Materials Research Proceedings 41 (2024) 2861-2870 https://doi.org/10.21741/9781644903131-313

Sustainability and economic assessment of an innovative automated filament winding process

BIANCHI Iacopo[1,a], DE PRISCO Nello[2,b], MANCIA Tommaso[1,c], MARTONE Alfonso[2,d], PALMIERI Barbara[2,e], SIMONCINI Michela[1,f], VERDINI Tommaso[1,g*]

[1]Università Politecnica delle Marche, Via Brecce Bianche 12, 60123 Ancona, Italy

[2]Advanced Tools and Moulds, A.T.M. srl, Via San Pasquale a Chiaia, 83, 80121 Napoli, Italy

[a]i.bianchi@pm.univpm.it, [b]nellodeprisco@atmsrl.com, [c]t.mancia@staff.univpm.it, [d]alfmartone@gmail.com, [e]barbara.palmieri@atmsrl.com, [f]m.simoncini@staff.univpm.it, [g]t.verdini@pm.univpm.it

Keywords: Filament Winding, CFRP, LCA, LCC

Abstract. The present paper aims at studying the environmental and economic impacts of an innovative Filament Winding (FW) process used to realize a tubular shape structural component in Carbon Fiber Reinforced Polymer (CFRP). To this purpose, the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies were applied using a "from cradle to grave" approach. Specifically, a towbar used for aircraft pushback was considered as case study. All phases of the life cycle of the analyzed component were included (from the raw materials extraction to the disposal phase). The comparison between the CFRP towbar investigated and a traditional one in aluminum alloy was performed. The LCC analysis was conducted by considering all costs associated with the automated filament winding process, from the initial investment costs. For all the considered impact categories, the CFRP towbar showed the lowest environmental impacts, mainly due to both the reduced weight and service life fuel consumption. The cost and carbon footprint of the innovative component were associated with raw materials use.

Introduction

Carbon Fiber Reinforced Polymers (CFRP) are gaining an increasing interest in many industrial fields, such as aerospace, automotive, biomedical, nautical and construction. Such materials are highly indicated for applications in which low weights and high mechanical performances are required. As a matter of fact, due to the higher specific properties of composites, weight reduction can be achieved while maintaining the same performance of traditional material components.

Among the processes carried out in CFRPs, Filament Winding (FW) represents a valuable solution for automated production of axisymmetric components. FW is a technology based on the winding of impregnated continuous fibers on a rotating mandrel [1]. By winding several layers of material at defined angles and following precise paths, high performance structures, such as pipes, tubes, pressure vessels, shafts and rotor blades, can be produced [2,3]. This technology can help overcome the issues related to labour intensive and expensive phases of traditional composite manufacturing techniques by completely automating the lay-up phase. In fact, high labour costs and long production time are common issue in different composite manufacturing technologies such as autoclave and vacuum bag molding [4]. These aspects are critical on an industrial level and can limit the spread of composite material use. Hence, FW can represent a relevant improvement with respect to other composite manufacturing techniques; as a matter of fact, automated fiber deposition methods could help to reduce the costs of composite parts, making them more competitive market alternatives.

In this contest, MIUR (Ministry of Education, University and Research) is funding the research project titled "Smart Tow Winding", involving the Marche Polytechnic University and ATM srl, concerning the development of an innovative process for the fabrication of composite components through filament winding technology characterized by increased performances and improved sustainability and cost with respect to traditional metal parts. The main outcome of the project is the development of an innovative CFRPs towbar for airplanes and helicopters pushback. Towbars are designed to connect a pushback vehicle to the front landing gear of aircrafts in order to safely maneuver them on the ground and prepare them for takeoff or push them back to the gates. They are traditionally realized in metals (e.g. low-carbon steels and aluminum alloys) but composite materials such as CFRPs produced via filament winding can be a valuable alternative to provide weight reduction while maintaining the same stiffness and safety factor [5].

From an environmental sustainability perspective, the weight reduction provided by CFRPs can help reduce fuel consumption and emissions associated with the service life of transport sectors components. However, composite parts manufacturing is typically characterized by high carbon footprint due to energy intensive processes for raw materials production (i.e. resin and carbon fibers) and molding processes [6]. These processes could counterbalance the benefits associated with weight reduction in terms of emissions reduction. For this reason, a Design for Environment approach is required to ensure that innovative composite parts are not only a valuable solution from a mechanical performance point of view but also in terms of sustainability. For the present case study, a detailed analysis of the economic and environmental impacts of composites and FW is crucial to ensure a sustainable development of the innovative towbar.

At present, several literature analyses investigated the possibilities in FW processes by considering, for example, sustainable materials, improved deposition trajectories and designs [7–9]. Few sustainability assessments concerning filament wound products can be found in literature; Schneider et al assessed the environmental impacts of CFRPs preform for ceramic matrix composites production via FW [10]. Rasheed et al compared FW and pultrusion processes for the production of glass-fiber composites from both economic and environmental perspectives [11]. Mindermann et al investigated the structural performances and sustainability of different natural fibers composites realized via FW [12]. However, literature lacks of studies concerning the design and life cycle analyses of high performance composite wound components employed as substitutes for traditional metal parts. Detailed evaluations of innovative production processes and comparison with traditional systems are required to determine possible criticalities and improvements of new products. In addition, cost analyses for CFRPs are required to provide industrial decision-making tools.

In this framework, the present paper concerns the design and environmental and economic sustainability of a CFRP towbar for aircraft pushback produced using an automated FW system and comparison with traditional metal towbar. An initial design phase was conducted on the composite part using different simulation software and the obtained data were employed in comparative Life Cycle Assessment and Life Cycle Costing analyses

Materials and Method

The first phase of this work concerned the design phase of an innovative composite towbar for aircraft pushback. The considered towbar has a length equal to 3000 mm and a circular cross section with a constant diameter of 80 mm. This component can be used to maneuver a 6000 kg helicopter. The part is essentially subjected to two possible load conditions: tensile loads related to the aircraft acceleration and compressive load associated with the braking phase. The maximum load value is equal to 177 kN and it can be calculated considering the aircraft weight, a impact load factor equal to 2 and a safety factor equal to 1.5. Data related to the components dimensions and structural requirements were provided by the industrial experts. The traditional steel towbar has a wall thickness equal to 3.6 mm and a total weight of 28.92 kg. The goal of the design phase is to determine a composite material layering for the towbar able to withstand the defined load and with a reduced weight with respect to the traditional component. To this purpose, an iterative design phase similar to that presented in previous literature was followed [13].

The composite part is produced by filament winding using a towpreg constituted by carbon fibers (68%wt) and an epoxy resin matrix (32%wt); starting from the constituents datasheets, the composite material mechanical properties were calculated using mixture rules (Table 1).

Table 1 Mechanical properties of the considered materials

	Carbon fiber	Epoxy resin	Composite material
Elastic modulus (E)	230 GPa	3500 MPa	75 GPa
Ultimate Tensile Strenght (	4900 MPa	73 MPa	750 MPa
Density (ρ)	1.8 g/cm^3	1.1 g/cm^3	1.5 g/cm^3

In accordance with previous literature, an iterative procedure based on the use two software was followed to define the composite layers number and orientation [13]. CADWIND was employed to create virtual models of composite layers with different winding angles. The software allows to simulate the filament winding process and calculate fiber paths and winding patterns. This also allows to create meshed models that represent the composite part and can be simulated in Finite Element Method (FEM) software considering parameters such as winding angles, bandwidth and number of layers [14]. The models created in CADWIND were imported in Siemens NX FEM software to simulate their structural response in a static structural solution (SOL 101). The previously defined compressive and tensile loads were applied to the structure and the stress and strain in each composite layer were obtained. Maximum stress and strain criteria (i.e. max strain equal to 0.007) were employed to determine whether or not the layering satisfied the structural requirements. In addition, buckling and fatigue resistance verifications were conducted. The final part configuration was obtained iteratively, by analyzing the output of the FEM simulations and changing the layer number (and therefore the part thickness) and orientation consequently. The design phase was also crucial for the Life Cycle Analyses as it provided primary data regarding the component material use and production phases.

Life Cycle Assessment

In order to evaluate the environmental effects of the CFRP towbar and to compare them to those of the traditional aluminium component, the standardized methodology outlined in the UNI EN ISO 14040-44 standard was applied.

Goal and scope definition

The present LCA analysis aims at quantifying the environmental impact of a composite materials towbar and comparing them to a commercial aluminium towbars. The functional unit (FU) is defined as the production and use of a towbar used to transport helicopters for 100000 pushback operations, with an average operation length of 1 km and an average speed of 9 km/h. The present analysis can be classified as "from cradle to grave" as it includes input and output from the extraction of raw materials to the final use of the components. Figure 1 shows all the cycle phases included in the study.

Hence, two scenarios were considered: Scenario 1 concerns the production of the CFRP towbar by means of a FW process; it includes raw materials production (carbon fibers and resin), prepregging phases, aluminium mandrel production, FW, curing and use phase. On the other hand, Scenario 2 deals with the production of an aluminum towbar; this scenario includes the extrusion of an aluminium circular tube, sandblasting, surface cleaning, powder coating to provide corrosion resistance and service life emission.

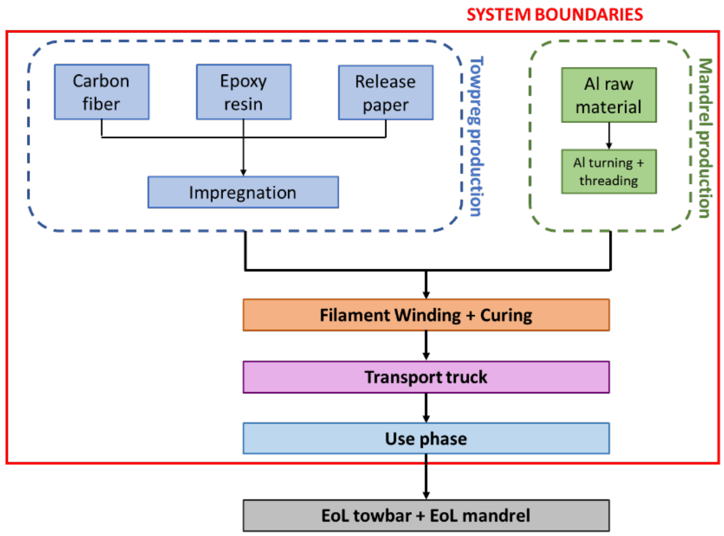

Figure 1 System boundaries of the LCA analysis of a CRFP towbar

Life Cycle Inventory (LCI)

Both primary and secondary data were employed for the LCI phase. Previous literature analyses and commercial database were used as secondary data source.

- Transport of fiber and epoxy resin was retrieved by the study conducted by Forcellese et al. [15];
- CF production was modelled according to Forcellese et al [15]; towpreg was considered to be constituted by 60%wt (in weight) by CF and 40%wt by epoxy resin;
- Preimpregnation process energy and material use (electric energy, raw materials use, consumables, release paper) was modelled according to Postacchini et al. [16];
- Energy consumption for the filament winding process for towbar production was taken from literature [17];
- "Curing phase" was modelled according to Forcellese et al. [15].
- The quantity of aluminium used for the mandrel construction was estimated considering its final dimensions and the amount of material removed by chipping operations; the data regarding the mandrel (e.g. weight and volume) were obtained from the part CAD model. It was assumed that it has a service life of 100 cycles;
- Starting from a commercial extruded bar in aluminium alloy, the mandrel was produced by means of turning operation. In addition, threading for attachment to the winding machine was considered. Machining operations were modelled considering the Ecoinvent database.
- The amount of material removed during threading of the aluminium mandrel was 50% of the chip previously produced during turning;

The defined service life of the FU and the average consumption value of a tug were used for the use phase modelling. The fuel consumption emissions were allocated to the functional unit considering its weight in each scenario.

Life cycle impact assessment (LCIA)

The impact categories used in this LCA analysis are ReCiPe and Global Warming Potential (GWP). ReCiPe provides a complete overview of environmental effects of products or processes, by considering 18 midpoint impact categories, whilst GWP quantifies the GreenHouse Gases (GHG) emission in the atmosphere and evaluates how they effect to global warming and climate change.

Table 2 Relevant LCI data

Mandrel production phase		
Aluminium quantity	31.60	kg
Aluminium removed by turning	0.07	kg
Aluminium removed by threading	0.03	kg
Preimpregnation phase		
Towpreg meter	5874.70	m
Carbon fiber quantity	1.02	g/m
Epoxy resin quantity	0.48	g/m
Acetone (polishing)	0.02	g/m
Polypropylene (release paper)	0.55	g/m
Freezer storage towpreg		
Electricity	7.50	kWh
Filament winding		
Kg CFRP	8.81	kg
Electricity	3.50	Wh/kg
Curing phase		
Electricity	9.54	KWh
Nylon 66 (vacuum bag)	0.28	kg
PET (breather)	0.21	kg
PTFE (release film)	0.031	kg
Organic solvent (release agent)	0.17	kg
Use Phase		
Electricity	36.3	kWh
Transport phase		
CF transport, ferry	1010	kgkm
CF transport, truck	899	kgkm
ER transport, truck	3830	kgkm
Mandrel transport, truck	2530	kgkm
Towbar transport, truck	204	kgkm

Life Cycle Costing

LCC summarizes the costs associated with all the life cycle phases of a product that are directly calculated starting from one are more cost factors in that life cycle. LCC follows a methodology similar to LCA, involving the establishment of FU and system boundaries [18].

The present LCC analysis aims at quantifying the costs associated with a CFRP towbar life cycle. In this case, FU and system boundaries are same as those used in previous LCA analysis.

Both primary and secondary data were employed for the cost evaluation. Lean Cost software was used for the evaluation of the mandrel costs and literature analyses were used for all other phases. Towpreg commercial cost per kg was considered in this analysis. For the filament winding phase, energy, material, labour, machine depreciation and maintenance, mandrel production costs were included. A service life of 100 cycle was considered for the mandrel in order to allocate its production cost to the FU [4]. The curing phase included energy, material, labour and autoclave costs [19]. Finally, in the refrigerated storage phase and use phase only include cost resulting from energy consumption (the depreciation costs of the freezer attributable to the material needed for the towbar construction are negligible).

Results and discussion

Preliminary FEM analyses were conducted considering single layers with different winding angles (from 20° to 85°) subjected to tensile load. Lower winding angles provide higher tensile stiffness and strength whit lower structure weight. In fact, due to anisotropic properties of towpregs, it is better to align the fibers along the load direction to improve the structural response of the composite part. Hence, focus was given to layering with the majority of low winding angle layers. Layers with angle close to 90° were also used as they provide high layers compaction during the production process. After several iterations, the final symmetrical layering was defined as follows:

$$[85/20/20/20/30/30/30/20/20/30/30/\overline{85}]_s$$

For this configuration, the maximum stress registered in the static structural simulation is equal to 193 MPa and it is lower than the ultimate tensile strength of the composite material (750 MPa). For what concerns the buckling simulation, the load the triggers the elastic instability is about 1.7 times higher than the applied load; hence, compressive loads do not result critical for the component. Similarly, the obtained maximum stress is below the fatigue limit of the material hence infinite life is expected. The obtained configuration leads to a towbar total weight equal to 9 kg, about a quarter of the equivalent components realized in aluminum alloy.

Sustainability assessment results

Figure 2 shows the LCIA results in terms of GWP for the considered scenarios. The CFRP towbar resulted the most sustainable solution, with total impacts about 65% lower than those of the commercial aluminium towbar (i.e. 318 kg CO2 eq vs 915 kg CO2 eq). The most impactful phase for the CFRP towbar is the prepregging phase (i.e. 261 kg CO2 eq, about 82% of the total). This is mainly due to the production process of the carbon fiber PAN-precursor required for the prepreg, as it includes the time consuming and energy intensive stabilization process. To reduce the environmental impacts in this phase bio-precursors like cellulose or lignin can be used. To increase the sustainability of CFRP recyclable thermoplastic resins could be employed as substitution for thermosetting epoxy resin. FW process is associated with negligible impacts, making this highly automated technology recommended to produce tubular components or vessel. Similarly, the materials used for the vacuum bag and the energy required for the polymerization of the towbar in the curing phase have low impacts. Towpreg refrigerated storage has negligible influence on the total impacts.

The most relevant phase in the Al towbar scenario is the extrusion process, which includes the extraction and production of raw aluminium and the extrusion process. Due to the energy consumption required for Al extraction, this phase accounts for about 90% of the total scenario impacts. The use phase of the Al towbar is associated with higher emissions if compared to CFRP towbar (i.e. 57 kg CO2 eq vs 13 kg CO2 eq). In fact, the weight reduction provided by the composite part leads to a decrease in energy consumption required for aircraft transport.

Figure 3 shows the comparison between impacts of the CFRP and Al towbars according to 18 ReCiPe midpoint categories. Data were normalized (i.e. divided for a reference impact value) and made dimensionless. As for GWP, CFRP towbar has the lowest life cycle impact in most of the midpoint categories. The CFRP towbar has a high impact in the Marine Ecotoxicity category due to air emissions of chemicals (particularly hydrogen cyanide) associated with carbon fibers production. The aluminium towbar has high impact on climate change due to the production of the raw material, which requires large amounts of energy for the electrolysis of alumina. In addition, it emits greenhouse gases contributing to global warming and may be associated with forest destruction for bauxite extraction. Since the energy for aluminium production comes from fossil sources, such as coal or oil, aluminium production also has a significant impact on the category “fossil depletion”, referring to the consumption of fossil resources with resulting economic and environmental consequences. To reduce environmental impacts is important to promote the adoption of renewable sources and aluminium recycling for secondary aluminium production.

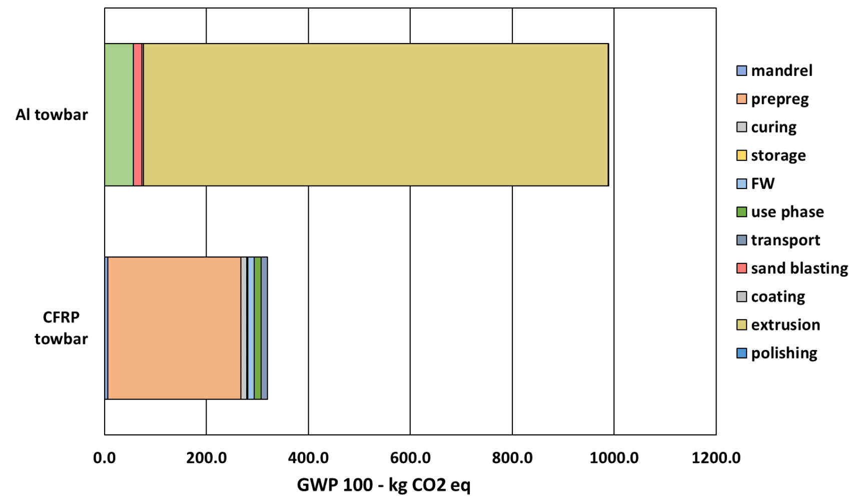

Figure 2 results and phases impact contributions for the two towbars

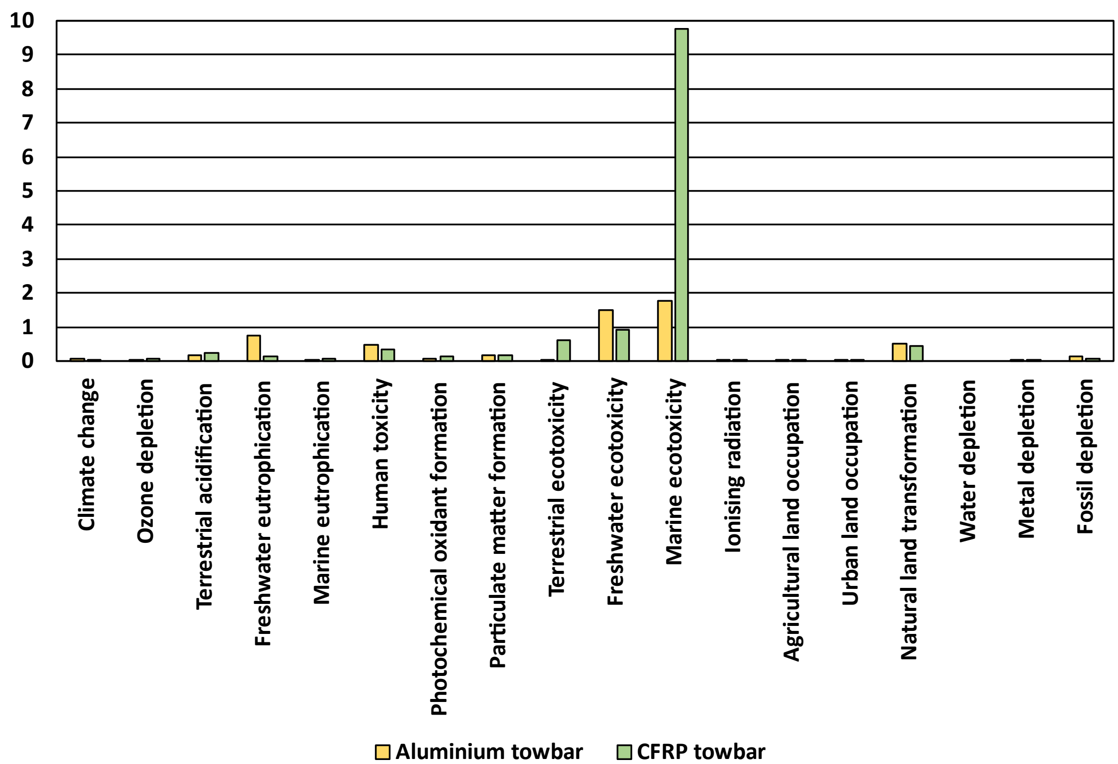

Figure 3 comparison between impacts of the CFRP and Al towbar according to ReCiPe midpoint categories

Life Cycle Costing results

LCC results are presented in Table 3 and Figure 4. As can be observed in Figure 4, the highest cost contribution is attributed to material purchase (i.e. 344€); specifically, around 90% of this category is due to the cost of the towpreg (i.e. 326 €). Another significant cost factor is labor (125€), which requires a high level of expertise for the filament winding process and molding and demolding phases of autoclave curing. Energy cost and machinery cost are similar; the latter includes maintenance and depreciation cost of machines over their service life. These costs were allocated to the functional unit considering the required production time and the machines service life. The total cost is the sum of all cost factor and amounts to 522.70€.

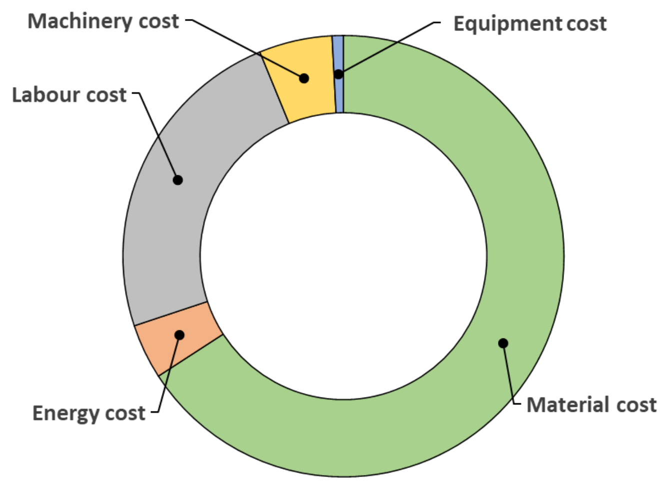

Figure 4 cost breakdown of CFRP towbar

Table 3 Cost evaluation

Mandrel		
Mandrel cost (calculated by Lean Cost)	431.69	€
Filament Winding Phase		
Energy cost	8.20	€
CFRP towpreg cost	326.05	€
Labour cost	80.00	€
Machining (machine cost + maintenance)	24.63	€
Mandrel (for each cycle of service life)	4.32	€
Freezer Storage Towpreg Phase		
Energy cost	1.57	€
Freezer (machine + maintenance)	0.04	€
Curing phase		
Energy cost	4.30	€
Labour cost	45.00	€
Ny 66 cost (vacuum bag)	2.04	€
PET cost (breather)	2.81	€
PTFE cost (release film)	0.13	€
Organic solvent cost (release agent)	13.20	€
Autoclave	3.39	€
Use Phase		
Energy cost	7.06	€

Conclusions and further developments

This paper presents the design and life cycle analyses of a CFRP towbar and comparison with traditional component. FEM software, LCA and LCC methodologies were employed to conduct the study. The main findings of the analysis are reported as follows:

- Overall, the final composite layering as defined as:

$$[85/20/20/20/30/30/30/20/20/30/30/\overline{85}]_s$$

- This leads to a composite part that weighs 9 kg, about a quarter of the traditional aluminum component (36 kg). This layering has stress value within material limits and has sufficient fatigue and buckling resistance.
- The CFRP towbar resulted in lower impacts with respect to the aluminum one in terms of both GWP and ReCiPe midpoint categories (e.g. 318 kg CO_2 eq vs 915 kg CO_2 eq). In

both cases, raw materials production resulted the most relevant contributor to the total impacts.
- The total CFRP towbar cost is equal to 522.70€; the largest cost factor is attributed to materials purhcase (344€).
- In future studies, different polymeric matrixes and reinforcement (i.e. thermoplastic polymers and natural fibers), could be considered as possible sustainable alternatives to reduce the environmental and economic impacts of the filament wound CFRP towbar. In addition, economic comparison with traditional alternatives could also be included.

Acknowledgements
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] M.A. Mateen, D.V. Ravi Shankar, M. Manzoor Hussain, Design and development of low cost two axis filament winding machine, Journal of Advanced Manufacturing Technology. 12 (2018) 117–126.

[2] M. Azeem, H.H. Ya, M. Kumar, P. Stabla, M. Smolnicki, L. Gemi, R. Khan, T. Ahmed, Q. Ma, M.R. Sadique, A.A. Mokhtar, M. Mustapha, Application of Filament Winding Technology in Composite Pressure Vessels and Challenges: A Review, J Energy Storage. 49 (2022) 103468. https://doi.org/10.1016/J.EST.2021.103468

[3] Ö.S. Sahin, A. Akdemir, A. Avci, L. Gemi, Fatigue crack growth behavior of filament wound composite pipes in corrosive environment, Journal of Reinforced Plastics and Composites. 28 (2009) 2957–2970. https://doi.org/10.1177/0731684408094068

[4] 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, International Journal of Advanced Manufacturing Technology. 105 (2019) 1967–1982. https://doi.org/10.1007/S00170-019-04384-9/FIGURES/12

[5] S. wen Chen, H. Liu, F. hai Li, Analysis of Boeing 737 aircraft towing accidents, Eng Fail Anal. 80 (2017) 234–240. https://doi.org/10.1016/J.ENGFAILANAL.2017.06.024

[6] S. Das, Life cycle assessment of carbon fiber-reinforced polymer composites, International Journal of Life Cycle Assessment. 16 (2011) 268–282. https://doi.org/10.1007/s11367-011-0264-z

[7] G.D. Shrigandhi, B.S. Kothavale, Biodegradable composites for filament winding process, in: Mater Today Proc, 2021: pp. 2762–2768. https://doi.org/10.1016/j.matpr.2020.12.718

[8] W. Polini, L. Sorrentino, Design of winding with two rovings for cost efficiency and quality in robotized filament winding, in: Proceedings of the ASME Design Engineering Technical Conference, 2003: pp. 177–186. https://doi.org/10.1115/detc2003/dfm-48151

[9] E. Wilson, C. Karr, S. Messimer, Genetic algorithm optimization of a filament winding process modeled in WITNESS, Materials and Manufacturing Processes. 18 (2003) 509–521. https://doi.org/10.1081/AMP-120022025

[10] T. Schneider, L. Wietschel, D. Schüppel, J. Riesner, K. Konrad, A. Thorenz, A. Tuma, D. Koch, Multicriteria optimization as enabler for Sustainable Ceramic Matrix Composites, Int J Appl Ceram Technol. 19 (2022) 3247–3254. https://doi.org/10.1111/IJAC.14174

[11] R. Rasheed, I. Anwar, F. Tahir, A. Rizwan, H. Javed, F. Sharif, Techno-economic and environmental sustainability analysis of filament-winding versus pultrusion based glass-fiber composite technologies, Environmental Science and Pollution Research. 30 (2023) 36276–36293. https://doi.org/10.1007/S11356-022-24817-5/FIGURES/10

[12] P. Mindermann, M.G. Pérez, J. Knippers, G.T. Gresser, Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding, Volume 15, Issue 9. 15 (3260). https://doi.org/10.3390/ma15093260

[13] B. Iacopo, F. Archimede, G. Francesco, G. Luciano, M. Chiara, T. Giulio, Process and structural simulation for the development of a pressure vessel through filament winding technology, Materials Research Proceedings. 28 (2023) 347–356. https://doi.org/10.21741/9781644902479-38

[14] C. Laval, CADWIND 2006 – 20 years of filament winding experience, Reinforced Plastics. 50 (2006) 34–37. https://doi.org/10.1016/S0034-3617(06)70913-4

[15] A. Forcellese, M. Marconi, M. Simoncini, A. Vita, Life cycle impact assessment of different manufacturing technologies for automotive CFRP components, J Clean Prod. 271 (2020). https://doi.org/10.1016/j.jclepro.2020.122677

[16] L. Postacchini, M. Simoncini, A. Forcellese, M. Bevilacqua, F.E. Ciarapica, G. Andreassi, A.C. Russo, Environmental assessment of an automated impregnation process of carbon fiber tows, in: Procedia CIRP, 2020: pp. 445–450. https://doi.org/10.1016/j.procir.2020.05.077

[17] A. Benitez, C. Wulf, A. de Palmenaer, M. Lengersdorf, T. Röding, T. Grube, M. Robinius, D. Stolten, W. Kuckshinrichs, Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fiber hydrogen tank, J Clean Prod. 278 (2021). https://doi.org/10.1016/j.jclepro.2020.123277

[18] W. Kloepffer, Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95), International Journal of Life Cycle Assessment. 13 (2008) 89–95. https://doi.org/10.1065/LCA2008.02.376/METRICS

[19] R. Tong, Cost Analysis on L-shape Composite Componenet Manufacturing, in: 2012. https://api.semanticscholar.org/CorpusID:167899775