Process and structural simulation for the development of a pressure vessel through filament winding technology

BIANCHI Iacopo[1,a *], FORCELLESE Archimede[1,b], GALLIANI Francesco[2,c], GRECO Luciano[1,d], MIGNANELLI Chiara[1,e] and TREVISAN Giulio[2,f]

[1]Università Politecnica delle Marche, Via Brecce Bianche 12, 60131 Ancona, Italy

[2]COMEC INNOVATIVE S.R.L., Via Papa Leone XIII 40, 66100 Chieti, Italy

[a]i.bianchi@pm.univpm.it, [b]a.forcellese@staff.univpm.it, [c]galliani.francesco@comecinnovative.it, [d]l.greco@pm.univpm.it, [e]c.mignanelli@pm.univpm.it, [f]trevisan.giulio@comecinnovative.it I

Keywords: Filament Winding, CFRP, Pressure Vessel, FEM Simulation

Abstract. Recently, Università Politecnica delle Marche and COMEC Innovative srl are involved in the research project "Smart Tow Winding" funded by MIUR (Ministry of Education, University and Research), concerning the development of an innovative process for the realization of a pressure vessel through Filament Winding (FW) technology. In this context, a design procedure for type IV composite pressure vessel is proposed. To design the component, the dedicated simulation software CADWIND was used to virtually generate the pressure vessel through the definition of the desired geometry, the type of prepreg, the number of layers and the bandwidth. The generated file was imported in the FEM simulation software Siemens NX with the aim of evaluating the structural resistance under an internal pressure of 70 MPa. Different external configurations of mandrels and stratification were tested in order to optimize the geometry of the vessel and the resistance to weight ratio. A high performance and low weight vessel configuration was finally identified.

Introduction

In recent years, the market for lightweight structural components has constantly increased and it has triggered the use of high performance composite materials such as Carbon Fiber Reinforced Polymers (CFRPs). These components find applications in several sectors such as sport equipment, energy production, and biomedical. Moreover, they are particularly suitable for road and aerospace transport applications. In fact, the weight saving achieved by means of high specific mechanical properties composites can result in a reduction in fuel use and, consequently, lower service life costs and environmental impacts [1-3]. Despite significant effort in automation [4], at present, carbon fiber parts production strongly relies on manual operations and it is therefore time consuming and expensive. For this reason, to achieve a sustainable development of composite materials and innovative transport systems, it is crucial to improve manufacturing systems automation and production speed [5].

In this context, MIUR (Ministry of Education, University and Research) is funding the research project titled "Smart Tow Winding" concerning the development of an innovative process for the fabrication of a pressure vessel through Filament Winding (FW) technology involving the Marche Polytechnic University and COMEC Innovative srl.

In this regard, the development of the technology of Smart Tow Winding constitutes an innovation in the corporate sector as it allows to combine an innovative material, such as composite, with an automated production process. This technology is an automated version of the conventional filament winding (FW) process, which is a widely practiced technique for high performance composite structures, such as pressure vessels, fuel tanks, pipes, and rocket motor cases. FW allows the production of composite parts by winding composite filaments over a rotating mandrel. The winding angle of the filament can be modified depending of the expected loads on the components, maximizing the mechanical resistance along the most stressed directions. In this way it is possible to satisfy the stringent structural requirements of the aerospace and transport industries.

Smart tow winding can be used for the construction of fuel storage tanks, containing from combustible gases to natural gases, which nowadays are an excellent solution to reduce CO_2 emissions. The traditional structure of tanks, used for on-board storage of gaseous fuel under pressure, present a central cylindrical body and two dome-shaped external caps; this is due to the fact that spheres incur the lowest membrane stress on their walls compared to any other shape [6,7]. These pressure tanks can be realized in metals, composite materials or obtained as a combination of these materials. In particular, five different types of vessels are defined [8]: Type I, II, III, IV, V. Type I is fully made by metal material, while Type II consist in an inner metal liner supporting 55% of the internal pressure load, reinforced with composite hoop wraps. Type III, is similar to Type II with an inner metal liner, externally covered by a composite reinforcement supporting up to 80% of the pressure load. For what concern Type IV, it is made externally of composite material and presents an inner liner made of plastic material, which does not support the load, but contains the gas and works as a mandrel for the Filament Winding process. The last typology, Type V, it is fully made by composite material, without internal liner.

Generally, gas used in industrial applications is stored inside cylindrical Type I tanks, since they are the least expensive, but the heaviest. Type II tanks, on the other hand, are commonly used at high pressures for stationary applications: they are lighter than Type I tanks, but at the same time more expensive. For uses where high lightness must be guaranteed, Type III, IV, and V tanks are used, in which the composite material is generally reinforced by means of glass, aramid, or carbon fibers [9].

Specifically, Type IV and V ones are the lightest ones at all, as they do not have metal liners; however, they are the most expensive due to the use of composite material.

With regard to the winding patterns with which these tanks can be made, they vary, depending on the geometry of the tank, the manufacturing process, the fiber arrangement, the precision of the machine, and the cost. Since filament-wound composite pressure vessels are more inclined to failure in domed sections, the shape of the dome and the winding of the fibers are important for the structural integrity of the vessel [10].

The high number of parameters related to pressure vessel production (e.g. number, percentage coverage and orientation of layers, filament path, raw materials, internal liner..) makes the design process complicated and time consuming. For this reason, a rapid and easy to apply design procedure for filament wound parts is required.

Hence, in the context of advanced composite manufacturing processes and simulations [11], this work focuses on the design and optimization of a type IV pressure vessel since it is a promising alternative in various applications (i.e. energy and transport) were low weight and high performances are required. After preliminary considerations with structural theories (netting theory, isotensoid vessel), virtual models were created by means of a FW dedicated software that allowed to define all the parameters of several possible composite layers. An iterative procedure with a FEA software was then used to optimize the structure parameters considering typical working loads (70 MPa internal pressure) and constraints.

Materials and Methods

In the present work, a preliminary design of a Type IV pressure vessel was investigated. The tank under pressure is characterized by a 380 mm diameter in the central cylindrical zone and a total length of about 540 mm. An internal thermoplastic liner, in high-density polyethylene (HDPE), is used as mandrel during the filament winding process. For the composite material used for the external winding, a towpreg composed by a thermosetting polymer matrix reinforced with carbon fibers, was chosen. The internal service pressure and burst pressure values were defined equal to 70 and 105 MPa, respectively, with a safety factor of 1.5, according to the suitable values in several transport applications [12]. Details about the material parameters according to their datasheet are reported in Table 1. The mechanical properties of the composite material were calculated considering the general "rule of mixture" and a fiber weight fraction equal to 68%.

Table 1. Mechanical properties of matrix, carbon fibers and composite material.

Material parameters	Unit	Values
Carbon fibers (Toray T700)		
Tensile strength	MPa	4900
Young modulus	GPa	230
Elongation at break	%	2.1
Density	g/cm³	1.8
Volume fraction	%	56.3
Epoxy resin		
Tensile strength	MPa	73
Young modulus	GPa	3.7
Elongation at break	%	9
Density	g/cm³	1.1
Volume fraction	%	43.7
Composite		
Tensile strength (longitudinal)	MPa	2790
Tensile strength (transversal)	MPa	~73
Young modulus (longitudinal)	GPa	131.1
Young modulus (transversal)	GPa	8.3
Density	g/cm³	1.6

To design the pressure vessel, an iterative procedure was followed (Fig. 1). Input geometric parameters were used to define the dome profile through a spreadsheet, while the design parameters, such as carbon fiber mechanical properties, service pressure and safety factor, were used to lead the netting analysis. The obtained results were implemented in CADWIND simulation software to virtually generate the pressure vessel through the definition of the desired geometry, the type of prepreg, the number of layers and the bandwidth. Then, the generated file was imported in the FEM simulation software Siemens NX with the aim of evaluating the structural resistance under the internal service and burst pressure values of 70 and 105 MPa. If the results obtained satisfy the safety structural requirements, the stratification analyzed can be considered as an acceptable design from the mechanical requirements perspective; otherwise, the study should continue identifying a new stratification that improves criticalities arising from the previous one. Moreover, other than the structural requirements, the weight of the structure was evaluated during each design iteration in order to identify the alternative that fulfils safety conditions and presents the lightest weight possible among the considered laminations.

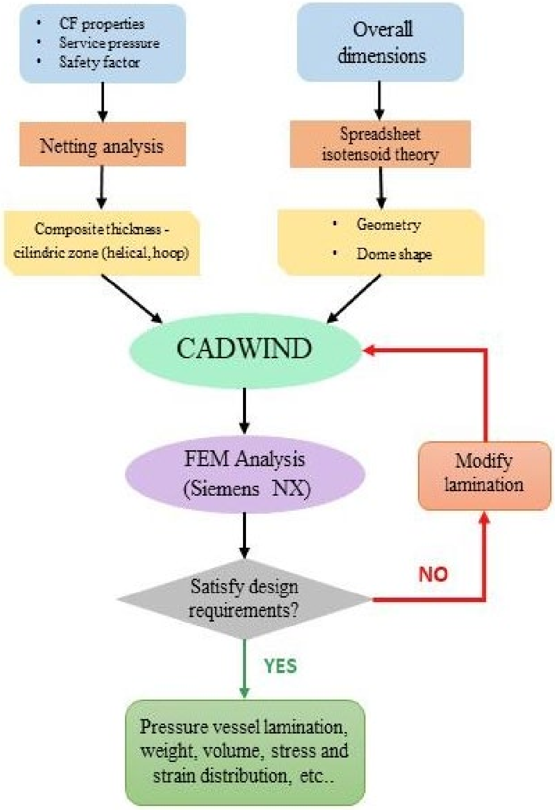


Fig. 1. Iterative design procedures applied for the definition of the optimal pressure vessel.

Netting analysis.

The netting analysis is a method that can be used to preliminarily estimate the thickness of helical and hoop layers of a composite tank that allow it to withstand the working loading conditions. The analysis considers that the pressure load is only supported by carbon fibers and the epoxy resin does not give any structural contribution. According to Mariotte theory, the internal pressure yields to two main stress components along the circumferential and axial directions. The first one is supported by helicoidal windings, while the second by hoop windings. For this reason, many tubular structures or tanks are produced using both low values of winding angles (helicoidal windings) and values near to 90° (hoop windings). Therefore, this theory allows to calculate the thickness of the fiber layers considering any combination of two different values of winding angles to obtain the tank laminate structure [13].

Spreadsheet isotensoid theory.

In order to guarantee high structural strength of the pressure vessel, the definition of the external geometry of the domes is fundamental since it is the most complex zone of the component. To generate the tridimensional geometry, a meridian curve was realized and then was rotated around a central axis. Referring to the European patent of isotensoid tanks obtained by filament winding process [14], this curve was defined by points through a spreadsheet in which input data of cylindrical zone diameter and length and opening end's diameter were inserted. The output information of this step was the meridian curve, which was than exported to a file compatible with the filament winding dedicated software CADWIND.

Filament Winding process simulation.

The simulation of filament winding process was performed using CADWIND software, which can simulate the winding process, based on a physical model, and calculate the fiber path and winding pattern (Fig. 2) [15]. After importing the geometry of the mandrel, composite laminates were created using different process parameters, which are listed in Table 2.

This allows to create a file to be imported in FEA software that reports information about the model mesh, and laminate stratification, orientation and thickness. With this model, the wound filament is considered perfectly straight and possible undulation and degradation of the composite mechanical properties are not considered [16].

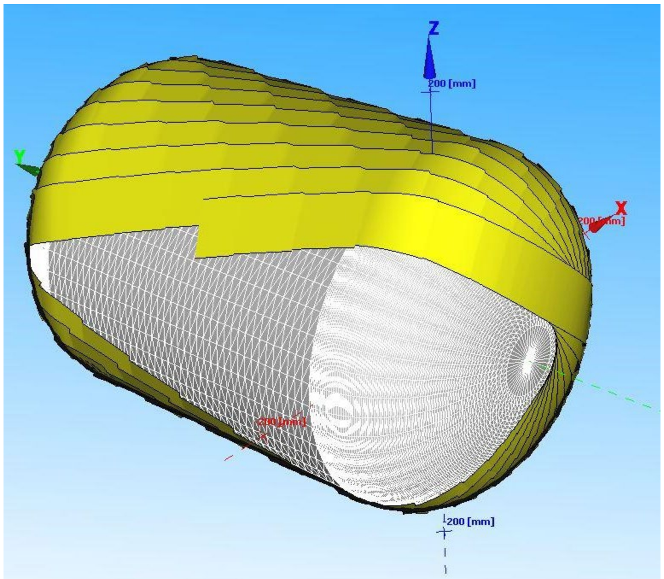


Fig. 2. Simulation of filament winding process performed using CADWIND software.

A friction factor equal to 0.3 was considered for the composite prepreg in the process simulation. The “Turning zone” represent the zone in which the filament orientation starts to change the winding angle in order to come back and wind the opposite mandrel side and the “Coverage” represents percentage of filament coverage on the mandrel. The associated values are defined to obtain a symmetric component avoiding a high overlap of the wound material that implicates a thickness increase. The material parameters are listed in Table 3.

Different external configurations of mandrels and stratification were tested in order to optimize the geometry of the vessel and the resistance to weight ratio.

An accurate choice of layering requires many considerations such as identifying the number of composite layers to deposit and defining the winding angle of each layer. The latter is fundamental, as the more the angle is reduced, the greater is tank’s area covered. The choice of the winding angle also influences the mechanical resistance of the component: if it is about 90°, the resistance to tangential stresses increases, while material layers with low values of winding angle better withstand axial stresses.

Table 2. Laminate parameters.

Laminaton	**Winding angle [°]**	**Turning zone front to**	**Turning zone back from**	**Coverage [%]**
1	10	20	105	102.1
2	15	14	111	133.3
3	20	8	117	107.0
4	25	5	120	102.1
5	30	7	118	130.1
6	35	5	120	122.8
7	40	6	119	147.1
8	45	9	116	153.6
9	50	12	113	150.2
10	55	15	110	140.3
11	60	17	108	120.7
12	65	27	98	123.8
13	70	30	95	188.2
14	75	35	90	155.5
15	80	41	84	162.2
16	85	40	85	184.7

Table 3. Material parameters.

TEX value (single roving) [g/km]	Bandwidth (single roving) [mm]	Fiber density [g/cm3]	Fiber volume fraction [%]	Fiber mass fraction [%]	Matrix density [g/cm3]	Resulting ply thickness [mm]
1000	6	1.8	56.5	68	1.1	0.16

Moreover, it is necessary to deposit some hoop layers after a defined number of helicoidal layers both to compact the underlying layers and to remove any resin's excess.

Once identified the layering to analyze, the FEM file created is imported on the software used to conduct FEM analysis.

Structural simulation of the pressure vessel.

In order to simulate the performances of the composite pressure vessel, the software Siemens NX was used, with the FEA NX Nastran solver. To this purpose, the file created in CADWIND was imported in NX to analyze the selected laminate. The model was imported as constituted by 2D shell elements with a defined laminate structure. The linear-elastic material mechanical properties were defined, and a structural linear simulation was carried out. The preliminary structural simulations of the pressure vessel conducted considering two fixed constraints on the most external frames, at the end of the domes.

Results and Discussions

Thickness distribution on pressure vessel.

The netting theory was used to evaluate the thickness distribution on layers with both hoop (~90°) and helical (variable θ) winding angles. The angle θ was continuously varied from 0° to 90°, and the resulting laminate thickness was registered. It was observed that by increasing the value of θ, the required thickness of helical layers increases while the number of hoop layers decreases.

For θ values between 54° and 55°, if constant internal pressure is considered, the total thickness value of the pressure vessel is minimized.

The resulting minimum total thickness of carbon fibers is about 10.18 mm, which is divided in 3.84 mm for helicoidal layers and 6.34 mm for hoop layers. Considering that netting theory evaluates only the fibers contribution and that fiber volume fraction is about 56.3%, the minimum thickness of total composite laminate is about 18.08 mm.

Pressure vessel model definition.

Based on pressure vessel dimensions, as described in section *Spreadsheet isotensoid theory*, a meridian curve that represents the external domes profile was obtained. The medium thickness of each layer depends on both the towpreg characteristics and the coverage percentage. In fact, in order to guarantee a good covering of the mandrel, the towpreg tends to overlap itself involving a greater coverage percentage than 100% on each layer. So, this confirm that the medium thickness of each layer which approximately various from 0.2 mm to 0.3 mm depends on the coverage percentage.

Considering these values and the results obtained by netting theory, to ensure that the tank operates safely at least 70 - 80 layers of towpreg are required. According to this information, the first layering tested was $[85_6/10_4/15_4/20_4/85_6/30_4/35_4/45_4/85_6]$.

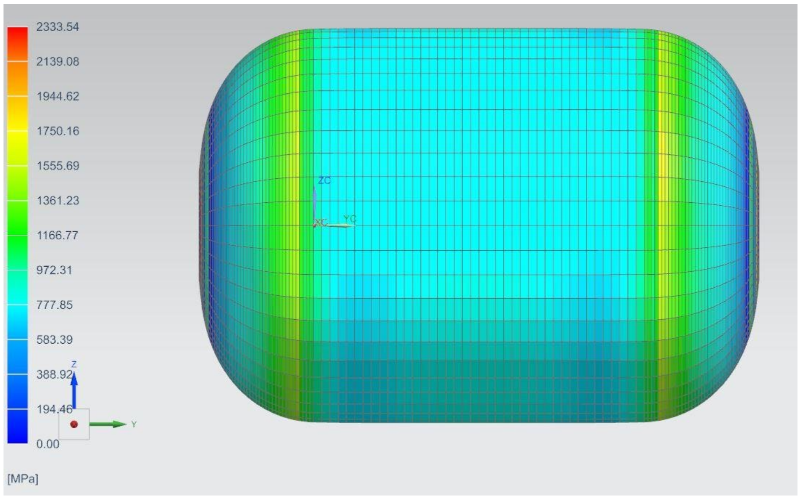
Table 4. Maximum stress and strain values of each reference layer.

Winding angle	**Maximum stress**		**Maximum strain**	
	Internal pressure 70 MPa	*Internal pressure 105 MPa*	*Internal pressure 70 MPa*	*Internal pressure 105 MPa*
85°	993 MPa	1500 MPa	0.004	0.006
10°	1290 MPa	2333 MPa	0.004	0.026
15°	899 MPa	1350 MPa	0.022	0.022
20°	788 MPa	1200 MPa	0.006	0.014
85°	990 MPa	1482 MPa	0.007	0.009
30°	720 MPa	1116 MPa	0.006	0.009
35°	800 MPa	1170 MPa	0.006	0.008
45°	820 MPa	1265 MPa	0.005	0.006
85°	992 MPa	1485 MPa	0.005	0.006

FEM simulations.

The mentioned layering was tested using both a service pressure of 70 MPa and a burst pressure of 105 MPa to analyze the pressure vessel structural response under bursting conditions. This laminate was characterized by 84 plies, a weight of 21 kg and a thickness of the cylindric zone of about 20 mm. To observe the resulting stress and strain values of the pressure vessel, the results obtained were analyzed considering a reference ply for each winding angle used in the laminate. Table 4 shows the maximum values of stress and strain along the fibers direction evaluated in each reference layers, imposing the different pressure values of 70 MPa and 105 MPa.

(a)



(b)

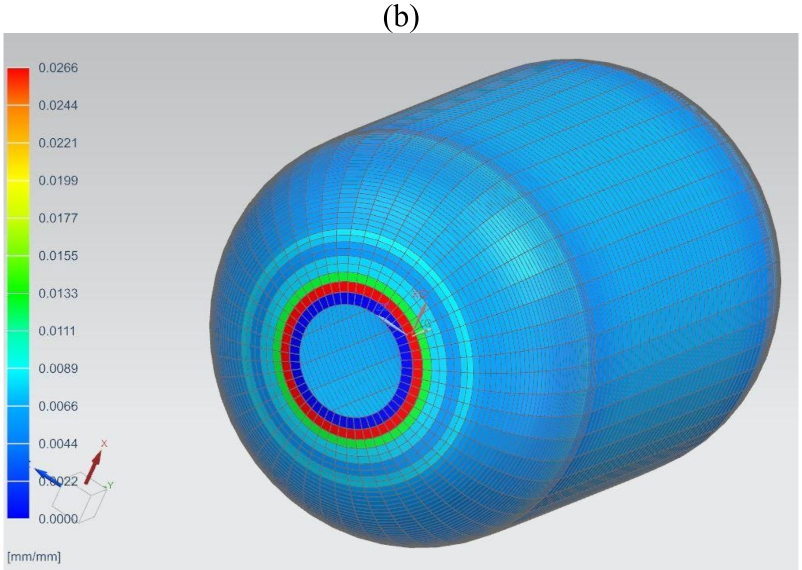


Fig. 3. (a) Strain and (b) stress distributions on the ply with 10° winding angle for the 105 MPa test.

Fig. 3 shows the strain and stress distributions on the ply with 10° winding angle obtained by CADWIND software simulations. As far as the stress values is concerned, Fig. 3b shows that the pressure vessel is in safe conditions also when internal burst pressure is applied; although there are some areas that are more stressed than others, they fall within the set limit values of 2500 MPa. For what concerns the strain values resulting from the service pressure analysis (Fig. 3a), the tank is generally in safe condition with the exception of the ends of external domes where the reached strain values are greater than the limit value of 0.007. As expected, it is noticed that stress and strain values resulting from the test performed using burst pressure (105 MPa) are greater than those obtained using the internal service pressure (70 MPa).

Summary

This study addressed the procedure used for the preliminary design and the structural analysis of a Type IV pressure vessel. The focus was both on the definition of external domes geometry and on the composite material used for the winding which confers the structural strength to the tank. The identified laminate sequence is chosen using CADWIND, a software which is dedicated to filament winding processes. Then it was analysed to verify its structural behaviour through Siemens NX FEA software. The main results are summarized below:

- According to netting analysis, the minimum value of total composite laminate thickness is about 18.08 mm. Considering the thickness of the cylindric zone, the netting theory provides results that are similar to those of the FEM simulations. However, more complex approaches are needed for the domes of the vessels.
- Using a spreadsheet and knowing pressure vessel's dimensions, the external domes isotensoid geometry was defined.
- Netting analysis combined with CADWIND allowed to determine the minimum number of layers to introduce on the layering, which is about 70 - 80 layers.
- The used laminate sequence is characterized by 84 plyes, a weight of 21 kg and a thickness of the cylindric zone of about 20 mm.
- The FEM analysis shows that the tank tested using an internal pressure of 70 MPa is in safe conditions in terms of stress and strain except for some criticalities on the ends of the external domes.
- Instead, the tank tested using an internal pressure of 105 MPa is in safe conditions in terms of stress only: strain values are higher than the limit on almost all layers analyzed.

This study can be considered as a starting point to optimize the layering through an iterative process. In this way it is possible to obtain a pressure vessel which is in safe conditions also considering strain values. Moreover, the procedure here presented can be used as a reference point for the design of filament wound components with different mandrel geometry. Future works could focus on a further optimization of the composite lamination by means of localized reinforcement (i.e. composite patches) that provides increased strength in the highest stress regions while reducing the number of laminate layers and the overall part weight. The FEM results will be validated by means of pressure test to determine the quality of the lamination and the proposed design procedure.

Acknowledgement

This research was supported by the Italian Ministry of University and Research (MUR, Ministero dell'Università e della Ricerca) within the National Operational Programme on Research and Innovation 2014-2022 (Programma Operativo Nazionale "Ricerca e Innovazione" 2014-2020 (PON "R&I" 2014-2020) - area di specializzazione "Fabbrica Intelligente") project "SMART TOW WINDING Nuove soluzioni ad elevata automazione per l'impregnazione e avvolgimento di Tow" (CUP: B19C20000340005, ARS01_00871).

References

[1] I. Bianchi, S. Gentili, L. Greco, M. Simoncini, Effect of graphene oxide reinforcement on the flexural behavior of an epoxy resin, Procedia CIRP 112 (2022) 602-606. https://doi.org/10.1016/J.PROCIR.2022.09.057

[2] A. Forcellese, T. Mancia, M. Simoncini, S. Gentili, M. Marconi, A. Vita, A. Nardinocchi, V. Castorani, Comparative life cycle assessment of carbon fiber reinforced composite components for automotive industry, ESAFORM 2021 - 24th Int. Conf. Mater. Form. (2021). https://doi.org/10.25518/ESAFORM21.2542

[3] A. Forcellese, T. Mancia, A.C. Russo, M. Simoncini, A. Vita, Robotic automated fiber placement of carbon fiber towpregs, Mater. Manuf. Process. 37 (2021) 539-547. https://doi.org/10.1080/10426914.2021.1885706

[4] F. Henning, L. Kärger, D. Dörr, F.J. Schirmaier, J. Seuffert, A. Bernath, Fast processing and continuous simulation of automotive structural composite components, Compos. Sci. Technol. 171 (2019) 261-279. https://doi.org/10.1016/j.compscitech.2018.12.007

[5] A. Vita, V. Castorani, M. Germani, M. Marconi, Comparative life cycle assessment and cost analysis of autoclave and pressure bag molding for producing CFRP components, Int. J. Adv. Manuf. Technol. 105 (2019) 1967-1982. https://doi.org/10.1007/s00170-019-04384-9
[6] R.C. Hibbeler, Mechanics of materials, Pearson Prentice Hall, 2011.
[7] F. Daghia, E. Baranger, D.T. Tran, P. Pichon, A hierarchy of models for the design of composite pressure vessels, Compos. Struct. 235 (2020) 111809. https://doi.org/10.1016/j.compstruct.2019.111809
[8] C.P. Fowler, A.C. Orifici, C.H. Wang, A review of toroidal composite pressure vessel optimisation and damage tolerant design for high pressure gaseous fuel storage, Int. J. Hydrogen Energy. 41 (2016) 22067-22089. https://doi.org/10.1016/J.IJHYDENE.2016.10.039
[9] H. Barthélémy, Hydrogen storage - Industrial prospectives, Int. J. Hydrogen Energy. 37 (2012) 17364-17372. https://doi.org/10.1016/J.IJHYDENE.2012.04.121
[10] H.S. Roh, T.Q. Hua, R.K. Ahluwalia, Optimization of carbon fiber usage in Type 4 hydrogen storage tanks for fuel cell automobiles, Int. J. Hydrogen Energy. 38 (2013) 12795-12802. https://doi.org/10.1016/J.IJHYDENE.2013.07.016
[11] P. Boisse, R. Akkerman, P. Carlone, L. Kärger, · Stepan, V. Lomov, J.A. Sherwood, Advances in composite forming through 25 years of ESAFORM, Int. J. Mater. Form. 1 (2022). https://doi.org/10.1007/s12289-022-01682-8
[12] E. Lainé, J.C. Dupré, J.C. Grandidier, M. Cruz, Instrumented tests on composite pressure vessels (type IV) under internal water pressure, Int. J. Hydrogen Energy 46 (2021) 1334-1346. https://doi.org/10.1016/J.IJHYDENE.2020.09.160
[13] G. Verchery, The netting analysis as a limit case of the laminated structure, Mater. Sci. (2013)
[14] J.C. Murphy, Filament-wound isotensoid pressure vessels having geodesic domes, European Patent EP0714753A2 (1995).
[15] C. Laval, CADWIND 2006 - 20 years of filament winding experience, Reinf. Plast. 50 (2006) 34-37. https://doi.org/10.1016/S0034-3617(06)70913-4
[16] C. Shen, X. Han, Damage and failure analysis of filament wound composite structure considering fibre crossover and undulation, Adv. Compos. Lett. 27 (2018) 55-70. https://doi.org/10.1177/096369351802700202