not be used as part of a GRP pipeline or piping system.

4.1. Flowcharts[36]

The ISO 14692:2002 is a very complex standard and it needs a thorough study. It makes a confused use of the concept of "qualified pressure P_q": sometimes related to the manufacturer components, sometimes related to the required performance, or to the verified.
Since no one is provided into ISO, a flowchart has been developed for a better comprehension of the qualification path and the design guidelines.
The flowchart unifies the procedures which are being described in the following paragraphs.
Furthermore, a summary of the core equations and auxiliary procedures concerning the qualification programme (qualified pressure and qualified stress) are given.

- **Flowchart A 2002**- provides the overall qualified pressure and qualified stress assessment paths, in addition to a recapitulation of the tests required.
- **Flowchart B 2002**– provides a recapitulation of the coefficients and factors calculation.
- **Flowchart C 2002**– provides a summary for the two qualification approaches regarding the qualified stress procedure: the fully measured and the simplified envelope assessments. (see later)

[34] The reinforced wall is the portion of the thickness that withstand the loads. The liner is not considered in this thickness because it does not give any structural resistance.
[35] The procedure is fully developed concerning the design of a plain pipe
[36] The Flowcharts are provided in A3 format as attachments at the end of the book and in PDF version.

It is recommended the help of the flowcharts while reading this document, and the legislation itself, to have a clearer overview of all the processes.

4.2. Qualification Programme – Qualified Pressure

The beginning of every design path is the determination of the performance properties needed and this basis on the demand requirements.
After defining the requirements of the total pipe system, concerning the performance properties described above, the manufacturer shall identify the minimum **Qualified Pressure $\boldsymbol{P_q}$** (then $\boldsymbol{P_{q0}}$), that each component should reach to compose a safety pipeline, according to the demand requirements and to the ISO standard.
This performance requiring key indicator, called $\boldsymbol{P_{q0}}$ into the flowchart, shall be evaluated by means of the standard procedure described later. It makes use of coefficients to take into account all the aspects of the pipeline system.

Then, the manufacturer develops a purchase quotation which consists on a proper series of components for the construction of the pipe system characterized by a **Proposed Qualified Pressure $\boldsymbol{P_q}$**.
The proposed qualified pressure P_q is a property of each component produced by the manufacturer, it is expressed in Mega Pascal [MPa] and should be equal or greater than the corresponding qualified pressure P_{q0}.

$$P_{q0} \leq P_q$$

The objective of the qualification procedure is to verify the proposed qualified pressure P_q of each component in accordance with the experimental testing requirements described in 6.2.2 – Table 37. With this procedure, it is possible to demonstrate that the **Verified Qualified Pressure $\boldsymbol{P_{q(v)}}$** is equal or greater than the P_{q0}.

Component	Product type	Qualification tests	Purpose
Plain pipe	Family representative[a]	**Full regression test** at 65 °C, or design temperature if higher (ASTM D2992:1996 – Procedure B)	Qualified pressure Qualified stress Gradient
Pipe plus joint, fittings and fabrication processes	Family representative[a]	**Full regression test** at 65 °C, or design temperature if higher (ASTM D2992:1996 – Procedure B) **or Default gradient**	Qualified pressure Baseline gradient for determining survival test pressure
	Product sector representative	Two 1 000-h survival tests at 65 °C, or design temperature if higher (ASTM D1598)	Qualified pressure
	Component variant	Two 1 000-h survival tests at 65 °C, or design temperature if higher (ASTM D1598) **or Scaling method** **or Design method** (in exceptional cases)	Qualified pressure

[a] Only one size of component diameter is required to be tested.

Table 37 – Full qualification procedure for pipes (plus joints) and fittings – p. 9:2 – 6.2.2

The qualification process for the qualified pressure assessment can be reassumed by the following equations:

$$if\ P_q \leq P_{q(v)} \quad \Rightarrow \quad P_{q0} \leq P_{q(v)}$$

where
P_{q0} is the qualified pressure needed, expressed in megapascals
P_q is the proposed qualified pressure of the component, based on manufacturer experience
$P_{q(v)}$ is the verified qualified pressure of the component, based on experimental testing

The qualification tests are proof tests of specific representatives of a given product family and do not need to be repeated for each order or project.

The qualification programme also includes testing of components in order to provide data for quality control and the system design.

4.2.1. Definition of the Qualified Pressure P_{q0}

The definition of the qualified pressure P_{q0} depends on the demand requests and from the configuration of the pipeline. The P_{q0} is the performance indicator attributed to the requested pipeline that represents the threshold to reach by each component.

The demand information to provide to the designer are:

- The type of fluid - gas or liquid and the characteristics.
- The design pressure P_d [MPa].
- The design operating temperature T_d [C°].
- The nominal diameter of the pipeline [mm].
- The environmental operating conditions.
- The design lifetime.

The Qualified Pressure P_{q0} is based on a standard service life of 20 years at a temperature of 65°C. The effect of operation at other temperature and chemical degradation from the transported medium shall be accounted for by partial factors A_1 and A_2.
The cyclic load conditions are taken into account for by the presence of the partial factor for cyclic load conditions A_3.

The request Qualified Pressure P_{q0} is calculated as:

$$P_{q0} = \frac{P_d}{A_1 \cdot A_2 \cdot A_3 \cdot f_2 \cdot f_3}$$

where
P_d is the design pressure [MPa]
A_1, A_2, A_3 are respectively the partial factor for temperature, chemical degradation, and cyclic load

f_2 is the safety factor
f_3 is the partial factor for the limited axial load capability

The evaluation of the factors is given in the following Factor paragraph.

4.2.2. Definition of the Qualified Pressure P_q

The proposed Qualified Pressure P_q, which should be greater than P_{q0} value, is related to the *manufacturer's nominal pressure rating* p_{NPR} [MPa].
It is based on the experience of the manufacturer and shall be approximated by means of the equation:

$$P_q = \frac{p_{NPR}}{f_2 \cdot f_{3,man}}$$

where
f_2 is the load factor (or safety factor)
$f_{3,man}$ is the factor to account for the limited axial load capability of GRP
p_{NPR} is the manufacturer's nominal pressure rating of the component.

The manufacturer uses recommended default values for the purchase quotation corresponding to $f_2 = 0.67$ and $f_{3,man} = 0.85$.

The definition of P_q relates the manufacturer experience in pipeline production with p_{NPR}, which is a parameter used to classify the manufacturer pipe production.
This means that a pipe of 400 [mm] diameter and 38 [mm] wall thickness has an assigned p_{NPR} of 20 [MPa] from the manufacturer.
This value is strictly related to the constructor and to his technical parameters, such as the wall thickness, winding angle, materials, … etc.

Therefore, the choice of a proper p_{NPR} identified component shall be done following the equation which takes into account even the temperature, chemical and eventually cycling load condition, as for the P_{q0}:

$$p_{NPR} = \frac{P_d}{A_1 \cdot A_2 \cdot A_3}$$

where
P_d is the design pressure [MPa]
A_1, A_2, A_3 are respectively the partial factor for temperature, chemical degradation, and cyclic load

Using these two equations, the manufacturer chooses the proper p_{NPR} identified component considering the corresponding P_q and the condition $P_{q0} \leq P_q$.

Then, the experientially evaluation of the $P_{q(v)}$ qualified pressure of the component chosen can be carried out.

4.2.3. Qualified Pressure $P_{q(v)}$

The procedure to evaluate the $P_{q(v)}$ qualified pressure depends on the nature of the component: plain pipe (family representative) or pipe plus joints & fittings and other fabrication processes (family representative, product sector representative and component variants).
The next paragraphs refer to Table 37 – "Qualification Test".

4.2.3.1. Family Representative: ASTM D 2992 Testing Evaluation

The scope of the qualified pressure assessment is to demonstrate that the component, as it has been designed and manufactured from the constructor, withstands to the design pressure, at the design temperature and chemical condition, all along the design lifetime.

"This regression qualification procedure determines the long-term hydrostatic pressure P_{LTHP} and the lower confidence limit pressure P_{LCL}in [MPa] of the family representative for plain pipe on a design lifetime of 20 years. Only one size of pipe diameter is required to be tested.
The qualified pressure $P_{q(v)}$ is P_{LCL}." [37]

Testing shall be carried out on product with a diameter of 50 [mm] or larger at, as minimum, 65°C or design temperature if higher than 65°C. The test fluid is potable water.

The evaluation of $P_{q(v)}$ is made through the ASTM D 2992 procedure B[38], which consists in a standard practice for obtaining hydrostatic design basis for GRP pipes.

The ASTM D2992 procedure B asks to carry out a series of hydrotest on plain pipe held at different pressures and record the time-to-failure for each sample. The sample must fail in a defined range of times and the test has a duration up to 2 years.

The regression line evaluated by means of statistical analysis can be drawn on a log-log cartesian graph as in Figure 86.

[37] ISO 14692:2002 part 2 – full qualification procedure - 6.2.3.1
[38] A description of the ASTM D 2992 is reported into the appendix.

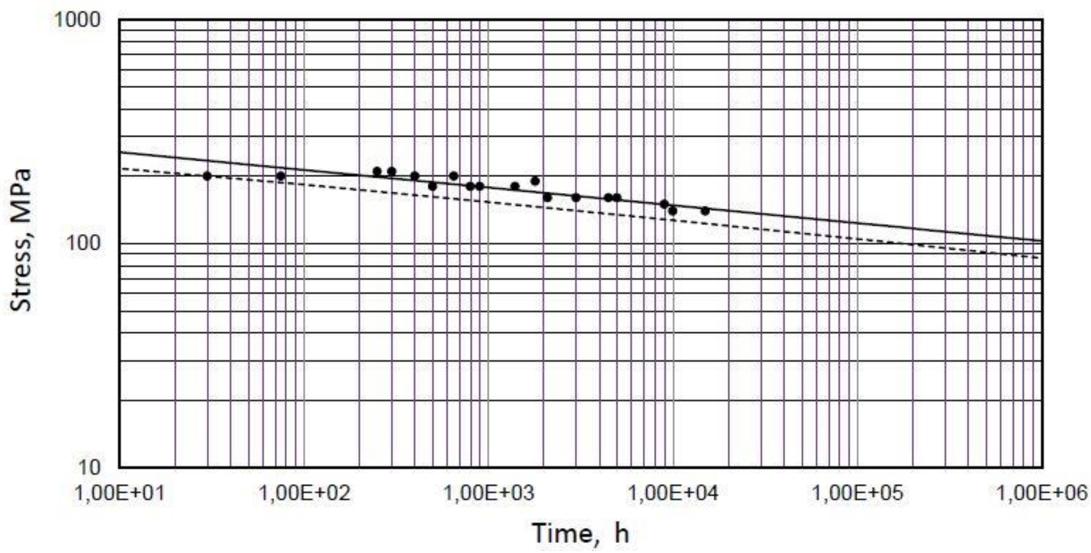


Figure 86 - Regression data representation from ASTM D2992

The continuous regression line interpolates directly the failure points and has the following equation:

$$\log(Pressure) = A - G\log(time)$$

where
Pressure is expressed in [MPa]
Time is expressed in [h], hours.

The long term hydrotest pressure, P_{LTHP}, identifies the predicted pressure which would provoke failure after 20 years, approximately 175400 [h].

$$\log(P_{LTHP}) = A - G\log(175400)$$

The qualified pressure $P_{q(v)}$ or P_{LCL} are related to the following equation:

$$P_{q(v)} = P_{LCL} = f_1 \cdot P_{LTHP}$$

where
f_1 provides a measure of the degree of scatter in the long-term pressure tests and it is the evaluation of the scatter band at the 97.5% confidence limit from test data as defined in ASTM D 2992 procedure B.

The analysis of the regression data to generate the statistical parameters of the mean, variance of the curves and the P_{LCL}should be carried in accordance with annex K of ISO 14692:2002 part 2.
The dotted line in Figure 86 represents the lower confidence limit.

This represents an experimental constraint to the **minimum reinforced wall thickness** of the pipe. In the case of pipes under inner pressure loading, the required P_{LCL} pressure lower confidence limit represents a more restrictive test, when compared to the ASTM D1599 hydrotest performed within the validation procedure for the failure envelope.

The procedure in ASTM D2992 allows also the evaluation of the $G\ gradient$ which describes the time degradation of the material, and basically, is the slope of the regression line.

After defining the qualified pressure $P_{q(v)}$ and taking into account the proper design lifetime, the manufacturer shall assign a **Qualified Stress $\boldsymbol{\sigma_{qs}}$**, to the pipe in accordance with equation:

$$\sigma_{qs} = P_{q(v)} \cdot \frac{D}{2t_r}$$

where
$P_{q(v)}$is the qualified pressure [MPa].
D is the mean structural diameter of the pipe in [mm].
t_r is the average reinforced wall thickness [mm].

The qualification program described up to this point applies for the determination of the $P_{q(v)}$ concerning the plain pipe family representative and the pipe plus joints family representative as defined in ISO 14692:2002.

4.2.3.2. Product Sector Representative: ASTM D 1598 Testing Evaluation

The family representative qualification procedures for plain pipe determines the $G\ gradient$ and the P_{LCL} lower confidence limits, and so the qualified pressure $P_{q(v)}$.

The product sector representative qualification procedure uses the $G\ gradient$ from the family representative to propose a qualified pressure P_q, which is verified by means of the ASTM D 1598[39].
The test consists on a 1000 h survival test carried out at a pressure which permits to demonstrate that the product sector representative's performance is equal, or superior, to that of the family representative. The qualified pressure $P_{q(v)}$ is equal to the P_{LCL}.

Here is the calculation procedure for the 1000 h test pressure.

[39] Appendix: ASTM D 1598 - 15a Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure

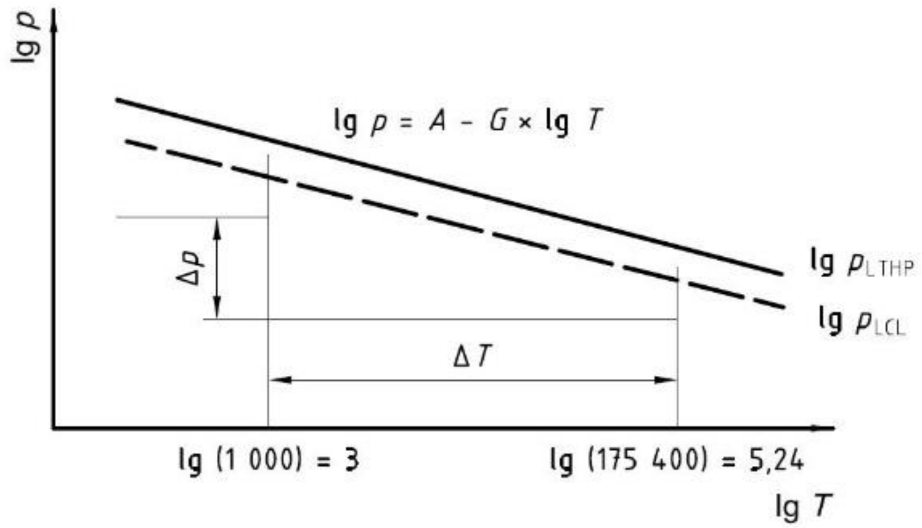


Figure 87 - Representation of the regression graph for the calculation of the pressure test in ASTM D1598

$\log(T_{P1000}) = \Delta p + \log(P_{LCL})$

$T_{P1000} = P_{LCL} \cdot 10^{\Delta p}$

$\Delta p = G \cdot \Delta Time = G \cdot [log(174500) - log(1000)] = 2.24 \cdot G$

$T_{P1000} = P_{LCL} \cdot 10^{2.24 \cdot G}$ [MPa]

Two replicated samples of the product sector representative shall be selected randomly and pressure-tested in accordance to the ASTM D1598 at 65°C or design temperature if higher. The product sector representative is qualified if it survives the test duration.

The component which are qualified by this procedure are the product sector representative.

4.2.3.3. Component Variant: ASTM D 1598 Testing

This qualifying procedure permits the qualification of the P_{LCL} of a component variant for pipe plus joint (same joint type as the product sector representative) based on either a 1000 h survival test or scaling methods.
The test procedure is the same of the product sector above presented, which is based on two ASTM D1598 tests.
The design procedure consists on scaling the results of the product sector representative using the mean diameter of the reinforced wall and the reinforced wall thickness of the pipe.
The procedure[40], which here is not presented, is suitable only for the components that have a smaller diameter than the product sector representative.

[40] ISO 14692:2002 part 2 - component variant validation procedure - 6.2.3.2.3

4.2.3.3.1. Lifetimes other than 20 years

This qualification procedures determine the gradient G, in MegaPascal per hours, of the family representative. The gradient G is used to determine the P_{LCL}, and so the $P_{q(v)}$, based on a design life of 20 years.

If the design lifetime exceeds the default 20 years, it is possible to convert the qualified pressure $P_{LCL-\ 20years}$ to a different lifetime $P_{LCL-\ T\ years}$ at T years by the following equations:

$$P_{LCL-\ 20years} = P_{LCL-\ T\ years} \cdot 10^{\Delta p}$$

$$\Delta p = G \cdot [1.3 - \lg(T)]$$

Alternatively, the same result can be obtained by substituting the 20 years (175400 h) into the definition of P_{LTHP}, so, for example, for a design lifetime of 33 years:

$$\log\left(P_{LTHP-33years}\right) = A - G\log(33 \cdot 365 \cdot 24)$$

where G is the appropriate gradient of the regression line, [MPa/h], for the component variant of interest.

4.3. Qualification Programme – Qualified Stress

The qualified stress procedure is not reported into the 2nd part of the ISO 14692:2002 which concerns the qualification programme. The only explicit reference appears into Table 37.

Component	Product type	Qualification tests	Purpose
Plain pipe	Family representative[a]	**Full regression test** at 65 °C, or design temperature if higher (ASTM D2992:1996 – Procedure B)	Qualified pressure Qualified stress Gradient

Table 38 - extract from table 1 - full qualification procedure for pipes (plus joints) and fittings

The procedure which is being described is the core of the part 3 of the ISO standard: System Design. The scope of this part is to give a guideline for the design of FRP piping systems, and the requirements apply to layout dimensions, hydraulic design, structural design, detailing, fire endurance, spread of fire and emissions and control of electrostatic discharge.

The qualified stress procedure is reported within the structural design ISO paragraph and its aim is to ensure that the pipe system performs satisfactorily, and sustains all stresses and deformations throughout the entire service life.

The general requirement is that the sum of all **hoop stresses** and the sum of **axial stresses**, $\boldsymbol{\sigma_{h,sum}}$ and $\boldsymbol{\sigma_{a,sum}}$, in any component of the piping system due to pressure, mass and other sustained loadings, and of the stresses produced by occasional loads such as wind, blast or earthquake shall not exceed the values defined by the factored long-term design envelope, derived from acquired regression data.

“If the sum of these stresses lies outside the factored long-term design envelope, then the pipe of next higher rated pressure shall be chosen from the product family, and the stress calculation repeated until the sum of the stresses lies within the factored long-term design envelope[41].”

This procedure shall be applied considering the most severe condition predictable during the service life of the pipeline.
The **qualified stress** $\boldsymbol{\sigma_{qs}}$ shall be evaluated as described into the qualified pressure qualification procedure for pipes. In the case of fittings, the value of the qualified stress, σ_{qs}, shall be calculated in accordance with the follow equation:

$$\left(\frac{\sigma_{qs}}{P_{q(v)}}\right)_{fitting} = \left(\frac{\sigma_{qs}}{P_{q(v)}}\right)_{pipe}$$

While the stress state (loads induced) shall be calculated using the equations presented in the Stress Analysis paragraph, the failure envelope varies as a function of $\boldsymbol{f_2}$ safety factor which takes into account the nature of load, whether occasional, sustained including and sustained excluding thermal loads.
A further description of the safety factor $\boldsymbol{f_2}$ is given into the Factors paragraph.

[41] Cit. ISO 14692:2002 part 3 – limits of calculated stresses due to loading – 7.10

Because of the difference nature of loads, whose list is reported in Stress Analysis paragraph, the qualified stress assessment divides into 3 sub-assessments:

a) Assessment of sustained loading excluding thermal effects

Unless otherwise specified by the user, the part factor, *f*2, used for the evaluation of sustained loads excluding thermal effects shall be set to 0.67.

b) Assessment of sustained loading including thermal effects

Unless otherwise specified by the user, the part factor, *f*2, used for the evaluation of sustained loads including thermal effects shall be set to 0.83.

c) Assessment of occasional loading

The part factor *f*2 to be used in the assessment of the combination of sustained loads such as pressure, and mass, and occasional loadings such as water hammer, wind or earthquake or blast loading shall be determined taking into account operating conditions and risk associated with the pipe system. The value to be applied for specific piping systems shall be specified by the user. Unless otherwise specified by the user, the part factor *f*2 shall be taken as 1.33 × 0.67 = 0.89 for the evaluation of this case.

The Figure 88 shows a simplified flowchart of the qualified stress assessment.

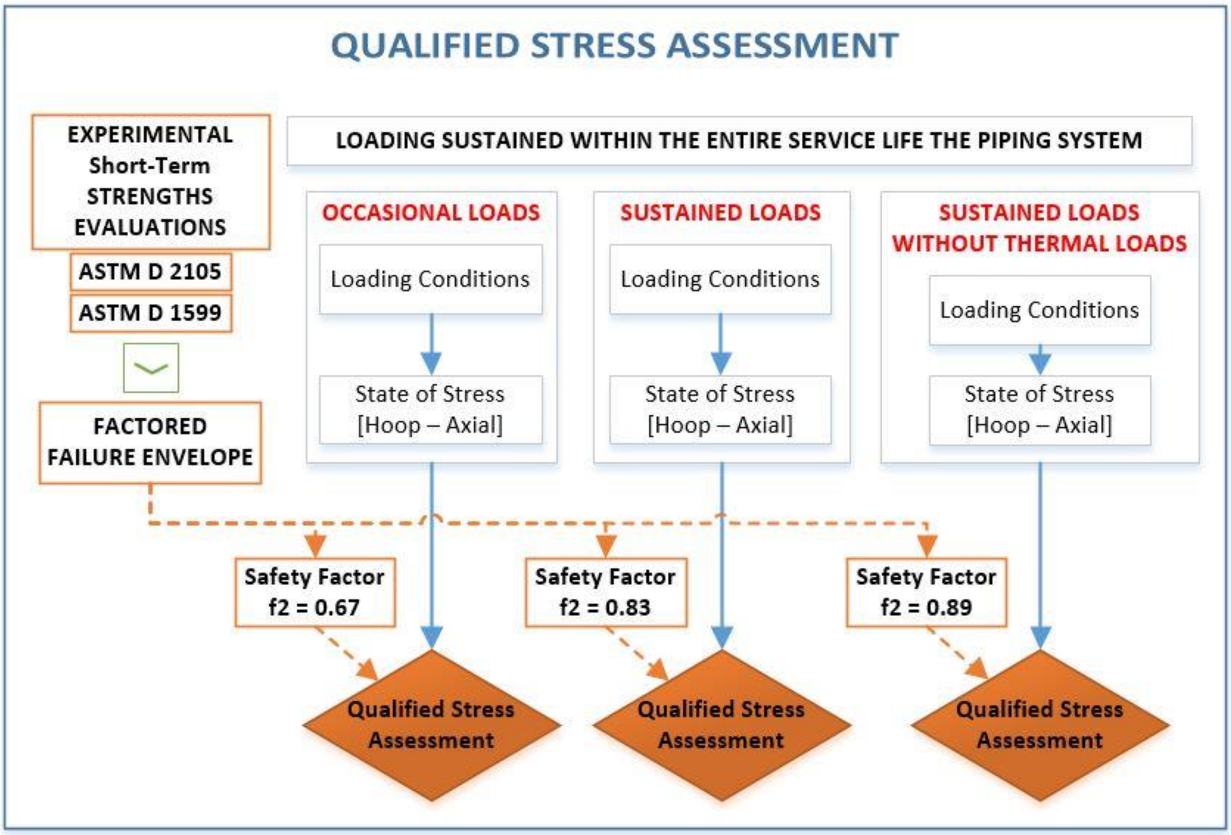


Figure 88 - Simplified Flowchart of the Qualified Stress Assessment

The qualified stress procedure used for the assessment is linear, but varies depending on the design choices and knowledge concerning the non-pressure-induced axial stress of the pipeline.

Two cases may present:

A) If the magnitude of **non-pressure-induced axial stress, $\boldsymbol{\sigma_{ab}}$,** is known, the allowable hoop stress $\sigma_{\mathrm{h,sum}}$ can be determined following the equation:

$$\sigma_{\mathrm{h,sum}} \leq f_2 \cdot f_3 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \sigma_{qs}$$

where

f_2 is the part factor for loading and shall be determined in accordance with the type of load considered (occasional, sustained, sustained without thermal loads).

A_1, A_2, A_3 are respectively the partial factor for thermal, chemical and cycle loading conditions.

f_3 is the part factor for axial loads. The calculation of the f_3 part factor is long and articulated, the full procedure is reported in the following factor paragraph.

B) If the magnitude of non-pressure-induced axial stress, σ_{ab}, is not known, the assessment by mean of a failure envelope is necessary. The failure envelope assessment explained in the next paragraphs uses either of two methods:

a. Method A – **Fully Measured Envelope**
b. Method B – **Simplified Envelope**

4.3.1. Failure Envelope

These following paragraphs describe how the failure envelope of the GRP pipe components can be determined to meet the requirements for the qualified stress assessment.
The two design options, the fully measured envelope or the simplified envelope, are defined depending on the viability of measured data.

Both the solutions determine a short-term envelope starting from experimental testing and then scale the curve by mean of proper coefficients up to the factored long-term design envelope, which represents the threshold for the stress state of the component under analysis.

The fully measured envelope is generally only available for plain pipe. For all the other component variants, the simplified envelope should be used. The less conservative procedure is the fully measured envelope.

Because of the fully measured envelope method requires more experimental tests than the simplified one, most of the manufacturers adopt only the simplified one, which, anyway, is more conservative than the fully measured envelope method.

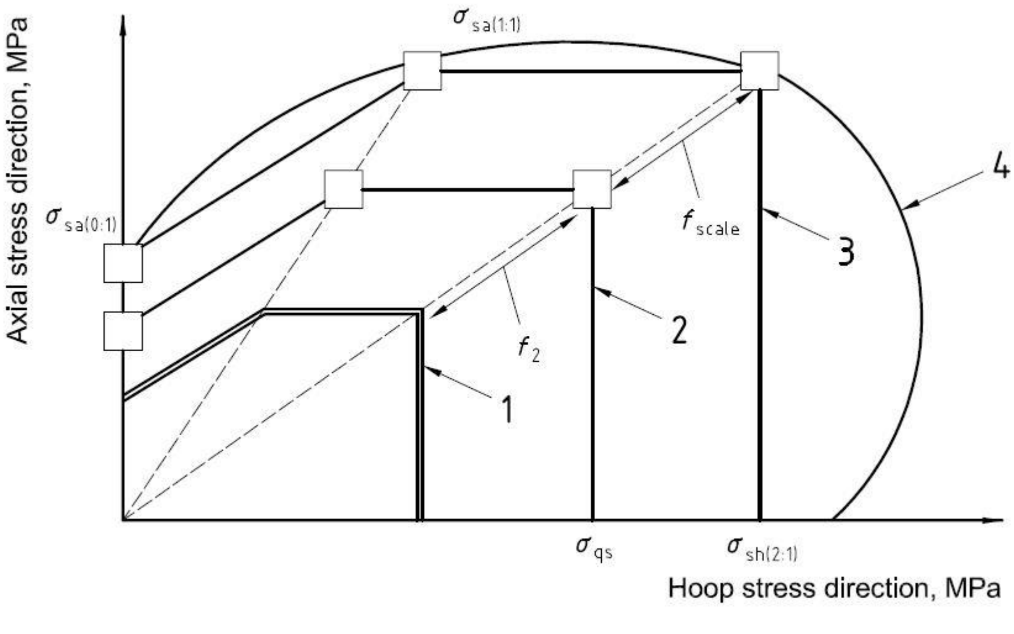
4.3.1.1. Fully Measured Envelope

The determination of the short-term envelope for the fully measured envelope method is given in Annex C – part 2 of the ISO standard.
The procedure gives a guidance on measurements of the strength data for GRP under different combination of hoop and axial stress. This procedure is relevant if it is possible to apply additional axial loads in addition to the induced axial load from internal pressure to the components.

As can be seen in Figure 89, the long-term design envelope is derived from either a fully measured short-term envelope (plain pipe) or a 1000h survival test envelope (fittings).
A minimum of 3 data points, collected for a different ratio of applied hoop and axial stresses, are required to define the short-term envelope.

The collected points are:

- *Point 1:* **0:1 hoop to axial stress**, i.e. axial tension only ($\sigma_{sa(0:1)}$), in megapascals, measured in accordance with ASTM D 2105. (see biaxial strength ratio r paragraphs 6.4.1 for the description)
- *Point 2:* **1:1 hoop to axial stress**, i.e. internal pressure and axial tension ($\sigma_{sa(1:1)}$and $\sigma_{sh(1:1)}$), in megapascals.
- *Point 3:* **2:1 hoop to axial stress**, i.e. internal pressure only ($\sigma_{sa(2:1)}$and $\sigma_{sh(2:1)}$), in megapascals, measured in accordance with ASTM D 1599. (see biaxial strength ratio r paragraphs 6.4.1 for the description).



Key

1 long-term design envelope
2 idealized long-term envelope
3 idealized short-term envelope
4 schematic representation of the short-term failure envelope

Figure 89 - Idealized envelopes for a single-wound-angle ply GRP pipe with winding angles in the range of approximately 45° to 75°

The idealized long-term failure envelope is geometrically similar to the short-term envelope with all three data points being scaled according to f_{scale}, where:

$$f_{scale} = \frac{\sigma_{qs}}{\sigma_{sh(2:1)}}$$

where
σ_{qs} is the qualified stress, in megapascal, as defined for pipe and fittings.
$\sigma_{sh(2:1)}$ is the short-term hoop strength, in megapascals.

The long-term design envelope is based on this idealized long-term envelope multiplied by an appropriate factor of safety f_2 depending on the nature of the load. (see factor paragraph).

So, the long-term design envelope depends on the types of loading whether occasional, sustained or sustained without the thermal one.

Finally, the long-term design envelope is further scaled by A_1, A_2, and A_3 partial factors for temperature, chemical and cyclic loading to become the factored long-term design envelope.

The factored long-term design envelope, which defines the safety area within the σ_{hoop} , σ_{axial} stress plane, is defined according to the equation:

$$g_{long}\left(\sigma_{h,sum}, \sigma_{a,sum}\right) \leq f_2 \cdot f_{scale} \cdot A_1 \cdot A_2 \cdot A_3 \cdot g_{short}\left(\sigma_{sh(2:1)}, \sigma_{sa(0:1)}\right)$$

where
A_1 is the partial factor for temperature;
A_2 is the partial factor for chemical resistance;
A_3 is the partial factor for cyclic service;
f_{scale} is the scaling factor;
f_2 is the appropriate safety factor;
$\sigma_{h,sum}$ is the sum of all hoop stresses, in megapascals;
$\sigma_{a,sum}$ is the sum of all axial stresses, in megapascals;
$g_{long}\left(\sigma_{h,sum}, \sigma_{a,sum}\right)$ is the shape of the factored long-term design envelope;
$g_{short}\left(\sigma_{sh(2:1)}, \sigma_{sa(0:1)}\right)$ is the shape of the idealized short-term envelope;
σ_{ab} is the non-pressure-induced axial stress;
σ_{ap} is the axial stress due to internal pressure;

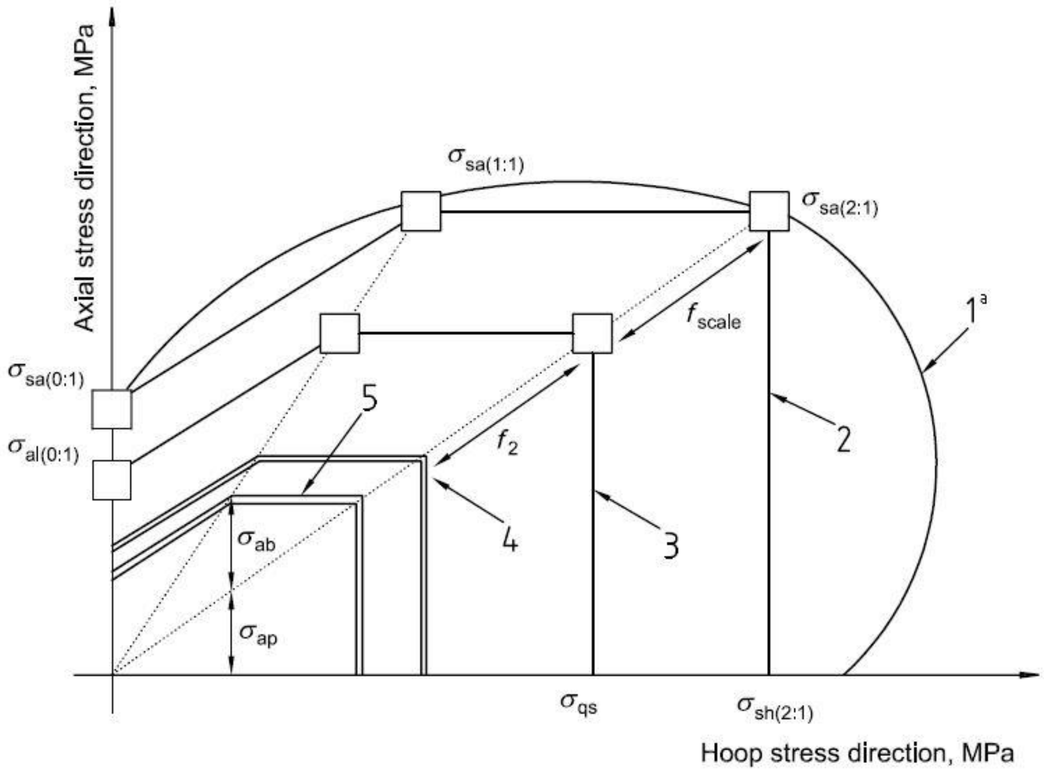


Figure 90 - Idealized long-term envelope for a single wound angle ply GRP pipe with winding angles in the range of approximately 45° to 75° degrees.

Key

1 – schematic representation of the short-term failure envelope
2 – idealized short-term envelope
3 – idealized long-term envelope
4 – non-factored long-term design envelope
5 – factored long-term design envelope

4.3.1.2. Simplified Envelope

The simplified envelope method makes use of the biaxial strength ratio r, as determined in 6.4.1. The shape of the envelope and its determination depends on the component under analysis, whether plain pipes, pipe plus joints, or fittings[42].

The procedure is similar for all the cases; here is the case for the **plain pipe** fully described.

The short-term and long-term failure envelopes for a single wound angle ply GRP pipe are qualitative represented in Figure 91, where the value of r can be expected to be less than 1[43].

The idealized long-term failure envelope is geometrically similar to the short-term envelope and it is derived according to the equation:

$$\sigma_{al(0:1)} = \sigma_{sa(0:1)} \cdot \frac{\sigma_{qs}}{\sigma_{sh(2:1)}}$$

or

$$\sigma_{al(0:1)} = r \cdot \frac{\sigma_{qs}}{2}$$

where
σ_{qs} is the qualified stress, in megapascals;
$\sigma_{al(0:1)}$ is the long-term axial (longitudinal) strength at 0:1 stress ratio, in megapascals;
$\sigma_{sa(0:1)}$ is the short-term axial strength at 0:1 stress ratio, according to ASTM D 2105;
$\sigma_{sh(2:1)}$ is the short-term hoop strength at 2:1 stress ratio, according to ASTM D 1599;
r is the biaxial strength ratio;

"The important feature of Figure 91 is that the axial tensile strength, $\sigma_{al(0:1)}$, is lower than the axial stress for the 2:1 internal pressure case, $\sigma_{sa(0:1)}$. The ratio of these strengths can range between 0.5 and 0.75 for plain pipe, depending on winding angle and specific pipe type.

The non-factored long-term design envelope is based on this idealized envelope multiplied by an appropriate part factor, f_s, depending on loading type."

[42] ISO 14692:2002 part 3 – simplified envelope and following paragraphs – 7.11.3
[43] If the value of r is more than 1, the "pipe plus joints" case applies – part 3 – 7.11.3.3

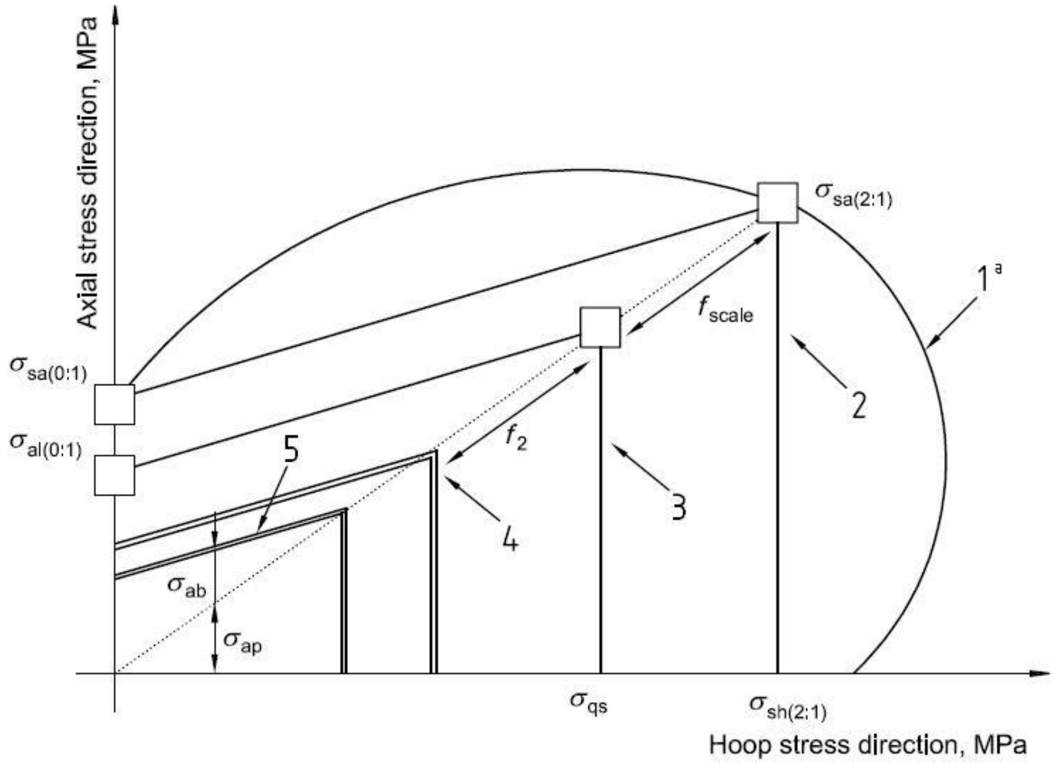


Figure 91 - Short and long-term idealized failure and design envelopes for a single wound angle ply GRP pipe with winding angles in the range of approximately 45° to 75° degrees.

Key

1 – schematic representation of the short-term failure envelope
2 – idealized short-term envelope
3 – idealized long-term envelope
4 – non-factored long-term design envelope
5 – factored long-term design envelope

The equations for defining the factored long-term design envelope for maximum hoop and axial stress eligible, respectively, are defined by the following equations:

$$\sigma_{h,sum} \leq f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \sigma_{qs}$$

and

$$\sigma_{a,sum} \leq \left(\frac{\sigma_{qs}}{2} - \sigma_{al(0:1)}\right) \frac{\sigma_{h,sum}}{\sigma_{qs}} + f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \sigma_{al(0:1)}$$

or

$$\sigma_{a,sum} \leq (1-r)\frac{\sigma_{h,sum}}{2} + f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \frac{r}{2} \cdot \sigma_{qs} \text{ ; assuming } r \leq 1$$

where

$\sigma_{h,sum}$ is the sum of all hoop stresses, in megapascals;
$\sigma_{a,sum}$ is the sum of all axial stresses, in megapascals;
A_1 is the partial factor for temperature;
A_2 is the partial factor for chemical resistance;
A_3 is the partial factor for cyclic service;

The last given equations describe the limits of the factored long-term design envelope in terms of hoop and axial stresses respectively. Both the criteria as described by these equations must be satisfied[44].

5. Stress Analysis – Determination of the pipeline sustained stresses

The stress analysis is necessary for the determination of the pipeline sustained stresses.
Either manual or computer methods shall be used for the structural analysis of piping systems.
The degree of the analysis depends on factors such as: pipework flexibility, layout complexity, pipe supports, temperature changes, system criticality and failure risk assessment.

The designers shall consider the loads given in Table 39 that can potentially be experienced by the piping system during the service life.

Sustained Loads	**Occasional Loads**
Internal, external or vacuum pressure	Water hammer, transient equipment vibrations, pressure safety-valve releases, hydrotest
Piping self-mass, piping insulation mass, fire protection mass, transported medium mass, buoyancy, other system loads	Impact
Inertia loads due to motion during operation Displacement of supports caused by flexing of the hull during operations	Inertia loads due to motion during transportation Earthquake-induced horizontal and vertical forces, where appropriate Displacement of supports caused by flexing during lifting
Thermal induced loads, electric surface heating	Installation loads, lifting loads, transportation loads
Environmental loads, ice	Earthquake, wind, Blast over-pressures
…	…

Table 39 - Loads Experienced by a GRP piping system

A summary of some of the loading cases which induce stresses within the pipe wall are reported in the following. The aim of the stress analysis is to define the $\sigma_{h,sum}$ and the $\sigma_{a,sum}$ stresses: respectively the sums of the hoop and axial stresses induced.

The fully calculation of the stresses is given into the ISO 14692:2002 part 3 section 8 – Stress Analysis.

[44] Extract from NOTE – ISO 14692:2002 part 3 – simplified envelope plain pipe – 7.11.3.2

5.1. External Pressure/Vacuum

The designer shall ensure that, where possible, vacuum conditions can be sustained by the selected component. The external collapse pressure, P_c, in megapascals, of GRP pipes shall be calculated by the equation which assumes that the length of the pipe is significantly greater than the diameter.
For thick and sandwich construction walls, the hoop bending modulus should be used in preference to the hoop tensile modulus.

5.2. Thermal loading

Thermally induced loads associated with the maximum operating or ambient temperature range shall be allowed for in the design.
When considering heating or cooling of the uninsulated pipe wall by the fluid contained within the pipe, the mean temperature change of the pipe wall to be used for stress analysis purposes should be calculated using the following equation:

$$\Delta T°_{eff} = k \cdot \Delta T°_{pa}$$

where
$\Delta T°_{eff}$ is the effective design temperature change to be used for stress analysis, in degrees Celsius;
$\Delta T°_{pa}$ is the temperature difference between ambient temperature and the process design temperature, in degrees Celsius;
k is a factor to account for the low thermal conductivity of GRP (i.e. the average wall temperature of the pipe is always less than the design temperature because of GRP low thermal conductivity). In the absence of further information, k should be taken as 0.85 for liquids and 0.8 for gases.

5.3. Stresses due to Internal Pressure

The hoop and axial induced stresses due to internal pressure shall be calculated using Mariotte's equations reported previously.

5.4. Stresses due to pipe support

"The designer shall consider the effect of contact stresses at the support of large-diameter liquid-filled pipes, which become more significant with increasing diameter and D/t ratio."
The calculation of axial stresses for pipes of diameter more than 600[mm] shall be in accordance with Annex E of part 3 of ISO standard, or in accordance with procedures agreed with the principal. The magnitude of the stresses can be reduced by the application of local reinforcement at the supports and use of an elastomeric pad to reduce the rigidity of the support conditions.

Further about the method for the evaluation of the support stress induced is given in ISO 14692:2002 part 3 section 8.6.

5.5. Buckling conditions

Buckling conditions shall be considered in the case of the axial loading is compressive. (see ISO).

6. Factors & Coefficients

Following, the descriptions of the partial factor used within the qualification programme of the ISO 14692:2002.

6.1. A_1 & A_2 – Partial factors for temperature and chemical resistance

The partial factors A_1 and A_2 quantify the degradation of the pipe performance caused by the chemical nature of the fluid processed and temperature
When an organic resin matrix is placed in contact with a liquid, there is invariably absorption of the liquid by the resin. This can lead to damage depending on the mutual compatibility between the liquid and the polymer.
The absorption of liquid accelerates viscoelastic processes such as creep, especially with uncrosslinked or inadequately crosslinked matrix resins.
The permeability of fluids into reinforced plastics increases rapidly with increasing temperature.
Furthermore, the temperature accelerates many of the degradation processes caused by the fluids when they have entered the matrix.

If the effects of temperature alone are being considered, it is acceptable to linearly extrapolate a value of A1 between a value of 1 at the qualification test temperature (minimum test temperature is 65° C), T_{qual}, and 0 at the T_g, i.e.

$$A_1 = \frac{T - T_g}{T_{qual} - T_g}$$

Where
T is the design temperature.
T_g is the glass transition temperature of the matrix.
T_{qual} is the temperature at which the test is carried out.

For some chemicals other than water, it is not possible to determine partial factors A_1 and A_2 separately, and testing will result in determination of the product $A_1 \cdot A_2$. There are many procedures for testing GRP materials at elevated temperature and/or exposed to chemicals, for example ISO 175 [2], ASTM C581 [3], ASTM D543 [4], but few provide acceptance criteria. This is because the acceptance criteria depend on the nature of the failure mode applicable to the specific pipe.

Possible test procedures that can be adapted to provide a means for deriving partial factors $A_1$and A_2 include ASTM D3681 [5] and prEN 13121-2 [6] for Vessels. [Annex D – 2]

If there are doubt about the values, a 1000h survival test should be carried out on the product sector representative in a simulated and appropriated temperature and chemical conditions.

Further information – Annex D part 2.

6.2. A_3 - Partial factors for cycle fatigue

Cycling loads influence the lifetime of any product. The standard considers the fatigue due to cycling load if the predicted number of pressure or other loading cycles, i.e. thermal, is more than 7000 over the design life.
If the predicted number of cycles is less than 7000, the service shall be considered static. If the predicted number of cycles exceeds 7000 over the design life, then the designer shall determine the design cyclic severity,R_c, of the piping system. R_c is defined as:

$$R_c = \frac{F_{min}}{F_{max}}$$

where F_{min} and F_{max} are the minimum and the maximum loads (or stresses) of the load (or stress) cycle.
The partial factor A_3 for cyclic service is given by[45]:

$$A_3 = \sqrt{\left({R_c}^2 + \frac{1}{16}\left(1 - {R_c}^2\right)\right)} \cdot e^{\left[(1-R_c)\left(1-\frac{N-7000}{10^8}\right)\right]}$$

The ability of components nominally qualified for static pressure ratings to also withstand limited cyclic service shall be demonstrated by limited cyclic pressure-testing of their representative product[46].

6.3. f_2 – part factor for loading conditions

The purpose of the part factor f_2 is to define an acceptable margin of safety between the strength of the material and the operating stresses for the three load cases, occasional, sustained including and sustained excluding thermal loads.
The following table provides default values of the safety factor depending on the nature of loads.

Loading type	Load duration	f_2	Example of load
Occasional	Short-term	0.89	Hydrotest
Sustained including thermal loads	Long-term	0.83	Self-mass, thermal expansion
Sustained excluding thermal loads	Long-term	0.67	Self-mass

Table 40 -The f2 as function of types of loads

[45] ISO 14692:2002 part 3 – Fatigue and cyclic loading – 7.4.4
[46] ISO 14692:2002 part 2 – Limited cycling qualification testing - 6.4.5

6.4. f_3 – part factor for axial loading

The calculation of the part factor for axial loading is long and articulated. It depends on the value of the **biaxial strength ratio r**, whose explanation follows in the next paragraph.

The value of the f_3 is defined according to whether r is greater than or less than 1.

If $r \leq 1$ then:

$$f_3 = 1 - \frac{2\sigma_{ab}}{r \cdot f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \sigma_{qs}}$$

If $r > 1$ then:

$$f_3 = r - \frac{2\sigma_{ab}}{f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \sigma_{qs}}$$

where σ_{ab} is the non-pressure-induced axial stress, expressed in megapascals.

The maximum value of f_3 shall be unity. When the sustained axial stress is compressive, excluding that due to pressure, the f_3 is equal to 1.

6.4.1. Biaxial Strength ratio r

The determination of the Biaxial strength ratio is further data required for the system design.
"For pipes, joints and fittings, the manufacturer shall assign a value r for the short-term biaxial strength ratio to the family representative".[47]
The value or r is defined as:

$$r = 2 \cdot \frac{\sigma_{sa(0:1)}}{\sigma_{sh(2:1)}}$$

where
$\boldsymbol{\sigma_{sh(2:1)}}$ is the **short-term hoop strength**, in megapascal, which shall be calculated according to the equation:

$$\sigma_{sh(2:1)} = P_{STHP} \frac{D}{2t_r}$$

where
D is the mean diameter of the reinforced wall of the family representative, in [mm].
t_r is the average reinforced wall thickness of the family representative, in [mm].
P_{STHP} is the short-term hydrostatic pressure, in megapascal, determined in accordance with the standard **ASTM D 1599** - 14ε1 (Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings).[48]

[47] ISO 14692:2002 part 2 – Further data required for system design - 6.2.6

[48] The determination of P_{STHP} recalls the restricted qualification procedure for low-pressure water applications which is not being described. The procedure permits other path for the determination of the short-term hydrotest pressure. Anyway, the ASTM D 1599 becomes mandatory for pressured pipelines which are the core of this guide.

$\boldsymbol{\sigma_{sa(0:1)}}$ is the **short-term axial strength** in megapascal, of the component, manufactured with no liner, determined using either of the following two methods:

a) by testing five replicate samples in accordance with **ASTM D2105** at SLT[49]. The $\sigma_{sa(0:1)}$ of the family representative shall be taken as the lower deviated (two standard deviations) value of the five replicate samples;
b) by considering 85 % of the lower of two replicate samples tested in accordance with the test procedures given in ASTM D2105 at SLT.

7. System testing

All closed GRP piping systems shall be hydrostatically pressure-tested after installation.
The purposes of the hydrotest are to assure the resistance of the GRP piping system to a higher pressure in respect with the design one, and verify the absence of leaks due to bad installation.
A formal risk assessment should be carried out prior to the hydrotest. All supports, guides and anchors shall be in place prior to pressure testing.
The **hydrotest** shall be conducted at a pressure (hydrotest pressure) equal to 1.5 times the design pressure or 0.89 times the qualified pressure, whichever is lower.
The value of 0.89 represents the part factor f_2 for occasional loading.

The hydrotest pressure shall be raised over a period of 30 minutes (or longer).
After the hydrotest, the **pressure-decay test** shall be conducted for a minimum of 1 hour.
A further **leak test** at a 1.1 times the design pressure should be carried out for a minimum of 24 hours.

[49] SLT – Standard Laboratory Temperature

8. QT2002 - Simulation of the ISO 14692:2002 Design Process

Since the evaluation of all the coefficients is long and complex, a tool for the automatic calculations of all the factor, coefficients and parameters concerning the qualification programme has been developed.
The **Qualification Tool, QT2002**, calculates, starting from the demand requests:

- A_1 and A_2 Partial factors for temperature and chemical degradation
- A_3 Partial factor for cycle fatigue
- f_3 Part factor for axial loading
- r Biaxial strength ratio (0.4 for plain pipeline).

Furthermore, it calculates the structural requirements to be achieved in order to validate the plain pipe, and so:

- the minimum required Qualified Pressure P_q to be verified – Qualified Pressure assessment
- The Qualified Stress σ_{qs}[50] – Qualified Stress assessment

After that, and after defined the matrix and the fibre properties, the evaluation of the characteristics of the lamina are given by mean of APT.
The prevision of the minimum plain pipe wall thickness in order to validate the P_q is calculated by means of the HST*[51] which simulates the procedure B of ASTM D 2992.

The Hydrostatic Simulation Tool has been adapted to this particular case, taking into account the following considerations:

The P_q calculated by the QT2002 and required by the ISO 14692:2002 is based on a default Lifetime Service of 20 years.
The design lifetime can be more than 20 years, and it can be taken into account by the equations explained in 4.2.3.3.1.
Let us recall that P_q is, per definition, the maximum pressure that the plain pipe can withstand for all the service lifetime, and that the HST* is not able to evaluate analytically the degradation of the lamina properties due to aging, and so, is not able to reproduce the ASTM D2992 procedure B test and its requirements. This requires to transpose the target value of P_q, based on the design service lifetime (25 years) to a shorter auxiliary lifetime, which does not require aging considerations.
This is done by mean of the equations given in 4.2.3.2 concerning the ASTM D 1598.
Basing on G gradient in its preliminary default value[52], it is possible to identify the target P_q correspondent to 1000 h, instead of 25 years.
So, the Qualified Pressure $P_q{}^*$can be calculated according to the given equation:

$$P_q{}^* = \frac{P_{q(Tdefault)}}{f_1} \cdot 10^{G \cdot [log(Tdesign) - log(1000)]}$$

[50] The Qualified Pressure and the Qualified Stress are thickness dependant. Since the iterative nature of the process, these values can be calculated as function of the thickness.

[51] * indicates that the HST has been adapted to this particular simulation.

[52] Default gradients of the plain pipes are given in ISO 14692:2002 part 2 – 6.2.3.2.1

where
f_1 is the scatter factor of the ASTM D2992[53].
$T_{default}$ is the default service lifetime of 20 years expressed in h, so, 175400 h
T_{design} is the design service lifetime expressed in hours (i.e. 25 years = 219000 h)
G is the default gradient for a plain pipe

The Figure 92 represents graphically the determination of the required P_q^* which shall be equal or greater than long-term hydrostatic pressure $P_{LTHP,1000h}$ evaluated at 1000 h.

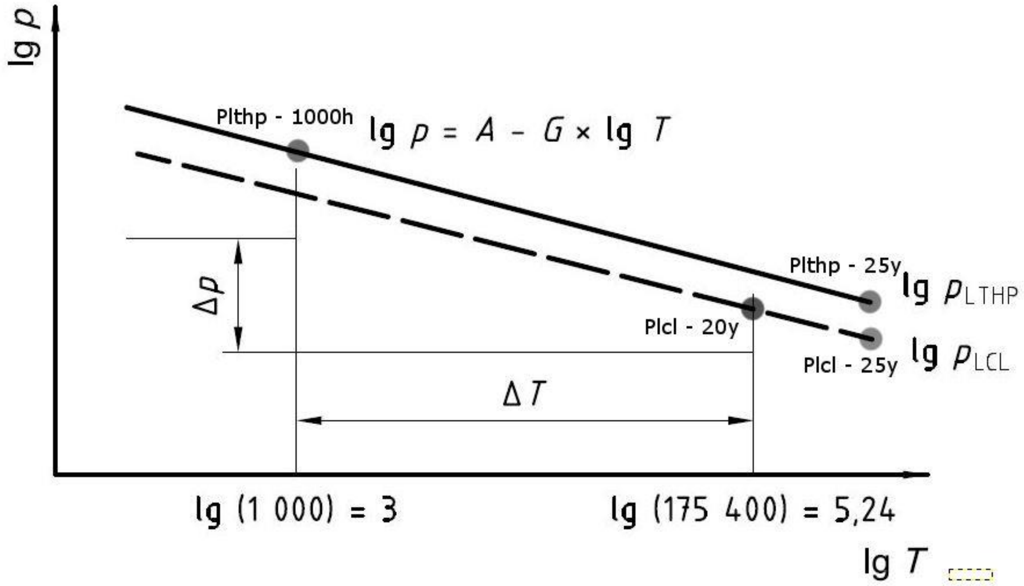


Figure 92 - Procedure for the calculation of the artificial long-term hydrotest pressure for the qualified pressure assessment

The service time of 1000 h is considered not to be aging dependant. And so, the Hydrostatic Simulation Tool HST* uses this new qualified pressure P_q^* to give a prevision of the wall thickness. This procedure is summarized in Figure 93.

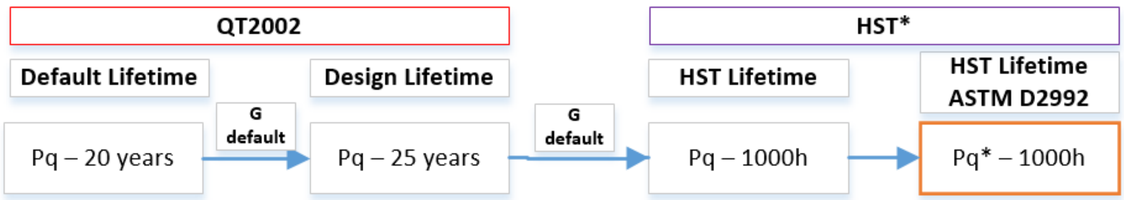


Figure 93 - Calculation procedure for the Qualified Pressure based on the auxiliary lifetime of 1000 hours

Performing the HST* as described, this process virtually extrapolates the minimum pipe wall thickness, depending on manufacturing parameters and material components[54], which verifies the Pressure Assessment.

[53] The f_1 factor increase the qualified pressure $P_{q(v)}$ to be reached by the plain pipe in hydrostatic condition (HST simulated) with respect to the qualified pressure P_q which is the prescribed by the qualification programme. The gap exists due to this factor. A description is given in Chap 5 – 4.2.3.1
[54] The parameters of winding-angle and volume fraction are being optimized inside the HST*.

The failure envelope, function of P_q (now $P_{q(v)}$), and the stress cases, function of the expected pipe wall thickness and loading conditions, are calculated.

Finally, if the equations concerning the Qualified Stress assessment are verified, the wall thickness previously calculated is to be intended as the final expected one.

The overall procedure follows the flowchart A reported previously and present into the appendix.

Concerning the high-diameter pipe under high inner pressure, object of this work:

- The simulation of the hydrotest ASTM D1599 for the validation of the failure envelope is not taken into account because it is less restrictive than the performed one for the qualified pressure assessment on the base of 1000 h.
- The simulation of tensile test in accordance with the ASTM D2105 for the validation of the axial stressed point 0:1 of the failure envelope is not considered. This because the overall qualification procedure of the plain pipe can be achieved without the experimental evaluation of this parameter, substituted by the defined value of the biaxial strength ratio r for the plain pipe and equal to 0.4.
- The experimental test for the evaluation of point *Point 2:* 1:1 hoop to axial stress is not simulated because the simplified envelope process is adopted.

So, the only experimental test which limits the value of the minimum reinforced wall thickness is the one performed in accordance with the ASTM D2992 procedure B concerning the Qualified Pressure assessment.

8.1. Case of Study Design Process - ISO 14692:2002

The design procedure described above has been applied to the requests of the case of study.
The Design constrains are:

- The Demand requests given in Table 20.
- The Matrix and Fibre properties are given in Table 11 and Table 12

The wall thickness value is evaluated under the following hypothesis:

- $A_1 = 1$, thus, considering a glass transition temperature higher than the qualified temperature;
- $A_2 = 0.9$, since the liner will act as chemical barrier for the composite: The value is not set to 1, conservatively.
- $A_3 = 0.957$, meaning a cyclic variation of the load of N = 10000 cycles;
- $f_2 = 0.67$, typical value of the part factor for sustained load excluding thermal loads;
- r = 0.4, the smallest biaxial stress ratio, which is suggested for a plain pipe in the ISO 14692:2002[55]
- $f_3 = iteratively\ calculated$
- $f_1 = 0.98$, this is a prevision of the value that shall be evaluated once the ASTM D2992 procedure B has been completed.
- Service Lifetime = 25 years - 219000 h
- $G = 0.075$ plain pipe default regression gradient from ISO 14692:2002

The QT2002 calculates the Qualified Pressure P_q as function of the pipe wall thickness. So, the values of $P_q(t_r)$ can be summarize in the following table, together with the values of the f_3, which are thickness dependant.
The values of $P_q(t_r)$ based on lifetime of 25 years are given, as well as the values of the auxiliary qualified pressure $P_q{}^*(t_r)$ based on lifetime of 1000 h and needed for the HST*.

Thicknes s [mm]	n°layers	HST Failure Pressure Vf=0.6 [MPa]	QT 2002				
			Pq* - 1000h	Pq - 25 years	Pressure Assessmen	Stress Assessmen	f3
30	150	15.4	24.66	16.46	V	V	0.8635
31	155	15.85	24.64	16.45	V	V	0.8641
32	160	16.5	24.63	16.44	V	V	0.8647
33	165	16.95	24.61	16.43	V	V	0.8653
34	170	17.5	24.60	16.42	V	V	0.8659
35	175	17.9	24.58	16.41	V	V	0.8665
36	180	18.5	24.55	16.39	V	V	0.8671
38	190	19.4	24.52	16.37	V	V	0.8684
40	200	20.5	24.49	16.35	V	V	0.8696
42	210	21.5	24.46	16.33	V	V	0.8708
44	220	22.5	24.43	16.31	V	V	0.8719
46	230	23.6	24.40	16.29	V	V	0.8731
48	240	24.6	24.35	16.26	V	V	0.8743
50	250	25.6	24.32	16.23	V	V	0.8755

Table 41 - Summary of the values of the qualified pressure as a function of the pipe wall thickness. Highlighted it's the limit of the wall thickness in accordance with ISO 14692:2002 limitations.

[55] The value of 0.4 it's the expected from the plain pipe, as describe in NOTE 1 – 7.11.4 – ISO 14692:2002 part 3.

The auxiliary qualified pressures $P_q^*(t_r)$ are calculated according to the equation reported in previous paragraph.

The expected thickness is evaluated comparing the QT2002 Qualified Pressures $P_q^*(t_r)$ and the Qualified (failure) Pressures $P_{q(v)}(t_r)$ calculated by mean of the HST*, using **0.6** as volume fraction.
The degradation due to aging, so, is being considered.

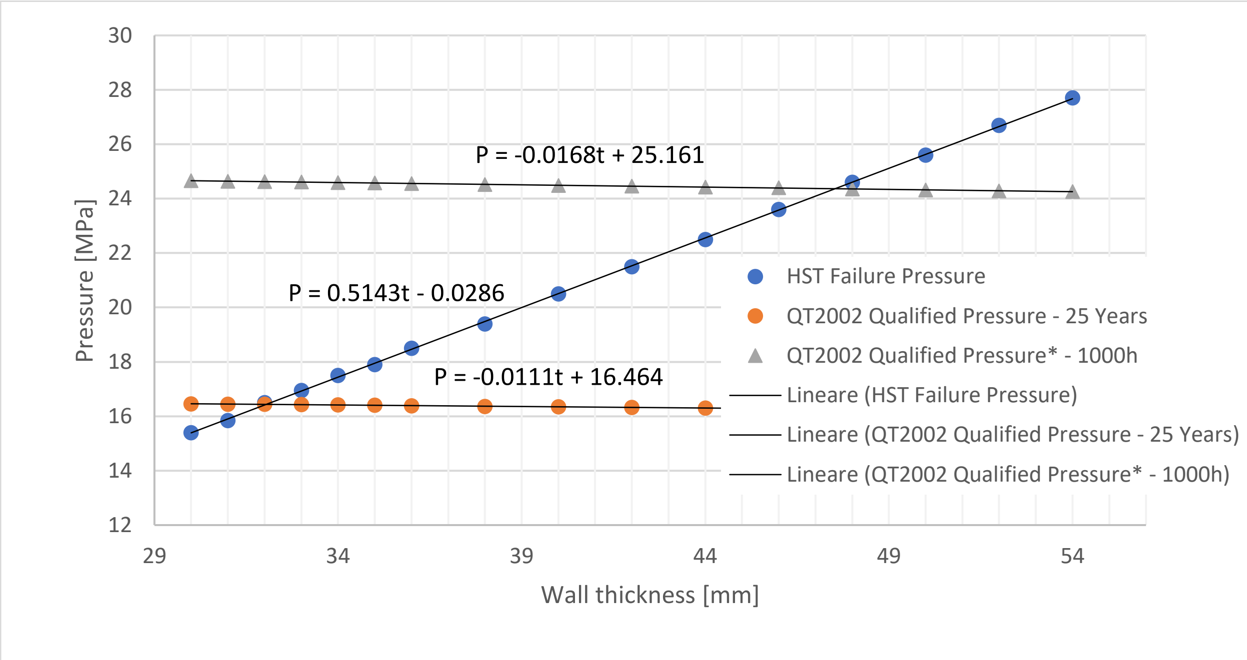


Figure 94 - Summary of the procedure for the identification of the reinforced pipe wall thickness in accordance to ISO 14692:2002

The gap between the qualified pressure P_q^* at 1000 h and the P_q at 25 years is around 8.97 [MPa]. It means that a pipe which fails later than 1000 h at the pressure of P_q^*, will be able to withstand a qualified pressure of P_q up to 25 years.

The prevision of the reinforced pipe wall thickness is 47.6 [mm], corresponding to 238 layers.
This is the value at which the blue and the grey line intersect in Figure 94.
The HST output follows.

HST – Thickness Evaluation – APT based											
Input Parameters				**Failure Indexes**				**Outputs**		
ID_r	400	[mm]		1	1	1		Wall Thickness	**47.6**	[mm]
P	24.4	[MPa]		1	1	1		n° of Layers	238	-
$\theta°$	55°	[deg°]		TH 0.8866						
V_f	**0.6**	-		TW 0.9915						

Table 42 - summary of input and output of the case of study simulation using APT and Volume fraction 0.6

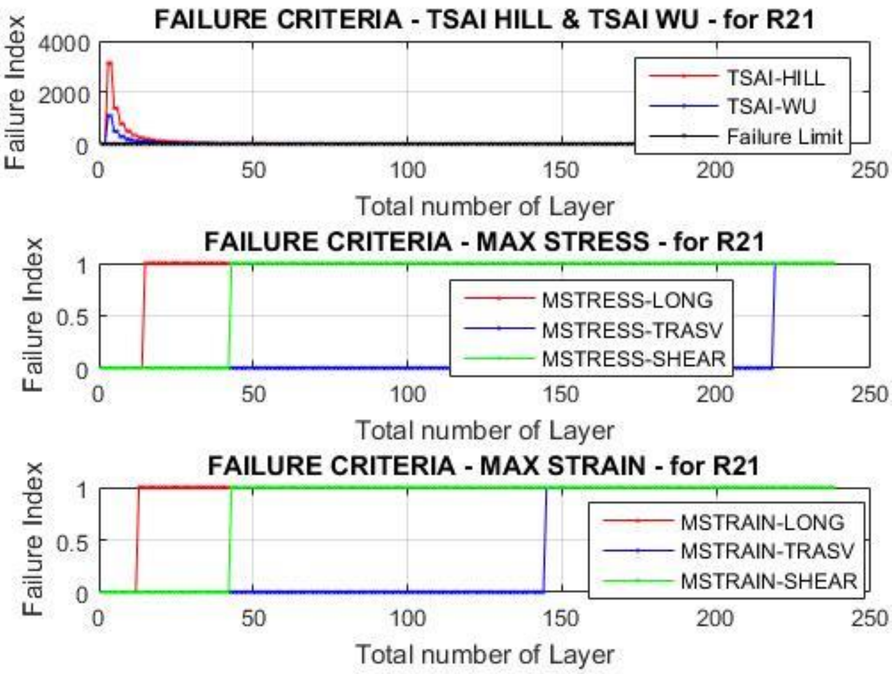


Figure 95 - Trends of Failure Criteria indexes

The value of 47.6 [mm] exceed the limits of applicability of the ISO 14692:2002 which declares that the maximum pipe wall thickness shall be smaller than $\frac{1}{10}$ of the Diameter, 400 [mm], giving the maximum allowable reinforced thickness equals to 40 [mm]. This value has been highlighted in table 38.

Since the strength performance of the pipe depends on the lamina properties, the same comparison is now performed using the volume fraction of 0.4 which optimizes the resistance of the composite pipe for this loading conditions.
The wall thickness so expected becomes 34.6 [mm], which corresponds to 172 layers.

HST – Thickness Evaluation – APT based										
Input Parameters				Failure Indexes				Outputs		
ID_r	400	[mm]		1	1	1		Wall Thickness	**34.6**	[mm]
P	24.4	[MPa]		1	1	1		n° of Layers	172	-
$\theta°$	55°	[deg°]		TH 0.8906						
V_f	**0.4**	-		TW 0.9935						

Table 43 - summary of input and output of the case of study simulation using FEM and Volume fraction 0.4.

This value is suitable because falls within the limits, but, as already said in chapter 3, 2.3 HST-design conclusions, this value of volume fraction, **0.4, is not in accordance to the volume fractions** reached in filament-winding process, and required by the ISO 14692:2002. For these reasons this value, as the first once, cannot be considered valid.

Finally, the prevision of the pipe wall thickness is performed using the acceptable value of volume fraction 0.6 and the FEM[56] based prevision tool for the lamina properties.

The wall thickness so expected is 23.6 [mm], which corresponds to 118 layers.

HST – Thickness Evaluation – FEM based										
Input Parameters				**Failure Indexes**				**Outputs**		
ID_r	400	[mm]		1	1	1		Wall Thickness	**23.6**	[mm]
P	24.8	[MPa]		1	1	1		n° of Layers	118	-
$\theta°$	55°	[deg°]		TH 0.8921						
V_f	**0.6**	-		TW 0.9978						

Table 44 - summary of input and output of the case of study simulation using FEM and Volume fraction 0.6.

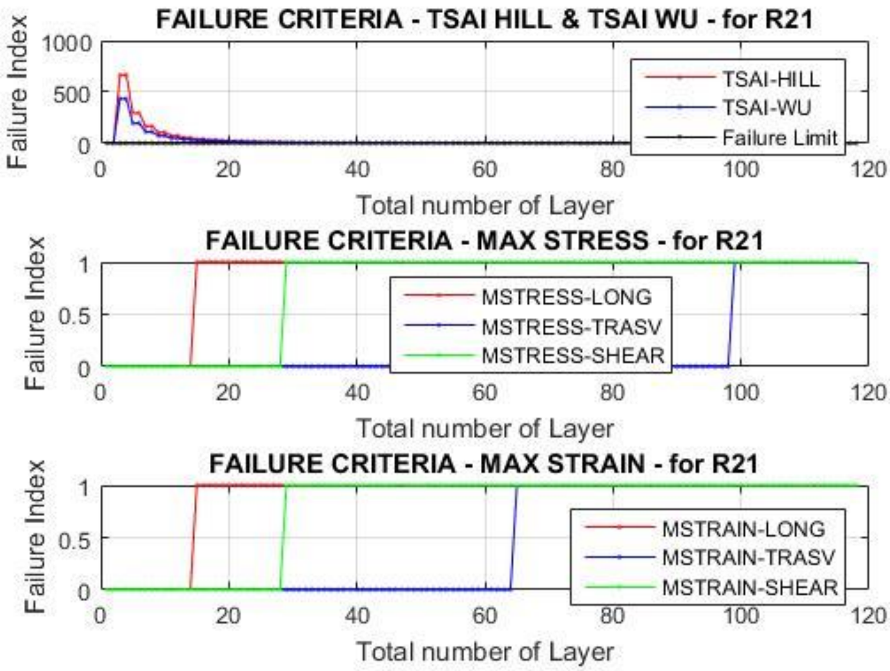


Figure 96 - Trends of Failure Criteria indexes

[56] Autodesk® Helius Composite 2016

8.2. Conclusions

The reinforced wall thickness of the plain pipe calculated to withstand the demand requests is highly dependent on the lamina prevision models.

Volume Fraction	Lamina Properties	Wall Thickness [mm]	ISO 14692:2002
0.6	APT evaluated	47.6	Wall thickness exceeds the limits of ISO (>40 [mm])
0.4	APT evaluated	34.6	Mass fraction exceeds the limits of ISO (<0.7)
0.6	FEM evaluated	23.6	In Accordance with ISO 2002

Table 45 - pipe wall thickness for the models considered

The wall thicknesses evaluated by means of the Analytical Prevision Tool do not fall within the limits of the standard.

The FEM based wall thickness is acceptable.

The range between the calculated thicknesses is wide, and it is a direct consequence of the high variability in the transversal tensile strength, already investigated in Chapter 1.

The Hydrostatic Simulation Tool is reliable, as the QT2002 for the data processing concerning the ISO 14692:2002. The whole simulation would predict a reliable expected value of pipe wall thickness if the lamina properties are known experimentally.

6. The ISO/FDIS 14692:2016

The ISO 14692, in its 2nd edition, “cancels and replaces the first edition which has been technically revised”. Even if several changes exist, in comparison with the 1st edition, it is suggested to read this edition after the first one.

The publication of the new edition of the ISO standard is scheduled for August 2017; the guide which has been developed in this work, as said, is based upon the ISO/FDIS 14692:2016. The FDIS acronym stands for Final Draft International Standard. Because of its draft nature, some changes may exist between the final draft and the published standard.

This second edition is more straightforward than the 1st edition and the main basic steps defined in Part 1 and concerning the entire ISO standard are given below:

- Step 1: The Bid Process.
- Step 2: Manufacturer's Data.
- Step 3: Qualification Process.
- Step 4: Quality Programme.
- Step 5: Generate Envelopes.
- Step 6: Stress Analysis.
- Step 7: Bonder Qualification.
- Step 8: Installation, Field Hydrotest.

A very clear flowchart of the steps of the whole ISO/FDIS 14692:2016 is reported in part 1, pages vi,vii. for a better comprehension of this guide, it is suggested to consider this flowchart in addition to the previous developed. A copy of these pages can be found into appendix.

Part 3 of the ISO standard in the 2nd edition, contrary to the previous edition, is no longer a guideline. The objective of this part is to ensure that the piping systems, when designed using components qualified in ISO 14692-2, will meet the specified performance requirements.

Since the description of the ISO/FDIS 14692:2016 is reported here from the designer point of view, the steps above, which describe the ISO standard structure itself, are not linearly followed.

1. Applications

As for the first editions, the ISO/FDIS 14692:2016 (all parts) applies to the specification, manufacture, testing and installation of GRP piping and pipeline systems associated with oil and gas industry production, processing, and utility service applications.
It is primarily intended for offshore applications on both fixed and floating topsides facilities, but it may be also used as guidance for GRP piping and pipeline system in oil and gas industry applications onshore.

Typical oil and gas industrial applications include those listed in Table 46.

Gas (methane,etc...)	Natural gas
Hydrocarbon	Oil
Cooling water	seawater
Diesel fuel	wastewater
Inert gas	Hydrogen chlorite gas (HCl)

Table 46 - Typical current and potential GRP piping oil and gas applications

Furthermore, this second edition may be used as general basis for specification of pipe used for pump caissons, stilling tubes, seawater lift risers and other similar items. ISO 14692 may be properly considered as the basis for piping and pipeline selection and design.

Finally, as in the case of the 2002 ed., the ISO/FDIS 14692:2016 (all parts) covers all the main components that form part of a GRP pipeline and piping systems (plain pipe, bends, reducers, tees, supports, flanged joints) with the exceptions of valves and instrumentations.

1.1. PBMS – Performance-based Material Selection

The ISO/FDIS 14692:2016 claims the use of a standard methodology for material selection that is based on performance and not specification.
The performance-based material selection (PBMS) reflects true functional needs, excludes arbitrary requirements, and does not specify materials.

The four key steps are:

1) Identification and documentation of all performance factors relevant to the application
2) Quantification of the functional performance requirements
3) Qualification of materials for technical acceptability
4) Final section

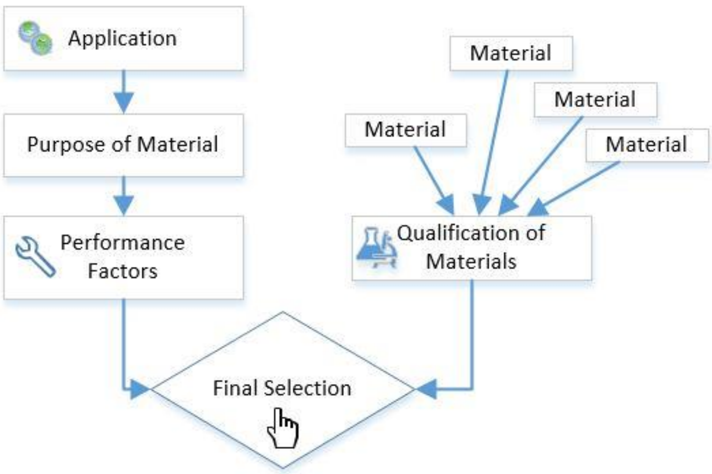


Figure 97 - Performance based material selection in ISO/FDIS 14692:2016

The above methodology provides a standardized auditable approach to material selection with no particular constraints.

2. Limitations

The 2nd edition of ISO has less limitation than the previous edition. The principle upon the ISO/FDIS 14692:2016 is a standard methodology for material selection based on performances. For these reasons, no limitations are given regarding the matrix resin. (see next paragraph)

The ISO/FDIS 14692:2016 shall be limited to the manufacture of rigid components made from fibre-reinforced thermosetting resins. Typical resins are epoxy, polyester, vinyl ester and phenolic. Thermoplastic resins are excluded.

2.1. Materials

The resin matrix for the products shall be classified as:

a) GRE – glass fibre reinforced epoxy
b) GRUP – glass fibre reinforced unsaturated polyester
c) GRVE – glass fibre reinforced vinyl ester
d) Other resins

This classification[57] influences the default temperature as shown in Table 47 and the default gradient (see gradient evaluation paragraph).

GRE	GRUP	GRVE
Default temperature = 65° C	Default temperature = 21° C	Default temperature = 21° C

Table 47 - Materials default temperatures

The principal reinforcement material of the component wall shall be glass fibre, i.e. continuous and/or woven rovings. Other types of fibre reinforcement, such as carbon or aramid fibre, may be used to provide local strengthening within joints and fittings.

The ISO/FDIS 14692:2016 (all parts) is not applicable to piping systems that incorporate internal thermoplastic or elastomeric liners. This is because such materials may introduce significant changes in performance characteristics of the FRP piping. The use of thermoplastic liner will result in change of the failure mode for pressure retention.
The adoption of a thermoset liner is tolerated, as in the case of the 1st edition.

The maximum allowable temperature is determined by the resin type, curing system and state of cure. Temperatures higher than the default are possible depending on compound.

External coatings may be used to provide thermal insulation, fire resistance, UV protection and/or chemical conductivity.

[57] NOTE 1 – ISO/FDIS 14692:2016 part 1 – Materials – 6: The resins as listed are generic compounds. Their performance and properties of thermal, mechanical and chemical resistance vary significantly depending on the resin and curing agent used to cure them. The user is cautioned to ascertain that the resin and curing agent are known for the resin system planned to be used.

The qualification programme requires the evaluation of the elastic characteristics of the composites by mean of standardized experimental tests. The experimental evaluation assures that the material is conformed to the design values. The list of tests is given in Table 49 - Summary of the qualification programme testingTable 49.

2.2. Dimensions

For guidance purposes, the typical maximum pressure-diameter range of piping in fluid service (e.g. water/hydrocarbon service) covered by ISO/FDIS 14692 (all parts) is given in Figure 98, which represents a compromise between the current application experience envelope of GRP pipelines and piping systems and commercial availability.
The curve in Figure 98 can be approximated by the following equation:

$$DN \cdot MPR_{xx} = 3000$$

where
DN is the Nominal diameter, expressed in [mm]
MPR_{xx} is the Maximum Pressure Rating at xx °C, expressed in [MPa] (see later)

A different constant applies for gas service[58]
There are no restrictions on the thickness to diameter ratios used in the structural calculations given in ISO 14692 (all parts).

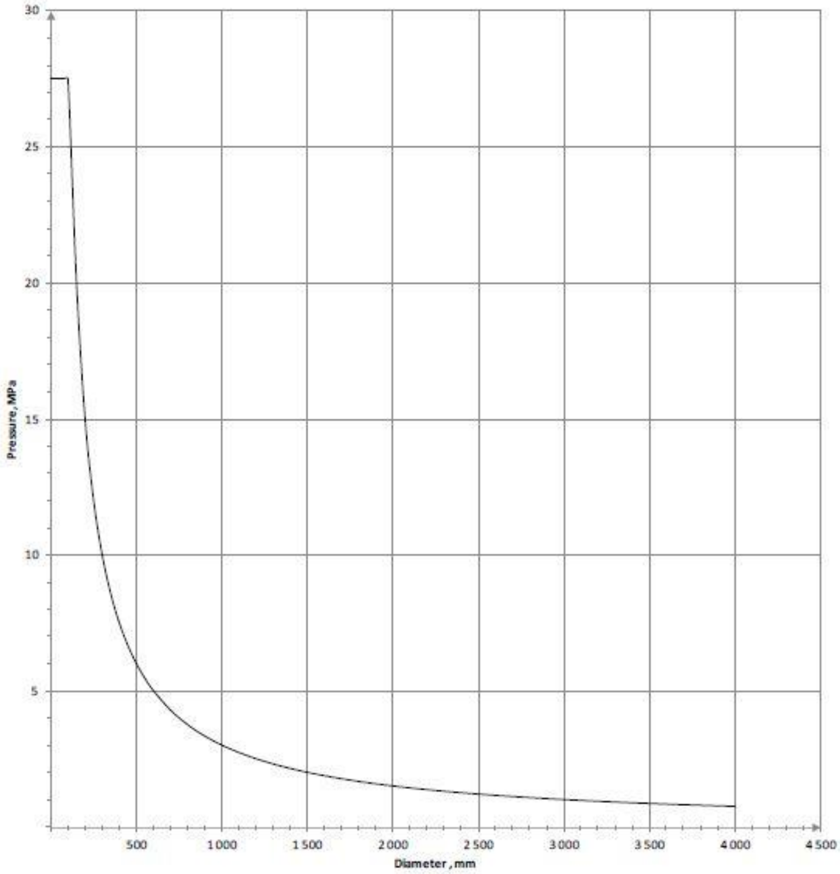


Figure 98 - Envelope of pressure/diameter range of GRP pipeline and piping systems based on current experience

[58] constant not given into the ISO/FDIS

2.3. Winding angle

There are no constraints in the design and qualification programme concerning the winding angle. The designer shall determine the best winding angle taking into account the induced stresses on pipe wall.
The angle of $\pm 54.75°$ [deg] is remarked to be optimizing for the inner pressure stress state case.

2.4. Mass Fraction

Contrary to the 1st edition, and in line with the PBMS concepts, there are no constraints concerning the mass or volume fraction of fibre of the lamina.

3. Components

The previous division in family representative, product sector representative and component variants no longer exists. The qualification programme and testing is the same for all the piping components. Some differences exist between the qualification of pipes and the qualification of pipe+joints, flanges, tees, reducers and other fittings, regarding the calculation of the validation test pressures. Flanges in particular, require a bending test under inner pressure.
Because the focus is on the pipe, only the qualification programme of pipe is fully considered.

3.1. Representative Products

The components to be tested can be any combination of diameter and pressure class.
When the qualification programme is complete for a single couple of diameter and pressure class (MPR_{xx}), a wider combination of dimensions and pressure components are automatically qualified.
The range of products that is qualified by a single component is limited by the following equations summarized in the qualification ranges table:

Product that has been tested	**Product that are considered represented by DN_1 and MPR_1**
$DN_1 > 300$ [mm] $MPR_1 > 5$ [MPa]	$0.5 \cdot DN_1 \leq DN_2 \leq 1.6 \cdot DN_1$ and $0.5 \cdot MPR_1 \leq MPR_2 \leq 1.6 \cdot MPR_1$ and $DN_1 \cdot MPR_1 \leq DN_2 \cdot MPR_2$

$DN_1 \leq 300$ [mm]	Same as above, except no limits on minimum DN $DN_2 \leq 1.6 \cdot DN_1$ and $0.5 \cdot MPR_1 \leq MPR_2 \leq 1.6 \cdot MPR_1$ and $DN_1 \cdot MPR_1 \leq DN_2 \cdot MPR_2$
$MPR_1 \leq 5$ [MPa]	Same as above, except no limits on minimum MPR $0.5 \cdot DN_1 \leq DN_2 \leq 1.6 \cdot DN_1$ and $MPR_2 \leq 1.6 \cdot MPR_1$ and $DN_1 \cdot MPR_1 \leq DN_2 \cdot MPR_2$

Table 48 - Qualification Ranges

In Table 48, DN_1 and MPR_1 represent the diameter and the maximu pressure ration of the plain pipe (or component) which is being qualified. DN_2 and MPR_2 refer to the sizes and pressures of the products that may be considered represented by of DN_1 and MPR_1.

Figure 99 and Figure 100 report two examples.

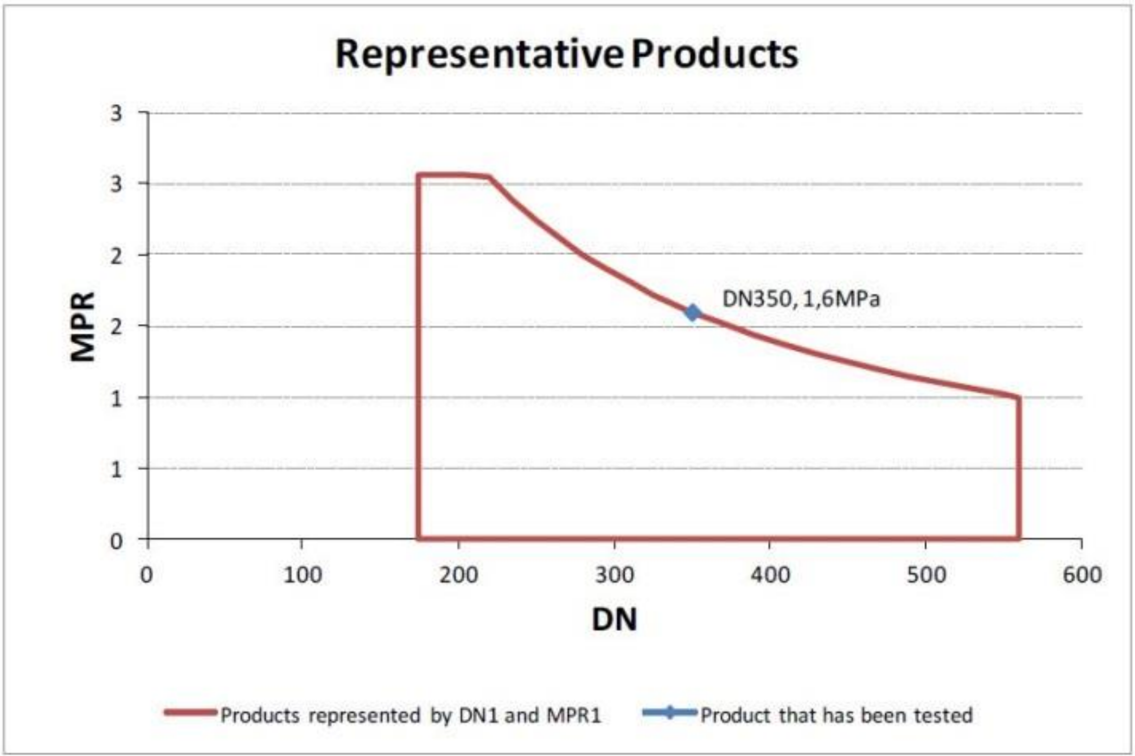


Figure 99 - Example where DN1=350 mm and MPR1 = 1.6 MPa

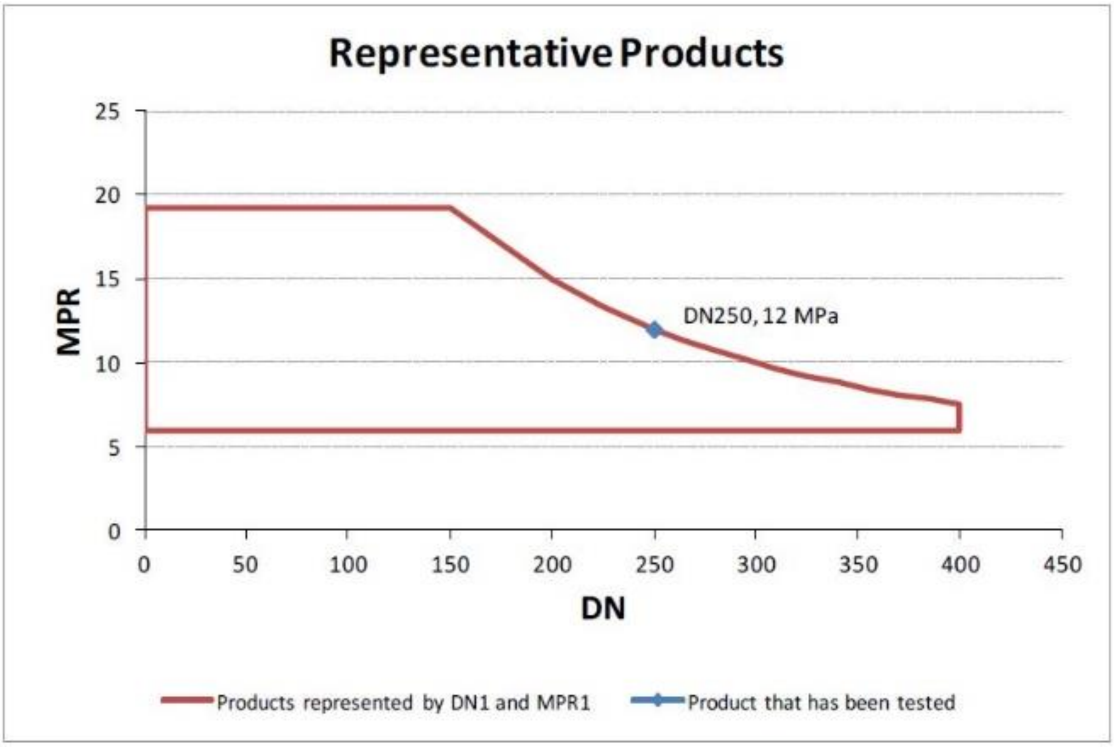


Figure 100 - Example where DN1=250 mm and MPR1=12 MPa

Since the qualification of the marked point has been successfully achieved, all the products inside the area are considered qualified.

The concept of a Product Family, Product Sectors, Product Sector Representatives and Component Variants that was used in the 2002 version of ISO 14692 is not used in the 2nd edition.
For a comparison, the concept might be referred to as a Floating Product Sector where the component to be tested is defined by the manufacturer and the corresponding product sector is defined by the equation reported previously.

This concept removes the burden of testing specific sizes and pressure classes and gives more flexibility to the manufacturer while maintaining the rigour of a robust qualification programme.

The whole components defined in the previous paragraph shall be included as a type of representative product.

4. Flowcharts

The ISO standard in its second edition provides a well-defined flowchart which guides the designer during the qualification programme.
As for the 1st edition, another flowchart has been developed.
The flowchart incorporates the qualification programme and the design given in the part 3 of the ISO/FDIS. The aim is to provide a friendly tool for the structural design of the pipeline in accordance with the qualification programme.

The flowchart is subdivided in:

- **Flowchart A 2016** – provides an overview of the full path needed for the determination of the minimum pipe reinforced wall thickness t_r [mm], starting from the demand requests, and in accordance with the qualification program.
- **Flowchart B 2016** – provides a recapitulation of the coefficients and factors calculation
- **Flowchart C 2016** – provides a revised copy of the flowchart present into the ISO/FDIS in addition to a summary of the calculation of gradient G_{xx} and the scaling ratio $rd_{1000,xx}$ procedures.

The flowcharts are provided in A3 format at the end of this book and in PDF version.

5. The Bid Stage

The first step of the design is the Bid Process.
The Bid Process has the aim to determine if the demand requests are compliant to the ISO/FDIS 14692:2016 field of application.
The Annex C of the part 1 provides a guideline of the checks which define the compliance of the ISO standard to the demand requests.

The Bid process is reported in Figure 101.

Furthermore, the bid stage requires to calculate an estimation value of the **Maximum Pressure Rating, $\boldsymbol{MPR_{xx}}(est)$**, which is defined as the maximum pressure rating at sustained conditions for a 20 years design life at the temperature of xx°C.

ISO/FDIS 14692-1:2013(E)

Annex C
(informative)

Guidance on Scope Limitations

Guidelines for determining if ISO14692 (all parts) is applicable to a product may be found in **Figure C.1**.

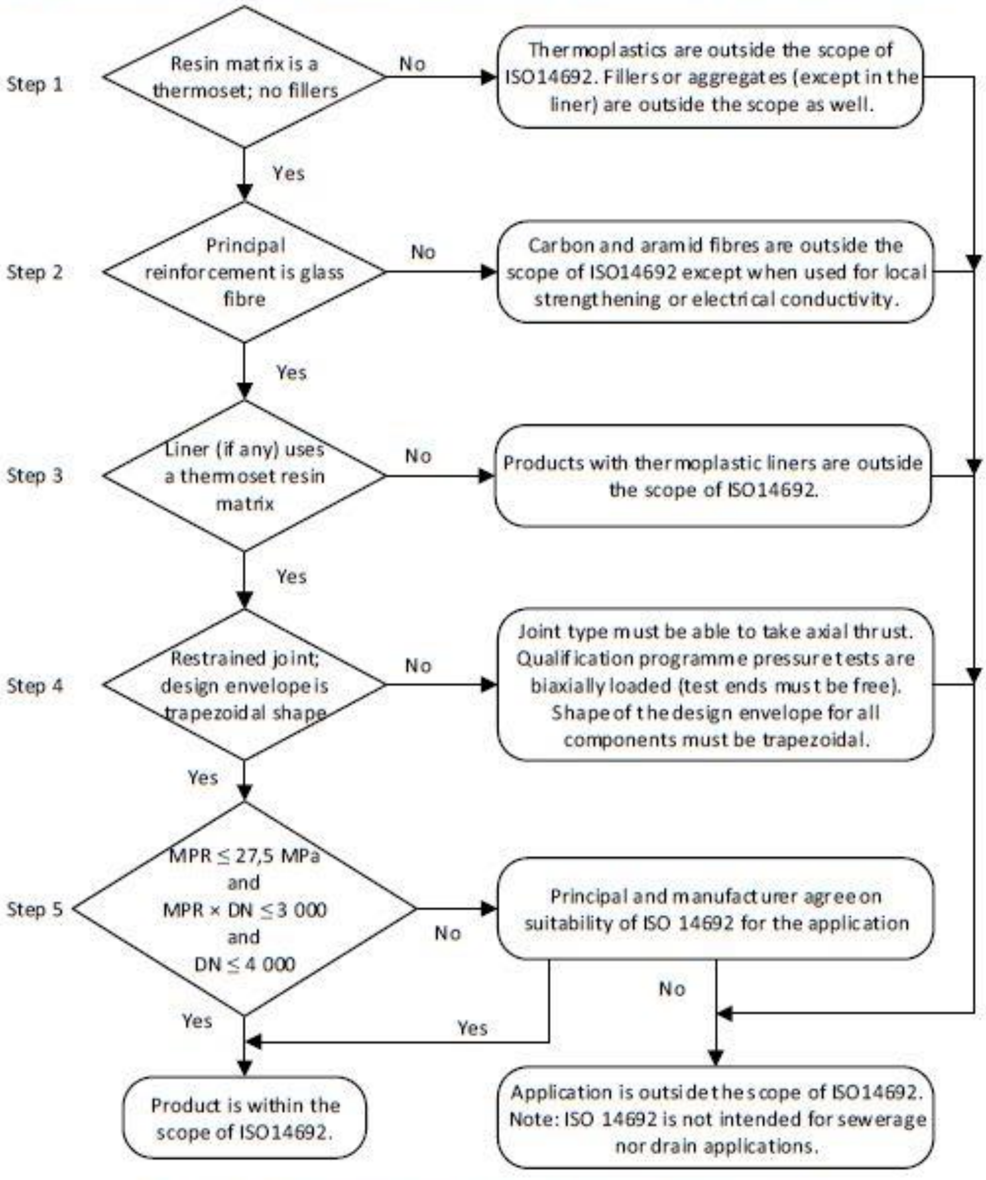


Figure C.1 – Flowchart for verifying the applicability of ISO 14692

38

Figure 101 - Bid stage flowchart

5.1. MPR_{xx} – Maximum Pressure Rating

The MPR_{xx} shall be the maximum catalogue value published by the manufacturer, in other hands, it is the key indicator which measures the performance of the pipe at the xx° temperature.
The default temperature of the MPR_{xx} depends on the resin material in accordance with Table 47.

Design temperatures higher than the default one can be chosen.

For the design purpose, it is proper to define the maximum pressure rating MPR_{xx} always referring to the required design temperature, at which all the tests must be carried out, as requested in the ISO/FDIS 14692:2016.

The estimation of the MPR_{xx} shall be determined with the following equation:

$$MPR_{xx}(est) = \frac{P_{des}}{f_{3,est} \cdot A_0 \cdot A_2 \cdot A_3}$$

where
$MPR_{xx}(est)$ is the Maximum pressure rating at T_{des}, expressed in [MPa]
P_{des} is the design pressure, expressed in [MPa]
$f_{3,est}$ is the part factor estimated at the bid stage of the project[59]
A_0 is the partial factor for design life
A_2 is the partial factor for chemical resistance
A_3 is the partial factor for cyclic service

[59] Factor calculation procedures can be found into Factor paragraph.

6. Design in accordance with Qualification Programme - Overview

The objective of the designer is to define **the minimum wall reinforced thickness[60] t_r [mm]** which assures the safety withstand of the pipeline to the induced stresses over its entire operation life in accordance with the demand requirements, as listed for the first editions (Diameter, P_{des}, T_{des},service life…).

The core of the design, according to the qualification programme, consists in the definition of a long-term (L.T.) failure envelope, plotted into the $\sigma_{hoop}, \sigma_{axial}$ plane, whose area, scaled by the f_2 loading factors, must contain the States of Stress (SoS) sustained by the pipeline along its entire service of life.

Similarly to the 1st edition concerning the qualified stress assessment, the f_2 scaled L.T. failure envelopes are three[61] design envelopes respectively for the occasional, sustained plus self-limiting and sustained loads.

Starting from the demand requests and mandatory post-installation pressure test[62], the SoS shall be evaluated by means of the failure analysis. The area and the shape of the long-term failure envelope depend respectively on the **Maximum Pressure Rating, MPR_{xx}**, and on the value of the $\boldsymbol{R_{test}}$ arbitrary chosen between 0.5 and 1.0.

$\boldsymbol{R_{test}}$ is a chosen value of the **R-ratio,** ratio of the hoop stress to the axial stress in particular test condition[63].

The design in accordance with the qualification programme, as described, is complete and valid IF:

1. The value chosen for the MPR_{xx} generates an enough wide design envelopes to contain all the stress states from the failure analysis and it is in accordance with the following equation:

$$MPR_{xx} \leq \frac{0.67 \cdot 2 \cdot t_r \cdot \sigma_{h,LT,2:1,xx}}{D_{r,min}}$$

where

t_r is the minimum reinforced pipe wall thickness, in [mm].
$D_{r,min}$ is the mean diameter of the minimum reinforced pipe wall, in [mm].
$\sigma_{h,LT,2:1,xx}$ is the Stress lower confidence limit, S_{lcl}[64], in accordance with the **ASTM D 2992 procedure B modified**. The full description of the modified procedure B is described in Appendix 2.3.

[60] The reinforced wall is the portion of the thickness that withstand the loads. The liner is not considered in this thickness because it does not give any structural resistance.
[61] The value of f_2 are respectively 0.89 – 0.83 – 0.67, further information in Factor paragraph.
[62] Including but not limited.
[63] $R_{ratio} = \frac{\sigma_{hoop}}{\sigma_{axial}}$; i.e. R=2:1 or R=2 correspond to a hydrotest, unrestrained-ends condition.
[64] The definition comes from a private communication with chairman ISO 14692 committee.

2. The Long-Term Failure Envelope, depending on the value of the MPR_{xx}, is validated by the two mandatory survival tests[65] below:
    a) **Survival Pressure test in R=2:1** condition, unrestrained ends, according with ASTM D 1598 modified[66].
    b) **Survival Pressure test in R=Rtest** condition, according with ASTM D 1598 modified.

The choice of the MPR_{xx} and the R_{test} is performed with the help of a graph as in **Figure 102**. It represents the states of stress and the design envelopes depending on the nature of the load taken into account.

Knowing the loads at which the pipe must withstand, is possible to represent the states of stress as point on the hoop-axial plane.
The value of the MPR_{xx} and the R_{test} modify the area and the shape of the envelope, and the choice of this values have to produce design envelopes which contain the states of stress considered.

More the knowledge concerning the loads, and so the states of stress, more the points on the chart to be contained by the design envelopes.

[65] The manufacturer shall have the option to use data from a previous process. However, the customer shall also have the option to require one or more of the tests in Table 49 to be conducted for their particular project.
[66] The test can be carried out during the ASTM D 2992 procedure B modified and its overcoming represent the validation test for the MPR_{xx}.

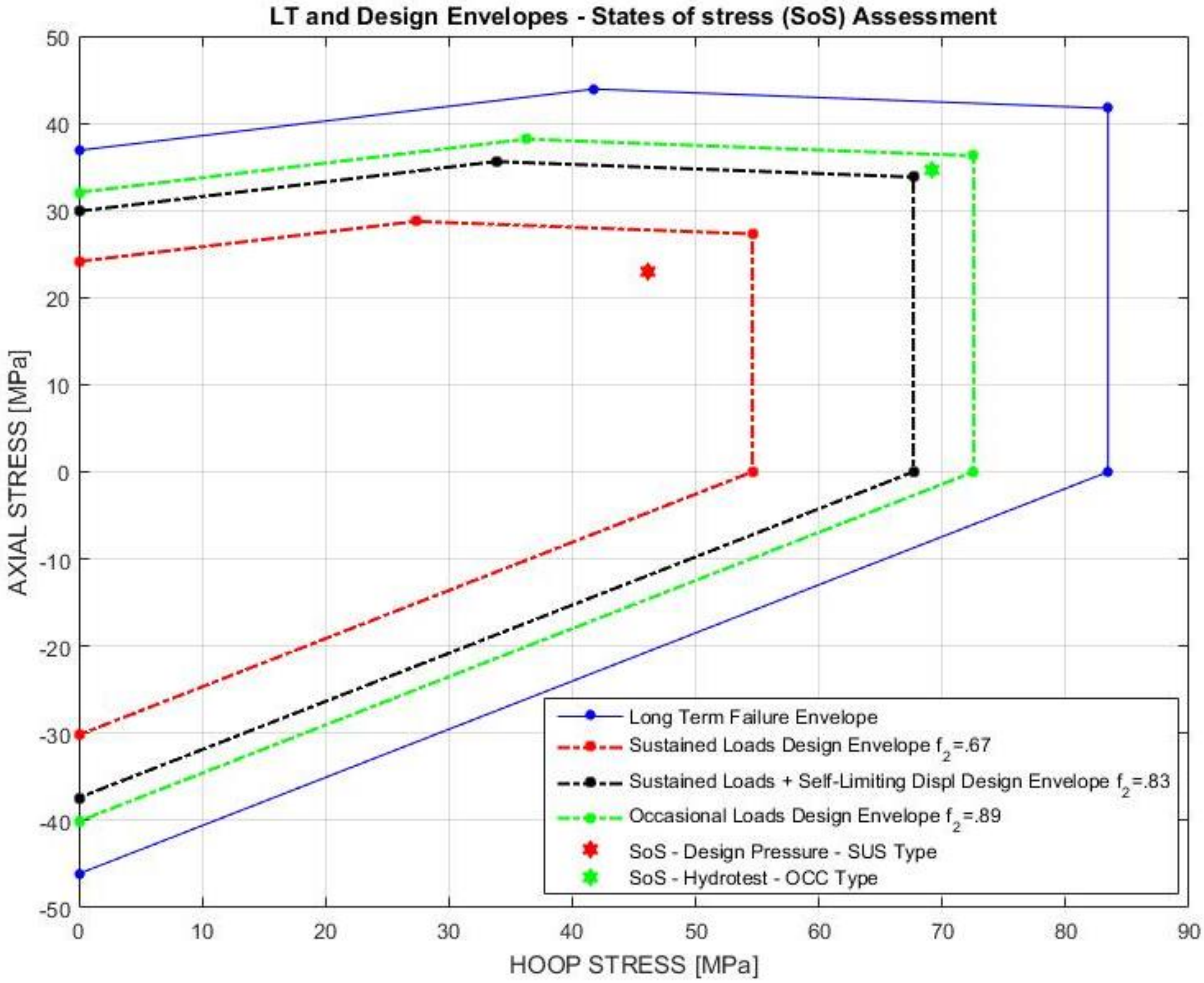


Figure 102 - Design envelope assessment for design pressure and post-installation hydrotest loading cases for a pipe of 400 [mm] diameter and 38.8 [mm] reinforced wall thickness. The SoS have to fall within the correspondent painted areas.

This FDIS of the 2nd edition of the ISO 14692 defines that all the tests must be performed at the operating design temperature.

The qualification programme is a one-time process and the default design service life is 20 years. This limit may be increased by mean of the A_0 part factor for lifetime coefficient, whose evaluation is described into the Factor paragraph.

Table 49 reassumes all the tests needed for the qualification programme.

The ASTM D1598 modified R=2:1 survival test ought to be carried out during the ASTM D 2992 modified[67] procedure B for the evaluation of GRP pipe statistical basis, as more explained in the following paragraphs.

[67] Futher descriprion in survival tests Paragraph.

The overall design process consists in:

0. Demand requirements
1. Definition of the State of Stresses, SoS
2. Definition of a the proper MPR_{xx}
    a. Check of the LT failure envelope and SoS positions
3. Validation of the MPR_{xx}
4. Validation of the LT Failure Envelope
    a. Survival test R=2:1
    b. Survival test R=Rtest

The explanations of these main topics follow:

- Determination of the L.T. Failure Envelope
- Characteristics of the validation survival tests
- Cases of loading and Failure Analysis

ISO/FDIS 14692-2:2016(E)

Table 1 – Summary of the qualification programme

No	Ref.	Test Procedure	Product(s)	Generated Data	Use
Product qualification					
1	4.1	ASTM D2992	Plain pipe or pipe+joint, one size	Measured G_{xx}	To validate $rd_{1\,000}$
2	C.2.2	ASTM D1598 as modified in 5.3.1	Plain pipe or pipe+joint, one size	R=R_{test} survival test	To validate the R=$Rtest$ data point on the threshold and long term envelopes
3	5.3.1	ASTM D1598 as modified in 5.3.1	Plain pipe, sizes per 5.2 and Annex E	Survival test	To validate the threshold and long term envelopes
4	5.3.1	ASTM D1598 as modified in 5.3.1	Pipe+joint and fittings, sizes per 5.2 and Annex E	Survival test	To validate the threshold and long term envelopes
5	5.3.1 and Annex D	ASTM D1598 as modified in 5.3.1	Flanges, sizes per 5.2 and Annex E	Survival test	To validate the threshold and long term envelopes
6		10 cycle pressure test			
7		Vacuum test			
8		Combined loading test			
9	5.3.2	Manufacturer's standard	Plain pipe, one pipe size	ρ	Weight
10	5.3.3	Manufacturer's standard or ASTM D696 or ISO 11359-2	Plain pipe, one pipe size	α_a	Axial pipe deflection
11	5.3.4	Section of 7.9 of ISO 14692-3 (by calculation)		External collapse pressure	Hoop pipe stability
Elastic properties					
12	5.4.2	ASTM D2105	Plain pipe, one pipe size	E_a	
13	5.4.3	Per API 15HR	Plain pipe, one pipe size	E_h and ν_{ah}	
14	5.4.4	Per Annex G	Plain pipe, one pipe size	ν_{ha}	
15	5.4.5	ASTM D2412 (buried applications only)	Plain pipe, one pipe size	E_{hb}	Hoop pipe stability, stiffness

Table 49 - Summary of the qualification programme testing

6.1. Long Term Failure Envelope

As in the bid stage the value of the maximum pressure rating, MPR_{xx}, gives an estimation of the performance required by the pipe, the manufacturer shall choose this value proper to satisfy the conditions for the qualification.

The failure envelope is generated starting from 2 points which are MPR_{xx} and has the following equations[68]:

$$\text{R=2:1 data point} \rightarrow \begin{cases} \sigma_{h,LT,2:1,xx} = \frac{MPR_{xx}}{f_2} \cdot \frac{D_{r,min}}{2 \cdot t_{r,min}} \\ \sigma_{a,LT,2:1,xx} = \frac{MPR_{xx}}{f_2} \cdot \frac{D_{r,min}}{4 \cdot t_{r,min}} \end{cases}$$

and

$$R = Rtest \text{ data point} \rightarrow \begin{cases} \sigma_{h,LT,Rtest,xx} = \frac{\sigma_{h,LT,2:1,xx}}{2} \\ 2 \cdot \sigma_{h,LT,Rtest,xx} \geq \sigma_{a,LT,Rtest,xx} \geq \sigma_{h,LT,Rtest,xx} \end{cases}$$

where

$\sigma_{h,LT,2:1,xx}$ is the hoop stress component of the R=2:1 data point
$\sigma_{a,LT,2:1,xx}$ is the axial stress component of the R=2:1 data point
$\sigma_{h,LT,Rtest,xx}$ is the hoop stress component of the R=$Rtest$ data point
$\sigma_{a,LT,Rtest,xx}$ is the axial stress component of the R= $Rtest$ data point

The $\sigma_{a,LT,Rtest,xx}$ is calculated according to the below equation and defines the $Rtest$ value as[69]:

$$R_{test} = \frac{\sigma_{h,LT,Rtest,xx}}{\sigma_{a,LT,Rtest,xx}}$$

The choice of MPR_{xx} and R_{test} influences the area and the shape of the L.T. failure envelope as explain in Figure 103, Figure 104, Figure 105.

The designer shall determine the most suitable values of MPR_{xx} and R_{test} taking into account the following considerations:

- The MPR_{xx} shall provide a wide enough LT envelope to generate design envelopes which contain the states of stress induced on the pipeline
- An increment of MPR_{xx} increases the pressures used into survival test, and so the thickness needed to withstand to the higher pressure. This increment influences the cost of the pipeline.
- LT failure envelopes with low values of R_{test} have high axial strength.
- As for the MPR_{xx}, a low value of R_{test} increases the pressure of the R_{test} survival test, and so the thickness and the cost of the pipe.

[68] The full generation process of the LT failure envelope is reported in ISO/FDIS 14692:2016 part 2 Annex C.
[69] The value of $\sigma_{a,LT,Rtest,xx}$ is the unknown.

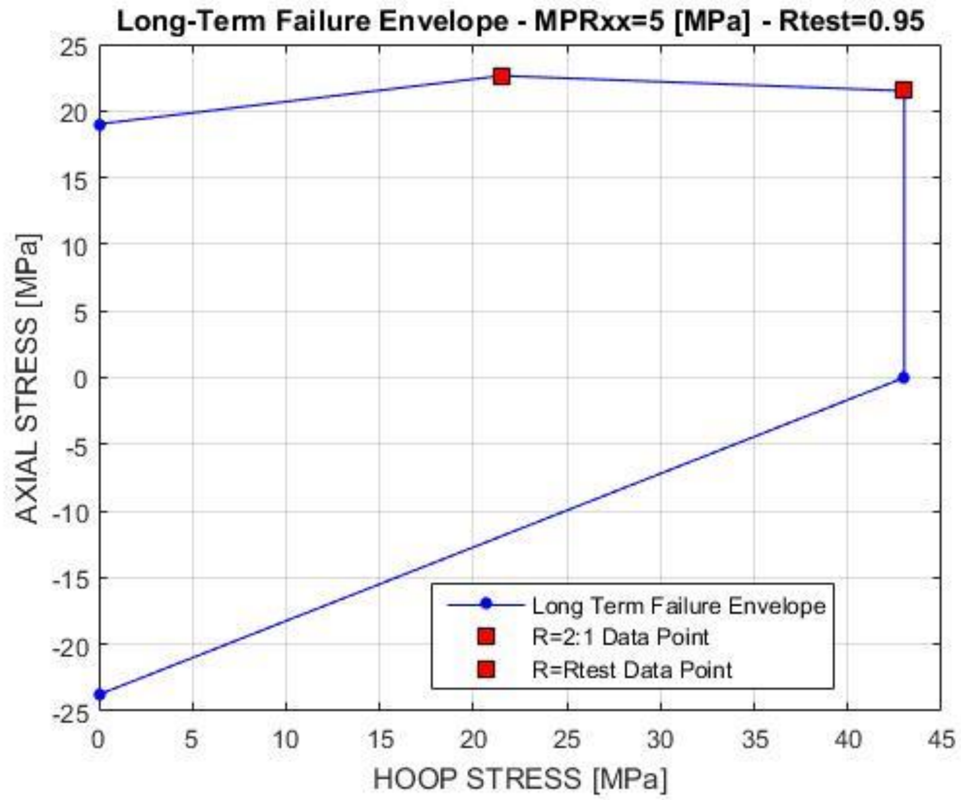


Figure 103 - LT Failure Envelope for MPRxx=5 and Rtest=0.95

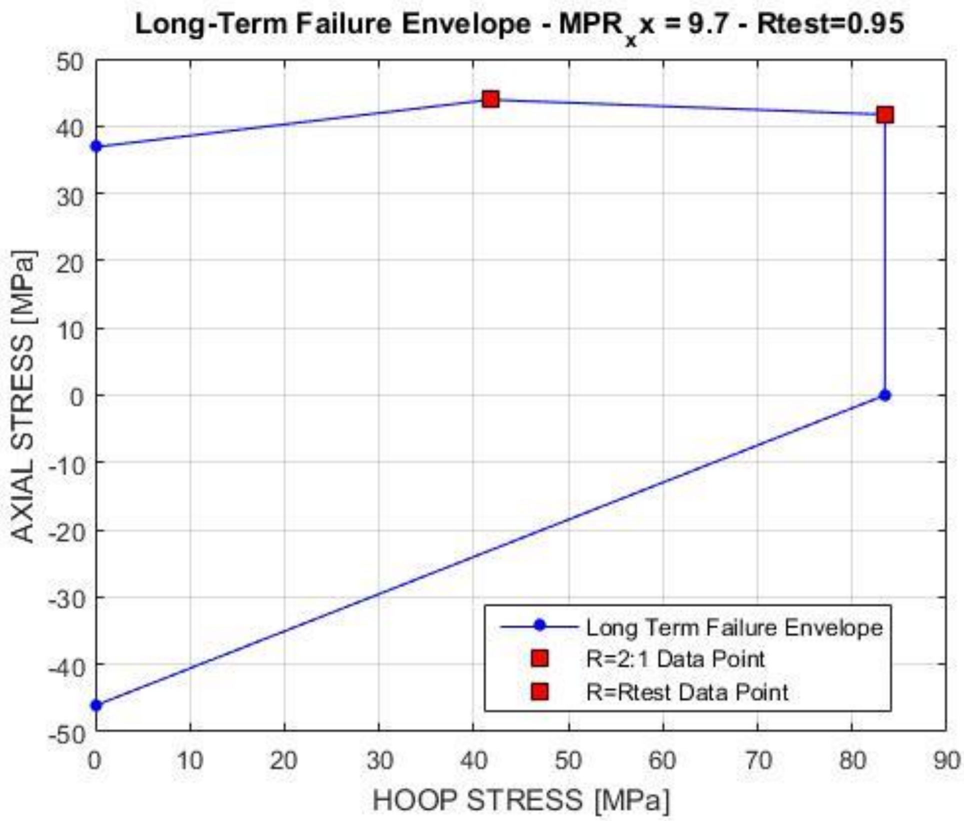


Figure 104 - LT Failure Envelope for MPRxx=9.7 and Rtest=0.95

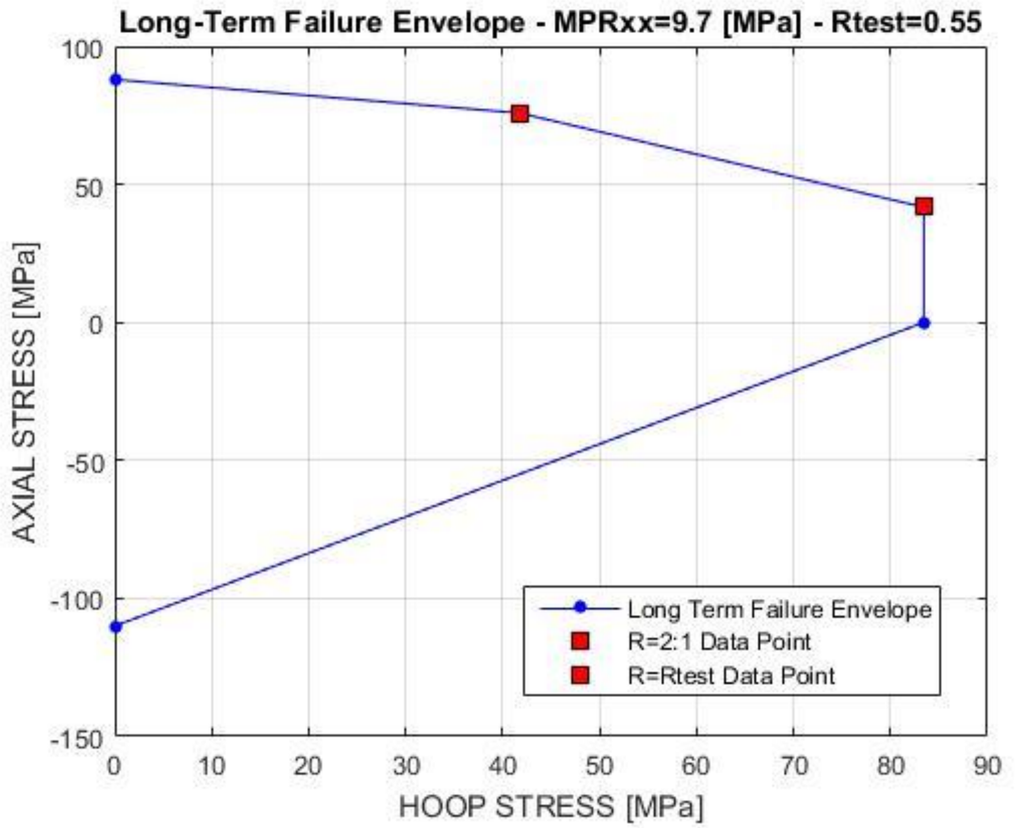


Figure 105 - LT Failure Envelope for MPRxx=9.7 and Rtest=0.55

Figure 103 and Figure 104 explain how the L.T. failure envelope is being scaled for a value of MPR_{xx} of 5 and 9.7 [MPa] for a pipeline of 400 [mm] diameter and 38.8 [mm] reinforced wall thickness.
The area of the L.T. failure envelope is linear to the value of the MPR_{xx}.

The R_{test} value modifies the shape of the LT failure envelope, i.e. the capacity of the envelope to contain axial stress states increases for low values of R_{test}. As shown in Figure 106.

6.2. Qualification Experimental Testing

To validate the design procedure, it is mandatory to follow the qualification programme, that consists in the three experimental sessions:

1. Determination of the S_{lcl} stress lower confidence limit and the gradient of the regression line G_{xx} in accordance with the ASTM D 2992 procedure B modified, for the validation of the MPR_{xx} and G_{xx} based calculations.
2. Survival Test in R=2: 1 condition for the validation of the long-term failure envelope in accordance with ASTM D 1598 modified – data point R=2:1
3. Survival Test in R=R_{test} condition for the validation of the long-term failure envelope in accordance with ASTM D 1598 modified – data point R=R_{test}.

6.2.1. ASTM D 2992 modified - procedure B

The description of this standard procedure has been already discussed within the ISO 14692:2002 qualification programme.
The manufacturer shall conduct the long-term regression on either a plain pipe or a pipe+joint, in a single pipe size, the size to be determined by the manufacturer[70].
The evaluation of gradient and lower confidence limit is in accordance with the default standard, whose description is reported in the appendix.
Anyway, the ISO/FDIS 14692, in part 2 – 4.1 and 5.1 paragraphs, imposes some modification to the default ASTM procedure:

- The experimental temperature shall be 65° C or higher for GRE and 21° or higher if not GRE.
- The experimental temperature shall not be less than design temperature if lower than the default temperature for the prescribed resin[71].
- The test fluid shall be potable water[72].
- All test shall be conducted with unrestrained (i.e. free) ends.

Whether in the case of 1st edition the regression is performed evaluating the pressure lower confidence limit, in the case of the 2nd edition the regression is performed evaluating the hoop stress lower confidence limit, as complained by the ASTM D 2992 – appendix X1.1.1

6.2.2. Survival test R=2:1 conditions

The R=2: 1 survival test, an hydrotest, is carried out in accordance with ASTM D 1598[73] modified procedure and is defined for the validation of the R=2:1 data point of the long-term failure envelope. This standard is the same which defines the operative methods adopted in ASTM D 2992.
The modifications from the original standard are similar to the listed for the ASTM D 2992:

- The experimental temperature is the design temperature T_{des}.
- The test fluid shall be potable water[74].
- All test shall be conducted with unrestrained (i.e. free) ends.

The survival test pressures are based on MPR_{xx}, design life and the scaling ratio $rd_{1000,xx}$. $rd_{1000,xx}$ is a function of G_{xx}.

[70] Because of economic reasons, the full regression shall be conducted on small size pipes. Is not clear whether the regression process would be conducted on pipe sizes different than the designed.
[71] NOTE 1 The one full regression curve does not have to be at or above the design temperature of the project. For example, the Enquiry sheet specifies a design temperature of 93 °C and the manufacturer has a full regression curve at 85 °C for GRE-Aliphatic Amine. Since the resin matrix is GRE and the temperature of the full regression curve is above 65 °C, the data is acceptable.
[72] Potable water is more aggressive test media than salt water. Test data using mineral oil should be rejected since mineral oil is not a degrading agent to the bond between the glass fibre end the resin matrix.
[73] A description of the ASTM D 1598 is reported into appendix.
[74] Potable water is more aggressive test media than salt water. Test data using mineral oil should be rejected since mineral oil is not a degrading agent to the bond between the glass fibre end the resin matrix.

The designer shall have the option to conduct the survival hydrotest at either 2000 h, 3000 h, 4000 h, 5000 h or 6000 h (i.e. in increments of 1000 h) instead of 1000h. $rd_{Time,xx}$ and the testing pressure ($P_{T\ Time,xx}$) shall be recalculated accordingly, where $Time$ is the predeterminated test time in h, and xx is the temperature in °C.
The survival test passes if the failure occurs after the predetermined test time.

The pressure for the hydrotest is calculated by mean of the following equation:

$$P_{T\ Time,xx} = rd_{Time,xx} \cdot \frac{MPR_{xx}}{f_2} \cdot \frac{t_{r,act} \cdot D_{r,min}}{t_{r,min} \cdot D_{r,act}}$$

$$rd_{Time,xx} = \left[10^{(\log(175200)-\log(Time))\cdot G_{xx}}\right]$$

where
$t_{r,min}$ is the minimum reinforced pipe wall thickness, expressed in mm
$t_{r,act}$ is the actual reinforced pipe wall thickness, expressed in mm
$D_{r,min}$ is the mean diameter of the minimum reinforced pipe wall, expressed in mm
$D_{r,act}$ is the actual mean diameter of the reinforced pipe wall, expressed in mm
$rd_{Time,xx}$ is the time h to 20 yr scaling ratio at xx °C
MPR_{xx} is the maximum pressure rating at xx °C, expressed in MPa
f_2 part factor for loading in the sustained condition, default value is equal to 0,67
$Time$ is the test time, either 1 000, 2 000, 3 000, 4 000, 5 000 or 6 000, expressed in hours
$P_{T\ Time,xx}$ is the pressure of survival test carried out at xx °C, expressed in MPa
G_{xx} is the gradient at xx °C

The actual mean diameter and thickness are evaluated by cutting the pipe at a cross-section. The survival test is validated if the actual values stand in the range of $\pm 5\%$ from the theoretical ones.

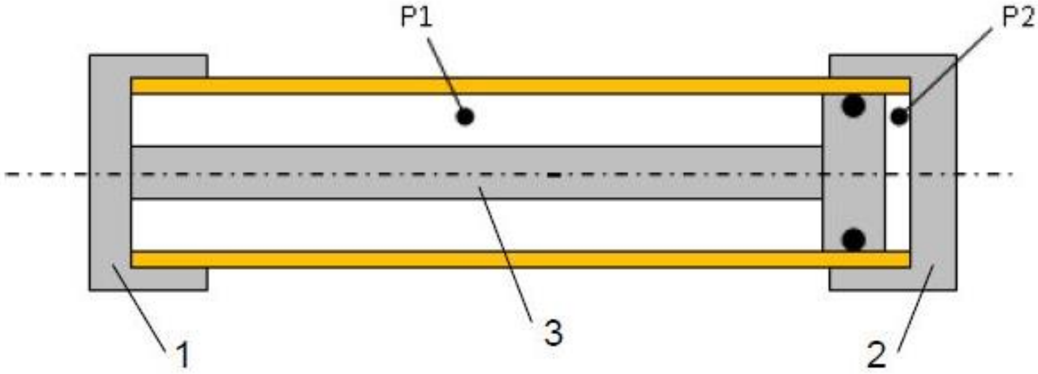
This validation test takes place inside the procedure for the validation of the failure envelope generation points.
The validation hydrotest ought to be done within the ASTM D 2992 modified procedure B by choosing the proper pressure as a test pressure for a sample of the regression.
If the failure of the sample occurs later than the chosen time, the test validates the generation point related to the hydrotest conditions, in addition to the MPR_{xx}.

In conclusion, considering the high costs of these tests, the validation of the data point R=$2:1$ should be developed within a proper designed ASTM D 2992 mod. procedure B.

6.2.3. Survival test R=R_{test} condition

The R=R_{test} survival test is carried out in accordance with ASTM D 1598[75] modified procedure and is defined for the validation of the R=R_{test} data point of the long-term failure envelope.

To reproduce the right state of stress an example of the test equipment is shown below.
Controlling the pressures P_1 and P_2, it is possible to generate the aimed combinations of hoop and axial stresses. Friction between inner diameter of pipe and plunger is to be minimized.
The experimental temperature is the design temperature.



Key
1 – Test head #1
2 – Test head #2
3 – Plunger + rod
P_1 is the pressure creating hoop stress on the test sample
P_2 is the pressure creating axial stress on the test sample

Remembering that the R-ratio is defined as $R_{test} = \frac{\sigma_{h,LT,Rtest,xx}}{\sigma_{a,LT,Rtest,xx}}$; the pressures shall be calculated by the following equations:

$$P_{T1\ 1000,Rtest,xx} = rd_{1000,xx} \cdot \sigma_{h,LT,Rtest,xx} \cdot \frac{2 \cdot t_{r,act}}{D_{r,act}}$$
$$P_{T2\ 1000,Rtest,xx} = rd_{1000,xx} \cdot \sigma_{a,LT,Rtest,xx} \cdot \frac{A_{r,act}}{A_{i,act}}$$

where

$P_{T1\ 1000,Rtest,xx}$ is the P1 pressure of survival test carried out at xx °C, expressed in MPa
$P_{T2\ 1000,Rtest,xx}$ is the P2 pressure of survival test carried out at xx °C, expressed in MPa
$rd_{1000,xx}$ is the scaling ratio at 1000 h
$t_{r,act}$ is the actual reinforced pipe wall thickness, expressed in mm
$D_{r,act}$ is the actual mean diameter of the reinforced pipe wall, expressed in mm
$A_{r,act}$ is the actual reinforced pipe wall cross section area
$A_{i,act}$ is the actual pipe inside bore area

[75] A description of the ASTM D 1598 is reported into appendix.

The test is valid if the measurement of the $t_{r,act}$ after the failure is within $\pm 5\%$ of the $t_{r,min}$.

The survival test succeeds if the failure occurs after 1000 h, which is the prescribed time of the test.
In this case, the LT failure envelope data point is valid.

7. Failure Analysis

The failure analysis determines the value of the stress starting from the load cases.

The type of loads considered are the same described into the 1st edition of the standard.

8. Partial Factors & Coefficients

The partial factor calculations are given into part 3 of the standard.

8.1. A_0 - Partial factor for design lifetime

The factor A_0 shall be used to scale the long-term envelopes to the design envelopes at design lives other than 20 years. The value of the partial factor shall be designed by the following equation:

$$A_0 = \frac{1}{10^{(\log(t) - log(175200)) \cdot G_{xx}}}$$

where
t is the time expressed in hours
G_{xx} is the gradient of the regression line at xx°C

The value shall not be greater than 1.

The procedure for the calculation of the gradient is given in ASTM D2992 procedure B modified.

8.2. G_{xx} Gradient determination

ISO/FDIS 14692:2016 provides default value of G_{xx} as function
All pipe wall thickness shall be qualified using the published default gradients $G_{xx,default}$.

The $G_{xx,default}$ are given as function of the resin materials and temperatures in Table 50. The Figure 106 gives a representation of the trends of the various gradients.

Resin System	Temperature						
	–35 °C	21 °C	50 °C	65 °C	80 °C	93 °C	121 °C
GRE, Anhydride	0,045	0,045		0,065	0,105		
GRE, Aliphatic Amine	0,045	0,045		0,065		0,100	
GRE, Cyclo-aliphatic Amine (IPD)	0,045	0,045		0,065		0,090	
GRE, Aromatic Amine (MDA)	0,045	0,045		0,065		0,090	0,115
GRUP, Polyester	0,055	0,055	0,070				
GRVE, Vinyl Ester	0,055	0,055	0,065	0,075			

NOTE 1 Interpolation of values is allowed.

NOTE 2 The omission of default gradients at higher temperatures may not automatically preclude the use of a particular resin system at that temperature. For example, most of the long term testing on GRVE resin systems is between 21 °C and 65 °C, thus default gradient are only established up to 65 °C. However, some GRVE resin systems have Tg values of 140 °C or higher. To use the resin system at these higher temperatures, the requirements in A.3.2 may have to be met.

EXAMPLE 1 G_{80} for an Anhydride Epoxy is 0,105.

EXAMPLE 2 G_{60} for GRVE is 0,072 (found by interpolation).

EXAMPLE 3 G_{-35} for GRUP is 0,055.

EXAMPLE 4 G_{105} for IPD epoxy is not available in this table since 105 °C is above the highest published temperature of 93 °C for IPD epoxy.

Table 50 - Default gradients Gxx

Referring to Figure 106, if the default gradient for the resin material is not given for the T_{des} design temperature, the evaluation of the correspondent default gradient is possible by increasing the length of the last segment of the resin material up to the design temperature.

In the case of joints, the value of the gradient G_{xx} shall be chosen as the higher between the default gradient $G_{xx,default}$ and the experimentally evaluated one in **ASTM D 2992 procedure B – Modified**, $G_{xx,D2992\ mod}$.

The manufacturer shall calculate the gradient G_{xx} of the regression line as defined in the **ASTM D 2992 procedure B – Modified**.
A description of this procedure is given into the ISO 14692:2002 chapter - Family Representative: ASTM D 2992 Testing Evaluation paragraph.

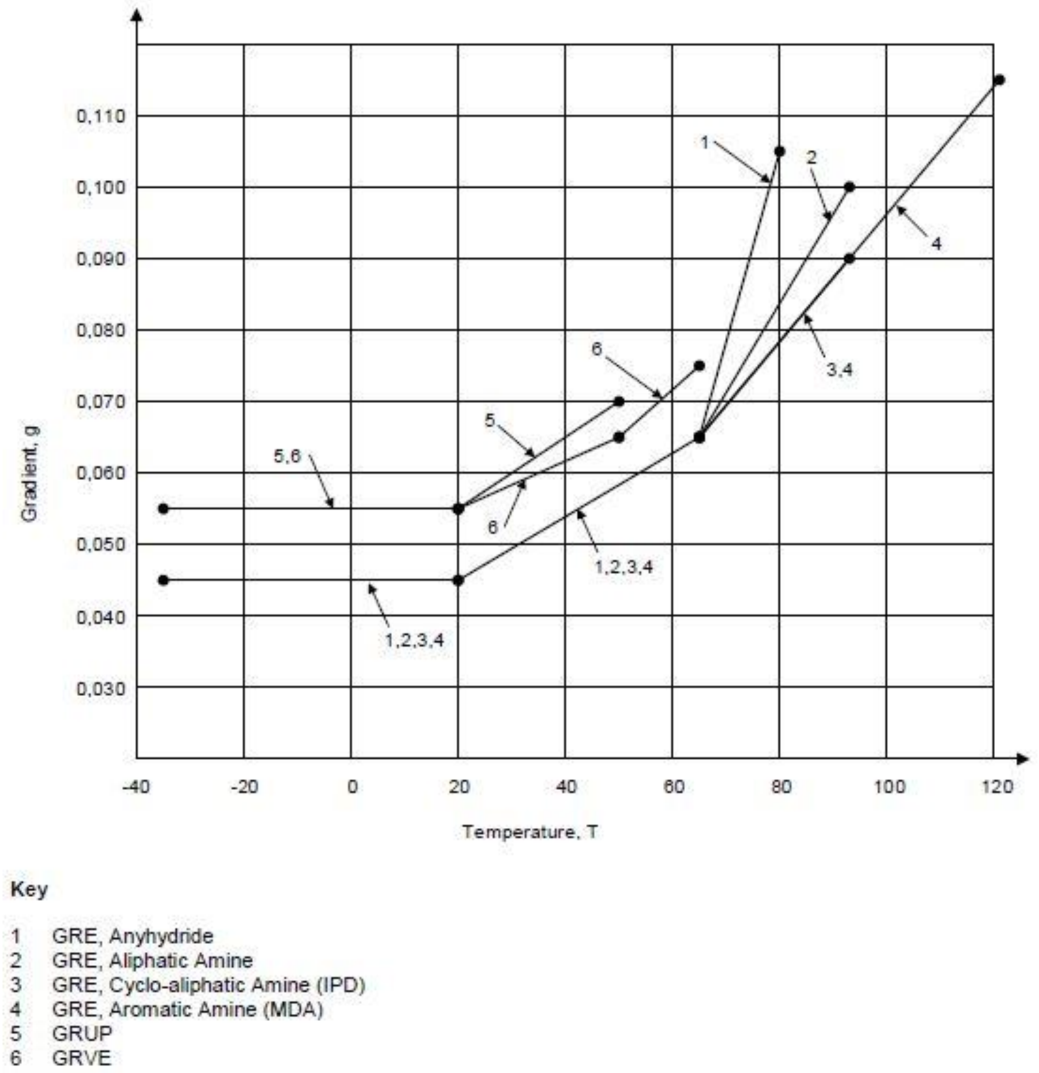


Figure 106 – Graphical description of the default gradients

8.3. A_2 - Partial factor for chemical degradation

A_2 shall be used to scale the long-term envelopes to the design envelopes to account for the effect of the chemical degradation.

The ISO/FDIS 14692:2016 define that "The value of A_2 partial factor shall be 1".

The partial factor for chemical degradation shall be applied to the rich resin liner. The design in the case of chemical aggression environments and fluids shall consider the presence of a liner barrier. This is because the chemical aggression may cause the breakdown of bonds between fibre and matrix, leading to the failure of the pipeline. So, the reinforced wall shall be as much as possible isolated from the chemical aggression, and its partial coefficient value for chemical degradation, as said, shall be equal to 1.

8.4. A_3 - Partial factor for cyclic loading

A_3 shall be used to scale the long-term envelopes to the design envelopes to account for the effect of the cyclic loading.

The value of A_3 is based on the definition of the cyclic long-term strength factor f_c, whose definition is given into the Annex B of the part 3 of the ISO standard, and depends on the ASTM D 2992 procedures A and B.
The conservative value of the f_c factor is 4.
The value of A_3 shall be calculated by the use of the following equations:

When $R_c > 0.4$:

$$A_3 = \left(\frac{1-f_c}{0.6\cdot f_c}\right)\cdot\left(\frac{1-R_c}{log(1.5\cdot 10^8)-log(7000)}\right)log(N)+$$
$$+1-TAN\left[\left(\frac{1-f_c}{0.6\cdot f_c}\right)\cdot\left(\frac{1-R_c}{log(1.5\cdot 10^8)-log(7000)}\right)\right]log(7000)$$

When $R_c \leq 0.4$:

$$A_3 = \left(\frac{1-f_c}{f_c}\right)\cdot\left(\frac{1-R_c}{log(1.5\cdot 10^8)-log(7000)}\right)log(N)+$$
$$+1-\left[\left(\frac{1-f_c}{f_c}\right)\cdot\left(\frac{log(7000)}{log(1.5\cdot 10^8)-log(7000)}\right)\right]$$

where
R_c is the cyclic loading ratio $\frac{\sigma_{min}}{\sigma_{max}}$
N is the prevision of the number of cycles during the entire service of life.

A representation of the value of the A_3 is given in the next figure as function of the number of cycles and the loading ratio.

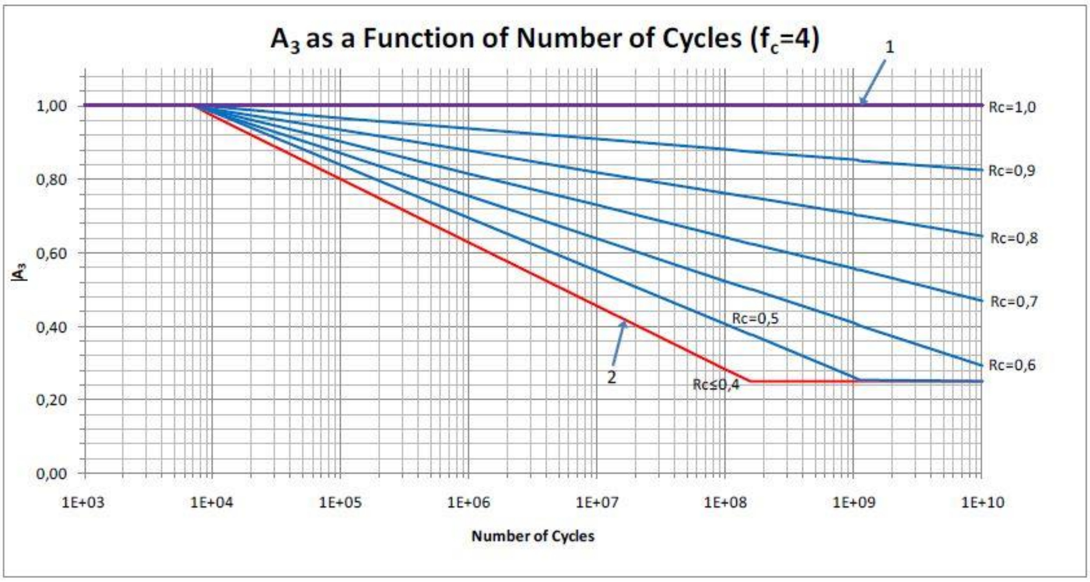


Figure 107 - Evaluation of the partial factor for cyclic loads

Key
1 – fully static loading
2 – fully cyclic loading
R_c is the cyclic loading ratio
f_c is cyclic long-term strength factor

Furthermore, if the calculated coefficient A_3 is higher than 0.9, the final value shall be 1.
If the calculated coefficient A_3 is less than 0.25, the final value to apply is 0.25.

8.5. f_2 – Part Factor for loading conditions

The part factor is defined similarly to the correspondent factor in the ISO 14692:2002.
Because of all the tests are carried out at the design temperature, the temperature no longer represents an unknown to factorize. The final pipeline design structure is often unknown during the preliminary structural design stage, the f_2 considers the possible presence of axial constraints which would increase the state of stress induced by the inner pressure, leading to failure.

The purpose of the part factor f_2 is to define an acceptable margin of safety between the strength of the material and the operating stresses for the three load cases, occasional, sustained plus self-limiting displacement conditions, and sustained.
The following table provides default values of the safety factor depending on the nature of loads.

Loading type	Load duration	f_2
Occasional	Short-term	0.89
Sustained plus self-limiting displacement	Long-term	0.83
Sustained	Long-term	0.67

Examples of loading cases are given in the next table:

Sustained, *f2*=0,67	**Sustained + Self-Limiting Displacements, *f2*=0,83**	**Occasional, *f2*=0,89**
Operating and sustained internal, external or vacuum pressures, MOP (maximum operating pressure), *Pdes*	Thermal induced loads, electric surface heating or other heat tracing methods	Hydrotest and other occasional pressures Water hammer or other pressure transients Pressure safety valve releases
Piping self-mass, piping insulation mass, fire protection mass, transported medium mass, buoyancy, other system loads	Installed curve radius (roping)	Impact Occasional vehicular traffic loads on buried pipes
Sustained inertia loads (e.g. daily wave action, ship movement, inundation through high tides, other	Ring bending due to long term vertical pipe deflection in a buried system	Occasional inertia loads (e.g. motion during transportation, storms, etc.) Earthquake-induced horizontal and

motions during operation) Displacement of supports due to operational conditions (such as flexing of the hull during operations)		vertical forces Displacement of supports due to occasional conditions (such as flexing during lifting)
Environmental loads, ice	Soil loads (burial depth)	Adiabatic cooling loads
Soil subsidence	Vehicular traffic loads on buried pipes	Wind (from occasional conditions such as a storm)
	Encapsulation in concrete	Blast over-pressures
		Thermal induced loads due to upset conditions

Table 7 - Examples of loads experienced by a GRP piping system

The part factor f_2 scales the long-term envelope to the 3 design envelopes which correspond to each value of the factor.

8.6. f_3 - Part Factor for axial load

The part factor f_3 for axial load is required to be estimated at the Bid Step.
Since the project is at the bid stage, there are no stress analysis available and estimates will have to be made of these axial stresses.

The estimation of $f_{3,est}$ shall be done by means of two methods. The selection process for $f_{3,est}$ is shown in Figure 106.

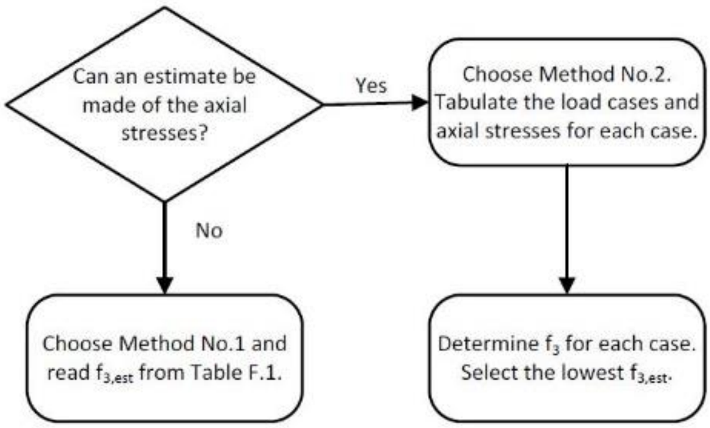


Figure 108 - Selection process for $f_{3,est}$

The method 1 provides guidelines for determining the part factor $f_{3,est}$ at the bid stage in Table 51.

Application	$f_{3,est}$	Notes
Process piping, Aboveground, Offshore & marine, max. 1,5 · P_{des} hydrotest	0,65 – 0,75	Occasional loads from wind and/or ship motions typically require a low $f3$. Special design conditions such as wave loads may require a much lower $f_{3,est}$.
Process piping, Aboveground, Industrial, max. 1,5 · P_{des} hydrotest	0,65 – 0,80	Higher temperature changes (e.g., above 40 °C) may require a lower $f_{3,est}$. due to axial and bending stress from thermal loads. Applications in some seismic zones may require a lower $f_{3,est}$..
Process piping, Aboveground, Oil field, max. 1,5 · P_{des} hydrotest	0,65 – 0,80	Same as aboveground industrial process piping.

Pipelines, Aboveground, Oil field, max. 1,25 $\cdot P_{des}$ hydrotest	0,70 – 0,85	Pipelines should have lower non-pressure axial stresses, so $f_{3,est}$. may be higher than for process piping applications. For process piping, the hydrotest case is likely to govern whereas for pipelines, a design case is likely to govern.
Process Piping, Underground, Industrial, max. 1,5 $\cdot P_{des}$ hydrotest	0,75 – 0,85	Hoop (circumferential) loads can dominate the design. Higher pressure (between 10 and 30 bar) underground pipelines with many fittings or direction changes where the longitudinal bending loads can be significant due to the axial thrust generated from the internal pressure. These systems may warrant an $f_{3,est}$. between 0,65 and 0,8.
Pipelines, Underground, Oilfield, max. 1,25 $\cdot P_{des}$ hydrotest	0,85 – 1,00	See note above for Process Piping, Underground, Industrial
NOTE: The guidelines for $f_{3,est}$ in this table are based primarily on $\pm 55°$[deg] filament wound pipe. For those pipes or other components manufactured by a method that has a higher axial strength capacity, a higher $f_{3,est}$ factor may be warranted. A component with equal amounts of reinforcement in both the axial and hoop direction may warrant an $f_{3,est}$ factor of 1,0. Evidence should be provided to justify a higher $f_{3,est}$ factor.		

Table 51 - Guidelines for determining $f_{3,est}$ at the bid stage - extracted from Annex F part 1

The method 2 for the evaluation of the $f_{3,est}$ at the bid stage is to consider the non pressure-generated axial stresses that could occur on the piping system, considering bending, curving external forces and thermal loads.
This calculation is long and articulated, further information can be found into Annex F of the part 1 of the ISO/FDIS 14692:2016 standard.

Anyway, the f_3 part factor will have to be calculated in the final design stage using method 2 which considers the stress analysis of the components of the executive structural pipeline project, including axial forcers due to bending, curving, external forces…

9. System Testing

Field hydrotest shall be carried out on all piping systems and shall involve both a strength test and a leak test.

The testing system is similar to the 1st edition of the ISO 14629 and consists in an in-field pressure hydrotest at $1.5 \cdot P_{des}$ for a duration of 30 minutes.
The stress state is considered to be occasional load (Design Envelope $f_2 = 0.89$).

The leak test for piping systems is carried out at pressure $1.1 \cdot P_{des}$ for at least 2 hours.
Further information in ISO/FIDS 14692:2016 part 4 section 4.

10. QT2016 - Simulation of the ISO/FDIS 14692:2016 Design Process

The Matlab® **Qualification Tool, QT2016**, has been developed based on the ISO/FDIS 14692:2016 in order to calculate all the factors, coefficients and parameters regarding the design process in accordance with the standard.

The flowchart[76] referred to this 2nd edition well represents the operations of the software, whose main steps are:

0. Definition of the design data, based on the design requests
1. Bid process.
2. Definition of the hypothetical reinforced wall thickness.
3. Definition of loading cases and calculation of State of Stress points (SoS) by means of stress analysis.
4. Choice of the MPR_{xx} and the R_{test}
    - Comparison between the design envelopes and the State of Stress points.
5. Validation of the MPR_{xx}
6. Parameters Evaluation of the survival validation tests:
    - $R = 2:1$ - $P_{T\ Time,xx}$
    - $R = R_{test}$ - $P_{T1\ 1000,Rtest,xx}$ and $P_{T2\ 1000,Rtest,xx}$

The QT2016 works as inputs source, as well as the APT[77], for the analytical simulation of the tests from which it is possible to determine the minimum pipe reinforced wall thickness.
The Hydrotest Simulation Tool, HST, properly adapted, simulates the following qualification tests:

1) **The validation of the MPR_{xx}**
2) **Survival test $R = 2:1$**
3) **Survival test $R = R_{test}$**

Each simulation represents a constraint to the minimum wall thickness. The final thickness is the minimum thickness which validates all the 3 tests contemporary.

- **The validation of the MPR_{xx}**

The MPR_{xx} is valid if the following equation is verified:

$$MPR_{xx} \leq \frac{0.67 \cdot 2 \cdot t_r \cdot \sigma_{h,LT,2:1,xx}}{D_{r,min}}$$

Knowing that $\sigma_{h,LT,2:1,xx} \equiv \sigma_{LCL}$ [78], as defined into ASTM D 2992 procedure B – modified,
The process is iterative, because it depends on the wall thickness, t_r.

The validation consists in the definition of the minimum wall thickness that reaches the $\sigma_{h,LT,2:1,xx}$ value.
The process is similar to the used for the Qualified Pressure assessment into the ISO 14692:2002 – chapter 5, paragraphs 8 and 8.1.

[76] Flowchart A,B,C 2016 can be found in appendix
[77] APT provides the lamina characteristic to the HST which simulates the validation and the survival tests.
[78] Private communication with chairman of international committee

Since $\sigma_h = \frac{pD}{2t_r}$, the equation can be simplified and becomes:

$$\frac{MPR_{xx}}{0.67} \leq P_{LCL}$$

where P_{LCL} is the pressure lower confidence limit found in ASTM D 2992.

The HST is able to calculate this value and the related pipe wall thickness, in accordance with the request and, in particular, with the service lifetime, using the $P_{lcl(1000h)}$ as the hydrotest pressure.

$$P_{LTHP(1000h)} = \frac{P_{lcl(175400)}}{f_1} \cdot 10^{G \cdot [log(175400) - log(1000)]}$$

The procedure is similar to the one adopted in the qualified pressure assessment within the 1st edition of the standard, where the pressure P_{LCL} is transposed from 25 years to 1000 hours, by means of the G gradient of the regression line.

In the case of the ISO/FDIS 14692:2016 all the procedures are always based on the default service lifetime of 20 years. The additional 5 years of duty are taken into account by means of the A_0 coefficient.
So, the hydrostatic auxiliary pressure will have to be transposed from the term of 20 to 1000h, as shown in the previous equation.

The hydrostatic simulation which uses the pressure $P_{LTHP(1000h)}$ declares the pipe wall thickness, t_{r1}, in accordance with the MPR_{xx} validation procedure.

As in the case of the 1st edition of the standard, this test is artificially transposed on 1000h. The real validation of the MPR_{xx} is made basing on the results of the performed ASTM D2992 procedure B modified.

- **Survival test $R = 2:1$**

The survival test consists in a hydrostatic simulation at the given pressure.
The duration of the test can be chosen, but in order to limit the aging of the material, it is better to perform the simulation based on the 1000 h test duration, and so, on the pressure $P_{T\ 1000,xx}$.

The HST performs the hydrotest and provides the pipe wall thickness, t_{r2}, in accordance with the survival test $R = 2:1$.

- **Survival test $R = R_{test}$**

The survival test $R = R_{test}$ is a pressure test where the value of the axial stress in increased[79].
The duration of the test is fixed and equal to 1000 h, and bases on the pressures $P_{T1\ 1000,Rtest,xx}$ and $P_{T2\ 1000,Rtest,xx}$.

The HST is modified into HST_{Rtest} to accomplish this simulation and provides, as for the other cases, the needed value of the pipe wall thickness, t_{r3}.
The final pipe wall thickness chosen is the higher among the three evaluated: t_{r1}, t_{r2}, and t_{r3}.

[79] The description of the test is given in 6.2.3

10.1. Case of Study Design Process – ISO/FDIS 14692:2016

As for the ISO 14692 1st edition, it is performed the design process applied to the case of study in conformity with the qualification programme of the ISO/FDIS 14692:2016.
The design procedure described above has been applied to the case of study demand requests.
The Design constrains are:

- The demand requests given in Table 20
- The Matrix and Fibre properties, given in Table 11 and Table 12

The wall thickness value is evaluated under the following hypotheses:

- $A_0 = 0.976$, which corresponds to a service lifetime of 25 years, (219000 h)
- $A_2 = 1$, part factor for chemical degradation, the chemical degradation is limited to the presence of the liner and the standard defines that this value shall be 1.
- $A_3 = 1$, this value is the calculated for N = 10000 cycles.
- $f_1 = 0.98$, this value shall be calculated once the ASTM D2992 procedure B has been completed.
- $G_{80,GRVE} = 0.105$ is the plain pipe default regression gradient from ISO/FDIS 14692:2016 evaluated for epoxies resins at the design temperature of 80°C[80].
- No further axial load due to non-pressure sources.
- Due to the presence of the $R = R_{test}$ survival pressure test in addition to the $R = 2:1$ hydrotest, the winding-angle θ°[deg] shall be optimized properly.
- $f_3 = 0.75$ default value coming from the bid stage.
- $R_{test} = 0.95$ because of no other axial loads in except to the derived from inner pressure are taken into account, the value of the R_{test} is chosen close to 1.

The design process for the calculation of the minimum pipe wall reinforced thickness, t_r, is more linear than for ISO 14692:2002. The use QT2016, HST and APT is combined and the scripts are based on the following steps of analysis.

1. **Bid Stage**

The bid stage provides, based on the calculated coefficients, a preliminary estimation of the MPR_{80} (est) of 11.69 [MPa]. Furthermore, the bid stage questionnaire assures that the ISO/FDIS 149692:2016 can be used for this project.

2. **State of Stress points and L.T. Failure Envelope.**

The design begins from the stress point definition.
The stress conditions taken into account are 2:

- SoS[81] due to the Design Pressure – Sustained load at 8 [MPa]
- SoS due to the in-site Hydrotest at $1.5 \cdot P_{des}$ – Occasional load at 12 [MPa]

[80] The default gradients increases within the 2nd edition of the standard.
[81] SoS: State of Stress

Because of the absence of axial loads other than inner pressure induced, the chosen $\boldsymbol{R_{test}}$ is **0.95**. This value "close" the shape of the failure envelope in axial direction because no further axial resistance is needed in addition to the necessary to withstand the stresses already considered.

In order to contain the SoS points, the **Maximum Pressure Rating $\boldsymbol{MPR_{80}}$** chosen is **9.6 [MPa]**

The relative position of the Long-Term Failure Envelope, function of MPR_{80} , and the SoS points results to be wall thickness independent.
The figure which follows shows how each design envelope contains the relative SoS point, depending on the type of the load and so of the safety factor f_2 to be applied.

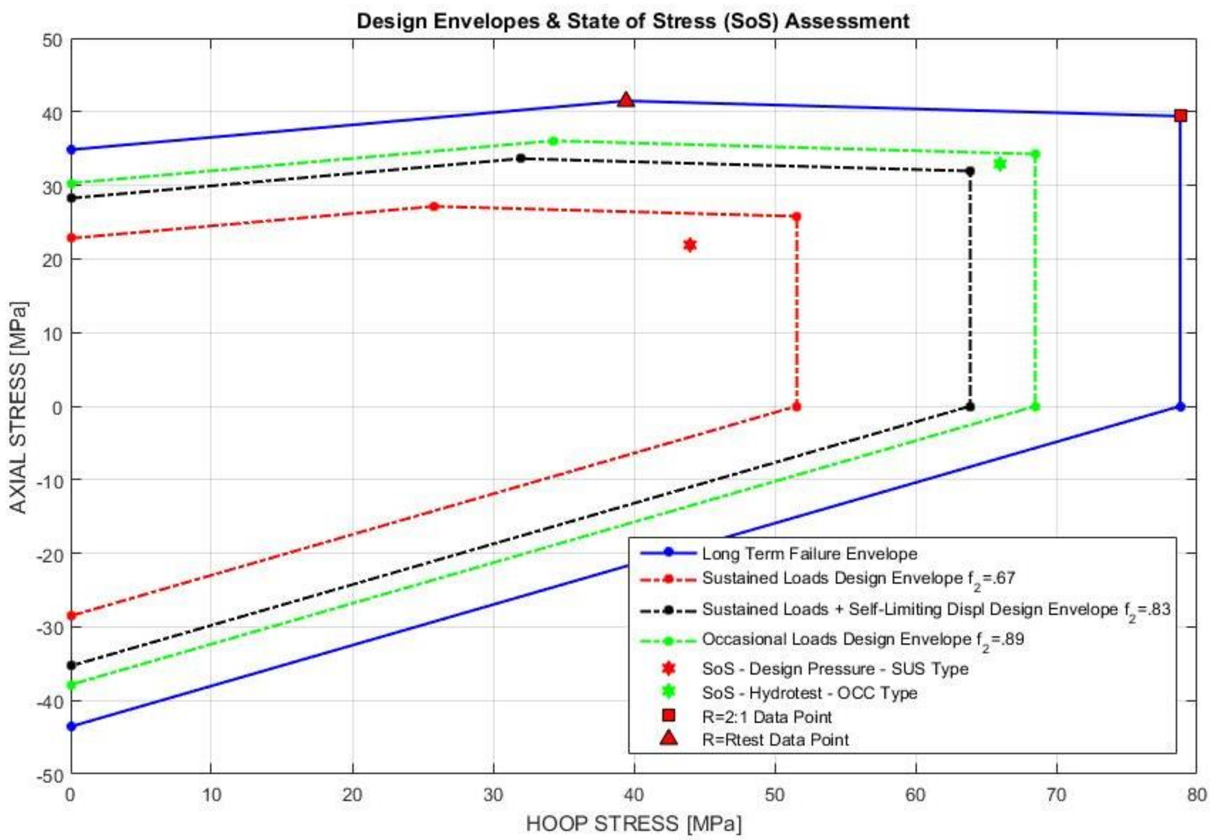


Figure 109 - LT and Design Envelopes with the state of stress considered in accordance with the ISO/FDIS 14692:2016

The values of the MPR_{80} and the R_{test} result to be appropriate.

3. **Product Family**

The qualification of this plain pipe, product representative, automatically qualifies the whole pipe whose pressure and diameter falls within the blue line, in accordance with the given equation in paragraph 3.1.

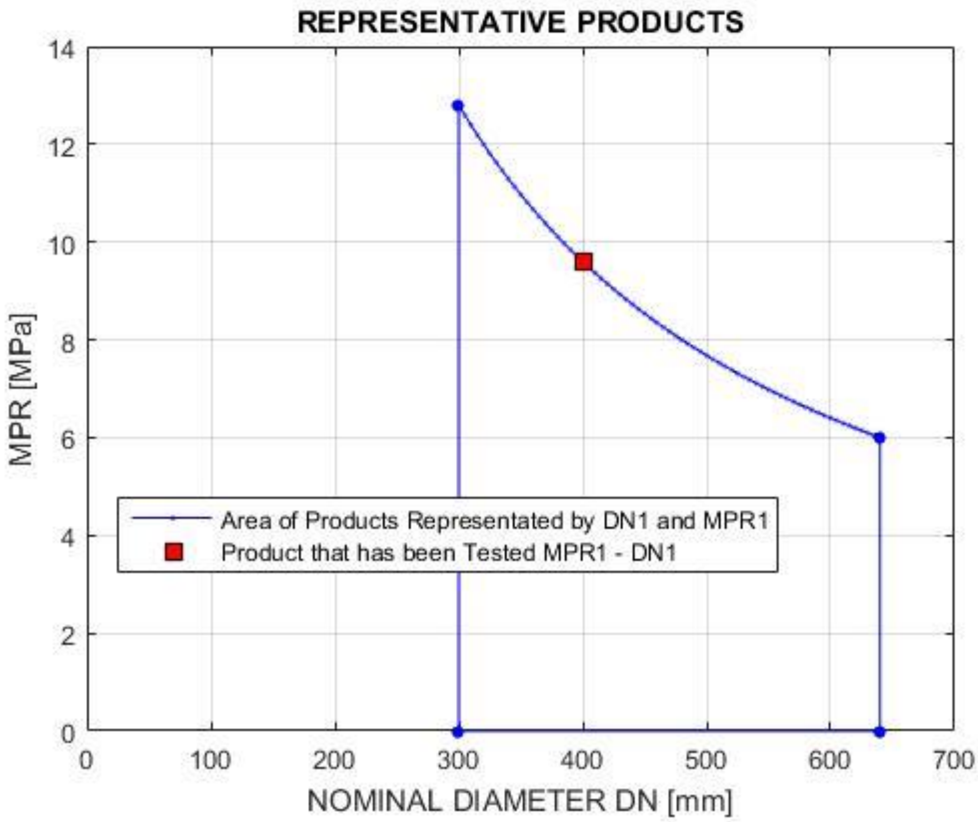


Figure 110 - Family represented by the tested pipe.

The qualification of these product does not need ASTM D2992 procedure B modified testing.

4. **Validation Tests Parameters**

Knowing MPR_{80} and R_{test}, it is possible the calculation of all the parameters needed to perform the simulation of the tests. This allows the evaluation of the final reinforced wall thickness of the plain pipe.
As said in the previous paragraph, there are 3 validation tests:

- **The validation of the MPR_{80}**

The validation pressure for the MPR_{80} , $P_{LTHP(175400h)}$, based on the default service lifetime of 20 years is 14.33 [MPa].
The transposed auxiliary value $\boldsymbol{P_{LTHP(1000h)} = 25.13}$ [MPa] is adopted in the HST simulation for the determination of the t_{r1}.

- **The validation of the $R = 2:1$ data point**

The pressure chosen for the survival hydrotest in accordance with the ASTM D1598 mod.
$P_{T\,1000,80}$ **is 24.65** [MPa].
The standard allows the execution of the R=2:1 hydrotest on times from 1000h to 6000h, changing the test pressure. The full range of the possible pressures are:

R=2:1 Test Duration	Hydrotest pressure		
1000 h	$P_{T\,1000,80}$	24.65	[MPa]
2000 h	$P_{T\,2000,80}$	22.91	[MPa]
3000 h	$P_{T\,3000,80}$	21.96	[MPa]
4000 h	$P_{T\,4000,80}$	21.31	[MPa]
5000 h	$P_{T\,5000,80}$	20.81	[MPa]
+6000 h	$P_{T\,6000,80}$	20.43	[MPa]

Table 52 - R=2:1 hydrotest pressures depending on the duration of the test chosen

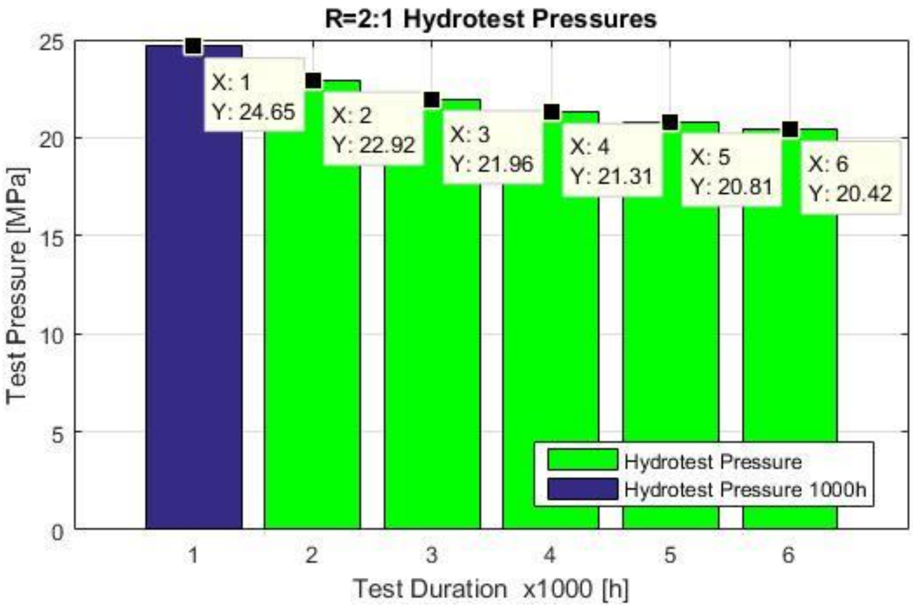


Figure 111 - Hydrotest Pressure Graph - Chosen Pressure for 1000h duration of the test

The choice to adopt the 1000h test is to limit the influence of the aging of the material which is expected leading to a significant scatter between the simulation and the real test. This because the HST is not able to predict the performance of the lamina as time dependant[82].
So, the HST is adopted to evaluate the relative minimum wall thickness t_{r2} due to the R=2:1 hydrotest constraint.

[82] If the time degradation trends are known (i.e. experimentally), it would be analytically possible consider the aging of the composite.

- **The validation of the $R = R_{test}$ data point**

The $R = R_{test}$ consists in a pressure test where an induced axial stress is present, in addition to an inner pressure load.
Remembering that the test is carried out by means of two pressure chambers as explained in the figure, the ISO/FDIS 14692:2016 provides the pressures of each section of the piston-like pipe.

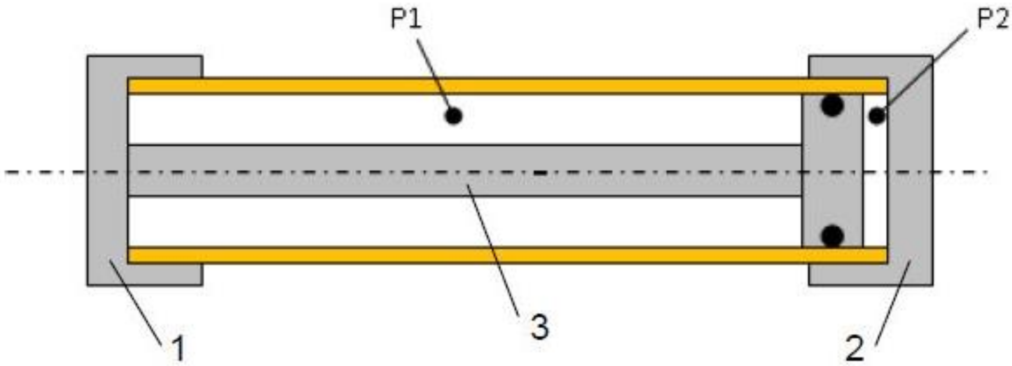


Figure 112 - test installation for the R=Rtest survival test

The pressure are:
$\boldsymbol{P_1 \equiv P_{T1\ 1000,Rtest,80}} = \mathbf{12.32}$ [MPa] is the pressure creating hoop stress on the test sample
$\boldsymbol{P_1 \equiv P_{T2\ 1000,Rtest,80}} = \mathbf{32.35}$ [MPa] is the pressure creating axial stress on the test sample

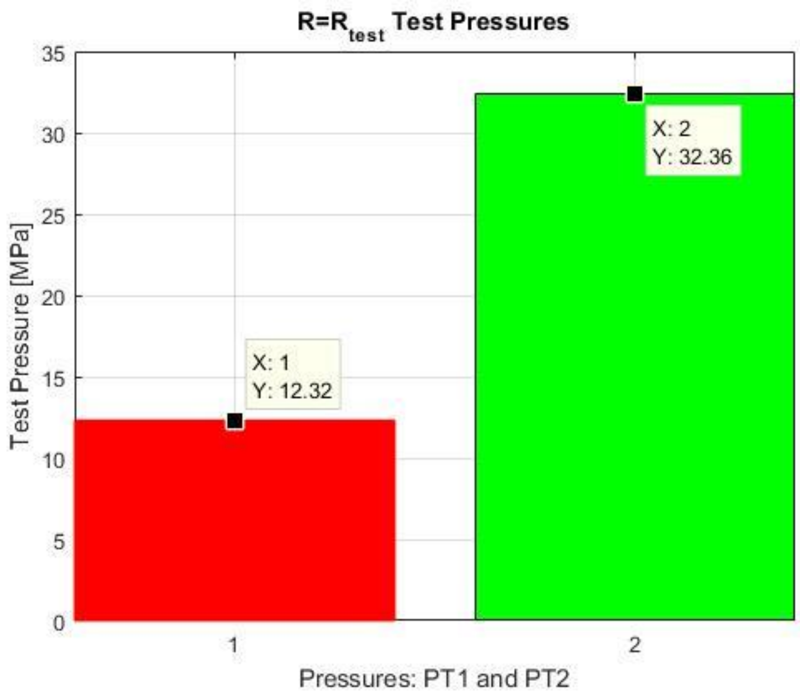


Figure 113 - R=Rtest test pressures PT1 (red) and PT2 (green) [MPa]

The duration of the test is 1000 h. A properly modified Hydrotest Simulation Tool, HST_{Rtest} is adopted to evaluate the relative minimum wall thickness t_{r3}.

5. **Determination of the optimal winding-angle**

Due to the request of the $R = R_{test}$ pressure test, the adoption of the optimal angle for hydrotest condition, which is $\theta° = \pm 55°[deg]$, may result not to be the best choice anymore.
The identification of the optimal angle is performed by means of a combined use of the QT2016, HST and HST_{Rtest}.
This script identifies the value of winding angle $\theta°$ which minimizes the pipe reinforced wall thickness by considering contemporary the 3 constraint tests listed above which evaluate t_{r1}, t_{r2}, and t_{r3}.
The curves for the MPR_{80} validation and the $R = 2{:}1$ survival hydrotest depend on the MPR_{80} value, 9.6 [MPa] and on the $G_{80,GRVE}$ gradient, 0.105.
The curve of the $R = R_{test}$ pressure test depends on the MPR_{80}, on the $G_{80,GRVE}$, 0.105, and strongly on the R_{test} chosen, which directly influences the state of stress.
R_{test} in this case equals to 0.95.

The Figure 114 describes the choosing process of the optimal winding angle.

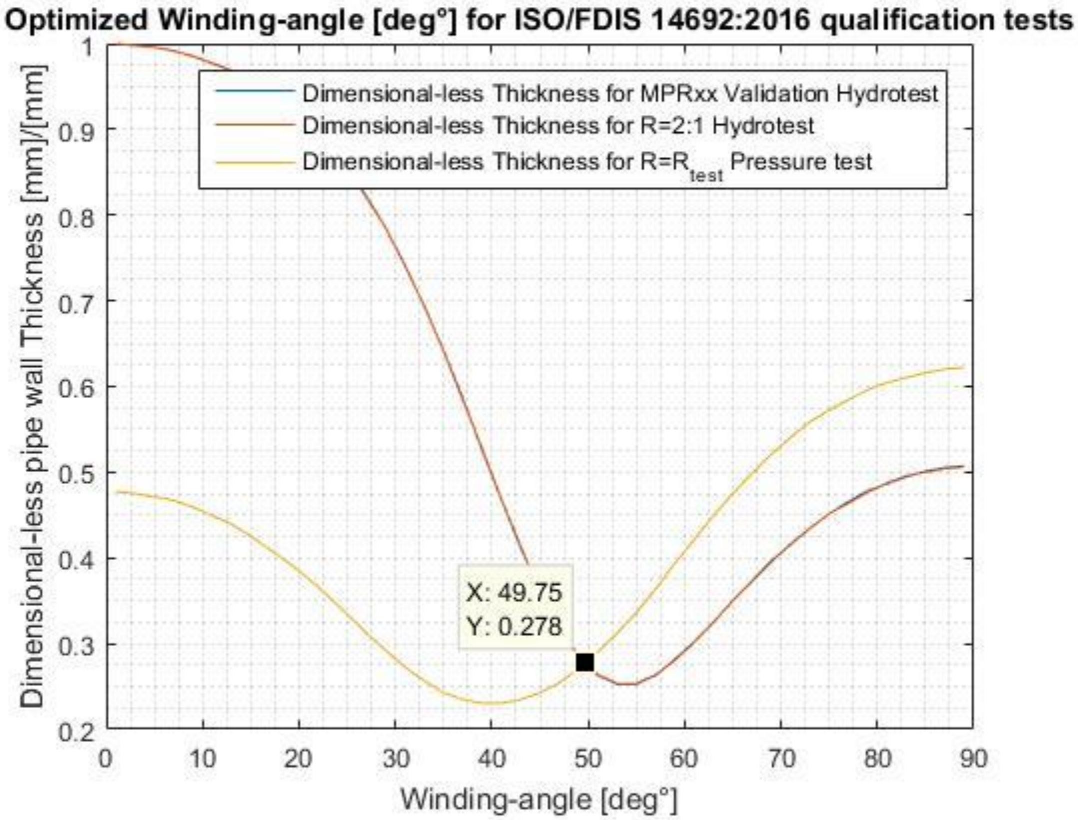


Figure 114 - Choice of the best winding angle for the case of study plain pipe manufacturing process

Knowing that the curves of the hydrotests are parallel, because the same hydrotest is performed at slightly different pressures, the chosen winding angle is the intercept point between 2 of the 3 curves.
The winding angle which minimizes the relative thickness required for all the tests required from ISO/FDIS 14692:2016 results to be in this case $\boldsymbol{\theta° = \pm 49.75°[deg]}$

6. **Results**

Knowing the optimal winding angle it is now possible to perform the simulation of the validation tests.
The QT2016 in addiction to the HST, HST_{Rtest} and APT, stating from the matrix and lamina properties described in chapter 1, gives the following plain pipe wall thickness results.
Because the $R = 2:1$ and the Validation MPR_{80} Simulations are both Hydrotests, the results of the one carried out at the higher pressure, so the MPR_{80} validation, are here reported.
It is expected that choosing of the optimal winding angle, as described, makes equal the pipe wall thickness evaluation coming from the two test simulations, and so $t_{r1} = t_{r3}$. The uncertainty concerning the graphical determination of angle causes a minimum gap between the expected thicknesses, which, however, does not exceed 3.7%[83].

APT based SIM 1 - Design Process in accordance with the ISO/FDIS 14692:2016						
Simulation data			**Analytical Simulations Results**			
Diameter ID_r	400 [mm]		Test	Test Pressures [MPa]	Wall Thickness [mm]	Layers
$\theta°$	49.75°		MPR_{80} val.	25.13	53.2	266
V_f	**0.6**		$R = R_{test}$	12.32 & 32.35	51.2	256
Lamina Model	**APT based**		**Chosen Plain Pipe Wall Thickness**		**53.2**	**266**

Table 53 - Simulation 1 based on APT, Summary

Since there are no expressed limits concerning the maximum pipe wall thickness within the ISO/FDIS 14692:2016, the result is to be considered valid. It is important to remark that Mariotte's equations for the evaluation of the hoop and axial stresses for the pipe wall are valid, from an engineering viewpoint, only under the hypothesis that the pipe wall thickness is equal or less than $\frac{1}{10}$ of the diameter.

In order to consider this engineering limit, and with the aim to reduce the pipe wall thickness under the limit of 40[mm], it is performed the simulation using the optimizing volume fraction for the APT based HST, equal to 0.4 (as previously done in the ISO 14692:2002 case of study).
The results are listed in Table 55.

APT based SIM 2 - Design Process in accordance with the ISO/FDIS 14692:2016						
Simulation data			**Analytical Simulations Results**			
Diameter ID_r	400 [mm]		Test	Test Pressures [MPa]	Wall Thickness [mm]	Layers
$\theta°$	49.75°		MPR_{80} val.	25.13	38.4	192
V_f	**0.4**		$R = R_{test}$	12.32 & 32.35	38	190
Lamina Model	**APT based**		**Chosen Plain Pipe Wall Thickness**		**38.4**	**192**

Table 54 - Simulation 2 based on APT, Summary

[83] This value could be decreased by providing a better calculation of the optimal winding-angle. However, the uncertainty concerning the realization of the plain pipe itself ranges some degrees. So, for this reason, the value as calculated is accepted.

The minimum reinforced wall thickness of the pipe is now under the engineering threshold value of the applicability of the Mariotte's equations. Furthermore, since there are no more limits to the mass fraction as happened for the 1st edition of the standard, the evaluated thickness shall be considered valid.

- **Fem Based Simulations**

The last simulation concerns the adoption of the FEM prevision tool for the lamina property instead of the Analytical one, APT. The simulations are carried out with the volume fraction of 0.6. The results follow:

FEM based SIM 1 - Design Process in accordance with the ISO/FDIS 14692:2016						
Simulation data			**Analytical Simulations Results**			
Diameter ID_r	400 [mm]		Test	Test Pressures [MPa]	Wall Thickness [mm]	Layers
$\theta°$	49.75°		MPR_{80} val.	25.13	27.6	138
V_f	**0.6**		$R = R_{test}$	12.32 & 32.35	26	130
Lamina Model	**FEM based**		**Chosen Plain Pipe Wall Thickness**		**27.6**	**138**

Table 55 - Simulation 1 based on FEM, summary

Even in this case the wall thickness is valid in accordance with the 2nd edition of the standard.

10.2. Conclusions

The reinforced wall thickness of the plain pipe calculated to withstand the demand requests, as in the case of the ISO 14692:2002, is highly dependent on the lamina properties, and so on the prevision models adopted.

Volume Fraction	Lamina Properties	Wall Thickness [mm]	ISO/FDIS 14692:2016
0.6	APT evaluated	53.2	Warning – Mariotte's Limits
0.4	APT evaluated	38.4	In Accordance with ISO/FDIS 2016
0.6	FEM evaluated	27.6	In Accordance with ISO/FDIS 2016

Table 56 - pipe wall thickness for the models considered

Because of the absence of specific manufacturing limits, in line with the concepts of the performance based material requirements explained in paragraph 1.1 PBMS concerning this 2nd edition, all the reinforced wall thicknesses, simulation evaluated, shall be considered valid.

The range between the thicknesses calculated is wide, and it depends on the high variability of the transversal tensile strength among the prevision tools, already investigated in chapter 1, 2 and 5.

The Hydrostatic Simulation Tool is reliable, as the QT2016 for the data processing concerning the ISO/FDIS 14692:2016.
The whole simulation would predict a reliable expected value of the pipe wall thickness, if the lamina properties are known experimentally.

10.2.1. The $R = R_{test}$ Survival Test - Considerations

It has observed that the presence of the $R = R_{test}$ pressure test within the design process in accordance with the ISO/FDIS 14692:2016 imposes an increment of the minimum pipe wall thickness.
This increment reflects the necessity to choose the optimal winding angle starting from the optimal one evaluated for the hydrotest.
Concerning the case of study, the wall thickness is shown to be dependent on all the 3 tests, i.e. the hydrotest for the R=2:1 data point validation, the validation of the MPR_{80} , and the pressure test for the $R = R_{test}$ data point validation.
The curves of these three tests are plotted in Figure 115 which explains the choice of $\pm 49.75°$ [deg] as the total optimal winding-angle.

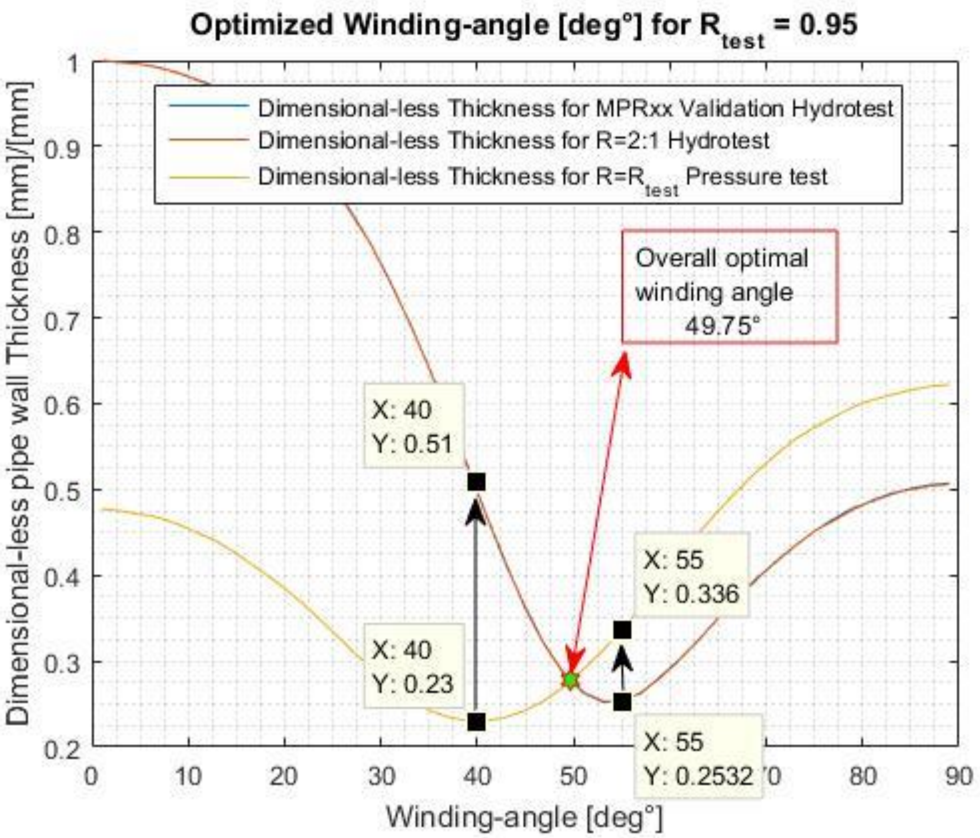


Figure 115 - Choosing procedure for the best overall winding angle within the design process in accordance with ISO/FDIS 14692:2016

Concerning the only hydrotests, the optimal winding angle is known to be $\pm 55°$ [deg]. The relative thickness results to be 0.2532. Since the same pipe must withstand to the $R = R_{test}$ pressure test, this value raises to 0.336.
The $R = R_{test}$ pressure test, for a value of R_{test} equal to 0.95, on the other hand, has a minimum relative thickness of 0.23 at a winding angle of $\pm 40°$. This results to be the smallest value, but the same pipe must withstand also the R=2:1 and MPR_{80} validation hydrotest, whose relative thickness raise the value to 0.51.
The lowest relative thickness which contemporary optimizes both the test types, Hydrotest and $R = R_{test}$, results to be $49.75°$ [deg], at the intersection point with a relative thickness value of 0.278.

The results above extrapolated depend on the value on the R_{test} chosen. The range of the R_{test} goes from 0.5 to 1. Consequently, the curve of the $R = R_{test}$ pressure test relative thickness translates inside the chart.
The following figures show how the curves move between the two range limits and for the chosen value in the case of study of 0.95.

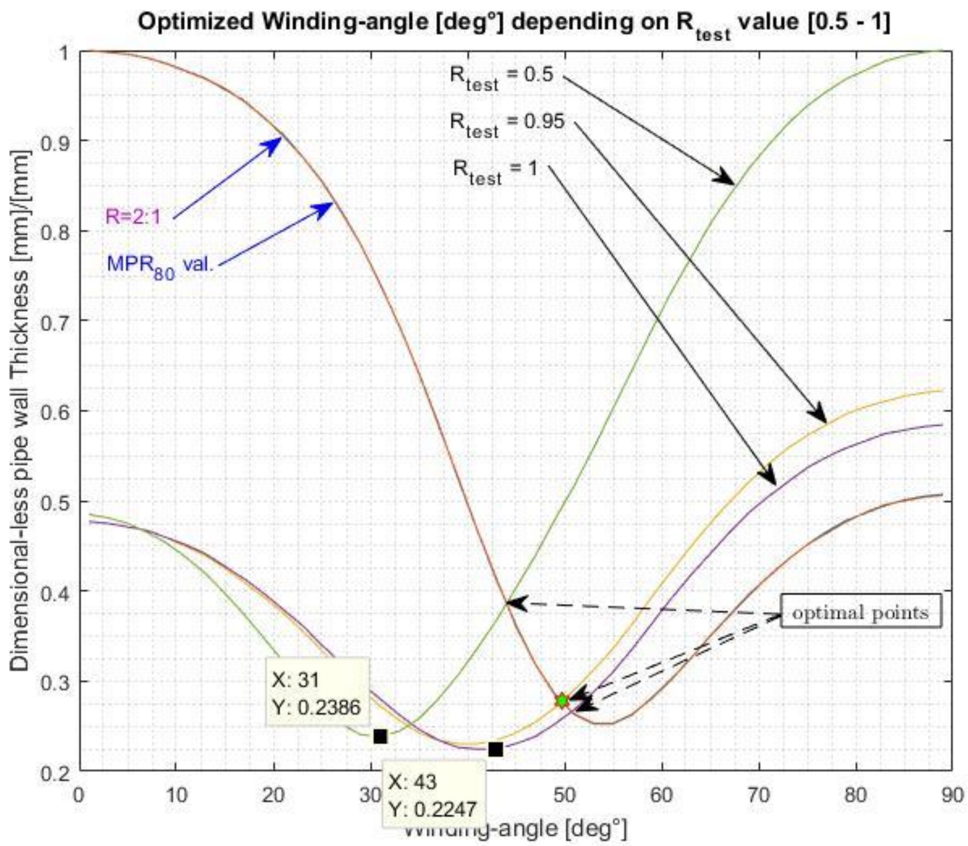


Figure 116 - Variation of the Rtest pressure test relative thickness curve as function of the Rtest chosen

An optimal winding angle of 31°, corresponds to the lowest value of the R_{test}, 0.5, related to the most severe axial loading condition. On the contrary, the least axial loading condition simulated by the pressure test relates to the value of 1 of the R_{test}, and to an optimal winding angle of 43°[deg].

The overall optimal angle range goes from $\pm\mathbf{51}$°**,** for $R_{test} = 1$, to $\pm\mathbf{44}$° for $R_{test} = 0.5$.

This comment follows the results presented in Figure 115 by looking at the optimal points highlighted by the dashed arrows. All these data are obtained by following the already described procedure.

The 2D charts before seen can be implemented into a 3D chart which represents the minimum reinforced pipe wall thickness evaluated considering the 3 mandatory tests concerning the validation of the MPR_{xx} and the $R = 2:1$ and $R = R_{test}$ data points.

The 2 variables are the winding angle and the R_{test}, where the R_{test} value, anyway, is determined during the long-term failure envelope and states of stress comparison.

So, this chart allows the determination of the optimal winding-angle for every R_{test}value and gives a prediction of the minimum pipe wall thickness that permits the qualification of the designed pipe in accordance with the ISO/FDIS 14692:2016.

The designer, after selecting R_{test}, is able to determine the optimal winding angle, and the predicted thickness as described at the beginning of this paragraph.

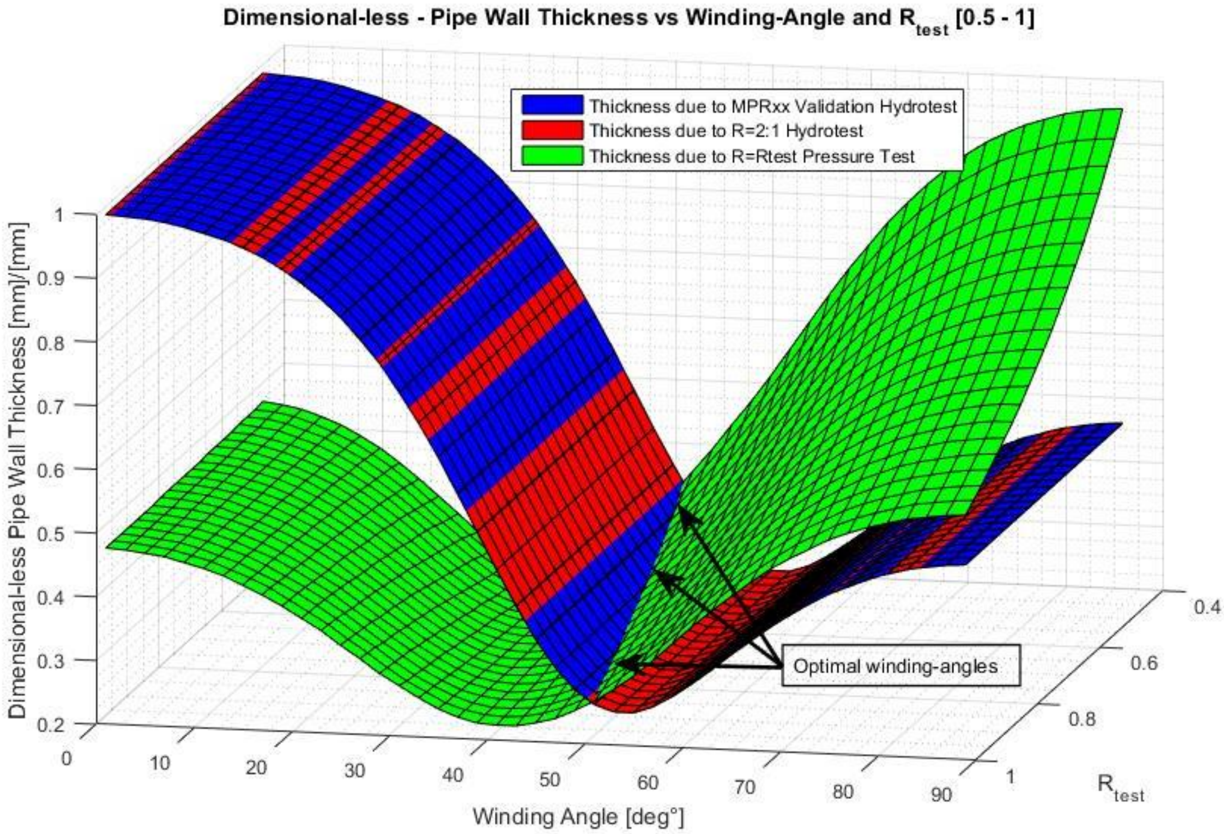


Figure 117 – The minimum wall thickness and the optimal winding angle depending on the 3 validation test described within the ISO/FDIS 14692:2016 and the arbitrary value of the Rtest.

As in the case of the 2D chart, the values generated by the validation hydrotest for the $R = 2{:}1$ data point validation and the hydrotest for the MPR_{xx} validation result to be almost overlapped, because the test is the same and the pressure is almost the same.

Moreover, following these considerations:

- The pressures of the survival tests for the validation of the $R = 2{:}1$ and $R = R_{test}$ data points depend on the MPR_{xx} , R_{test}, and G_{xx}
- The MPR_{xx} does not change the relative position of the curves related to the 3 mandatory tests because have the same dependence on each of them
- The G_{xx} is a default value which does not modify the relative position of the slopes generated by the $R = 2{:}1$ and $R = R_{test}$ mandatory survival tests for the validation of data points

It is possible to declare that the 3D chart evaluated for the case of study is valid for every pipe.
The relative position of the 3 surfaces is not dependent on the MPR_{xx} or on the Size Diameter of the pipe considered, which are the two mains input of the qualification process, and so of the design in accordance with the ISO standard.
Only a slight variation exists between the $R = 2{:}1$ and MPR_{xx} validation test generated surfaces, which depend on the G_{xx}, but it is very limited.

Furthermore, in the real case, where the ASTM D2992 mod. test can be performed, or data of a previous ASTM D2992 mod. are provided[84], the only two surfaces to analyse are the $R = 2:1$ hydrotest and the $R = R_{test}$ pressure test generated.

The presence of the $R = R_{test}$ mandatory survival test represents a news of the ISO/FDIS 14692:2016 and obliges the designer to manufacture a pipeline which shall be able to withstand the axial loads, even if these kinds of loads are not listed in the demand request or are unknown.
If one deems that the presence of these loads is low or limited, due to pipeline path or types of supports, the value of the R_{test} to be chosen as 1. Otherwise, if the presence of these loads is ensured, but limited and not as high to require an increment of the MPR_{xx} too, the chosen value of the R_{test} needs to be 0.5.
This operation, as said, modifies the shape of the Long-term Failure Envelope, and so the design envelopes, incrementing the resistance to axial loads. This can be seen in Figure 118 which represents the variation of the shape of the long-term failure envelope as function of the R_{test}.

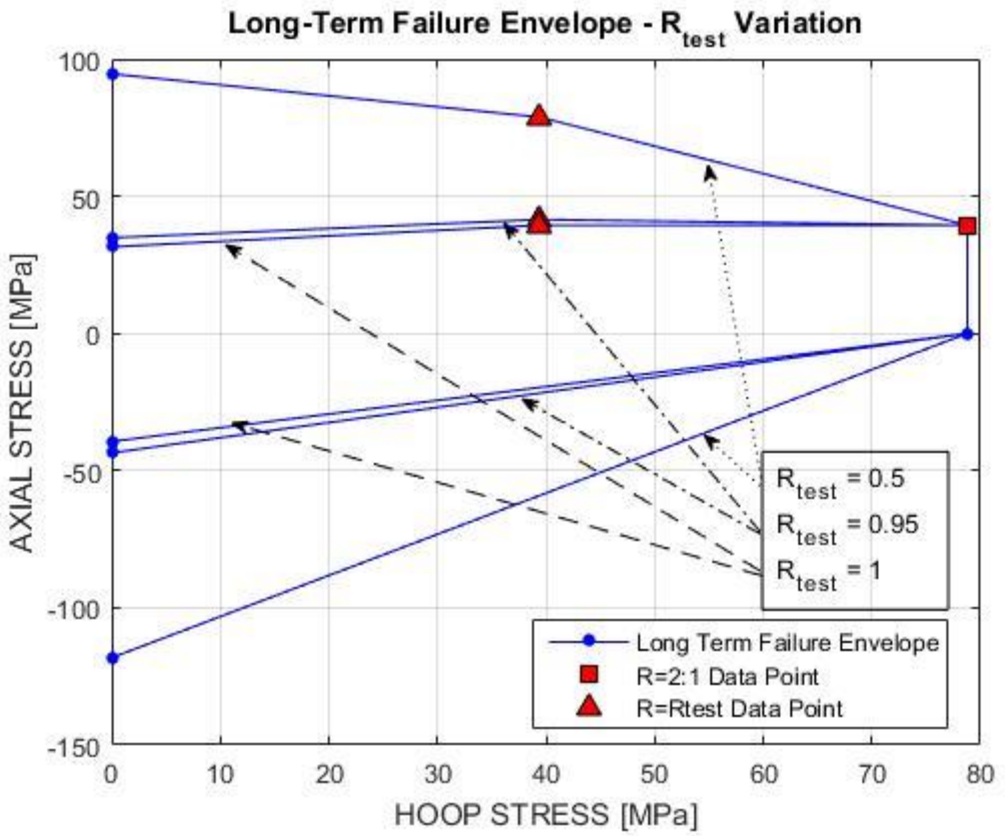


Figure 118 - Variation of the long-term failure envelope depending on the value chosen of the Rtest

[84] Concerning the same laminate

7. Comparison and Conclusions

1. Conclusions

The objective of this work is to investigate the composite adoption as new material for pipelines production in the Oil & Gas industries, where its low weight, high strengths and high resistance to corrosion properties would lead to a maintenance reduction, increment of service life, and so significant benefits in term of costs and safety[85].
The specific application considered in this thesis work deals with high pressure and high temperature pipes.
The experience in manufacturing and use of pipelines is well consolidated and several international standards regulate the sector.
Unfortunately, there are no standard procedures for the design of the composite pipeline.

The scope of this thesis is to reassume the design approaches in literature and to propose a design method aimed to qualify the pipeline in accordance with the ISO 14692:2002 and then with the ISO/FDIS 14692:2016. This is obtained by self-developing Matlab® based analytical tools which could be a valuable help to the designer and regard:

- the prevision of the lamina property, APT
- the simulation of the plain pipe hydrotest, HST
- the determination of the qualification parameters concerning the ISO 14692:2002, QT2002
- the determination of the qualification parameters concerning the ISO/FDIS 14692:2016, QT2016

Moreover, the studies described into the chapters of this work and concerning:

- the materials, matrix and fibre
- the filament-winding process parameters, volume fraction and winding angle
- the optimized design to inner pressure resistance of a plain pipe
- the design in accordance with the qualification process within ISO 14692:2002
- the design in accordance with the ISO/FDIS 14692:2016

lead to the conclusion that the use of composite in pipeline in oil and gas industry is possible and that the regulation authorities are continuously improving the effectiveness of the new versions of the standard basing on producers' experience.

The **Chapter 1 – Composite Materials** investigated the resin and the fibre characteristics. Among the many possible solutions, the requirements of high strength, high resistance to corrosion and temperature lead to the choice of a high-performance epoxy resin filled with E-CR glass fibres.
The choice is also driven by the low cost of these components which makes affordable its use in large scale and for wide pipeline systems. The use of vinyl-ester, which may reach higher performances than epoxies, shall be limited to critical components due to its high costs. On the other hand, the reinforcement fibre shall be exclusively the EC-R glass which is the only fibre able to endure in time when applied into the corrosion environment of crude oil and methane.

[85] Due to the reduction of high critical operation, especially, in off-shore environment.

The expected lamina properties, needed for the design of the composite pipeline, are evaluated by means of analytical models as a function of the volume fraction V_f focusing in the range between 0.3 and 0.6 which is available in filament winding manufacturing of pipes.

Bibliographic sources declare that the reliability of these models, compared to the experimental values, are acceptable concerning the elastic properties and the longitudinal mechanical properties. On the contrary, the experimentally evaluated values of transversal mechanical properties often deviate from the expected values. The expected transversal tensile and the in-plane shear strengths may underestimate the real value up to 100%.

The prevision of these properties is declared to be very difficult and has to take into account random phenomena such as bubbling formation, crack propagations and composite inaccuracy due to manufacturing.
Since the object of this chapter is to produce an Analytic Prevision Tool, APT, for the automated evaluation of lamina properties, and so, with the intention of being a script of comparison between different materials and different volume fractions, the analytical trends of a chosen matrix and fibre have been compared with the trends given by a finite element based prevision tool.

The comparison is performed by means of Autodesk® Helius Composite 2016, a non-editable finite element based tool for the lamina characteristics prevision.
The prevision of the elastic properties is similar for both the methods and the percentage deviations are limited to 1% within the close range 0.3-0.6.
On the contrary, it seems that the finite element software better estimates the transversal and the in-plane shear strengths, resulting in higher values than the analytical models, with deviations up to 100%, and so, theoretically, in line with the same differences reported between analytical expected and experimental values reported in bibliography.
These observations lead to the conclusion that the analytical models are useful as a tool of comparison between different component materials in that step of the design where it is important to identify the most suitable materials for the application. The analytical nature of the model, moreover, permits the automation of all the calculation, allowing the creation of a more complex tool which simulates the manufacturing and the failure assessment of the final composite.

The finite element tool cannot be implemented in this way, even if it seems to be closer to the real behaviours. Furthermore, Autodesk® does not provide any technical information concerning the parameters of the finite model, which results to be a "black box" software, fast and easy to use, but not editable and controllable.
For these reasons, the final design process which determines the performance of the composite must be based upon experimentally evaluated values of elastic and mechanical characteristics.

The **Chapter 2 – Pipe Production Processes** describes the filament winding manufacturing process. The filament winding is the most efficient method to produce plain pipes and, in general, axial-symmetric composites.

This process permits to reach high volume fractions and a fast deposition rate of repetitive fibre patters, such it happens in the case of pipeline. The most significant parameters of this production process are the Volume Fraction V_f and the Winding Angle $\theta°$ [deg].

After investigating the materials and the production process, the **Chapter 3 – Structural Design and Simulation with Composite** explains the general steps and theories for the design with composite materials and applies them to the case of the design of a plain pipe.
The aim is to investigate the behaviour of a plain pipe under inner pressure loading and it is carried out by means of a Hydrostatic Simulation Tool, HST, developed in Matlab®. Basing on the materials of the components previously identified and on the APT for the evaluation of the expected lamina properties, the HST evaluates the dependency of the reinforced pipe wall thickness to the main four independent factors which characterize a pipe: Diameter, Inner Pressure, Volume Fraction, and Winding Angle.

The dependences on Diameter and Pressure are linear. The minimum wall thickness, needed to withstand the inner load, linearly grows with the diameter or pressure increase, as from Mariotte's equations.

The optimal winding angle which minimizes the wall thickness related to an inner pressure loading case is found to be $\pm 55°$ [deg]. Considering the volume fraction, finally, the wall thickness is strictly dependant on the model taken into account: the analytical model minimizes the thickness for a value of 0.4, while the optimal value for finite element model results 0.6.

Furthermore, the properties which influence the most the wall thickness are the transversal tensile strength and the in-plane shear strength of the lamina, which are the least reliable in the prevision models.

The hydrostatic simulation tool has been compared to a numerical simulation performed with Abaqus® 6-14, whose results show a gap around the 3% concerning the wall thickness evaluation.
For these reasons, it is expected that the simulator is reliable in calculating the pipe wall thickness, if it is based on values lamina properties experimentally evaluated.

The production, purchase, use and installation of composite pipeline systems shall be made under international regulations. Among the many analysed, the BS EN ISO 14692 *"Petroleum and natural gas industries – Glass-reinforced plastics (GRP) piping"* turned out to be suitable with respect to the pipeline under analysis. Moreover, it results to be the most complete. Both the active version of the standard ISO 14692:2002 and the final draft of the upcoming 2nd edition ISO/FDIS 14692:2016 have been taken into account, and the relative qualification processes fully analysed concerning the case of a plain pipe. The reviews of the standard are summarized in the **Chapter 5 – The ISO 14692:2002** and the **Chapter 6 – The ISO/FDIS 14692:2016**.

The design procedures aim to identify the minimum pipe reinforced wall thickness which allow to withstand the mandatory requirements of the standard. These requirements consist on experimental tests which differ among the two editions of the ISO 14692, and cause difference on the wall thickness evaluations.
Considering the qualification procedures for the plain pipe several considerations may be done.

The ISO 14692:2002 qualification programme is divided in two processes, the qualified pressure and the qualified stress assessment. It investigates the resistance of the plain pipe more focusing on hydrostatic pressure and temperature variations. In fact, the load types subdivide into occasional, sustained with and without considering thermal loads, when compared with the design envelope within the qualified stress assessment.
Moreover, the only mandatory pressure test is carried out under hydrostatic conditions.

The resistance to axial loading is less investigated. The experimental tensile test of the plain pipe is carried out at ambient pressure and, furthermore, its execution does not represent a real constrain to the design. In addition, the design in accordance with the 1st edition is performed basing on default value of strength ratios, depending on components, which allow to consider the axial test as not constraining to the design.
Following this procedure, the minimum pipe reinforced wall thickness evaluated, considering the case of study, results in **23.6**[86] [mm] with a winding angle of $\pm 55°$, the optimal to resist at hydrostatic pressure conditions.

The analysed case does not consider any axial load in addition to the stress induced by the hydrostatic pressure.

The wall thickness evaluated depends exclusively on the required performance concerning the experimental testing in accordance with the ASTM D2992-b, which mainly consists on hydrotests performed on samples at different pressures up to failure.

The ISO/FDIS 14692:2016 qualification programme differs from the 1st edition and consists in the comparison between the states of stress sustained by the plain pipe, along its entire service lifetime, and the design envelopes based on two experimental tests. The qualification procedure consists on defining a design envelopes which contain all the states of stress points subdivided into the three types: occasional, sustained and sustained with self-limited displacement.
The area of the envelope is linearly dependant on the $MPR_{xx°}$[87] while its shape, and more precisely, its resistance to the axial loading depends on the R_{test} which vary from 0.5 to 1.
The choice of these two parameters within the design in accordance with the ISO/FDIS 14692:2016 determines the pressure and the loading conditions of the experimental, survival, tests whose overcoming validate the design envelopes, and so, the pipe.

This approach assures the resistance of the pipeline to the axial loads more than the 1st edition. While the experimental hydrotest, performed at R[88] $= 2:1$ conditions, assures the resistance of the pipeline to the inner pressure, the $R = R_{test}$ is carried out at an inner pressure halved and at an axial stress more than doubled with respect to the hydrotest.
This assures that the pipe can withstand the axial stress. Moreover, the mandatory nature of the tests, obliges the designer to design a pipe which is able to resist to axial stresses even if these are not explicitly considered or known.

[86] Calculated using the FEM Helius for the prevision of the lamina properties at a volume fraction on 0.6.
[87] Maximum Pressure Rating evaluated at xx° temperature. It represents the maximum pressure which can be sustained by the pipeline, continuously, without failure.
[88] R represents the loading condition within a pipe wall, and it is defined as the ratio between the hoop stress and the axial stress. The hydrotest, so, is carried out at R=2:1 loading conditions.

This is the situation of the case of study, where the only known load is the inner pressure.
The choices of the values of $R_{test} = 0.95$ and $MPR_{80°} = 9.6$ [MPa] lead to a pipe reinforced wall thickness of **27.6** [mm][89]. The winding angle is no more optimized for hydrostatic condition.
It is calculated considering both the survival tests, and the value which minimize the minimum pipe wall thickness resulted to be $\pm 49.5°$. This value is strictly dependant on the value of the chosen R_{test}.

The 2nd edition, which focuses more on axial loads, enforces an increment of 4 [mm] to the pipe wall thickness of the case of study which correspond to the 17%.
Similar increments between the two editions have been found investigating other volume fractions and calculating the expected lamina properties by means of the analytical models.

Furthermore, the winding angle change from $\pm 55°$ of the 1st ed. to the $\pm 49.5°$ of the 2nd.
The fact that the winding angle has to be optimized considering two loading conditions and not only the hydrostatic one, as happened in ISO 14692:2002, has been investigated.

While the optimal angle concerning the hydrostatic loading condition is $\pm 55°$**,** the optimal value concerning the $R = R_{test}$ varies depending on the chosen value for the R_{test}.
Lower the R_{test}, lower the angle, and higher the resistance of the pipeline to the increments of axial stress induced. So, the optimal angle for the $R = R_{test}$ goes from $\pm 31°$ to $\pm 43°$ corresponding to R_{test} of 0.5 and 1.
The trade-off, which considers both the tests, identifies the overall optimal winding angle as $\pm \mathbf{51}°$**,** for $R_{test} = 1$, and $\pm \mathbf{44}°$ for $R_{test} = 0.5$.

Since the $MPR_{xx°}$ and the diameter of the pipe influence in the same way the evaluation of the pipe wall thickness, incrementing linearly the value, the considerations concerning the overall optimal winding angle range can be extended to all the sizes and pressures. This means that, within the ISO/FDIS 14692:2016, the winding angle becomes a parameter which depends on the R_{test}.
So, the designer defines the R_{test} and can directly calculate the optimal winding angle of the plain pipe, focusing on the optimization of the performance of the pipe which depends on the volume fraction and on the materials.

In conclusion, the ISO/FDIS 14692:2016 "replace and cancels" the 1st edition of the standard, filling the gap concerning the important rule of axial loads. The tests are carried out at the design temperature, and the presence of the hydrotest and the $R = R_{test}$ test contribute to limit the composite weaknesses concerning its anisotropic behaviour and the design process, which is not as linear as in the case of the design with steel.

[89] The lamina properties are evaluated with FEM and the volume fraction is 0.6, so the same condition of the calculation in accordance with 1st edition of the standard.

2. Future Works

The presented investigation covered all the steps concerning the design of composite pipeline for Oil & Gas application. Future works may be proposed focusing on single aspect of the design path.

The design of the plain pipe has been processed by assuming that the disposition of fibre is executed with the same angle. The investigation on variable pattern may provide more efficient solution for the plain pipe loading case.

The ISO/FDIS does not represent officially the 2nd edition of the ISO 14692. A future work would be the check of the final draft with the published standard.

The design in accordance with the standard ISO 14692 has been fully developed only considering the plain pipe. Since a pipeline system is formed also by other components, the design of flanges, fitting, tees, and elbows should be investigated.

The scripts developed in this work, that matter more than 17000 lines of code, would be reassumed into a standalone software which could represent a valuable help the pipeline systems designer.

8. Disclaimer

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Furthermore, this document is intended to be read ONLY in conjunction with the international standards and DO NOT substitute in any way the standards, which remain the only regulation documents.
ALL RESPONSIBILITIES ARE DECLINED.

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10. Appendix

1. Flowchart from the ISO/FDIS 14692:2016

ISO/FDIS 14692-1:2013(E)

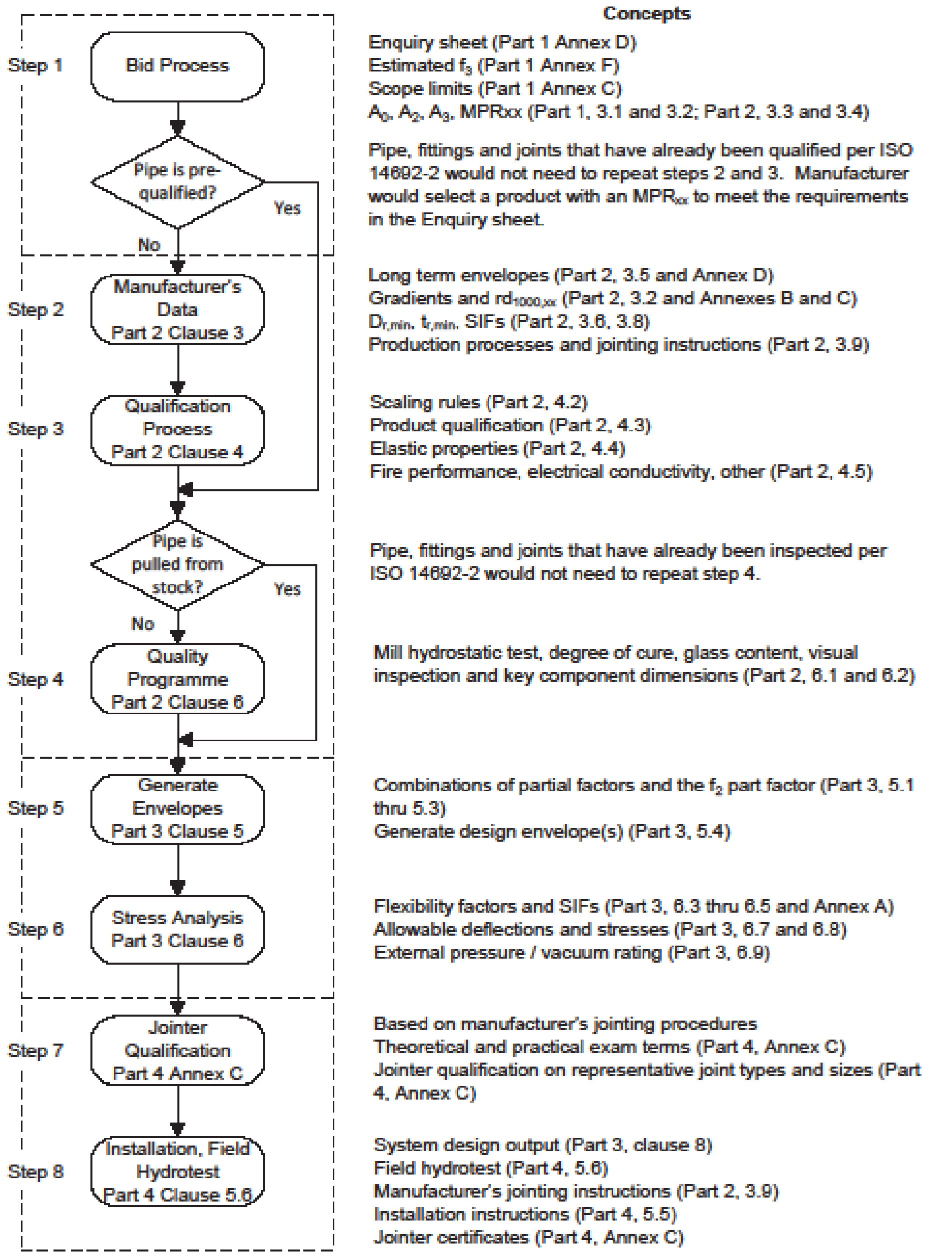


Figure 1 – Guidance on the use of ISO 14692 (all parts)

vi

Step 1: The Bid Process. Here, the principal completes an enquiry sheet (refer to Annex D) that defines the design pressures and temperatures of the piping system as well as the application, required pipe sizes and required components (bends, tees, reducers, flanges, etc.). The principal also verifies that the scope of the application is within the limits of ISO 14692 (refer to Annex C). The principal and manufacturer shall also come to an agreement on the value of the estimated value of the part factor $f_{3,est}$ (refer to Annex F).

In some cases, the manufacturer may wish to offer a product that 1) meets or exceeds the requirements in the Enquiry sheet and 2) has already been manufactured, qualified and inspected per ISO 14692-2. In this case, steps 2 thru 4 would not need to be repeated.

Step 2: Manufacturer's Data. Recognizing that long term regression testing can easily take 2 or more years to complete, the manufacturer will most likely have already selected target values for MPR_{xx}, the long term envelope(s) and the minimum reinforced wall thicknesses. The manufacturer shall determine the appropriate gradient and $rd_{1\,000,xx}$ can then be calculated to suit the survival test duration. Additional basic data such as pipe sizes, wall thicknesses, SIFs, production processes and jointing instructions shall also be provided.

Step 3: Qualification Process. Here, the manufacturer conducts survival tests to qualify the pressure and temperature. If applicable, the manufacturer shall also qualify fire performance and electrical conductivity properties. Elastic properties, potable water certification, impact and low temperature performance are also addressed in this step. Just as with Step 2, the manufacturer may have already completed part or all of the qualification process prior to Step 1, the bid process.

Step 4: Quality Programme. Step 4 defines the basic requirements for the manufacturer's quality management system.

Step 5: Generate Envelopes. Step 5 is the first major step in ISO 14692-3. Here, partial factors and part factors are identified and combinations of these factors are determined. Formulae are then provided to calculate the design envelope(s).

Step 6: Stress Analysis. Step 6 identifies the flexibility factors and SIFs to be used in the stress analysis. It also defines the allowable values for vertical deflection, stresses and buckling. An analytical formula for external pressure is provided.

Step 7: Bonder Qualification. Step 7 is the first major step in ISO 14692-4 where the bonder qualification process is defined.

Step 8: Installation, Field Hydrotest. Step 8 is the last major step where installation issues are addressed.

2. Auxiliary Standards

Because of the ISO 14692 is a huge international standard, it recalls many other standards such as ASME and ASTM, mostly regarding the measurements of the raw materials characteristics, composite performances, and the testing.
Some significant for the comprehension of ISO 14692 are reported as a brief description.

2.1. ASTM D 1598 - 15a
Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure

This test method covers the determination of the time-to-failure of composite pipe under constant internal pressure. Standard D2992 recalls D1598 as the base test method.
"The data obtained by this method are useful for establishing stress versus failure time relationships in a controlled environment from which the hydrostatic design basis for plastic pipe materials can be computed. (refer to Test method D2837 and Practice D2992)" Cit. [22].
Procedure consists on attach pressurizing system to the unrestrained closed-ends pipe and fill each specimen completely with the test fluid conditioned to the test temperature. It's very important that the test temperature is stabilized before beginning of the test.
The pressure is then increased in small incremental steps until the required is reached. This can take quite some time as well i.e. a few MPa for 1 hour. Then the pressure is maintained within ±2% of test value and the test temperature within ±2%.

2.2. ASTM D 1599 - 14$^{\varepsilon 1}$

Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings

This test method covers the determination of the resistance of reinforced resin pipe, tubing, or fittings to hydraulic pressure in a short time period.
The test consists of loading a specimen up to failure which may occurs between 60 and 70 seconds from the beginning of the test.
The test is carried out in a controlled-temperature environment.
The samples are unrestrained, closed end pressure vessels.
Failure time range is sometimes difficult to achieve due to various practical reasons: size specimen, pump, and uncertainties at what pressure the specimen will ultimately fail. "Mostly this requirement has been replaced by failure shall occur at greater than 60 seconds." Cit. [15].

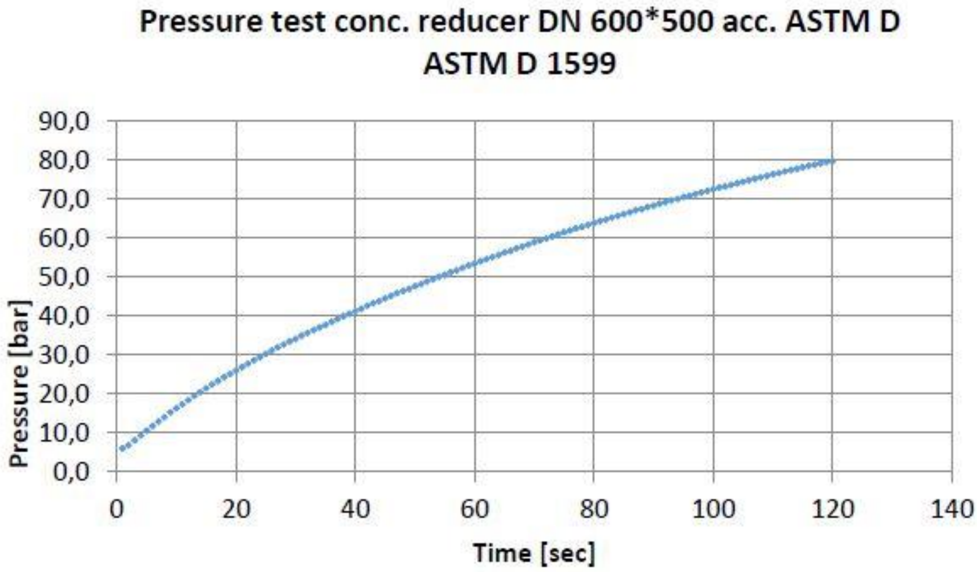


*Figure 119 -: Hydro test: Concentric Reducer 600*500 mm according to ASTM D 1599, Report Fiberdur November 2010 nr. 2 (witnessed by DNV GL).*

The ASTM D 1599 gives the value of the short-term hydrotest pressure P_{STHP}, which is the failure pressure.

Concerning the application of this standard within the ISO 14692:2002, the P_{STHP} is determined using either of the following two methods:

a) by testing five replicate samples in accordance with ASTM D1599. The P_{STHP} of the representative product shall be taken as the lower deviated (two standard deviations) value of the five replicate samples;
b) by taking 85 % of the lower of two replicate samples tested in accordance with the test procedures give in ASTM D1599.

2.3. ASTM D2992-12
Standard Practice for Obtaining Hydrostatic of Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting -Resin) Pipe and Fittings – procedure B

The scope of this standard is "to establish two procedures, Procedure A (cyclic) and Procedure B (static), for obtaining a Hydrostatic Design Basis (HDB) or a Pressure Design Basis (PDB) for fiberglass piping products, by evaluating strength-regression data derived from testing pipe or fittings, or both, of the same materials and construction, either separately or in assemblies." Cit. [21]

The test consists of at least 18 samples. The samples are plain pipe with a closed-ends which may be restrained or not and the test setup is a pressure vessel.

The samples are subjected to a different pressure and held at constant pressure until failure.

The pressure test medium is usually water.

The ISO 14692 in both editions asks to perform the Procedure B with unrestrained ends, so the stress in the pipe wall is biaxial (2:1 hoop:axial) and according with the test method ASTM D 1598 with some exceptions.

After the pipes are pressurized the time to failure is recorded. Because of a certain number of failures may occur in a specified time ranges, the loading pressures may be properly chosen.

Hours to failure [h]	Failure point
10 to 1000	at least 4
1000 to 6000	at least 3
After 6000	at least 3
After 10'000	at least 1
Total	at least 18

So, the test duration is about 10'000 hours. The temperature of the tests must be at least 65°C or equal to the design temperature if higher.

The pipes pressure data are plotted in log stress – log time graph where the linear regression line can be calculated (slope and intercept).

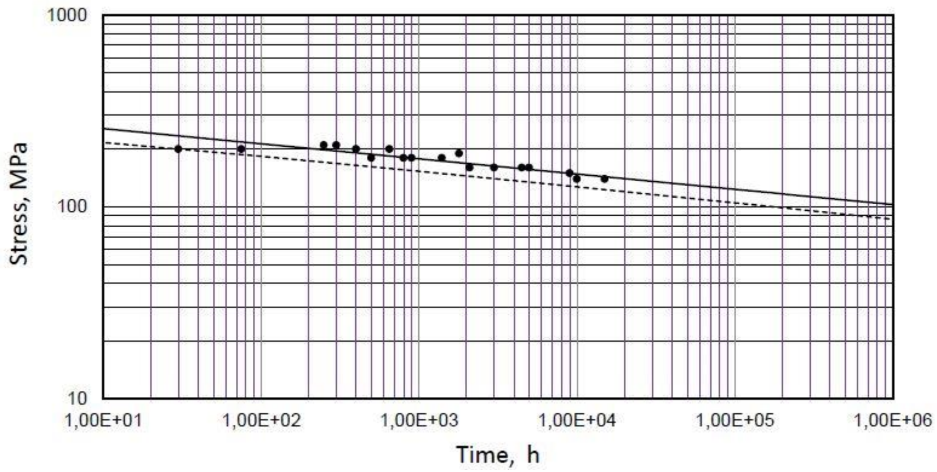


Figure 120 - Typical linear regression line

The dotted line in Figure 120 is based on the lower confidence limit of 95% (LCL). This line is calculated according to ASTM D2992 with t-student statistics and gives an idea of the data scatter by mean of the f_1 scatter factor.
A least square fit calculates the regression line formula:

$$\log(Pressure) = A - G\log(time)$$

Where G is the gradient which define the slope and A is the intercept.

"This equation means that the degradation of the material between 1 hour and 10 hours is the same as between 10 and 1000h or 10 years and 100years!" cit. [15].
The regression technique may be applied only if all the samples fail in a similar way and if the relationship between logarithm of stress and the logarithm of time is reproducible and linear.

As reported into appendix X1.1, the standard allows the use of hoop stress instead of pressure as a more convenient parameter to plot when attempting to predict long-term hydrostatic strength of a material. Its use reduces scatter in the data by compensating for varying dimension in the test specimens.
Substitution is made by mean of Mariotte's equation, where the wall thickness may be the measured one after the failure.

$$\sigma_{hp} = \frac{pD}{2t_{r,meas}}$$

where
p: pressure [MPa]
D: pipe diameter [mm]
$t_{r,meas}$: measured reinforced pipe wall thickness [mm]

2.4. ASTM D 2105 – 01 (Reapproved 2014) Longitudinal Tensile Properties of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube

"This test method covers the determination of the comparative longitudinal tensile properties of fiberglass pipe when tested under defined conditions of pre-treatment, temperature, and testing machine speed." cit. [24]. The method is generally limited to pipe diameter of 150 [mm] or smaller; larger diameter may be tested if the required apparatus is available.
The test consists on placing the specimen in the grips of the testing machine and perform a traction test with a constant velocity of separation of grips.
The test ends with the failure of the specimen.
Records of loads and corresponding deformations are made.
At least five specimens shall be tested for each sample.
This test allows the evaluation of the tensile strength, percentage elongation, and elastic modulus.

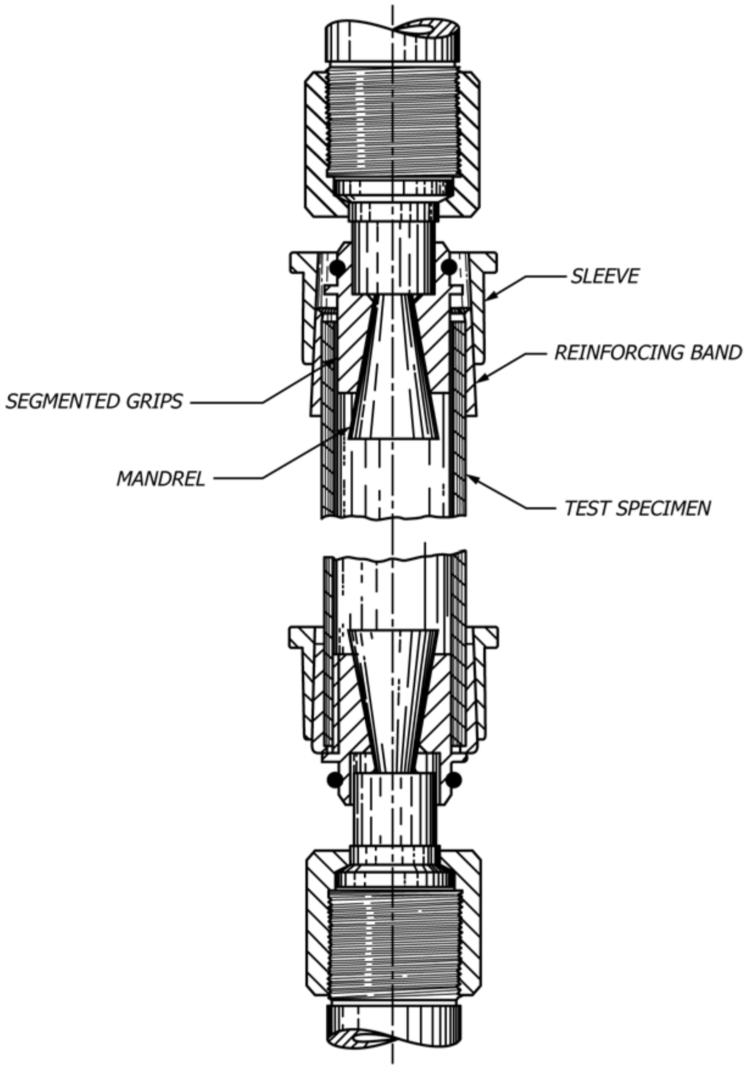


Figure 121 - Suggested Holding Device for Tension Test Specimen-ASTM D2105

GRP PRESSURED PIPELINE STANDARDS COMPARISON - LIMITATION - SPECIFICATION - DESIGN CRITERIA - CONSTRUCTION and INSTALLATION

PIPELINE STANDARD COMPARISON - 1		**EN ISO 14692:2002** GRP piping system design		**API 15 HR** High pressure fiberglass line pipe - 4th edition		**ASTM 2996 -** Specification for Filament Wound Fiberglass (Glass fiber reinforced thermosetting Resing) Pipe	
		Design and Qualification Standard		**Qualification Standard**		**Qualification Standard**	
		Complete Design and qualification standard. It provides calculation about how to design piping systems and then a series of verifications and tests aimed to qualify the producted pipeline.		Api is a Technical Content that provides requirements for performance, design, materials, tests and inspection, marking, handling, storing and shipping - This specification provides a guide about how to qualify piping systems		6 total pag - Specification in which are present classification system, methods of testing, requirements for materials, mechanical properties, dimensions, performance and making - This Specification does not provide any specific design method and fix classes for filament-wound reinforced and then, tests to qualify piping systems	
		Data	**References**	**Data**	**References**	**Data**	**References**
LIMITS	Jurisdiction of Regulatory Authority	UE	-	American Petroleum Industries	-	ASTM international standards	-
	Jurisdiction of Standard	pipeline systems	part1sec7	Limited to mechanical connections - High pressure line pipe and couplings. Fittings. Flanges. Reducers and adapters.	1.1.1 - 1.2.1	ONLY for RTRP machine made reinforced thermosetting resin pressure pipe	-
	Exclusions and Limitations	valve systems	part1sec7	-	-	-	-
	--- MATERIALS ---						
	Composite Matrix / Mechanical Resin	Thermoset	part2sec5.3	Thermoset	-	-	-
	Resin's glass Transition Termperature	above 95°C	part2sec5.3	-	-	-	-
	Liner	Thermoplastic Not Allowed	part1sec6note4 - part2sec5.3 IMP	nothing listed	-	-	-
	Fiber type	Glass or other	part2sec5.2note1-2	Glass Fiber (filament Winding) NO reference Listed	1.1	-	-
	Fibre Class Content	70-82% mass*	part2sec8.3.6 TAB	-	-	-	-
	External Coating	Permitted	part2sec5.3		-	-	-
	--- SERVICE CONDITIONS---						
	Temperature	max [150°-70°C] min [-35°C]*	part1sec6 - min lower F(ResinType)	65.5° but Higher temperature rating is possible if tested	1.2.2-5.1.1	-	-
	Standard qualification temperature	65°C	part2sec5.3	65.5°C	1,2,2	-	-
	Pressure range	Variable - Pmax=F(diam) - expected max 35 MPa at 508mm Diameter	part1sec7sec8 - part3sec7.11	MPa 3,45 - 34,5	1,1,1-4.2	-	-
	Definition of Design Pressure	Delta Pressure (int-ext)	part1sec2.2.18 - part1sec8 - part2sec6.1	Absolute Pressure	-	-	-
	Wall Thickness	Sp/D =< 0,1 - Sp>5mm	part1sec7 - part2sec5.5 IMP	Sp min = F(diameter)		D_out/Sp > 10:1	1note2
	Diameter range	nominal diameter shall be choosen ISO 7370:1983	part2sec7	-	5.2-5.3 Threared connections	up to 60"	1scope
	Joints	Described	Annex	-	-	-	-
	Joints Types	Adesive - Mechanical -Threaded	part1sec5.4 - part4sec5.5.6 - part4AnnexC construction guide	-	-	-	-
	Joints Lengths	Variable	part2sec7.3	-	-	-	-
	Design service life	20 years default - variable	part2sec6.2.7	20 years	1,2,2	-	-
	Fluid enviroment	-		salt water	1,2,2	-	-
	Fluid processed	Oil & Gas	part1	-	-	-	-
QUALIFICATION PROGRAM	Qualification Procedure	part2ANNEXes - part2sec6 - part2sec6.2.2TAB		-	-	D2996 qualificate pipe thougth tests method	scope
	quality program for manufacture	part2sec8…		-	-	-	-
	static internal pressure	V	part2sec6.1	-	-	V	APPENDIX
	elevated temperature	V	part2sec6.1	-	-	-	-
	chemical resitance	V	part2sec6.1	-	-	-	-
	electrostatic performance	V	part2sec6.1 - part2sec6.6	-	-	-	-
	fire resistance perfonance	V	part2sec6.1 - part2sec6.5	-	-	-	-
	impact	V	part2sec6.1	-	-	-	-
	low temperature	V	part2sec6.1	-	-	-	-
	limited cyclic pressure performance / FATIGUE	V	part2sec6.1	-	-	V	APPENDIX

PIPELINE STANDARD COMPARISON - 2		**EN ISO 14692** GRP piping system design		**API 15 HR** High pressure fiberglass line pipe - 3rd edition		**ASTM 2996 -** Specification for Filament Wound Fiberglass (Glass fiber reinforced thermosetting Resing) Pipe	
DESIGN CRITERIA	MAIN DESIGN GUIDE	part3 - ANNEXes are a guide to design		There is no Design Guide		basis design D2310 - D2992	4.1.4
	Hydraulic Design	V	part3sec6.1 + ANNEXes IMP	ASTM 2992 proceure B	6.1.1	-	-
	fluid mean velocity continuos service	[1 - 5 m/s] - max peaks 10 m/s	part3sec6.3	-	-	-	-
	erosion	V	part3sec6.4.2 - DNV RP 0501	-	-	-	-
	adesive beads limits	V	part6sec6.4.3 - part4	-	-	-	-
	Structural Design	V	part3sec7 - part3sec7.8-.9-.10-.11 - part3sec7NOTE IMP	-	-	-	-
	fatigue and cyclic loading	for cycling loads more than 7000/life	part3sec7.4.4	-	-	-	-
	Loads details	SEE TAB loads legenda	part3sec7.6.2.2 TAB	-	1,2,2	-	-
	external pressure / Vacuum	ETA [1.5-3.0] for pipe and fittings	part3sec7.6.3	-	-	-	-
	displacements	deflection (less than 12.5mm or 0.5%span length/supports) + ovalization max 5%	part3sec7.7	-	-	-	-
	stress analysis guide	manual and/or FEM	evaluation of all design parameters: part3sec8...	-	-	-	-
	Fire endurance	V	part3 + Annex	-	-	-	-
	spread of fire	V	part3 + Annex	-	-	-	-
	Electrostatic disharge emission and control	V	part3 + Annex	-	-	-	-
	Dynamic FEM analysis	-	-	-	-	-	-
CONSTRUCTION AND INSTALLATION	**Main guide**	part4		-	-	-	-
	tolerances	TAB	part4sec5.5.4.3	-	-	-	-
	on site fittings fabrication	allowed and tested	part4sec5.5.5	-	-	-	-
	system testing data	V	part4sec5.6	-	-	-	-
	system inspection guide	V	part4sec5.7	-	-	-	-
	Defects	API Spec 5B	part4AnnexA	-	-	-	-
TIPS		Good Annexes Guides	design guide, joints construction and installing guide	Use API 5B Specification for Threading, Gauging, and Thread Inspection of Casing,Tubing, and Line Pipe Threads (U. S. Customary Units).		includes: classification system and requirements for materials, mechanical properties, dimensions, performance, methods of test, and making. - this standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.	
The unique Design guide found is into ISO 14692. All others are a qualification standards which adopt prototype testing, so procedure may be Design with ISO and then qualified with the Standard indentified							

GRP PRESSURE VESSELS STANDARDS COMPARISON - LIMITATION - SPECIFICATION - DESIGN CRITERIA

june 2017

VESSELS STANDARD COMPARISON	**BS EN 13923** Filament wound FRP pressure Vessel (2005)		**BS EN 13121** GRP tanks and Vessel (2016)		**PED** (2014)		**ASME X** Fiber-Reinforced Pressure Vessel (2015)	
	This EN is specific for Filament-Wound FRP vessels and totally refers to BS EN 13121. It amplify the range of application of EN 13121 in the pressure area from 1 to 20 Mpa (HP Vessels). Two Design methods are presentented, including acceptance tests to run in order to qualify each vessel.		EN basis standard. Describe Raw material's requirements, Chemical specifications, Design procedures and Workmanship of LP Vessels. This standard has an huge Design guide and methods of test section which provide non mandatory standards in calculation processes. BS EN 13923 considers also PED's tests as a part of the qualification procedure.		PED is a political standard which aims to regulate fabrication, special requirements, conformity assessment and commerce of pressure vessels whithin the UE. Each new vessel made* in UE or commercialized under UE jurisdiction must comply with this standard. This standard is general and not specific for GRP vessels		ASME Section X is the American Standard for Design, fabrication, material requirements, qualification and testing specific for GRP pressure vessels. Classification divide vessels in 3 types (classes). For each there's a huge guide that covers both specific Design and Testing procedures. ASME X provide also guides for design of personell accesses, supports..etc	
	Data	**References**	**Data**	**References**	**Data**	**References**	**Data**	**References**
Jurisdiction of regulatory authority	CEN	-	CEN	part1	UE - pructed into UE or used, imported by third parts	intro-(4)	ASME	-
Jurisdiction of Standard	Multi-directional filament winding GRP vessels for storage and processing fluids	1scope	GRP vessels	-	"attrezzatura a pressione"	intro-(13)	Vessel and integral communicating points	RG-120
Type of Use	Above the Ground	-	Above the Ground	part1scope	General Use	Articolo4	General Use	RG-120
Exclusion and Limitation	tanks and vessels for the transport of fluids	-	tanks and vessels for the transport of fluids	part3scope	Sistemi Oil&Gas connessi ai pozzi - ..unità mobili off-shore, Attrezzature destinate a bordo di questi veicoli	Articolo1Ambito di applicazione: i) - n)	Processing of Lethal Fluids	3.5.4 - RG-114 - RG-121
	--- VESSEL'S MATERIALS ---							
Type of Composite Resin	Thermoset	6.2.2	Thermoset	part1sec4 TAB	-	-	Thermoset: Polyester - VinylEster - Epoxy - Phenolic - Furan	RM-121
Presence of Additives / Pigments into Resin	Pigments allowed ONLY with Design Method A	6.2.4	Allowed	check part1sec7	-	-	-	-
Internal Liner	Allowed	EN BS 13121	Allowed	part1scope	-	-	Allowed - non loading-shearing liners-	RD-120
Liner's Material	all EN 13121 plus	6.2.3	Thermoplastic - PVC-U; PP-H,B,R; PVDF; E-CTFE; FEP; PFA	part1sec8 - TAB part1sec8	-	-	Metallic / Non Metallic - comply with ASTM D4097	RD-101
Metallic Parts	-	-	-	-	-	-	For Class 1 Vessels : parts must comply with ASME 8 div.1 - hydrostatic leakage	RM-211
Reinforcing materials	Fibers in 6.2.1 in accordance with A.3 BS EN 13121-2	6.3 - BS EN 13121	Glass Type - E; E-CR; AR; A; C	part1sec6 TAB	-	-	Glass Type - A; E; S; E-CR; C for bonding surface treated* - Carbon Type…	RM-100 - RM-111
Fiber Supply - Chopped stand mat	In Structural Laminate are ONLY allowed Continous Roving, in accordance with 6.6 and 9.11 BS EN 13121-1	6.2.1 - BS EN 13121	cut length [25-50mm] with mass/unit area [225-600g/mq]	part1sec6.4-ISO 2559	-	-	-	-
Fiber Supply - Continuous strand mat			mass/unit area [225-600g/mq]	part1sec6.4-ISO 2559	-	-	-	-
Fiber Supply - Woven fabrics			mass/unit area [240-1200g/mq]	part1sec6.5-ISO 2113	-	-	-	-
	--- DESIGN ---							
General	-	1scope	-	SCOPE - ANNEX G	-	-	Class 1 Vessels	RG-120 - RG-404
Design Temperature	[120°C -30°C]	1scope	[120°C -40°C]	part3Intro	-	-	Class 1: [120°C -54°C]	3.4
Design Pressure	max [20 Mpa]	1scope	max [1 MPa]	part3scope	min [0,5] Bar - max F(bar*Volume)	Articolo 4	Class 1 Filament-wound Vessels [max 10 MPa] - with polar boss openings [max 20 MPa]	3.1 - RG-111
Qualification througth Prototype's Testing	Method A YES - Method B NO*	7.1	-	-	-	-	YES - (d) no mandatory equations for the design of Class I vessels. mandatory rules for testing the prototype vessel thus constructed, as set forth in RD-311 or RD-312. - Fabr. prove that the design withstand the specifications througth Prototypes	RG-321.1 - RD300 - Article RD-1 General
Design Guide	Standard presents 2 Methods: Methods A and Method B, both based on calulations and design principles	7.1	Introduction	part3Introduction	-	-	design calculation in Nonmandatory Appendix AA - Requirements for filament winding procedure qualification RQ-4	RG-100scope - RD-120 - **RG-321.1 - Article RQ-4 - Article RD-1**
Types of loads	same as BS EN 13121	BS EN 13121	See Index	part3sec9	-	-	See Index	RD-120
Pressure	V	part3sec9.5.2	V	part3sec9.5.2	-	-	V	RD-120
External loads	V	part3sec9.2	V	part3sec9.2	-	-	V	RD-120
Various loads	Snow - Wind - Seismic - Insulation - connection's - Pressure due to inadeguate venting - Personel loading - Thermal stress	9.2.1 to 9.2.9	Snow - Wind - Seismic - Insulation - connection's - Pressure due to inadeguate venting - Personel loading - Thermal stress	9.2.1	-	-	Snow - Wind - Seismic - Insulation - connection's - Pressure due to inadeguate venting - Personel loading - Thermal stress	RD-120
Agitation	V	9.2.6	V	9.2.6	-	-	-	-
Impact Loads	-	-	-	-	-	-	V	RD-120
Degradation Design	-	-	-	-	-	-	V	RD-140
Fatigue	V	cyclic loads	V	cyclic loads	-	-	V	cyclic loads
### TIPS ###	Hydrostatic pressure test must be perfomed: check test stipulated in PED for vessel under 2°,3°,4° category (our should be 4th category) - 12.3		Guides for the design of personel accesses, supports…etc are based on max 1 Mpa.				Elliptical ends are suggested with ellipse ratio not greather than 2:1 - Quick Actuating Closures Allowed - Access and Inspection Openings design guides provided. - 3.2 - Article RD-8; RD-10	

Flowchart A 2002 – Design Procedure in accordance with the Qualification Process of ISO 14692:2002

- Specific for PLAIN PIPE - More ISO14692-3:2002 for other parts

8.2.1 General

The designer shall evaluate the total piping system, inclusive of system criticality and risk of failure due to operating/material factors, in order to assess the need for flexibility/stress analysis. At large diameters, the design of the pipe may be determined more by the support conditions than the internal pressure conditions. Anchor (support) loading shall be checked for acceptability. The information listed in 8.2.2 and 8.2.3, as a minimum, shall be obtained before performing flexibility/stress analysis.

ANNEX C gives further information about the material properties.

The application of stress intensity factors (S_I), flexibility factors, and pressure stress multipliers shall be in accordance with **ANNEX D**, or in accordance with procedures agreed with the principal.

Design Parameters → **Hypotetical Thickness: t_r [m]**

Pipe Stress Components
- σ_{HP}: Hoop stress due to Internal Pressure – 8.5
- σ_{AP}: Axial stress due to Internal Pressure – 8.5
- σ_{AB}: Axial stress due to Bending – 8.6
- $\sigma_{A.\Delta T°}$: Axial stress due to thermal expansion – 8.4

TAB

Total Induced Pipe State of Stress
- $\sigma_{A[SUM]}$: Sum of Axial stresses acting on pipe
- $\sigma_{H[SUM]}$: Sum of Hoop stresses acting on pipe

Sum of **axial stresses** operating on plain pipe

$$\sigma_{A[SUM]} = \sum (\sigma_{AP} + \sigma_{AB} + \sigma_{A.\Delta T°})$$

σ_{AP} = Axial Stress due to internal pressure [MPa]
σ_{AB} = Axial Stress due to total weight [MPa]
$\sigma_{A.\Delta T°}$ = Axial Stress due to ΔT° [MPa]

Sum of **hoop stresses** operating on plain pipe

$$\sigma_{H[SUM]} \equiv \sigma_{HP}$$

σ_{HP} = Hoop Stress due to internal pressure [MPa]

Ai & Part Factors Evaluation
- **A1:** Partial factor for Temperature – Annex D - *TAB*
- **A2:** Partial factor for Chemical Resistance – Annex D - *TAB*
- **A3:** Partial factor for Cyclic Loadign – 7.4.4 – *TAB*
- **f2**: Part factor for Loading – 7.6.2 -TAB

Minimum required Qualified Pressure: P_{Q0} [MPa]

Factors Eval.
- **f3**: Part factor for Axial Loading – 7.10 - *TAB*
  *Experiments: **ASTM D2105 & ASTM D1599***

Iteration 1
Pq0: e1a, e1b
up to convergence

Target Qualified Pressure P_Q [MPa]
$P_{Q0} \leq P_Q$

P_Q

$P_Q(v)$(25years)

Pressure Assessment
$P_Q \leq P_Q(v)$

True → **1) Qualified Pressure Assessment VERIFIED** → **Proceed using: $P_Q(v)$ Value**

False → Pipe Thickness Tr is insufficient – Increase Tr

Calculate factors using P_Q from D2992B - S_{QS}, S_{FS}, S_{AL} -

$\sigma_{A[SUM]}$
$\sigma_{H[SUM]}$

Stress Assessment

Simplified Envelope 7.11.3 -Disequations-

A) $\sigma_{H[SUM]} \leq f2 \cdot A1 \cdot A2 \cdot A3 \cdot \sigma_{QS}$
$\sigma_{H[SUM]} \leq f2 \cdot \sigma_{FS}$

B) $\sigma_{A[SUM]} \leq (\sigma_{QS}/2 - \sigma_{AL(0:1)}) \cdot (\sigma_{H[SUM]}/\sigma_{QS}) + f2 \cdot A1 \cdot A2 \cdot A3 \cdot \sigma_{AL(0:1)}$

C) $\sigma_{A[SUM]} \leq (1-r) \cdot (\sigma_{H[SUM]}/2) + f2 \cdot A1 \cdot A2 \cdot A3 \cdot r/2 \cdot \sigma_{QS}$

Failure Envelope -TAB

False → Pipe Thickness Tr is insufficient – Increase Tr Or Reduce induced Stresses

True → **2) Qualified Stress Assessment VERIFIED**

EXPERIMENTS → ASTM D2105 & ASTM D1599

Experimental Evaluation of r Biaxial Stress Ratio & Failure Envelope

ASTM D2105

Standard test method for longitudinal tensile propreties

NB: 1.2 «this test method is generally limited to pipe diameter of 150mm…»

Type of Experiment: Tensile test of pipe
Number of samples: 5 replicates
Experiment duration: up to Tensile breakdown
Experiment Temperature: Standard Laboratory Temperature – 22.7°C, 50%humidity
Statistical analysis procedure: ASTM D2015 and ISO14692(2) 6.2.6

Outputs: Tensile Stress…(2 st.dev lower than mean of 5 samples)

→ **$\sigma_{SA(0:1)}$** THE SHORT-TERM AXIAL STRENGTH UNDER AXIAL LOADING ONLY.

ASTM D1599

Standard test method resistance to short-term hydraulic pressure of pipe

Type of Experiment: Ramp loading and burst each sample.
Display results in a time to failure-s; burst pressure-MPa plot and perform statistical Analysis – *Procedure A to determine Burst Pressure*.
Number of samples: 5 replicates – free-end closures (2:1 induced stress)
Experiment duration: burst may occurs between 60s-70s
Experiment Temperature: Standard Laboratory Temperature or Design Temperature (see ISO14692(3))
Statistical analysis procedure: ASTM D1599 and ISO14692(2) 6.2.4

Outputs: Short-Term Hydrotest pressure…(2 st.dev lower than mean of 5 samples)

→ **$\sigma_{SH(2:1)}$** THE SHORT-TERM HOOP STRENGTH UNDER 2:1 STRESS CONDITIONS

Deriving Long-Term Failure Envelope

Evaluation of **r** biaxial state of stress ratio – ***TAB***
Evaluation of **f3** Part factor for Axial Loading - ***TAB***

Wall thickness - tr -

FULLY MEASURED FAILURE ENVELOPE - TAB

SIMPLIFIED FAILURE ENVELOPE - *TAB*

Design Data
- Inside Diameter - **IDr [mm]**
- Enviroment - **Corrosive**
- Fluid - **Gas**
- Resin type - **GRE**
- Design Pressure - **Pdes [Mpa]**
- Operating Temperature - **T°des [C°]**

EXPERIMENT → ASTM D2992 – Procedure B

Experimental Evaluation of P_Q

ASTM D2992 – B

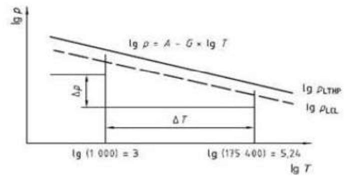
Obtaining Hydrostatic design basis for GRP pipes
Plain Pipe Qualification (Family representative) – 6.2.3.1(2)

Type of Experiment: Static loading and burst at different internal pressure for each sample.
Display results in a Log(time-h);Log(pressure) plot and perform statistical Analysis
Number of samples: 18 at leasts – free-end or restrained-end closures (2:1 or 2:0 induced stress)
Experiment duration: up to 10'000h
Experiment Temperature: 65° or Design temperature if higher
Statistical analysis procedure: ANNEX K ISO14692(2) (preferred) or D2992

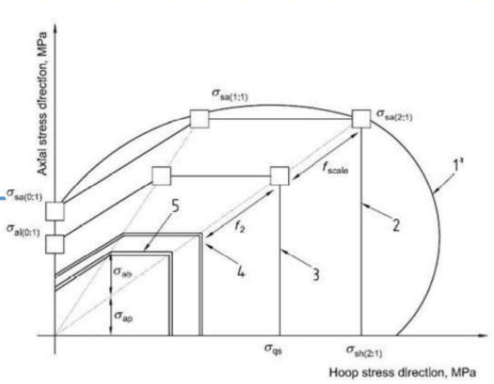
Outputs: P_{LCL} (years) – Pressure lower confidence limit ≡ P_Q(years)
G – Gradient of regression curve

Design lifetime other than 20 years – 6.2.7(2)

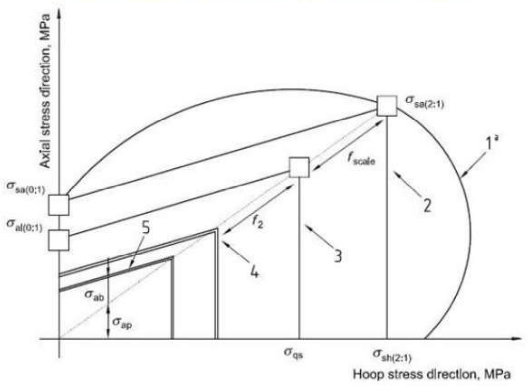
P_{LCL} (years) ≡ P_Q
G gradient



Method A: Fully measured Envelope 7.11.2



Method B: Simplified Envelope 7.11.3



Flowchart B 2002 – Calculation Procedures for Coefficients and Factors within the ISO 14692:2002

A1 & A2 – PARTIAL FACTOR FOR TEMPERATURE ANNEX D ISO 14692-2:2002

The permeability of fluids into reinforced plastics increases rapidly with increasing temperature. The absorption of liquids also accelerates viscoelastic processes such as creep, especially with uncrosslinked or inadequately crosslinked matrix resins. Temperature also accelerates many of the degradation processes caused by the fluids when they have entered the matrix.

For some chemicals other than water, it is not possible to determine partial factors *A*1 and *A*2 separately, and testing will result in determination of the product *A*1 · *A*2. There are many procedures for testing GRP materials at elevated temperature and/or exposed to chemicals, for example ISO 175 [2], ASTM C581 [3], ASTM D543 [4], but few provide acceptance criteria. This is because the acceptance criteria depend on the nature of the failure mode applicable to the application.

If the effects of temperature alone are being considered, **it is acceptable to linearly extrapolate** a value of ***A*1** between a value of 1 at the **qualification test temperature** (minimum test temperature is 65 ºC), *T*qual, and 0 at the *T*g, i.e.

$$A_1 = \frac{T - T_g}{T_{qual} - T_g}$$

where T is the required design temperature.

If *A*1 is extrapolated from the qualification test temperature, then the maximum design temperature limitations as defined in 6.8.2.2 shall apply.

Possible test procedures that can be adapted to provide a means for deriving partial factors *A*1 and *A*2 include **ASTM D3681** [5] and **prEN 13121-2 [6] for Vessels**.

If there are doubts about the values of *A*1 and *A*2, a 1 000 h survival test should be carried out on the product sector representative at the appropriate temperature and chemical conditions in accordance with 6.2.3.2.2. Consideration should be given to ensuring that the test media is given sufficient time to permeate into the walls of the GRP pipe in order to achieve representative saturation conditions of the material prior to carrying out the survival test. The test pressure should be 1,15 times the value determined according to Equation (7), to provide a 15 % margin of safety.

A3 – PARTIAL FACTOR FOR CYCLIC LOAD CONDITIONS 7.4.4 ISO 14692-3:2002

If the predicted number of pressure or other loading cycles is less than 7 000 over the design life, the service shall be considered static. If required

If the predicted number of pressure or other loading cycles exceeds 7 000 over the design life, then the designer shall determine the design cyclic severity, R_c, of the piping system.

$$R_c = \frac{F_{min}}{F_{max}}$$

where F_{min} and F_{max} are the minimum and maximum loads (or stresses) of the load (or stress) cycle.

The partial factor, A_3, for cyclic service is given by:

$$A_3 = \sqrt{\left(R_c^2 + \frac{1}{16}(1 - R_c^2)\right)} \times \exp\left[(1 - R_c)\left(1 - \frac{N - 7000}{10^8}\right)\right]$$

where *N* is the total number of cycles during service life.

This equation is intended for cyclic internal pressure loading only, but may be applied with caution to axial loads provided they remain tensile, i.e. it is not applicable for reversible loading.

If required, the limited cyclic capability of pipe system components can be demonstrated according to 6.4.5 of ISO 14692-2:2002.

R BIAXIAL STRENGTH RATIO – 6.2.6 ISO 14692-2:2002

The biaxial strength ratio *r* is as defined in 6.2.6 of ISO 14692-2:2002.

$$r = 2 \cdot \frac{\sigma_{sa(0:1)}}{\sigma_{sh(2:1)}}$$

$\sigma_{SA(0:1)}$ is the short-term axial strength, in megapascals, under axial loading only. **(ASTM D2105 @SLT)**

$\sigma_{SH(2:1)}$ is the short-term hoop strength, in megapascals, under 2:1 stress conditions **(ASTM D1599)**

In the absence of data from the manufacturer, the default values given in 7.11.4(3) shall be used:

#NOTE 1 The value of r for plain pipe should always be avaible from the manufacturer. A typical value for 55° filament-wound glass epoxy pipe is about 0.4; but may be lower for other resin systems and winding angles.

SEE **TAB**: FULLY MEASURED SHORT-TERM ENVELOPE METHOD A.1 – ANNEX C of ISO 14692-2:2002

F2 - PART FACTOR FOR LOADING – 7.6.2.2 ISO 14692-3:2002

DEFAULT VALUES for f2

Occasional load – Short-Term – **0.89**

Sustained including Thermal Load – Long-Term – **0.83**

Sustained exluding Thermal Load – Long-Term – **0.67**

DESIGN LIFETIMES OTHER THAN 20 YEARS - 6.2.7 ISO 14692-2:2002

The standard or default lifetime of components for this part of ISO 14692 is 20 years. To convert the qualified pressure, P_{LCL} (20 years), as derived in this qualification procedure to a qualified pressure at a different lifetime, ***P_{LCL}* at *T* years**, use is made of Equations **(13)** and **(14)**:

$$p_{LCL}\,(20\text{ years}) = p_{LCL}\,(T\text{ years}) \times 10^{\Delta p} \quad (13)$$

$$\Delta p = G \times [1{,}3 - \lg(T)] \quad (14)$$

where *G* is the appropriate gradient of the regression line, megapascals per hour, for the component variant of interest.

F3 – PART FACTOR for AXIAL LOAD – 7.10 ISO 14692-3:2002

Part factor *f*3 is dependent on the value of the biaxial stress ratio *r* such that:

Part factor *f*3 is defined according to whether *r* is greater than or less than 1.

if *r* ≤ 1 → $f_3 = 1 - \frac{2\sigma_{ab}}{r \times f_2 \times \sigma_{fs}}$

if *r* > 1 → $f_3 = r - \frac{2\sigma_{ab}}{f_2 \times \sigma_{fs}}$

σ_{AB} is the non-pressure-induced axial stress, in megapascals, see Figure 1 - **8.6(3)**

σ_{FS} is the Factored Stress - **7.9(3)** $\sigma_{fs} = \sigma_{qs} \cdot A_1 \cdot A_2 \cdot A_3$ ← $\sigma_{qs} = p_q \times \frac{D}{2t_r}$

The maximum allowable value of *f*3 shall be unity. When the sustained axial stress, excluding that due to pressure, σ_{AB}, is compressive, *f*3 is equal to 1.

The procedures for calculating part factor *f*3 are applicable to both pipe and fittings. For the purposes of the calculation of part factor *f*3 for fittings, an equivalent qualified stress, σ_{FS}, is determined using Equation (10).

STRESS ANALYSIS - 8 ISO 14692-3:2002

8.3 External Pressure/Vacuum

The designer shall ensure that, where possible, vacuum conditions can be sustained by the selected component.

The external collapse pressure, Pc, in megapascals, of GRP pipes shall be calculated by the following equation which assumes that the length of the pipe is significantly greater than the diameter:

$$p_c = 2\left(\frac{1}{F_e}\right) \cdot E_h \left(\frac{t_r}{D}\right)^3 \quad (25)$$

D is the mean pipe diameter of reinforced wall, in millimetres, = (*Di* +2*t* − *tr*);
tr is the average reinforced wall thickness, in millimetres;
t is the nominal wall thickness, in millimetres;
Di is the pipe inner diameter, in millimetres;
Eh is the hoop modulus, in megapascals;
Fe is the safety factor as defined in 7.6.3.

For thick and sandwich construction walls, the hoop bending modulus should be used in preference to the hoop tensile modulus.

The axial stresses, if compressive, shall be checked with the allowable stresses and checked with the axial buckling criteria given in 8.7.1 and 8.7.2.

8.4 Thermal Loading

Thermally induced loads associated with the maximum operating or ambient temperature range shall be allowed for in the design.

When considering heating or cooling of the uninsulated pipe wall by the fluid contained within the pipe, the mean temperature change of the pipe wall to be used for stress analysis purposes should be calculated using Equation (26).

$$\Delta T_{eff} = k\,\Delta T_{pa} \quad (26)$$

Δ*T*eff is the effective design temperature change to be used for stress analysis, in degrees Celsius;
Δ*T*pa is the temperature difference between ambient temperature and the process design temperature, in degrees Celsius;
k is a factor to account for the low thermal conductivity of GRP (i.e. the average wall temperature of the pipe is always less than the design temperature because of GRP's low thermal conductivity). In the absence of further information, *k* should be taken as 0,85 for liquids and 0,8 for gases.

The axial stresses shall be checked with the allowable stresses and when the stress is compressive, the stresses shall be checked with the axial buckling criteria given in 8.7.1 and 8.7.2.

8.5 Stresses due to Internal Pressure

See 8.5 ISO14692-3:2002

The hoop stress, in megapascals, due to internal pressure for plain pipe shall be calculated using Equation (27):

$$\sigma_{hp} = \frac{p \cdot D}{2 \cdot t_r} \quad (27)$$

p is the pressure, in megapascals;
D is the mean pipe diameter of reinforced wall, in millimetres, = (*Di* +2*t* − *tr*);
Di is the pipe inner diameter, in millimetres;
t is the nominal wall thickness, in millimetres;
tr is the average reinforced wall thickness of the pipe, in millimetres.

The equivalent hoop stress, σ_{hp}, for fittings shall be calculated using Equation (28):

$$\left(\frac{\sigma_{hp}}{p}\right)_{fitting} = \left(\frac{\sigma_{hp}}{p}\right)_{pipe} \quad (28)$$

The axial stress, in megapascals, due to internal pressure for plain pipe shall be calculated using Equation (29):

$$\sigma_{ap} = \frac{p \cdot D}{4 \cdot t_r} \quad (29)$$

8.6 Stresses due to pipe Support

The designer shall consider the effect of contact stresses at the support of large-diameter **liquid-filled pipes**, which become more significant with increasing diameter and *D*/*t* ratio.

The calculation of axial stresses for pipes of **diameter more than 0,6 m** shall be in accordance with Annex E, or in accordance with procedures agreed with the principal.

For **gas service** and small- and medium-diameter **pipes** for liquid service, the **support stresses are considered insignificant** compared to the bending stresses at mid-span.
The magnitude of the axial stresses shall be calculated in accordance with Equations (30) and (31) and checked with the appropriate allowable stresses. If the stress is compressive, the stresses shall be checked with the axial buckling criteria given in 8.7.1 and 8.7.2.

Considering a single span simply supported, the additional axial tensile stress due to self-mass induced through bending, σ_{AB} in megapascals, of the GRP pipe shall be calculated using Equation (30).

$$\sigma_{ab} = \frac{M_i\left[(D_i + 2t)/2\right]}{I_p \times 10^6} \quad (30)$$

NOTE Equation (30) ignores the effect of the pressure profile produced by the head of fluid within the pipe.

*I*P is the second moment of area about an axis through the centroid normal to the pipe axis, in metres4 (m4); $= \frac{\pi}{64}\left[(D_i + 2t)^4 - D_i^4\right]$ which for thin-walled pipes = $\pi D^3 t_r / 8$
D is the mean pipe diameter of reinforced wall, in metres = (*Di* +2*t* - *tr*);
Di is the pipe inner diameter, in metres;
t is the nominal wall thickness, in metres;
tr is the average reinforced wall thickness, in metres;
M is the bending moment due to dead weight, one- and two-span beam, in newton metres;
$= \rho_o \times 9{,}81 \times L_s^2 / 8$
Ls is the support span, in metres – **5.3.3(3)**
ρo is the combined pipe and fluid linear mass, in kilograms per metre
$= \rho_{eff} \cdot \frac{\pi D_i^2}{4}$
ρeff is the effective density of the combined fluid pipe material, in kilograms per cubic metre = $\left(\rho_L + 4\frac{\rho_c t}{D_i}\right)$
ρc is the density of GRP, in kilograms per cubic metre;
ρL is the density of fluid within the pipe, in kilograms per cubic metre (kg/m3).

The total axial stress, $\sigma_{a,bp}$, in megapascals, due to internal pressure and bending due to self-mass at the bottom and top of the pipe is given by Equation (31).

$$\sigma_{a,bp} = \frac{p \cdot D}{4 \cdot t_r} \pm \sigma_{ab} \quad (31)$$

The equations used for calculating the deflection due to dead weight (pipe and fluid mass) shall be

$$\delta = (5 \times \rho_o \times 9{,}81 \times L_s^4 \times 10^{-3})/(K_s \times E_a \times I_p)$$

δ is the deflection due to dead weight, in millimetres, one-and two-span beam and anchored beam;
Ks is the the support type factor, (dimensionless);
= 384 for single span beam (two supports);
= 925 for two span beam (three supports);
= 1 920 for anchored beam (two fixed supports built-in at both ends);
Ea = axial flexural (bending) modulus at design temperature, in megapascals.

See all section 8 for all stresses

Flowchart C 2002 – Definition of the Failure Envelopes – Fully Measured and Simplified envelope assessments within the ISO 14692:2002

DETERMINATION OF FAILURE ENVELOPE – 7.11 ISO 14692-3:2002

This subclause describes how the failure envelope of the GRP pipe components can be determined to meet the requirements of 7.10. **Two design** options are defined *in order to derive the* ***Long-Term Failure Envelope***, depending of the availability of measured data, which can be either a **fully measured envelope**, **7.11.2** or a **simplified envelope**, **7.11.3**.
The fully measured envelope is generally only available for plain pipe. For all other component variants, the simplified envelope should be used. **The least conservative procedure is the fully measured envelope.**

NOTE For filament-wound GRP pipes, the design approach adopted by most manufacturers is to optimize performance for the 2:1 pressure condition (system with closed ends). Therefore the hoop strength is significantly greater than the axial strength.

Method A
Fully Measured Envelope 7.11.2

Most Used → **Method B**
Simplified Envelope 7.11.3

→ Long Term Envelope

Method A: Fully Measured Envelope 7.11.2

The long-term envelope is derived from a fully measured short-term envelope according to the procedures given in **Annex C** of ISO 14692-2:2002.

FAILURE ENVELOPE – ANNEX C (2)

This **Annex C** provides guidance on the measurement of strength data for GRP pipe under different combinations of hoop and axial stress. This procedure is relevant if it is possible to apply additional axial loads over and above the induced axial load from internal pressure to the component.

To generate the regression curve, the **test details and measurement** should be in accordance with 6.2.3.1(2) → in accordance with ASTM2992

The long-term (factored) envelope, see Figure C.1, is derived from either a **fully measured short-term envelope (Method A.1)** or a **1 000 h survival test envelope, see 6.2.3.2.2(2) (Method A.2)**

→ **1 000 h survival test envelope** 6.2.3.2.2(2) **(Method A.2)**
Avaible for **Product Sector Representative**

STOP

→ **fully measured short-term envelope (Method A.1)** → *TAB*

The **idealized long-term failure envelope** is geometrically similar to the short-term envelope with all three data points being scaled according to **fscale**, where:

Pq is Known → $\sigma_{qs} = p_q \times \frac{D}{2t_r}$ → $f_{scale} = \sigma_{qs} / \sigma_{sh(2:1)}$ ← **σSH(2:1)**

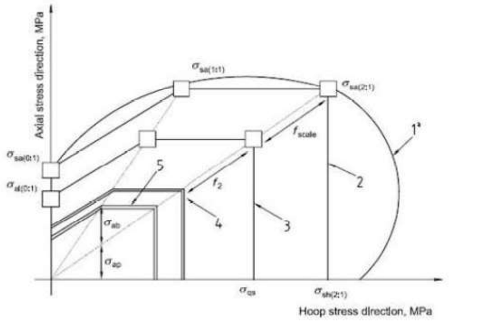
Equation (7)

The **long-term design envelope OR non-factored long-term design envelope** is based on this idealized long-term envelope multiplied by an appropriate factor of safety, ***f2*** , depending on loading type.

The factored long-term design envelope is defined according to Equation (16):

$$g_{long}(\sigma_{h,sum}, \sigma_{a,sum}) \leqslant f_2 \cdot f_{scale} \cdot A_1 \cdot A_2 \cdot A_3 \cdot g_{short}(\sigma_{sh(2:1)}, \sigma_{sa(0:1)}) \quad (16)$$

Stress Assessment



Key
1 schematic representation of the short-term failure envelope
2 idealized short-term envelope
3 idealized long-term envelope
4 non-factored long-term design envelope
5 factored long-term design envelope

ª For design purposes, the shape should be based on actual measured data points.

Figure 1 — Idealized long-term envelope for a single wound angle ply GRP pipe with winding angles in the range of approximately 45° to 75°

A1 is the partial factor for temperature;
A2 is the partial factor for chemical resistance;
A3 is the partial factor for cyclic service;
σab is the non-pressure-induced axial stress;
σap is the axial stress due to internal pressure;
σa,sum is the sum of all axial stresses,
σh,sum is the sum of all hoop stresses, in megapascals, (pressure plus system design);
*g*long(σ h,sum, σ a,sum) is the shape of the factored long-term design envelope;
*g*short(σsh(2:1), σsa(0:1)) is the shape of the idealized short-term envelope.

FULLY MEASURED SHORT-TERM ENVELOPE METHOD A.1 – ANNEX C of ISO 14692-2:2002

A minimum of **3 data points** is required to define the short-term envelope.

The hoop and axial loads shall be applied simultaneously, not sequentially. The manufacturer shall record the load application rate.

These data points shall be collected for a fixed ratio of applied hoop stress to axial stress, and are defined as:

Point 1: 0:1 hoop to axial stress, i.e. axial tension only **σSA(0:1)** measured in accordance with **6.2.6.**

Point 2: 1:1 hoop to axial stress, i.e. internal pressure + axial tension (**σSA(1:1)** and **σSH(1:1)**)

Nothing about How to Evaluate this Point, standard..etc.

Point 3: 2:1 hoop to axial stress, i.e. internal pressure only (**σSA(2:1)** and **σSH(2:1)**) measured in accordance with **6.2.6.**

$\sigma_{sh(2:1)} = P_{STHP} \times \frac{D}{2t_r}$ → **PSTHP 6.2.4(2)**

PSTHP is the short-term hydrostatic test pressure, in megapascals, determined in accordance with the method given in 6.2.4
D is the mean diameter of the reinforced wall of the family representative, in millimetres.
tr is the average reinforced wall thickness of the family representative, in millimetres.

ASTM D2105 – Two Methods ← **σSA(2:1)**

a) by testing **five replicate** samples in accordance with ASTM D2105 at SLT. The σSA(0:1) of the family representative shall be taken as the lower deviated (two standard deviations) value of the five replicate Samples.

b) by taking 85 % of the lower of two replicate samples tested in accordance with the test procedures given in ASTM D2105 at SLT.

ASTM D1599 - Two Methods ← **σSH(2:1)**

a) by testing **five replicate** samples in accordance with ASTM D1599. The PSTHP of the representative product shall be taken as the lower deviated (two standard deviations) value of the five replicate samples.

b) by taking 85 % of the lower of two replicate samples tested in accordance with the test procedures given in ASTM D1599.

Qualifing at 80°C do we have to test at 80°C ?

Testing shall be at SLT (Standard Laboratory Temperature). The rated temperature for a component qualified by this option shall not exceed 65°C. See also 5.3 with respect to minimum required resin *Tg*.

NB: The manufacturer may carry out additional short-term testing at other stress ratios at his discretion.

SIMPLIFIED MEASURED SHORT-TERM ENVELOPE METHOD B – 7.11.3 of ISO 14692-3:2002

Method B: Simplified Envelope 7.11.3

This method makes use of the **biaxial strength ratio *r***, which is the ratio of axial stresses at 0:1 and 2:1 stress ratios determined in 6.2.6 of ISO 14692-2:2002 - ***TAB***
If a value of ***r*** for a component is unavailable, the default value given in 7.11.4 should be used.

For Plain pipe 7.11.3.2

Figure 2 shows short- and **long-term failure envelopes** for a single wound angle ply GRP pipe with winding angle in the range ± 45° to 75° where the value of *r* can be expected to be less than 1. If *r* is greater than 1, e.g. hand lay-up pipe, 7.11.3.3 applies.
The idealized long-term failure envelope is geometrically similar to the short-term envelope and is derived according to Equation (17) or (18):

$$\sigma_{al(0:1)} = \sigma_{sa(0:1)} \times \frac{\sigma_{qs}}{\sigma_{sh(2:1)}} \quad (17)$$

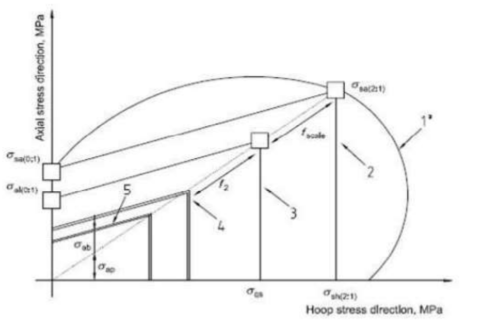
or

$$\sigma_{al(0:1)} = r \times \frac{\sigma_{qs}}{2} \quad (18)$$

σQS is the qualified stress, in megapascals;
σAL(0:1) is the long-term axial (longitudinal) strength at 0:1 stress ratio, in megapascals;
σSA(0:1) is the short-term axial strength at 0:1 stress ratio, in megapascals;
σSH(2:1) is the short-term hoop strength at 2:1 stress ratio, in megapascals;
r is derived according to Equation (12).

σSA(0:1) → **ASTM D2105**
σSH(2:1) → **ASTM D1599**
→ **Points 1 - 3**

The important feature of Figure 2 is that the axial tensile strength, σAL(0:1), is lower than the axial stress for the 2:1 internal pressure case, σSA(2:1). The ratio of these strengths can range between 0,5 and 0,75 for plain pipe, depending on winding angle and specific pipe type.
The non-factored long-term design envelope is based on this idealized envelope multiplied by an appropriate part factor, *f*2, 7.6.2, depending on loading type.



Key
1 schematic representation of the short-term failure envelope
2 idealized short-term envelope
3 idealized long-term envelope
4 non-factored long-term design envelope
5 factored long-term design envelope

ª For design purposes, the shape should be based on actual measured data points.

Figure 2 — Short and long-term idealized failure and design envelopes for a single wound angle ply GRP pipe with winding angles in the range of approximately 45° to 75°

The equations for defining the factored long-term design envelope for hoop and axial stress, respectively, are defined such that:

Stress Assessment

$$\sigma_{h,sum} \leqslant f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \sigma_{qs} \quad (19)$$

or

$$\sigma_{h,sum} \leqslant = f_2 \cdot \sigma_{ls} \quad (20)$$

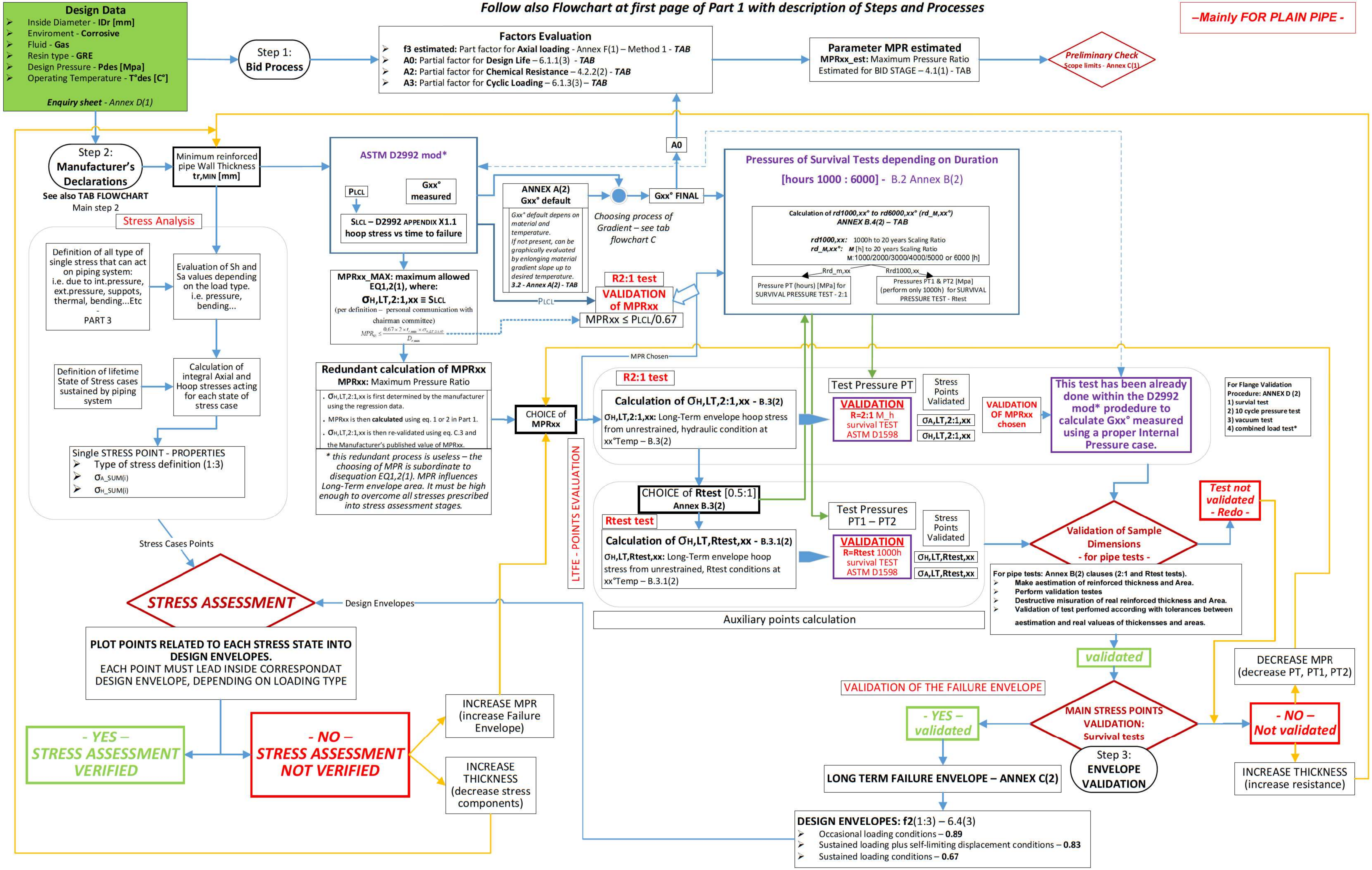
and

$$\sigma_{a,sum} \leqslant \left(\frac{\sigma_{qs}}{2} - \sigma_{al(0:1)}\right)\frac{\sigma_{h,sum}}{\sigma_{qs}} + f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \sigma_{al(0:1)} \quad (21)$$

$$\sigma_{a,sum} \leqslant (1-r)\frac{\sigma_{h,sum}}{2} + f_2 \cdot A_1 \cdot A_2 \cdot A_3 \cdot \frac{r}{2} \cdot \sigma_{qs} \text{ assuming } r \leqslant 1 \quad (22)$$

Flowchart A 2016 – Design Process in accordance with ISO/FDIS 14692:2016

Follow also Flowchart at first page of Part 1 with description of Steps and Processes



Flowchart B 2016 – Coefficients and Factor calculation within the ISO/FDIS 14692:2016

Step 1 - F3 – PART FACTOR for AXIAL LOAD – ANNEX F (1)

There are two Methods available for selecting the *f3,est* part factor.

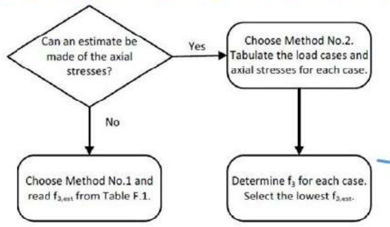


Figure F.1 – Selection process for $f_{3,est}$

Determing *f3,est* – Method No.1

Since the project is at the bid stage, there will be no stress analysis available and estimates will have to be made of these axial stresses. Guidelines for determining the part factor *f3,est* at the bid stage are provided in Table F.1.

Table F.1 – Guidelines for determining $f_{3,est}$ at the bid stage

Application	$f_{3,est}$	Notes
Process piping, Aboveground, Offshore & marine, max. 1,5 × P_{des} hydrotest	0,65 – 0,75	Occasional loads from wind and/or ship motions typically require a low f_3. Special design conditions such as wave loads may require a much lower $f_{3,est}$.
Process piping, Aboveground, Industrial, max. 1,5 × P_{des} hydrotest	0,65 – 0,80	Higher temperature changes (e.g., above 40 °C) may require a lower $f_{3,est}$ due to axial and bending stress from thermal loads. Applications in some seismic zones may require a lower $f_{3,est}$.

...continues

NOTE 3 the guidelines in this table are based primarily on 55°degree filament wound pipe. For those pipes pr pther components manufactured by a method that has a higher axial strength capacity, a higher value of f3_est factor may be warrented.

Determing *f3,est* – Method No.2

The second method for determining $f_{3,est}$ at the bid stage is to consider the non pressure-generated axial stresses that could occur on the piping system.

Non pressure-generated axial stresses arise from:

a) σ_{AB} - bending
b) σ_{AC} – curving/roping
c) σ_{AF} – esternal forces
d) σ_{AT} – thermal loads

It should be possible to estimate typical values for these axial stresses for the proposed pipe installation. The first step is to identify a suitable GRP product type and a typical associated long term axial strength, $\sigma_{a,LT,0:1,xx}$. This can be obtained from published vendor data.

...continues

Step 1 - A3 – PARTIAL FACTOR FOR CYCLIC LOAD – 6.1.3(3) – ANNEX B(3)

A3 is the de-rating factor of the effects of **cyclic variation in pressure**:

When $R_c > 0,4$ →

$$A_3 = \left(\frac{1-f_c}{0{,}6f_c}\right)\left(\frac{1-R_c}{\log(150\times10^6)-\log(7\,000)}\right)\log(N) + 1 - TAN\left[\left(\frac{1-f_c}{0{,}6f_c}\right)\left(\frac{1-R_c}{\log(150\times10^6)-\log(7\,000)}\right)\right](\log(7\,000)$$

When $R_c <= 0,4$ →

$$A_3 = \left(\frac{1-f_c}{f_c}\right)\left(\frac{1}{\log(150\times10^6)-\log(7\,000)}\right)\log(N) + 1 - \left(\frac{1-f_c}{f_c}\right)\left(\frac{\log(7000)}{\log(150\times10^6)-\log(7\,000)}\right)$$

Rc – cyclic loading ratio → $R_c = \sigma_{min} / \sigma_{max}$

fc – cyclic long term strength factor **(Default value is 4.0)** → $f_c = \frac{\sigma_{Static100\,000}}{\sigma_{Cyclic150\,000\,000}}$

The cyclic long term strength factor, *fc*, is defined as the ratio of the projected stress values at 100,000 hours (static) and 150,000,000 cycles (cyclic) respectively. These values shall be determined from regression analysis as defined in the ASTM D2992-96, Procedures A (cyclic) and B (static).
In case no test data is available, a conservative value of 4,0 shall be used.

A3 must be greater than or equal to *1 / fc*.
A3 shall be 1,0 if the calculated value is between 0,9 and 1,0.
At 7 000 cycles or less, ***A3*** shall be 1,0.
The minimum value for **A3** shall be 0,25.

IMPORTANT → B.3 Theory and Background

Step 1 - F2 - PART FACTOR FOR LOADING – 6.2(3)

The part factor for sustained loading, f_2, to be used in the assessment of sustained loads, shall be determined taking into account operating conditions and risk associated with the piping system. The value to be applied for specific piping systems shall be specified by the user. Recommended typical values for f_2 are

DEFAULT VALUES for f2:

Occasional loading conditions – **0.89**

Sustained loading plus self-limiting displacement conditions – **0.83**

Sustained loading conditions – **0.67**

Step 1 - A2 – PARTIAL FACTOR FOR CHEMICHAL DEGRADATION – 6.1.1(3) – 4.4.2(2)

A2 shall be 1,0.

NOTE 1 It is the resin rich liner, not the structural cage, that is designed to prevent chemical degradation. A partial factor applied to the reinforced wall thickness would provide little to no value in preventing chemical degradation.

NOTE 2 Water permeates thermoset resins quite quickly. The silane coupling agent is the key component providing resistance to breakdown from water attack. Without the silane coupling agent, water permeation would occur followed by a breakdown of the bond between the glass and resin followed by etching of the fibers and finally fiber failure.

NOTE 3 While the silane coupling agent provides resistance to breakdown from water attack, other chemicals may attack the bond between the resin and the glass reinforcement. Some of these chemicals include strong acids and bases such as sodium hydroxide. It is these chemicals that require a resin-rich, reinforced liner of sufficient thickness to protect the structural layers from permeation of these chemicals and attack of the bond between the glass and the resin. Fortunately, most of these chemicals do not permeate quickly, so practical liners are possible. Other standards, such as **ASTM D3681** or **EN 13121-2**, **may be suitable as a qualification programme to predict the thickness of the liner** based on exposure to various chemicals in a stressed condition.

Step 1 - A0 – PARTIAL FACTOR FOR DESIGN LIFE other than 20 Years – 6.1.1(3)

A0 shall be used to scale the long term envelopes to the design envelopes at design lives other than 20 years.
A0 shall be defined by the following equation.

$$A_0 = \frac{1}{10^{(\log(t)-\log(175\,200))\times G_{xx}}}$$

t time expressed in hours
Gxx gradient of regression line at xx °C AS DEFINED IN **ANNEX A(2) – SEE TAB**

A0 shall not be greater than 1,0

Flowchart C 2016 – Auxiliary calculations within the ISO/FDIS 14692:2016

Main Step 2 - MANUFACTURER'S DECLARATIONS - 4(2)

Prior to the start of the qualification programme, the manufacturer shall declare **1) Gxx**, **2) MPRxx**, **3) the long term envelope data points**, **4) the threshold envelope data points**, **5) dimensional data** and **6) baseline values for degree of cure**, **barcol hardness** (GRUP and GRVE only) and **glass content**, where applicable.
The data shall be based on a standard design life of 20 years. Refer to Figure 1 for a flowchart of the procedure for declaring the manufacturer's data.

A) Manufacturer conducts **long term regression testing (4.1)** on a single pipe size and pressure class. → For GRE, temperature is ≥ 65 °C. For GRUP and GRVE, temperature is ≥ 21 °C.

ASTM D2992 mod - TAB → PLCL ; Gxx measured - TAB

B) Manufacturer **calculates the measured gradient Gxx** and identifies a **suitable σH,LT,2:1,xx.** → suitable σH,LT,2:1,xx

C) Manufacturer uses the long term regression data to **select** and **declare a gradient Gxx** (4.2 and Annex A). → For GRE, declare MPR65. For GRUP and GRVE, declare MPR21. MPRxx may also be declared at other temperatures.

Gxx Final - TAB

D) Manufacturer uses the long term regression data to **declare MPRxx using eq. 1 or 2(1)** in ISO 14692-1. → **The calculation of σH,LT,2:1,xx is redundant.** σH,LT,2:1,xx is first determined by the manufacturer using the regression data. MPRxx is then **calculated** using eq. 1 or 2 in Part 1. σH,LT,2:1,xx is then re-validated using eq. C.3 and the Manufacturer's published value of MPRxx. → **MPRxx**

ERRORE C.3 → B.3

E) Manufacturer calculates **σH,LT,2:1,xx** (Annex B, eq. B.3). → σH,LT,2:1,xx ; σA,LT,2:1,xx

F) Manufacturer conducts the R=Rtest1000 hr survival test at the default temperature. See B.3. Calculate σh,LT,Rtest,xx and σa,LT,Rtest,xx. → σH,LT,Rtest,xx ; σA,LT,Rtest,xx

End of Figure 1 – Procedure for declaring manufacturer's data

G) Manufacturer calculates the remaining long term envelope data points, σh,LT,1:0,xx, σa,LT,0:1,xx and σa,LT,0:-1,xx. See Annex C.

H) Manufacturer uses the survival test qualification data to generate long term envelope data points at other temperatures (Annex B and C). → **If survival tests are only conducted at the design temperature, additional long term envelope data points are not calculated.**

i) Manufacturer declares DN, ID, Dr,min, tr,min, tl, laying lengths and bend radii (4.6).

L) Proceed to clause 5 and Figure 2 for the qualification programme

End of Figure 1 (continued) – Procedure for declaring manufacturer's data

Step 2(A) - ASTM D2992 Modified*

No preferred procedure A or B of D2992 defined in ISO

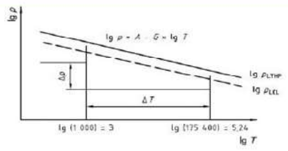
Check 4.1(2) and 5.1(2) for modifications

ASTM D2992 - B
OBTAINING HYDROSTATIC DESIGN BASIS FOR GRP PIPES
Plain Pipe Qualification

Type of Experiment: Static loading and burst at different internal pressure for each sample. Display results in a Log(time-h);Log(pressure) plot and perform statistical Analysis
Number of samples: 18 at leasts – **Unrestrained ends closures (2:1 induced stress)**
Experiment duration: up to 10'000h
Test Fluid: Potable Water (more aggressive than salt)
Experiment Temp.: **65°** or higher for GRE (21° or Higher if not GRE) if inside resin default gradient temperature – **LT Scaling allowed!**
T°DES if above resin default gradient temperature – **LT Scaling NOT allowed**
Statistical analysis procedure: D2992 - **4.1(2) LT regression Testing**
Outputs: PLCL (20 YEARS) – PRESSURE LOWER CONFIDENCE LIMIT
Gxx – MEASURED GRADIENT OF REGRESSION CURVE – ***SEE TAB***

DATA REFERS TO 20 YEARS LIFE
Design life data scaling made using **A0**

Gxx° Measured



rd 1000,xx :1000h to 20 years SCALING RATIO at xx°C – ANNEX B.4(2)

rd1 000,xx is the ratio between the survival test pressure, *PT1000,xx* and *MPRxx / f2* and is defined by equation (B.13)

$$rd_{1\,000,xx} = 10^{(\log 175\ 200 - \log 1\ 000)\times G_{xx})}$$

rd1 000,xx is a function of the gradient Gxx.

Gxx gradient at xx °C
f2 part factor for loading in the sustained condition, default value is equal to 0,67

See Table B.1 for values of *rd1 000,xx* based on the default gradients, a 20 year design life and 1 000 h test time.

Table B.1 — Default 1 000 h test ratios

Resin System	Temperature						
	−35 °C	21 °C	50 °C	65 °C	80 °C	93 °C	121 °C
Anhydride	1,26	1,26		1,40	1,72		
Aliphatic Amine	1,26	1,26		1,40		1,60	
Cyclo-aliphatic Amine (IPD)	1,26	1,26		1,40		1,59	
Aromatic Amine (MDA)	1,26	1,26		1,40		1,59	1,81
Polyester	1,33	1,33	1,44				
Vinyl Ester	1,33	1,33	1,40	1,47			

Values are based on a 20 year design life and 1 000 h test time.

Interpolation of values is allowed.

EXAMPLE 1 $rd_{1\,000,65}$ for GRE is 1,40.

EXAMPLE 2 $rd_{1\,000,21}$ for GRVE and GRUP is 1,33.

EXAMPLE 3 $rd_{1\,000,80}$ for an Anhydride Epoxy is 1,72.

EXAMPLE 4 $rd_{1\,000,60}$ for GRVE is 1,45 (found by interpolation).

EXAMPLE 5 $rd_{1\,000,-35}$ for GRUP is 1,33.

EXAMPLE 6 $rd_{1000,105}$ for IPD epoxy is not available in this table since 105 °C is above the highest published temperature of 93 °C for IPD epoxy. If a manufacturer intended to use an IPD epoxy at 105 °C, follow the requirements in A.3.2. Use the gradient, G_{xx}, calculated in A.3.2, in the applicable equations (B.1) thru (B.13) to calculate the survival test pressure.

Step 2(B) - Gxx – GRADIENT of THE REGRESSION at xx C° - ANNEX A(2)

➢ **All pipe wall thickness shall be qualified by 1000 hr survival using the published <u>default gradients</u>.**

➢ **Piping systems (joints and components)** that utilize prescribed threaded joints (i.e. threaded joints that meet the requirements of API 15HR) may be qualifed:
1) using the default gradients and performing survival testing per 5.3.1(2), or
2) using measured gradients as per API 15HR.

. Piping systems utilizing restrained joints other than the prescribed threaded joints shall be designed using default gradients.

SEE FLOWCHART - ANNEX A(2) as GUIDANCE for Piping Systems

A comparison between **Default Gradient** and **Measured Gradient** is made:

A.3 Default Gradients → **Gxx° Default**

CHOOSE HIGHER Gxx° → **Gxx° FINAL**

Gxx° Measured

Annex A - Gradients and Temperature Limits – FOLLOW FLOWCHART

Default gradients as a function of temperature and resin system are provided in **Table A.1** and **Figure A.2.**

Table A.1 – Default gradients, Gxx

Resin System	Temperature						
	−35 °C	21 °C	50 °C	65 °C	80 °C	93 °C	121 °C
GRE, Anhydride	0,045	0,045		0,065	0,105		
GRE, Aliphatic Amine	0,045	0,045		0,065		0,100	
GRE, Cyclo-aliphatic Amine (IPD)	0,045	0,045		0,065		0,090	
GRE, Aromatic Amine (MDA)	0,045	0,045		0,065		0,090	0,115
GRUP, Polyester	0,055	0,055	0,070				
GRVE, Vinyl Ester	0,055	0,055	0,065	0,075			

NOTE 1 Interpolation of values is allowed.

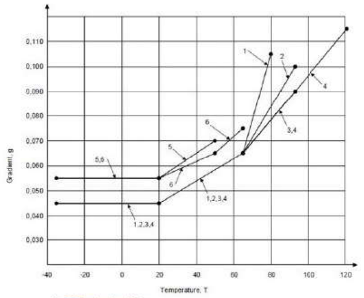
NOTE 2 The omission of default gradients at higher temperatures may not automatically preclude the use of a particular resin system at that temperature. For example, most of the long term testing on GRVE resin systems is between 21 °C and 65 °C, thus default gradient are only established up to 65 °C. However, some GRVE resin systems have Tg values of 140 °C or higher. To use the resin system at these higher temperatures, the requirements in A.3.2 may have to be met.

EXAMPLE 1 G_{80} for an Anhydride Epoxy is 0,105.

EXAMPLE 2 G_{60} for GRVE is 0,072 (found by interpolation).

EXAMPLE 3 G_{-35} for GRUP is 0,055.

EXAMPLE 4 G_{105} for IPD epoxy is not available in this table since 105 °C is above the highest published temperature of 93 °C for IPD epoxy.



1 GRE, Anyhydride
2 GRE, Aliphatic Amine
3 GRE, Cyclo-aliphatic Amine (IPD)
4 GRE, Aromatic Amine (MDA)
5 GRUP
6 GRVE

A.3.2 Higher design temperatures

<u>**IMP** If a manufacturer qualifies a product using one of these resin systems at a **design temperature above** the temperatures in Annex A, the following requirements shall apply.</u>
a) The manufacturer shall provide a measured gradient for one pipe (or pipe+joint) size at the design temperature.
b) The manufacturer shall extrapolate a value from the default gradients, using the two data points at the highest temperatures. This extrapolated value shall be the default value and shall be used in steps 5 and 6 of Figure A.1 to determine the gradient.
c) The manufacturer shall qualify the components with 1 000 h qualification testing.
rd1 000,xx shall be calculated per Annex B. Scaling rules per Annex E and Annex F apply.

EXAMPLE A manufacturer wishes to qualify **GRVE** at 120 °C. This is above the highest value in the default gradient table, 65 °C. The two highest data points are 0,065 at 50 °C and 0,075 at 65 °C. Extrapolating these two values to 120 °C is 0,075 + (0,075 – 0,065) × (120 – 65) / (65 – 50) = 0,112. The manufacturer's measured gradient shall be greater than or equal to 0,112 and shall be used as Gxx in Annex B.

A.2 Measured Gradients

The manufacturer shall determine the measured gradient in accordance with **ASTM D2992 (mod)**

NOTE 2 The measured gradient is the slope of the line. Even though the slope is negative, the measured gradient is defined as a positive number.

Measured gradients that are less than 0,030 shall be set to 0,030.

NOTE 1 There is a difference in Equation A1.21 of ASTM D2992:2006 and *σ2* in eq. K.10 of ISO 14692-2:2002. Equation A1.21 in ASTM D2992:2006 is missing a factor of 2. The equation should read *σe2 = 2λσδ2*. There is also a difference in Equation A1.20 of ASTM D2992:2006 and *Var(YL)* in eq. K.15 of ISO 14692-2:2002. ISO 14692-2:2002 will calculate the variance of the line, *Var(YL)*, smaller than the method in ASTM D2992:2006. Consequently, Annex K of ISO 14692-2:2002 will calculate an LCL value that is larger than the method in ASTM D2992:2006.

A.3.3 Other resin systems

...continues

IMP If a manufacturer qualifies a product using a resin system not shown in Figure A.2, the following requirements shall apply.

A.3.4 Lower design temperatures

Refer to 5.5.5.