Review Paper

A cross-sectoral review of the current and potential maintenance strategies for composite structures

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Abstract

The interest in the use of composite materials in thin-walled structures has grown over the last decades due to their well-known superior mechanical performance and reduced weight when compared with traditional materials. Notwithstanding, composite structures are susceptible to damage during manufacturing and to fatigue degradation during service, which grants inspection and maintenance strategies outstanding importance in the duty of mitigating premature failures and reducing whole life cycle costs. This paper aims to provide a cross-sectoral view of the current and potential maintenance strategies that are drawing the attention of the different industries and researchers by reviewing the current use and limitations of composites structures, the impact of maintenance in the whole-life cycle of the composite structures, the health and condition monitoring techniques applied, and the benefits and limitations of the currently used and potential maintenance strategies. Finally, the health and condition monitoring techniques and maintenance approaches used by the different industries are contrasted to identify trends and divergences and suggest research gaps and industrial opportunities.

Keywords Polymer–matrix composites (PMCs) · Composite structures · Structural Health Monitoring (SHM) · Maintenance · Cyber-physical structures (CPS)

Abbreviations

CBM	Condition-based maintenance
CFRP	Carbon-fiber-reinforced polymer
CPS	Cyber-physical structures
FPN	Fuzzy petri nets
FRP	Fiber-reinforced polymer
I&M	Inspection & maintenance
iPHM	intelligent PHM
LCOE	Levelized cost of energy
O&M	Operation & maintenance
PdM	Predictive maintenance
PHM	Prognostics and health management
PMCs	Polymer–matrix composites
PNs	Petri nets
PPNs	Plausible petri nets
PvM	Preventive maintenance
PWAS	Piezoelectric wafer active sensors
ROI	Return on investment
RUL	Remaining useful life
SCADA	Supervisory control and data acquisition
SDGs	Sustainable Development Goals

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1 Introduction

The commitment towards global sustainable development was signed by all United Nations Member States in 2015 and resulted in the 2030 Agenda for Sustainable Development.[1] This agreement is based on 17 Sustainable Development Goals (SDGs) which target the most critical issues that we need to face as a society. Fiber-reinforced polymer (FRP) composite materials are high-efficiency and high-durability lightweight materials that have the potential to positively impact several SDGs driving a change towards sustainability. Notwithstanding, a paradigm shift in the use of these advanced materials by the different industries is challenged by several issues, among which the following stand out: uncertainty about long-term damage behaviour and reliability [1], inadequacy or absence of design standards in several industries, lack of technological demonstrators [2], unreliable manufacturing [3], shortage of long-term durability data [4, 5], high material costs [6], and recyclability issues [7, 8]. These issues mainly derive from an immature knowledge about the optimal monitoring and maintenance strategies throughout the lifetime of these materials within a healthy balance between safety and cost for safety-critical applications. Hence, the use of composite materials by the different industries is still dissimilar, depending on their attitude towards risk and their expectancy about the use of composites.

These reasons call for cross-sectoral research and development approaches to overcome the constraints of each of the industries with the knowledge and experience of the others. The more profound knowledge and technology development of the aerospace industry in the use of composite structures along with the extensive experience of lower risk industries such as the automotive and wind energy can be utilised in favour of less developed industries such as the civil and naval. In general, we can envisage that the (open) data and knowledge provided by the more advanced industries will boost the adoption of composites materials by increasing the confidence of the stakeholders of different industries to design, produce, manage and utilise composite structures. However, finding common grounds and knowledge to overcome the particularities of each type of industry is a significant challenge, which, to the authors' best knowledge, has not been tackled before in the open literature. This work represents a first step in this direction.

In particular, this paper provides a cross-sectoral overview of the potential and limitations of different maintenance technologies and operation strategies for thin-walled composite structures through the analysis of their role in four key industries, namely: aerospace, wind energy, civil and naval. These industries are currently employing FRP materials in their applications [9], and accrue a high percentage, between 50 and 60%, of the total use of carbon-fiber-reinforced polymers [10]. To this end, a cross-sectoral maturity analysis is firstly provided by means of a *maturity index* which measures and ranks the position of the refereed industries in the use of composites. Next, the possibilities brought about by the recent advances in Structural Health Monitoring (SHM) across industries are investigated in application to the inspection and monitoring of composite structures. Finally, an overview about the different maintenance strategies suitable for composite structures and their impact across the industries is analysed. In essence, this research has revealed that, although relevant developments have been carried out in the field of SHM [11–16] and more recently in the field of Prognostics and Health Management (PHM) in application to composite structures [17–21], these have not yet been translated into optimised and predictive maintenance strategies. In this context, the development of predictive maintenance strategies for composite structures assisted by PHM technologies and Physics-Enhanced Artificial Intelligence methods have been concluded as a key element to boost the adoption of composites across industries by reducing the uncertainty surrounding their future performance and reliability [22]. This predictability allows inspection and maintenance strategies to be tailored for a particular structure, which, in turn, translates into an extended lifetime and therefore increased sustainability. In this context of sustainability, evidence is shown here through a quantitative analysis that composites across the different industries can significantly contribute to two important SDGs, in particular, SDG 7 (*Affordable and Clean Energy*) and SDG 9 (*Industry, Innovation and Infrastructure*).

The rest of the paper is structured as follows. First, Sect. 2 identifies the current use and limitations of plate-like composite structures within the aforementioned industries and presents innovative technologies and approaches being currently explored. Following this, Sect. 3 reviews the current developments on SHM in application to composite structures along with its use and limitations as per the different industries. After the introduction of SHM, Sect. 4 provides a brief description of the different existing maintenance strategies and their characteristics along with an analysis of the impact of maintenance on whole life cycle costs of composite structures in the context of these industries. Later, Sect. 5 builds on the necessary steps towards intelligent PHM (iPHM) and the constraints to be overcome to integrate all the information to produce Cyber-Physical Structures (CPS). Finally,

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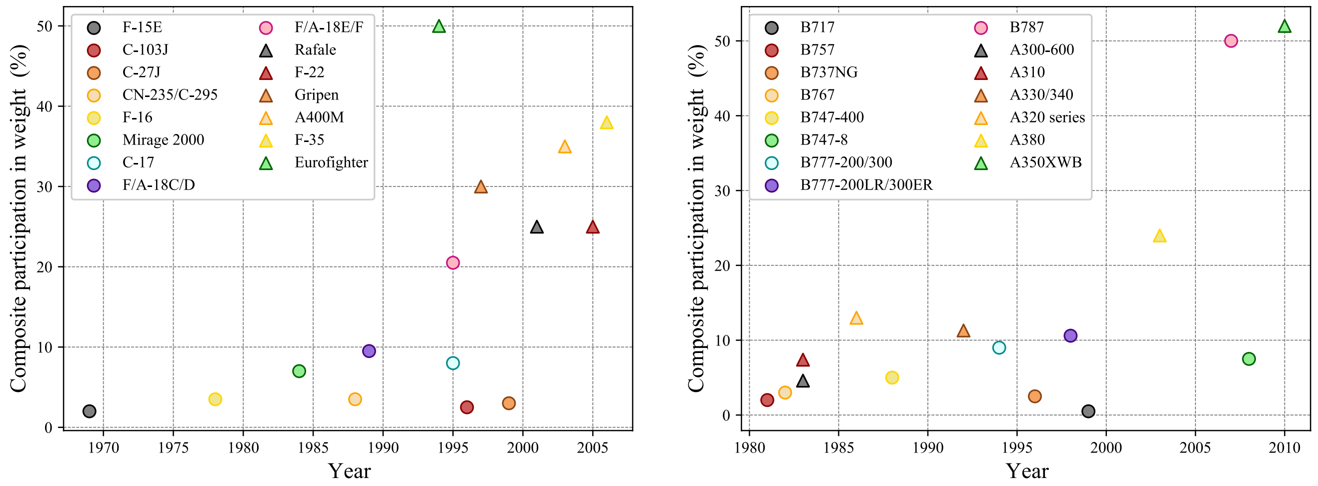
[1] https://sdgs.un.org/goals.



(a) Military sector **(b)** Civil aviation sector

Fig. 1 Aircraft's composite participation in weight [24]

Sect. 6 briefly summarises the findings and conclusions of the paper.

2 Overview of the main technological applications of composite structures: use and limitations

In this section, the degree of maturity and the main applications of composite structures are reviewed within the context of four key industries: aerospace, wind, civil construction, and naval.

2.1 Aerospace industry

Since its early days, this industry has pushed the technological limits of materials due to the harsh environment to which they are exposed. The aerospace industry adopts strict requirements for structures [23], such as very high reliability (even higher in civil aviation applications), mechanical and chemical durability, aerodynamic performance, multi-role applications, stealth, and all-weather operation. Traditionally, these requirements were partially met by the use of advanced metallic alloys; however, these are heavier and prone to corrosion. Thus, composites have achieved an important role in aerospace due to their high strength-to-weight and stiffness-to-weight ratios, greater fatigue and corrosion resistance, and ability to tailor stiffness and strength to specific design loads [23]. This allowed the expansion of application cases of composites structures over military and civil aircraft, helicopters, satellites, launch vehicles, etc. [24–26].

Indeed, the use of FRP composites in aircraft has increased since 1970 and has reached around 50% of its total mass in some cases (e.g., the Boeing 787 structure) [27]. Initially, composite materials were used as secondary structures to provide weight savings, although nowadays they are increasingly being used for primary plate-like structures [28]. The early development of composite structures in aviation was specially notorious in small fighter aircraft, achieving weight content of composites above 20% for F/A-18E/F, Rafale, F-22 and Gripen models produced during the decades of the 1970s to 1990s [24], as depicted in Fig. 1a. It is noticeable that this development has seen a maximum participation of composites in the military aircraft with content above 50% by weight in the Eurofighter [29]. Regarding the application in the civil aviation, the available data from reference aircraft manufacturers such as Boeing and Airbus show a slower adoption of composites use with a rampant tendency since the last two decades, as shown in Fig. 1b. In fact, in the last years, these manufacturers have taken a great shift passing from composite participation in weight around 12% and 25% in their B777 and A380, respectively, to more than 50% in their latest B787 and A350.

These weight reductions translate into fuel savings which, apart from the monetary savings for operators, directly impact SDG 12 (*Responsible Consumption and Production*). In fact, despite the initial manufacturing emissions being higher for hybrid composites and carbon-fiber-reinforced polymers (CFRP) than for classical aluminium and steel solutions, the whole-life CO_2 emissions during operation are lower, and break-even times range from 60 to 320 flight hours [30].

Besides, despite the positive experience and maturity of the production market, there are still some concerns with the use of composites in plate-like structures in the aerospace industry. Some researchers point to the severity and conservatism of the current airworthiness regulations [31] as limitation towards an efficient use of composite structures thus leading to over-conservative and over-sized structures [25]. In addition to this, the need for clear guidance in the operation and maintenance of composite structures by their operators has been highlighted in works like [32]. Another concern with the use of composite materials is their lack of ductility during the fracture process. Brittle micro-cracks and delamination cracks [33], which are difficult to detect visually, appear and progress during operation due to fatigue [34], impact [35], and lighting strikes [36, 37], leading to an uncertainty increase about their mechanical performance. In recent years, different solutions have emerged to partially solve the latter drawbacks through the use of hybrid and advanced composites [38, 39] although they typically imply a reduction of the strength-to-weight and stiffness-to-weight ratios.

2.2 Wind industry

Despite the fact that the first steps of electric power generation from wind date from the late nineteenth century, it was in the 1970s when the production of wind turbines experienced a rampant increase. Initially, classical materials such as steel were used for turbine blades, like the one manufactured by the U.S. company S. Morgan-Smith in 1941 experiencing failure after a few hundred hours of intermittent operation. This induced the need for a transition to high-performance blade materials such as composites, despite the reduced knowledge about these tailored materials at that time. Moreover, in response to the 1973 oil crisis, NASA started a program in 1975 to develop wind turbines [40] with composites as primary blade materials based on the knowledge gained from the application to the aerospace industry. Since then, the production of wind turbines has experienced an unceasing increase which still continues nowadays.

The growth of this tendency has been accelerated during the last decades since the world is moving towards greater utilisation of renewable energy due to its environmental and economical advantages. Indeed, the wind is one of the most efficient renewable energy resources for its numerous advantages [41], and today it is becoming strongly cost competitive in relation to other power generation methods [42]. This efficiency explains how fast the wind industry is growing worldwide. For example, the EU goal is to increase the use of renewable energy to 27% of the total energy generation by 2030 and to cut greenhouse emissions by 80–95% by the year 2050 [43].

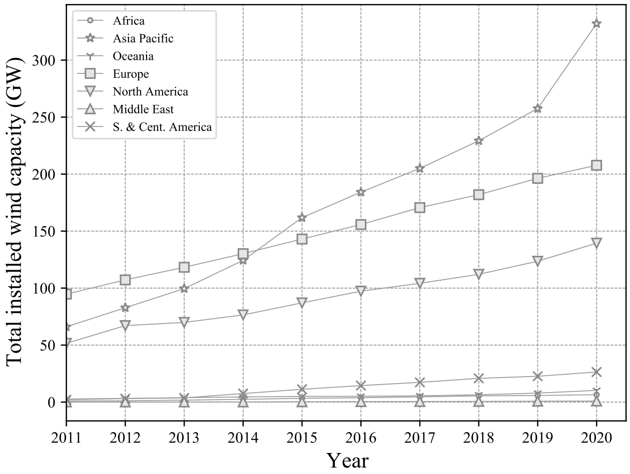


Fig. 2 Evolution of wind energy capacity by region. Data taken from [46]

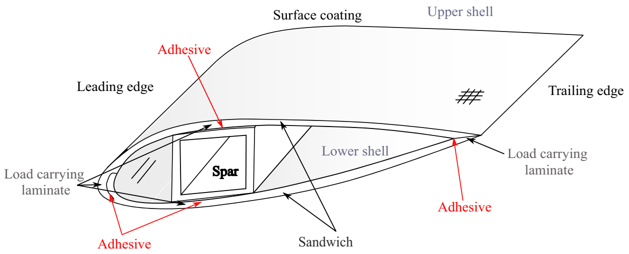


Fig. 3 Typical turbine blade cross-section

China has experienced an increase of 27% in the growth rate of the electricity generated from wind between 2016 and 2017 [44]. The United States set a target to increase the electricity generated from wind to 20% of the total electricity generated [45]. Figure 2 depicts the tendency and growth of installed wind capacity by region from 2011 until 2020, which reveals an increase of worldwide installed capacity from 220,019 MW in 2011 to 733,276 MW in 2020 [46]. Moreover, there are expectations of future growth for electricity generated from wind and solar photovoltaics, which will probably continue to expand reaching 29% of the market share in 2021 from 28% in 2020 [46].

These trends indicate an increasing need for composite materials mostly applied in turbine blades.

Typically, laminates used on wind turbine blades (refer to Fig. 3 for a cross-section schematic view) are made of e-glass fibers and thermoset matrices, such as epoxy, polyester, or vinylesther, with fiber content of about 75% in weight. Notwithstanding, the increasing demand for larger wind turbine blades driven by offshore applications has opened up the possibilities of carbon fibers to provide greater strength and stiffness-to-weight ratios,

Table 1 Published composite design guidelines

Document	Details
EUROCOMP	Structural Design of Polymer Composites (Design Code and Handbook, Finland, France, Sweden, UK, 1996)
CUR 96	Fiber Reinforced Polymers in Civil Load Bearing Structures (Dutch Recommendation, 2003)
BD90/05	Design of FRP Bridges and Highway Structures (The Highways Agency, Scottish Executive, Welsh Assembly Government, the Department for Regional Development, Northern Ireland, May 2005)
DIBt	Medienliste 40 für Behälter, Auffangvorrichtungen und Rohre aus Kunststoff, Berlin (Germany, May 2005)
CNR-DT 205/2007	Guide for the Design and Construction of Structures made of Pultruded FRP elements (Italian National Research Council, October 2008)
ACMA	Pre–Standard for Load and Resistance Factor Design of Pultruded Fiber Polymer Structures (American Composites Manufacturer Association, November 2010)
DIN 13121	Structural Polymer Components for Building and Construction (Germany, August 2010)
BÜV	Tragende Kunststoff Bauteile im Bauwesen [TKB]—Richtlinie für Entwurf, Bemessung und Konstruktion (Germany, 2010)

thus improving their resistance to gravitational loads and fatigue life [47].

Irrespective of the recent advances in manufacturing for large size blades of different composite materials [48], there are still some unveiling challenges with the use of composites in the wind industry, with the most important being damage detection , location and identification [49–51], long-term reliability under damage [52], and remaining useful life prognosis [53, 54]. There is a long perception that the current design safety factors are too high; arguably as a consequence of the aforementioned challenges, among others. Further improvements and developments in those could help to reduce the Levelized Cost Of Energy (LCOE) [55].

In particular, with regards to damage diagnostics, SHM has shown promising results using different techniques (see for example [56–60]). Similarly, there have been some attempts to provide fatigue damage and erosion modelling [61–64], damage progression [65] and prognosis [66, 67]. Even though the feasibility of these approaches seems encouraging, the experiments were predominantly conducted in controlled laboratory environments using simplified loading and damage scenarios. Therefore, the long-term and reliable performance of these systems in real operating conditions remain to be proven [67]. Notwithstanding, some research groups such as the Sandia National Laboratories have developed several projects such as the Continuous Reliability Enhancement for Wind (CREW) database [68] that aims to provide data-driven tools for the industry to self-assess the performance of wind turbines and adapt the operation and maintenance accordingly. Other studies focus on the fatigue behaviour of wind turbine blades under real conditions [69–71].

The opportunities for availability and revenue improvement that SHM and predictive maintenance can bring to the industry are analysed in detail in Sects. 3 and 4.2, respectively.

2.3 Civil construction industry

For around 200 years until today, steel and concrete have dominated the civil construction industry. For several decades, this industry has been reluctant to incorporate composite materials for primary structures except for certain applications [72] and pilot projects, with the most relevant ones shown in Tables 2, 3 and Fig. 4. Composite materials have unique properties that make them appealing to the civil industry [6, 73, 74], in particular their superior resistance to corrosion in aggressive environments along with their high strength-to-weight ratio [75–77] and high fatigue capacity (mainly for CFRP [78]). Also, composites provide important weight reductions as compared to traditional materials which would enable new architectural designs [79], easier and faster building procedures [75, 76], extended lifetime [80], and therefore, improved sustainability [81]. However, irrespective of their potential, there are important reasons that are limiting the adoption of composites by this industry, amongst which the following are identified as the major ones: (1) lack of standards and design codes [82], (2) high material costs [83], (3) lack of experience and conservationism of the industry [84].

In regards to the lack of regulatory design codes, the NIST (the US National Institute of Standards and Technology) has recently warned about the lack of design codes and standards as one of the barriers against the adoption of composites in sustainable infrastructure [82]. Yet, the US Congress passed the Composite Standards Act in August 2020 that will publish guidelines and standards for using composites in infrastructure applications [85]. In Europe, there are plans to create such a *FRP Design Eurocode* [86], as stated in a recent report from the European Commission [87]. In the meantime, some European countries have developed their own guidelines, with the most relevant ones being summarised in Table 1.

In regards to the high material costs in comparison with traditional materials such as concrete and steel, this is a

Table 2 List of pedestrian composite bridges

Location	Year	Type	Details and notes
Kolding, Denmark	1997	100% GFRP	40 m long and 3.2 m wide, 15 years of operation without any damage [87, 96]
Svendborg, Denmark	2009	pultruded GFRP deck	40 m long and 3.2 m wide, installed in just 2 h [87, 97]
Esbjerg, Denmark	2012	steel beams adhesively bonded to pultruded GFRP deck	18 m long and 3 m wide [87]
Grosseto, Italy	2004	GFRP pultruded profile	27 m long, installed in an archeological area [87]
Harderwijk, Netherland	2013	100% GFRP made by vacuum infusion technology	22 m long and 6.3 m wide [87, 98]
Rotterdam, Netherlands	2013	GFRP sandwish inside VARTM made core	62 park bridges with lengths ranging between 1.5 m and 4.5 m [87, 99]
University of Salerno, Italy	2014	GFRP pultruded I-beam with GFRP sandwich panels deck	148 m long and 37 m main span [87]
Floriadeburg, Netherland	2012	Steel beams covered with GFRP pultruded deck	127.5 m long and 6 m wide, designed to carry heavy vehicles (12t weight) [87]
Nørre Aaby, Denmark	2007	100% pultruded Glass FRP (GFRP)	23 m long, installed in just 2 h, it replaces an old RC bridge that is 20 times heavier [87, 100]
Moscow, Russia	2008	FRP profiles moulded by infusion	22.6 m long and 2.8 m wide, the first bridge made of composite moulded by vacuum infusion [87]

Table 3 List of road composite bridges

Location	Year	Type	Details
Oxfordshire, UK	2002	100% GFRP and CFRP pultruded profiles	The first composite public road bridge, no damage found when inspecting it after 12 years of service life [101, 102]
Klipphausen, Germany	2002	100% GFRP	The first GFRP road bridge in Germany [87, 103]
Utrecht, Netherlands	2013	Hybrid GFRP-steel bridge made with VARTM injection	142 m long and 6.5 m wide, composite deck carry Eurocode traffic loads and all the horizontal loads [104]
Karrebæksminde, Denmark	2011	pultruded GFRP deck	100% pedestrian and cycle bridge was hung on the side to increase capacity, the first Danish road bridge made with a composite deck [87, 105]
Delft, Netherlands	2014	Vacuum infused GFRP sandwish structures with steel members	34 m long and 12 m wide [106]
Lancashire, UK	2006	GFRP pultruded profile	52 m long, Carry up to 400 KN weight [87, 90, 107]

long-standing claimed issue by the construction industry that becomes exacerbated by the massive material utilisation in this industry. A shift from the initial-construction-cost viewpoint to a holistic lifecycle approach considering the higher durability of composite materials in a circular economy context would help; however, these lifecycle methods are still not widely adopted in civil engineering practice [80, 88]. Notwithstanding, the development of efficient manufacturing techniques such as pultrusion [89] and filament winding [90] among others [91, 92], along with the need for strengthening and rehabilitation of existing structures [74], have opened up opportunities for composite materials in the construction sector [93]. In particular, the repair and strengthening of ageing structures using FRP materials is arguably the most promising application of composites in civil engineering up to date, as revealed by the extensive literature in this area (see for example the following reviews papers [77, 94, 95]).

Finally, as for the lack of experience and conservationism in the construction industry, the knowledge gained during decades (even centuries) about the use of traditional materials makes the adoption of new materials a difficult and competitive task. However, this barrier could be expected to diminish as long as new evidence and pilot applications of FRP composites become available. In general, most of FRP applications in civil engineering structures including the aforementioned pilot projects are relatively new, and therefore, the longer the service life of these structures, the more useful information can be collected. This will contribute to reducing the uncertainty

Fig. 4 Applications of composite material in bridges. **a**–**j** pedestrian bridges. **k**–**p** Road bridges. locations: Kolding, Denmark (**a**), Svendborg, Denmark (**b**), Esbjerg, Denmark (**c**), Grosseto, Italy (**d**), Harderwijk, Netherland (**e**), Rotterdam, Netherlands (**f**), University of Salerno, Italy (**g**), Floriadeburg, Netherland (**h**), Nørre Aaby, Denmark (**i**), Moscow, Russia (**j**), Delft, Netherlands (**k**), Karrebæksminde, Denmark (**l**), Utrecht, Netherlands (**m**), Klipphausen, Germany (**n**), Oxfordshire, UK (**o**), Lancashire, UK (**p**)

about the long-term reliability of composites and therefore boost the application of composites in the civil engineering sector.

2.4 Naval Shipbuilding industry

Steel and aluminium alloys have been the traditional materials massively used by the naval industry for decades. The use of composites started in the US NAVY between the mid-1940s and 1960s in the shape of non-critical structures and predominantly in small boats [108]. Slightly later, the Royal Navy and the French Navy started to make use of composites as structural material mainly for their acoustic transparency (*stealth*) [109, 110]. For this reason, composites started as preferred materials in minehunting ships in the 1970s [111]. Since those military applications, and mostly during the last few decades, the use of FRP in naval shipbuilding has grown significantly, although there are authors pointing out that the full potential of these materials is yet to be realised in this industry [112].

Three main benefits drive the interest in the use of FRP in this industry, namely weight reduction, good fatigue resistance, and high durability in the marine environment [113]. The weight reduction due to the greater strength-to-weight ratio directly translates into increased payload, range, hydrodynamic performance, greenhouse-gas emissions savings, and durability [111, 112]. Some authors have reported that expected weight reduction with FRP could reach up to 30% and could result in fuel consumption savings up to 15% ([112]), which directly impacts SDG 12. As a drawback, moisture absorption degrades the FRP by reducing tensile and bending strengths [114]. Notwithstanding, this type of damage is less severe than the experienced by metals (e.g., corrosion [115–117]) and repairs are easier and less expensive [116, 118], providing FRP an overall better suitability for the marine environment. Even the lower stiffness of e-glass FRP can favour areas with high local stress concentrations where the structures are prone to suffer fatigue cracking such as deckhouses [119].

Table 4 Score values for maturity factors

Factor	Description	Score				
		5	4	3	2	1
Participation	Relative participation of composites in the industry	Very high	High	Medium	Low	Very low/nonexistent
Standards	Time since first standards were published	More than 20 years	Between 10 and 20 years	Between 5 and 10 years	Less than 5 years	Nonexistent
Publications	Equivalent number of publications in 40 years	Greater than 7000	Between 5000 and 7000	Between 3000 and 5000	Between 1000 and 3000	Below 1000

Thus, considering the positive balance provided by FRPs, there is a natural tendency to favouring their wider application, but still for small/sport vessels or for non-structural components [120, 121]. As with other industries, these reasons are predominantly centred on the shortage of knowledge and lack of reliable data about FRP performance in the marine environment [120]. The lack of knowledge poses to all stages of the production of the structure, starting from its design, following by its validation, and ending with its manufacturing. With regards to the design stage, there is a lack of design codes and reference models to optimise the designs of large complex vessels [120]. To overcome this problem, the traditional approach has been to increase the safety factors in the design [122, 123], which results in diluting the weight-saving benefits of FRP. In the verification stage, Safety Of Life At Sea (SOLAS) regulations did not contemplate the use of a material other than steel until 2002. After 2002, FRP composites can be considered structural materials but the verification process has been reported as long, expensive, and with a significant level of uncertainty to get the final approval [124]; in fact, this reduces the motivation of designers to use composite materials. Finally, there is a lack of open databases to estimate the cost of fabricating naval structures with composites and a lack of high-quality and low-cost manufacturing processes for massive composite structures. In this context, the European Union has recently funded two research projects to address the lack of knowledge that is limiting the expansion of FRP, namely, RAMSSES and fiberShip [2]. These projects aim at providing the tools, data, and demonstrators of FRP vessels to overcome the code and knowledge constraints mentioned and familiarise the stakeholders of the industry with the requirements and processes of FRP structures.

2.5 Cross-sectoral maturity overview of composites and contribution to SDGs

As shown before, the different industries have unequal experience and track record in the use of composite materials. To quantify this observation, a maturity index *m* is proposed here to measure and rank the relative position of these industries in regards to the use of composites. Three contributing factors ranging from 1 to 5 have been considered in this index: the relative participation of composites in structures suitable for these materials (Participation *P*); the time since the first standards or regulations of the use of composites were released (Standards *S*); and the equivalent number of publications during the last 40 years in the field of composite structures applied to the industry (equivalent number of Publications Pu_{eq}), where Pu_{eq} is computed as:

$$Pu_{eq} = \frac{\sum_{i=1981}^{2020} n_i(2021 - i)}{40} \tag{1}$$

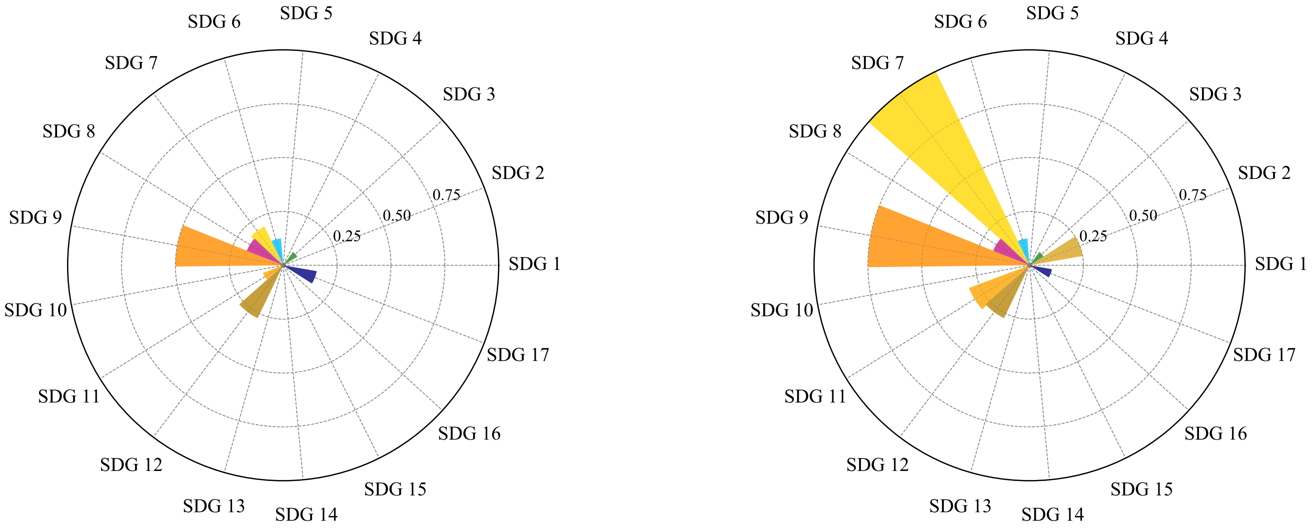
with n_i being the number of composite publications at year *i*. Table 4 summarises the aforementioned factors and the criteria used to assign the different scores.

Finally, the maturity index, *m* for each industry is calculated as $m = (P + S + Pu_{eq})/15$ and the results are shown in Table 5.

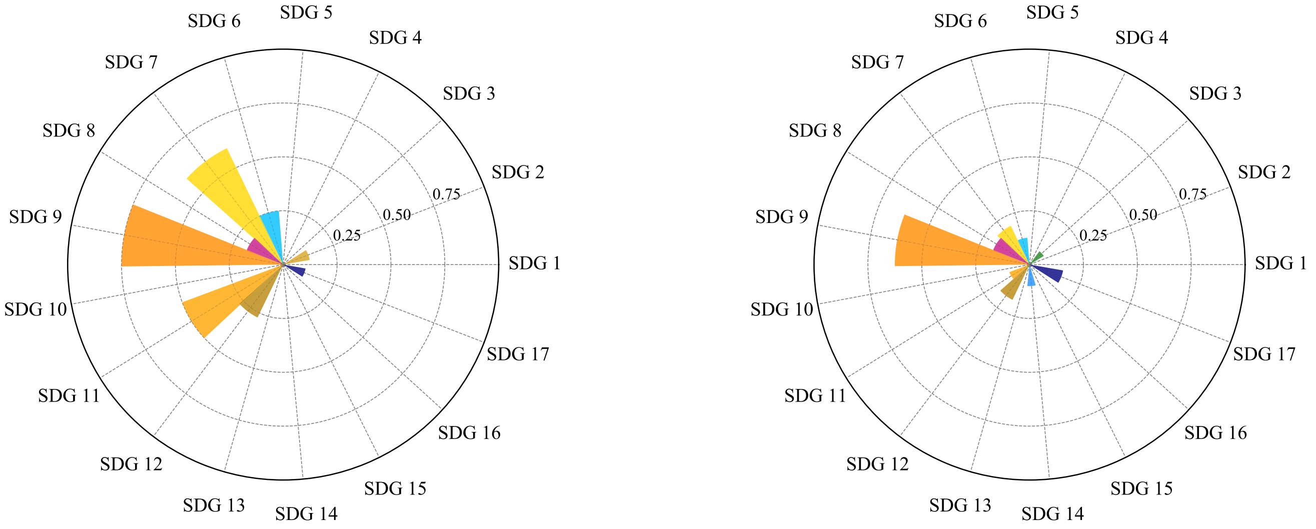
These results reveal that, according to the proposed index, the aerospace industry has achieved the greatest

Table 5 Maturity factor values by industry

Industry	Participation	Standards	Publications	Maturity
Aerospace	3	5	5	0.867
Wind	5	4	1	0.667
Civil	2	1	2	0.333
Naval	1	1	1	0.200



(a) Aerospace **(b)** Wind



(c) Civil **(d)** Naval

Fig. 5 Schematic view of the analysis of contribution of composite materials towards the achievement of the SDGs

maturity followed by the wind industry, which is the one with the highest rate of participation of composites. On the contrary, results show a gap between the aforementioned industries and the civil and naval industries in the use of composites, with the naval being the worst positioned industry in the use of composites.

Apart from the maturity, the contribution of the use of composite materials across industries in the achievement of the SDGs is presented next. To this end, the 17 SDGs (described in Table 7 in Appendix 2) are considered by the achievement indicators of their corresponding targets [125]. These indicators are assigned a unitary value if composites directly contribute towards their achievement and 0 otherwise. The analysis for each of the industries is presented in Appendix 2, specifically in Tables 8 to 10. The results are summarised using polar bar charts in Figure 5. These results show that a wider use of composite structures across the different industries can significantly contribute to SDGs 7 (*Affordable and Clean Energy*) and 9 (*Industry, Innovation and Infrastructure*). Besides, to a lower extent, composites have a positive impact on SDGs 11 (*Sustainable cities and communities*) and 12 (*Responsible consumption and production*), with the remaining SDGs being minimally affected by composites (unitary indices equal to or lower than 0.25).

In contrast, there are a few concerning issues that need to be addressed to reduce the potential negative impact of the use of composite materials: the recyclability of composite materials after decommissioning; the rampant increase in the extraction of raw materials for the production of constituent materials (matrix, fibers); and the higher demand of energy for the manufacturing of FRPs as compared to traditional materials. These issues have captured the attention of the research community as seen in a number of recent publications [81, 126–130] and constitute impacting research challenges to address in a near future.

3 Health monitoring of FRP composites across industries

The long-term reliability and the complexity of the inspection and maintenance of thin-walled composite structures have emerged as barriers to the expansion of these materials among different industries. In this context, the SHM technology has the potential to overcome these barriers as it enables a quasi-real-time data acquisition by attaching sensors to the structure or even by incorporating them into their internal structure [11, 131]. This data provides the basic information for damage prognostics and predictive maintenance [22]. Table 6 provides a synoptic view of the most established SHM sensing techniques for composite structures across industries, including their advantages and limitations. In the following, the role of SHM technology and its connection with CBM is discussed for the industries considered in this study.

3.1 Aerospace industry

As with the use of composites, military aircraft has pioneered the use of SHM. It was in the late 1950s when the UK Royal Air Force started using a device based on accelerometers to evaluate the in-flight loads experienced in fighter airplanes [163]. Since then, the interest of the aeronautic industry in non-destructive testing (NDT) and SHM (both civil and military) has steadily grown [164]. At the same time, the literature on this topic has seen a rampant development and a number of new sensing techniques and damage identification methods have been proposed during the last few decades. Rocha et al. [11] provides a recent review of the literature on SHM in aerospace composites. They conclude that the adequacy of the selection of an SHM system lies in a set of multidisciplinary factors such as the specificity of the structure, shape, size, constituent materials, expected damage location and type, and maintenance. In Towsyfyan et al. [164], a comprehensive review of the capabilities and limitations of certificated NDT technologies for aerospace composite structures is provided.

As evident from the literature, there is a general consensus about SHM as an effective technology for optimised condition-based maintenance. In fact, the main manufacturers of the aviation industry have identified the potential benefits of SHM predominantly in the field of maintenance [165, 166]. In this industry, damage detection, primarily based on visual inspection, takes a considerable part of the maintenance budget. Indeed, access to inspection areas is one of the major drivers of maintenance costs for aircraft. A clear example is provided by Cawley [167], which reports that Boeing calculated that out of the 25,000 h required for corrosion inspection for a 747-400 aircraft, 21,000 h were spent gaining access to the inspection areas (over 80% of the inspection time). These figures make clear the industry's interest in SHM. Another driver for SHM as enabling technology for advanced maintenance is life extension of existing aeroplanes that are close to their nominal end-of-life. SHM provides valuable information about the actual degree of damage that can be used for informed life-extension decision-making [168].

Despite the aforementioned benefits of SHM and the feasibility of their use in composite structures, there are also concerns that limit their use in the aerospace industry (and to some extent in other industries). The first concern is about the reliability of the damage detection, location, and quantification of damage for in-service real structures. Most of the current progress about SHM in aerospace composites has been carried out in coupons, plates, and scaled structures under laboratory conditions [20, 169, 170]. However, irrespective of some insightful progress on in-situ damage monitoring technologies [19, 171], there is still much uncertainty about the performance of onboard SHM technology during long periods of time and against harsh and changing environmental conditions. In this sense, Unmanned Aerial Vehicles (UAV) are seen as an interesting opportunity to test SHM systems in real conditions while reducing economic and safety risks [172, 173]. Secondly, there is a lack of publicly available data for SHM developers to work with. The research community would highly benefit from the use of open datasets to build robust models for damage detection, quantification and prognosis, and therefore increasing the reliability of the systems. Thirdly, there is uncertainty surrounding how SHM systems can deal with patched or bolted repairs. In this context, the SHM system shall be able to evaluate and monitor the repaired condition of the structure so that the system has the same reliability as the original structure; otherwise, the main advantage of SHM (reducing inspection costs) will be jeopardised. Finally, there is a need for

Table 6 List of structural health monitoring techniques used in fiber reinforced polymers

SHM Technique	A/P	Detectable Damages	Advantages	Limitations	References
Acoustic emission	P	Impacts, micro-cracks, cracks, delaminations	Highly sensitive to damage and its location	Requires knowledge about the attenuation of the component to produce accurate results and is sensitive to background noise	[132–135]
Guided waves	A	Impacts, micro-cracks, delaminations, cracks, debonding	Low signal attenuation, highly sensitive to damage, can be integrated inside thin members	Experiences difficulties in complex structural components	[14, 136–138]
Acousto-ultrasonic	A/P	Delaminations, cracks, debonding	Sensitive to both surface and subsurface discontinuities	Requires calibration of the system and knowledge to analyse and interpret the data, presents difficulties in evaluation of irregular materials and further research on disbond detection	[139–142]
Digital image correlation	A	Cracks, debonding	Sensors (cameras) do not need wiring and can cover large areas	Unable to identify internal small damage	[143–146]
Electromechanical impedance spectroscopy	A	fiber cracks, delamination, cracks, debonding	Uses short wavelength and can detect small and incipient cracks	Can only detect damage relatively close to the sensors	[147–149]
Electrical impedance tomography	A	fiber cracks, delaminations, cracks	Low cost of sensors	Attenuated in depth, only feasible for shallow damage	[150, 151]
Strain monitoring	P	Impacts, delamination, cracks	Easy to integrate within the structure and mature technology	Needs a considerable number of sensors to identify damage since detection range is low	[152–154]
Vibration monitoring	A/P	Cracks and large debonding	Sensors can be easily integrated within the structure, reliable and mature technology	Low resolution, can only detect the presence of large damage and experiences problems with environmental disturbances and measurement errors	[155–158]
Comparative vacuum monitoring	A	Cracks, debonding	Sensors can be discretely placed along the structure	Not reliable for internal damage	[159]
Infrared thermography	A/P	Debonding, cracks and delamination	Cameras can cover large areas of the structure	Is affected by environmental temperatures and material thermal conductivity	[160–162]

A/P active/passive monitoring

a publicly available demonstrator project investigating the whole SHM process for composite structures. A direct comparison of the whole life cycle costs of the application of SHM against the current inspection strategies would help close the existing gap between academic research and industrial needs in SHM.

3.2 Wind industry

In the wind industry, the turbine blades along with the gearbox and electrical generators, have been identified as the turbine components with the highest failure rates [174, 175]. Moreover, the damage in the blades is regarded as one of the most expensive and difficult to detect among the potential failures of the turbine and has the potential to act as a precursor of secondary damages in other parts of the turbine [176]. Thus, deploying SHM technology on turbine blades will translate in maintenance optimisation and fewer operation costs for the entire system [177]. A variety of damage types have been identified as susceptible to appear in composite blades during their lifetime [50, 178]; these are, damage in the adhesive layer between the skin and flanges of the spar (debonding); damage in the adhesive layer between the top and bottom skins along the leading or trailing edge (debonding); damage in sandwich panels between the face and the core (debonding); delamination caused by tensional or buckling load; fiber failure in tension; laminate failure in compression; buckling of the skin (debonding); and cracks in the gelcoat or debonding of the gelcoat from the skin. Among them, delamination and adhesive joint failures are reported as the most usual ones [52]. A number of SHM techniques have appeared in the literature dealing with one or more of the damages mentioned above [16], including vibration analysis [179–181], strain monitoring [182, 183], acoustic emission [184, 185], ultrasonic detection [186, 187] and infrared thermography [188]. Several authors [50, 189] have provided recent literature surveys about the state-of-the-art damage detection techniques for turbine blades. Of the existing techniques, acoustic emission and strain monitoring have demonstrated efficiency on damage detection in real case scenarios [177, 190], whilst Lamb-wave monitoring is recently being explored for its efficiency in damage location in large thin-walled composite structures. [191, 192]

In practice, there are commercially available monitoring systems for the drive train and gearbox components using information from Supervisory Control and Data Acquisition (SCADA) along with other vibration control systems [193]. However, the monitoring of the blades is still in its infancy although an increasing research effort is reported in the literature with sound solutions [16, 50, 180, 189, 194, 195]. The existence of data already available registered through the SCADA system has encouraged some researchers to further explore the data so as to find meaningful features for the blades [196–198]. Nonetheless, an effective blade damage detection and evaluation need dedicated blade SHM systems [189]. Indeed, a dedicated SHM system for the blades opens up the possibilities of blade pitch control (*derating*) as a way of no-growth control of existing damage or lifetime extension [199]. In addition, it has been reported to provide a more balanced and stable load for the rotating parts of the drive train and gearbox and thus extending their lifetime [200].

As a general comment, current SHM systems for wind turbine blades are able to provide data in controlled environments and meaningful damage indicators [201]. Notwithstanding, there is no proof of the systems performing during long time periods and under harsh-condition environments. How the system is going to react to uncertain and harsh environments remains unknown and conform one of the technological challenges of this industry. A non-durable SHM system will end up adding more maintenance costs and downtime on its own.

3.3 Civil construction industry

Generally, civil engineering structures are designed for long service life periods, about 100 years, and they usually require minimum maintenance throughout a significant part of their service life. In this context, the structural asset management strategy followed by this industry has been oriented to reactive maintenance mainly [202]. Notwithstanding, an increasing amount of structures are nowadays reaching their nominal lifetime and the use of SHM is gaining attention as a rational tool to support a reliable and cost-efficient life extension [203]. Life extension reduces the environmental impact of decommissioning and constructing a replacing structure and, therefore, it can be considered as a sustainable development strategy [204].

After damage has been detected and evaluated (e.g., corrosion in concrete structures), structural retrofitting is the natural step towards the life extension of the damaged component. In this regard, FRP composite materials have proven efficiency for retrofitting or rehabilitation of civil engineering structures [94, 205–207], as explained before. Notwithstanding, a key challenge that still remains open is the long-term reliability assessment of the retrofitted structure [208], to which dedicated SHM and PHM solutions are needed [94, 205, 209].

The literature about SHM in FRP structures for the civil industry is still very limited and mainly focused on the vibration analysis and the performance monitoring of FRP bridges. In [210], state-of-the-art SHM technologies in some demonstration FRP bridge projects in Canada are reported. Guan and Karbhari [211] provide a framework for a web-based SHM of an FRP composite bridge based on the vibration analysis and modal identification along with its variation throughout time considering the degradation of the structure. Following this, the same authors presented an application of this framework for the Kings Stormwater Channel Composite Bridge [212]. Separately, Mikołaj et al. [213] investigated the rheological effects of long-term loading on an FRP bridge using SHM. According to their study, no rheological effects were found for a 3-month test load. Long-term degradation was studied in [214], where the performance of the first all-composite bridge in Poland was controlled for 8 months finding no relevant degradation of the structural behaviour.

As a general comment, SHM has the potential to contribute to overcoming some of the main barriers posed in this industry to the extensive use of FRP composites; however, the literature on this topic is still limited and this potential is not fully exploited.

3.4 Naval shipbuilding industry

It is well known that the environmental impact of ship failures is massive, perdurable in time, and especially difficult to revert. Each year, around a hundred large ships end up sinking according to Allianz's Safety and Shipping Review [215] being ship hull damage among the top five causes of sinking. The predominant types of structural issues of ships made of traditional metal materials are related to corrosion and fatigue cracking. Currently, the ship's design life cycle is estimated at around 30 years over which the reliability of the structure should be maintained. The current practice in structural health assessment of ships is the deployment of NDT when the ship is dry-docked. The approach followed, unless there is an existing and known flaw in the ship, consists of the inspection of strategic areas of the hull to determine the thickness of the plate and extrapolate the corrosion rate to other parts of the ship; inspecting the complete hull including its welds would be impractical, time-consuming and expensive [216].

As with other industries, SHM in naval ships can provide insightful information regarding the actual condition of the structure and the loads that the structure is supporting. This translates into optimal design, maintenance and operation of the structures and uncertainty reduction in fatigue-life prediction [217]. The SHM approaches predominantly followed in naval vessels are vibration analysis [218, 219] and wave propagation analysis [216]. Passive systems (e.g., acoustic emission) instead of active systems (e.g., guided waves) have been reported as more practical for at-sea implementations since they require less energy and infrastructure to work [220].

Despite the existence of some SHM systems deployed on metallic hulls, they represent a tiny proportion that does not allow the potential of this technology to be fully explored. One of the reasons why SHM has not been intensively used in naval vessels is the difficulty to deal with the size and shape complexity of their structural systems [220, 221]. Thus, there is a clear space for this technology to be further developed in this industry and demonstrate its potential for reliability and serviceability increase and maintenance cost savings [222–224].

As explained before, FRP structures are currently limited to small vessels and therefore, the application of SHM is practically nonexistent. Even though corrosion is not expected to be such a relevant issue for FRP vessels, degradation due to water ingress and fatigue need further exploration in practice. The latter could constitute a rich research and application area in the context of SHM; however, to the best of the authors' knowledge, SHM in FRP hulls has been mostly limited to the study of small components and connections, as reported in [131, 222, 225, 226].

3.5 Cross-sectoral SHM overview

Whilst the studied industries present different levels of expertise in the use of SHM in composites, the wide range of sensing technologies and their development level increases the likelihood of its effective application. In terms of experience in the use of SHM solutions, the aerospace industry has been using it for longer in military and civil aircraft. The military sector, more prone to innovation due to lower certification constraints, provides a real testing environment for SHM solutions. In this sense, these military SHM solutions are being used to gain knowledge and transfer similar solutions to the civil sector. In the case of the wind industry, most existing SHM solutions are installed in components different from the blade, such as the drivetrain or the bearings. This industry is currently more reliant on visual inspection and further NDT in case of detecting any issue on the blade rather than on the use of SHM solutions. In contrast, the civil industry has adopted on-board SHM for singular and critical structures, typically based on vibrations (accelerometers) to detect changes in the native response of the structure. Considering the dimensions of the civil structures, SHM technology is being used to detect large damages on metal or concrete structures. Finally, the naval industry shows less experience in the use of SHM and is currently reliant on the visual inspection of hotspots of the hull of the boat while dry-docked to detect damage. The literature does not show evidence that this industry will adopt SHM technology in the near future at a rate similar to the other analysed industries.

Some common concerns across industries are related to the reliability, optimisation and absence of open data for the further development and deployment of SHM systems. The higher initial costs and the difficulty of access to the structure in some of the industries such as the aerospace, wind or naval, have directed the spotlight onto their reliability. They shall be designed so that an additional burden is not posed on the maintenance of the structure and the limited experience in their long-time application is seen as a potential risk for their deployment. Separately, the added weight of sensors and wiring could dilute the potential benefits of their use, primarily in the case of the aerospace industry. Whilst one of the principal arguments in favour of the transition to composite materials is the positive environmental effects of weight reduction, the higher complexity and evolution of non-visible damage types in these materials require a more profound knowledge of the state of the structure. Finding a balance to provide effective damage detection, location and quantification with the increase of weight caused by the addition of sensors requires a careful study of the structure. This issue feeds back into the absence of data with which developers could optimise and compare the results of different SHM system solutions, creating a complicated environment for the integration of these systems within the structures.

4 Maintenance of composite structures across industries

Long-term reliability and durability have been highlighted among the most relevant factors that drive the industry towards the use of composites in their structures. Maintenance is directly related to both of them, and its impact can be decisive enough to condition the design of the structure and the materials used. In this section, the impact of maintenance and its relation with composite structures of some of the most relevant industries using composite structures will be analysed.

4.1 Overview of existing maintenance strategies

In general terms, there are four broad categories of maintenance strategies currently in use by the industry. These categories evolved throughout time starting from the less efficient ones, Corrective Maintenance (CM) and Preventive Maintenance (PvM) to the more efficient and technological ones, Condition-Based Maintenance (CBM) and Predictive Maintenance (PdM) [227]. The selection of the most suitable type of maintenance for a given application is non-trivial and has been studied by many authors. For instance, Zhu et al. [228] presented and compared different maintenance strategies (CM, PvM and PdM) for wind turbine blades based on the necessary leading time to prepare and perform maintenance actions and the associated costs of these. This study showed that inspection costs may greatly influence the choice of the most cost-efficient maintenance policy. Also, Chen et al. [229] presented a comparison of different maintenance strategies (PvM, hybrid CBM combining scheduled inspections and continuous monitoring, and pure CBM) for aircraft made of composite parts. Their findings show that the hybrid CBM strategy, which could resemble the current way in which CBM is applied in the aerospace industry, is the most expensive maintenance strategy, and that this could be related to the reluctance to use SHM in the sector. Additionally, Florian and Sørensen [230] studied the cost implications of optimising the inspection intervals for PvM considering debonding damage of wind turbine blades. PvM costs were found lower than those for CM for most of the range of inspection intervals considered.

The most basic maintenance strategy, CM, also known as run-to-fail maintenance, has as fundamental principle not to interfere until the failure of the system. Its main disadvantage is the risk of sudden failure leading to unscheduled maintenance and the structure being out of service during unpredictable time. This results in significant unforeseen costs that include those related to production, downtime, and inventory since workers should be always prepared with spare parts for a sudden failure. Besides, it may lead to more severe damage modes resulting in higher repairing costs. In contrast, the advantage of CM is that it does not require strong planning due to its simplicity, so it makes sense for non-safety-critical assets only when the repair and downtime costs are less than the operating costs using other maintenance types. In essence, CM would be suitable for composite or any type of structure; however, it is acceptable for non-critical and lightly loaded structures only [14].

As a more advanced maintenance concept, researchers and industry started to focus on PvM in the 1960s [231]. PvM is also known as time-based or scheduled maintenance because it is performed periodically based on a prespecified schedule [232]. The main advantage of PvM over CM is the scheduled planning, therefore, eliminating the unforeseen costs of the run-to-fail strategy. It also reduces maintenance time by preparing beforehand the required parts, supplies, and manpower. In addition, it enhances the safety level with respect to CM since failure is prevented by routine inspection and maintenance activities [233]. On the other hand, an important disadvantage of PvM is that it is scheduled based on previous experience, which, depending on the case, can be reduced or even biased [234]. In practice, this uncertainty translates into unnecessary maintenance actions to keep failure risk to an acceptable level. For example, matrix micro-cracks, as the first sign of fatigue in composites, tend to accumulate sharply at the beginning of the fatigue life of the structure. Thus, inspections should ideally be unevenly distributed to properly track this damage mode, instead of inspections at periodic intervals. Furthermore, the actual maintenance costs depend on the degradation level when performing maintenance and the duration of the required maintenance action; both of them are time-varying variables [235] whereas PvM is performed periodically ignoring this variability. These limitations, among others, make PvM unsuitable for composite structures where degradation evolves in a highly nonlinear fashion. A sample of the relevance of adjusting inspection and maintenance intervals is a comprehensive study on the reduction of operation and maintenance costs for wind turbine blades through the optimisation of these intervals based on the maintenance cost by Yi and Sørensen [236]. Another example is provided in [237], where the inspection interval for an FRP aircraft wing is optimised and compared with the MSG-3 PvM planning philosophy (the classical maintenance planning approach for aircraft), providing a quantitative procedure to optimise the inspection and maintenance of civil aircraft.

In this context, the development of SHM enabled monitoring continuously or as needed opened the doors to CBM, in which maintenance is applied based on the actual degradation condition of the structure. CBM was introduced around 1975 [238–242] and it is defined as the maintenance triggered by the evidence of the current state of the system exceeding a predefined threshold. With CBM, unnecessary inspections can be avoided thereby reducing unnecessary downtime and costs. However, defining the proper threshold for maintenance requires accurate knowledge in order to guarantee a healthy balance between safety and cost under different (and uncertain) conditions [243]. In addition, performing maintenance based on the knowledge of the current damage state only could result in unscheduled maintenance activities leading to higher running costs due to the lack of anticipation. An example of the importance of the definition of an optimum maintenance threshold was provided by Zhang and Chen [244], who developed an optimised CBM policy for wind turbine blades based on a fatigue crack growth model including imperfect repairs in which the crack length repair threshold was tuned.

To overcome the drawbacks of CBM, more attention is recently moving toward PdM. Both CBM and PdM rely on monitoring the state of the system through SHM, but they differ in the way maintenance is planned. In CBM, the maintenance decision is made depending on the current damage state, so there might not be enough time before the maintenance threshold is reached. Whereas in the case of PdM, the decision is planned not only based on the current damage state, but also on an anticipation of the future degradation of the system. The prediction of the RUL of the structure is therefore central to allowing a dynamic adaptation of the maintenance planning in advance. An example of the potential of PdM was provided by Griffith et al. [245], where the optimisation of wind turbine blades O&M strategies based on SHM and PHM was studied. The inclusion of smart operation modes during high wind periods to increase fatigue life and contain damage progression was explored showing promising O&M cost reduction.

In summary, the literature provides evidence showing that the criticality safety of some applications such as aerospace, along with the current state of maturity of SHM for large structures, pose a barrier in the adoption of innovative and optimised maintenance strategies, being PvM and CBM the most frequently used in FRP structures currently. In the aerospace sector, the requirements for maintenance and reliability are notably strict and these are limiting the full potential of PdM. Notwithstanding, considering the high inspection costs of this industry, the situation could change in the future with the development of SHM and the acquired knowledge using composite structures [229]. In contrast, the wind industry has the potential to evolve rapidly into the adoption of PdM given the lower risk of unexpected failures and the numerous opportunities highlighted in the sector for life cost reduction. To the authors' best knowledge, the research in the remaining industries covered in this review is very limited due to the immaturity of the use of composite structures in those, as explained in Sect. 2.

4.2 Impact of maintenance in whole-life cycle costs

There are many examples in the literature showing evidence about the impact of maintenance on the life-cycle cost of industrial and physical assets. See for example [246–250], to cite but a few. The same applies to composite structures; however, the literature on this field is still incipient. In the following sections, this literature is reviewed across the industries considered in this work.

4.2.1 Aerospace industry

Worldwide air traffic has been continuously growing during the past years with an annual average of 4.6% and it is expected to double in 15 years [251]. With this growth in the aviation industry, some authors have foreseen that by 2050 the amount of accumulated aircraft composites waste will reach 500,000 tons [252]. Besides, the uncertainty about the long-term reliability of composite materials [1] along with their faster fatigue damage accumulation rate (in relation to metals) may speed up the formation of composite wastes from this industry. Optimising maintenance and inspection strategies can help extend the service life of composite aerostructures considerably by controlling and slowing down deterioration. This aspect has been treated in the aerospace literature but for materials different from composites. For example,

Guo et al. [253] provided several examples of military aircraft like the Canadian CF-188 [254], the Australian F-111C [253], and the American F-4 and B-52 fleets [255] that are operating beyond their nominal lifespan by virtue of intensive maintenance. However, frequent inspections may require disassembly and reassembly of the parts, which, in composites, it may result in an increased probability of damage [256]. Also, frequent inspections can result in delays, which in turn lead to additional operating costs that can reach up to 78 $/min [252, 257].

A proof of this is the development of Boeing's B787, in which the inclusion of maintenance costs and aeroplane availability among the evaluated factors in the design stage has resulted in a composite participation of over 50% in weight [258]. This shift in the design has proven to be effective, resulting in a number of damage occurrences equal to or lower than those for an equivalent metal structure [259].

Also, it is estimated that $5 million dollars can be saved during the lifetime of an aircraft by reducing the downtime and maintenance costs using SHM with CBM [260], but the installation of permanent sensors can cause an additional load to the aircraft. Dong and Kim [260] found that it will require 10,000 PWAS (piezoelectric wafer active sensors) to cover the fuselage areas of a Boeing 737, and this can lead to an extra 1000 lbs load which will result in losing the savings from maintenance and downtime. This illustrates the necessity of lightweight and long-range sensors for SHM in aerospace. Composites provide a good alternative in this context since FBG sensors can be directly embedded inside the material from the manufacturing stage [261] requiring no additional cabling and reducing the weight with respect to a traditional PWAS solution. Another equally important action is the optimal positioning of the sensors thus reducing the number of sensors (and therefore the weight, cable length, etc.) to a minimum with enhanced detectability [262]. Approaches related to this topic are based on either the value of information [263, 264], cost-benefit analysis [265, 266], or a combination of both.

4.2.2 Wind industry

The growing trend in the wind industry, as depicted in Sect. 2.2, is accompanied by the increase in wind turbine size that has led to a rise in FRP utilisation in the bigger blades. The majority of the structural components of the wind turbine can be easily recycled except the composite blades since the recycling of composite materials is still difficult with the current technology [8]. Only considering the wind industry, the amount of composite waste is expected to increase rapidly and reach around 483,000 tons of accumulated CFRP by 2050 [252]. To address this problem, Jensen and Skelton explored the possibility of using composite waste in a circular economy context by using different alternatives (reusing/repurposing, recycling and recovering); notwithstanding, they note that the experience in reusing wind turbine composite materials in new applications such as bridges, fibres in concrete, playground, urban furniture, etc. is very little [8]. Their reuse for public infrastructure presents the main difficulty of verifying its state and strength whilst recycling and recovering technologies are not ready for all composite materials. In this context, elongating the lifespan of turbine blades can be considered the only feasible choice today to postpone and control the future explosion of composite waste, thus, offering the opportunity and time for finding better recycling solutions for this problem. Besides, life extension can increase the ratio of the energy generated per waste produced, increases the Return On Investment (ROI) and decreases the LCOE [267]. Utilising SHM/CBM systems to continuously assess the health of the structure can be an efficient way to extend the service life of the wind turbine when accompanied by an evaluation of the factors that influence O&M costs and the critical failure modes of the system [267]. Griffith et al. [245] found that monitoring the health of the blade to regulate the load and power generation can help in elongating its fatigue life by 300%. Besnard et al. [268] considered different strategies of inspection and online condition monitoring and the result was different optimal maintenance schedules with different life-cycle costs for each of the strategies. In regards to the offshore wind turbines, the impact of one or another maintenance strategy on life-cycle costs is even more accentuated, especially when considering end-of-life scenarios and the possibility of life extension [246, 269]. In offshore wind farms, the operation and maintenance costs are predicted to be about 30% of the total life cycle costs [270], and this can vary from two to five times the land-based costs [271]. This makes the energy costs of offshore turbines larger than land-based ones [272]. These costs can be reduced by using SHM technology and proactive maintenance in a profitable way taking into account the state of the structure, and this can also lead to an increase in the overall profit and availability of the turbine [245].

4.2.3 Civil construction industry

As stated in Sect. 2.3, the main drawback of the massive adoption of FRP materials in civil engineering construction is the high material costs, which can represent up to a 50% increase when compared to traditional solutions in the case of bridges [273]. Therefore, a key to the success and expansion of these materials in the construction industry will be the accurate prediction of the life cycle costs of the composite structures. Indeed, the choice of the wrong maintenance strategy can further increase the cost of these structures by incrementing unnecessary inspection and maintenance costs [274]. In this sense, the adoption of CBM strategies using state-of-the-art "on-board" SHM techniques seems a suitable approach in this direction. Orcesi and Frangopol [275] developed a generic approach to include the effects of SHM in the life cycle costs and to optimise the maintenance strategies based on monitoring data. In their study, the knowledge about the criticality and occurrence of the failure modes and the integration of SHM data were highlighted as the challenges for decision-making requiring further analysis for O&M cost reduction. Zhao et al. [276] performed a life cycle assessment comparing traditional concrete-filled steel tubular columns with several options including concrete and FRP from an economic and environmental perspective considering PvM maintenance. The results revealed that, considering uncertainties, the traditional approach using steel and concrete is likely to be more economically and environmentally efficient. It is important to note that different parts, loading scenarios and maintenance policies can result in different life cycle analysis outcomes and that the optimised solution for a specific structure may be a combination of traditional and composite material parts and different maintenance strategies.

4.2.4 Naval shipbuilding industry

As stated in Sect. 2, the use of FRP composites as primary structural materials in shipbuilding is still limited in spite of their potential [113]. Accordingly, to the best of the authors' knowledge, there are no references in the literature investigating the impact of FRP composites in life cycle cost reduction, service life and sustainability in the naval shipbuilding industry. However, several papers in the literature presented generic methodological approaches for ship maintenance optimisation that could be extended in the case of marine composite structures. For example, Liu et al. [277] integrated risk and maintenance cost reduction and increase in availability to optimise the repair actions that help in extending the ship's service life. Garbatov et al. developed a risk-based framework for maintenance optimisation from the design stage and for updating future maintenance plans while satisfying safety transportation requirements [278]. Dong and Frangopol [279] developed an approach for maintenance optimisation and optimal inspection scheduling while minimising the life cycle costs and risk of failure. They formally found that an optimum inspection and maintenance plan can reduce the risk of prolonged exposure of the structure to corrosion and fatigue. In summary, a high impact would be expected from a massive application of FRP composites in the naval industry with life-cycle cost reduction being prominent; however, this needs to be confirmed by more research and new applications.

5 Discussion

As previously discussed in Sect. 4, most inspection and maintenance approaches currently adopted by the composite industry are based on preventive/corrective maintenance methodologies with maintenance activities being scheduled in planned calendars. These approaches can be seen as economically and managerially efficient in the short term; however, they heavily penalise the serviceability and availability, and therefore, the life cycle cost and sustainability of the composite structures in the longer term when compared with predictive maintenance. The need for continuously reducing the costly and possibly unsafe maintenance and inspection cycle of key composite structures, like those from aircraft and turbine blades, requires ad-hoc, on-board, yet intelligent systems, able to efficiently transfer data to knowledge [280] and knowledge to decision-making as a paradigm shift towards the *Maintenance 4.0*. The latter is aligned with Goal 9 (*Industries, Innovation and Infrastructure*) of the United Nations' SDGs [281], which enforces a radical new vision for structural asset management leading to more predictable, sustainable, and resilient assets. In such a context, these obsolete asset management solutions can be replaced by predictive maintenance, where decisions are taken based on the actual and predicted state of health of the structures.

Among the potential needs to successfully materialise the PdM paradigm in composite structures, we can highlight two key technology enablers, namely the PHM and CPS technology. The following subsections revise these two technology enablers in the context of composite structures and provide critical perspective and discussion about desirable research needs towards the aforementioned objective.

5.1 Intelligent Prognostics and Health Management (iPHM)

Prognostics is the science of predicting the remaining useful life (RUL) of physical assets (e.g., a turbine blade) given the information about the current degree of damage of the asset, the load history, and the anticipated future load and environmental conditions [282]. Technically speaking, PHM is a natural extension of SHM where the focus is not only on detecting, isolating and sizing a fault mode, but also on predicting the remaining time before the failure occurs with quantified uncertainty, which is further used for rational and anticipated PdM decision-making [22]. From a practical viewpoint, it is a continuous process of update-predict-reassess which requires periodical measurement updates to increasingly improve the predictions of the RUL.

In application to composite structures, RUL predictions are subject to significant uncertainty that comes not only from uncertain inputs (upcoming loads, environmental conditions, material's voids, etc.) but also from the lack of knowledge about the physics of the damage process. This uncertainty, and the associated computational complexity of the prediction problem, is exacerbated when dealing with large-scale thin-walled composite structures under real operating conditions using noisy, sparse or missing SHM data [283]. This is mainly the reason explaining why probability-based frameworks have been preferred for prognostics in composites, rather than deterministic or point-valued RUL estimations. Damage prognostics for structural applications have been recently explored by several researchers [17, 170]. In the current literature, available damage prognostics approaches for composites are capable of only capturing some (but few) of the specific damage modes such as micro-crack propagation, delamination, etc., which are only representative of some of the potential deterioration patterns of a full-scale composite structure [18–20, 171, 284]. Moreover, the vast majority of PHM research to date deals with predicting the RUL of structural coupons or small structural parts and generally under laboratory-controlled damage conditions. Thus, there is a clear research opportunity to effectively deploy iPHM methods in real-world composite structures subject to realistic load and environmental conditions.

At this standpoint, it is important to remark that a keystone to deal with the abovementioned achievement relies on the availability of an effective sensing system to obtain real-time online data about the structural health state. Indeed, as previously specified in Sect. 3, ultrasonic guided waves and acoustic emission have exhibited strong potential as SHM solutions for detecting damage signatures in composite structures [19, 169, 171]. However, to the best knowledge of the authors, available SHM systems in composites still lack integrated, yet long-term reliable solutions adequate for working under operational conditions. Thus, there is a fundamental technological and scientific issue that still remains open, which is to effectively integrate these SHM sensors on-board a composite structure properly working in operational (loading and environmental) conditions in the long-term.

The latter requires a deeper understanding of the sensing technology capable to cover a wider range of damage signatures (as no single sensor type can cover all), and most importantly, technology development for effective manufacturing methods which enable sensor network integration with minimal or no affection to the structural response of the composite. The aforementioned challenges imply a need for the development of novel manufacturing methods to render smart composite materials [285, 286], which include robust, accurate and minimally invasive embedded systems for on-board, continuous, yet reliable monitoring.

Finally, we remark that the energy supply of on-board installed sensors and communication nodes supposes a major concern for efficiently deploying PHM solutions in composite structures. Energy harvesting methods are today a major research topic within the composites field providing suitable solutions mostly for structures subjected to dynamical excitation [287–291]. This, together with the development of low-consume sensors, might shed light on making on-board long-term embedded SHM systems feasible.

5.2 Structural composites as cyber-physical structures

The concept of CPS is at the core of AI and its related disciplines, like the Internet-of-Things (IoT) and robotics. CPS integrate physical assets with embedded sensing, processing, communication, and networking capabilities, whereby cyber and structural components form a collaborative integration transforming the monitored structure from being a physical asset to a cyber-physical entity [292].

Recent works [293, 294] propose that CPS can result in autonomous self-managed systems with diagnostics, prognostics, and decision-making capabilities using online SHM and PHM information. Indeed, the anticipation of CPS to structural damage can be granted by self-adaptiveness of operational decisions (e.g. go/no go for inspection) based on PHM predictions. Through self-adaptation, the predicted information is updated to dynamically accommodate health state changes and provide autonomous maintenance decisions, therefore increasing the system efficiency and making it more resilient to the new conditions.

However, important research breakthroughs are needed for CPS to be directly applied to composites structures. Apart from scaling up the PHM techniques under demanding real conditions, as previously discussed in the last subsection, a key challenge still lies in formulating system-level mathematical tools to represent and simulate the dynamics of the CPS entity. The latter implies the development of expert system models capable of integrating

SHM data, PHM predictions (whether model-based or data-based), and expert knowledge with system-level I &M non-linearities[2]. There are some available system-level modelling paradigms in the literature to mathematically represent expert systems [295, 296], like for example Hybrid automatas, Mixed logical dynamical models, Piecewise affine models, Petri Nets and max–min–plus-scaling systems [297–300].

Among the aforementioned approaches, Petri nets (PN) [301] are typically regarded as powerful modelling tools for expert systems due to their ability to account for resource availability, concurrency, and synchronisation, which are common aspects that underline the majority of the aforementioned system-level non-linearities. Moreover, new PN variants like the fuzzy Petri nets (FPN) [302–304], Possibilistic Petri nets [305, 306], and Plausible Petri nets (PPNs) [307] have appeared in the literature to account and react to uncertain information (e.g. from sensors, experts, etc.), which are of special interest of CPS of composites due to the unavoidable presence of uncertainty in the damage predictions. Particularly, the recently formulated PPNs have demonstrated good results as self-adaptive expert-level models using off-line degradation data and expert knowledge [307], and might constitute a useful tool to mathematically represent the dynamics of cyber-physical composite structures at system-level.

It is important to note that, in a literature search, one can realise that the idea to integrate expert systems with other technologies is as old as AI, and this trend still continues in the new generation of expert systems [308, 309]. Particularly, expert systems applied as decision support tools for structural damage assessment date back earlier than the boost of the SHM technology [292], but not as cyber-physical systems.

Nowadays, the cyber-physical technology is being superseded by the *digital twin* concept [310] which combines interactive knowledge-based and geometrical virtual (digital) models with their physical counterparts within an IoT-based sensing environment [311], typically using cloud-computing and data intelligence. Within the context of composite structures, a desirable scenario would be so that PHM predictions and damage models were integrated within a system-level virtualisation that can be updated using data from the physical twin (namely the IoT-based monitored composite structure) to enable optimal dynamic task allocation, operations sharing, and PdM decision-making.

The latter is the so-called Level-5 Digital Twin technology and, together with new efficient-lightweight PHM and learning algorithms that can do on-board edge or cloud computing [293], constitute a potentially fruitful research direction to enable efficient and reliable I &M strategies in composite structures.

6 Concluding remarks

The use of FRP composites in thin-walled structures for safety-critical applications has seen a notable rise over the last few decades, especially in the aerospace and wind industries with evidence of reliability, durability, life cycle cost reduction and sustainability. Other industries such as the civil and naval have not seen such a rampant increase so far presumably due to the uncertainty about the long-term performance, the lack of technological demonstrators, and the absence of codes and standards.

To overcome this, the development of policies and codes regulating the design with composites along with a cross-sectoral knowledge transfer among industries could be the levers that unlock a greater use of these high-efficiency materials. Moreover, while still relatively immature for industrial application, converting composite structures into cyber-physical structures seems promising to promote the transition into predictive and optimised inspection and maintenance strategies and overcome the long-term performance uncertainty of FRP structures.

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Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Research involving human participants and/or animal rights The authors declare that no research involving human participants and/or animals has been performed for these studies.

Informed consent Informed consent is not required and/or applicable for these studies.

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[2] System-level I &M non-linearities are understood here as artificial I &M actions and other human-based events that influence the "natural" damage and ageing progression of the composite structure.

Table 7 The 17 Sustainable Development Goals (SDGs)

Sustainable Development Goals
Goal 1: No poverty
End poverty in all its forms everywhere.
Goal 2: Zero hunger
End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
Goal 3: Good health and well-being
Ensure healthy lives and promote well-being for all at all ages.
Goal 4: Quality education
Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
Goal 5: Gender equality
Achieve gender equality and empower all women and girls.
Goal 6: Clean water and sanitation
Ensure availability and sustainable management of water and sanitation for all.
Goal 7: Affordable and clean energy
Ensure access to affordable, reliable, sustainable and modern energy for all.
Goal 8: Decent work and economic growth
Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
Goal 9: Industry, innovation and infrastructure
Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
Goal 10: Reduced inequalities
Reduce inequality within and among countries.
Goal 11: Sustainable cities and communities
Make cities and human settlements inclusive, safe, resilient and sustainable.
Goal 12: Responsible consumption and production
Ensure sustainable consumption and production patterns.
Goal 13: Climate action
Take urgent action to combat climate change and its impacts.
Goal 14: Life below water
Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
Goal 15: Life on land
Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
Goal 16: Peace, justice and strong institutions
Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
Goal 17: Partnerships for the goals
Strengthen the means of implementation and revitalize the global partnership for sustainable development.

Source [125]

Appendix 1: Acronyms

See Abbreviations.

Table 8 Boolean indicators of contribution of composite materials to SDGs 1 to 8, as per considered industries

Target	Aerospace	Civil	Wind	Naval
(a) SDG 1				
1.1	0	0	0	0
1.2	0	0	0	0
1.3	0	0	0	0
1.4	0	0	0	0
1.5	0	0	0	0
1.A	0	0	0	0
1.B	0	0	0	0
Total	0/7	0/7	0/7	0/7
(b) SDG 2				
2.1	0	0	0	0
2.2	0	0	0	0
2.3	0	1	1	0
2.4	0	0	1	0
2.5	0	0	0	0
2.A	0	0	0	0
2.B	0	0	0	0
2.C	0	0	0	0
Total	0/8	1/8	2/8	0/8
(c) SDG 3				
3.1	0	0	0	0
3.2	0	0	0	0
3.3	0	0	0	0
3.4	0	0	0	0
3.5	0	0	0	0
3.6	0	0	0	0
3.7	0	0	0	0
3.8	0	0	0	0
3.9	1	0	1	1
3.A	0	0	0	0
3.B	0	0	0	0
3.C	0	0	0	0
3.D	0	0	0	0
Total	1/13	0/13	1/13	1/13
(d) SDG 4				
4.1	0	0	0	0
4.2	0	0	0	0
4.3	0	0	0	0
4.4	0	0	0	0
4.5	0	0	0	0
4.6	0	0	0	0
4.7	0	0	0	0
4.A	0	0	0	0
4.B	0	0	0	0
4.C	0	0	0	0
Total	0/10	0/10	0/10	0/10
(e) SDG 5				
5.1	0	0	0	0
5.2	0	0	0	0
5.3	0	0	0	0
5.4	0	0	0	0
5.5	0	0	0	0
5.6	0	0	0	0
5.A	0	0	0	0
5.B	0	0	0	0
5.C	0	0	0	0
Total	0/9	0/9	0/9	0/9
(f) SDG 6				
6.1	0	0	1	0
6.2	0	0	0	0
6.3	1	1	1	1
6.4	0	1	0	0
6.5	0	0	0	0
6.6	0	0	0	0
6.A	0	0	0	0
6.B	0	0	0	0
Total	1/8	2/8	1/8	1/8
(g) SDG 7				
7.1	0	0	1	0
7.2	0	0	1	0
7.3	1	1	1	1
7.A	0	1	1	0
7.B	0	1	1	0
Total	1/5	3/5	5/5	1/5
(h) SDG 8				
8.1	0	0	0	0
8.2	1	1	1	1
8.3	0	0	0	0
8.4	1	1	1	1
8.5	0	0	0	0
8.6	0	0	0	0
8.7	0	0	0	0
8.8	0	0	0	0
8.9	0	0	0	0
8.A	0	0	0	0
8.B	0	0	0	0
Total	2/11	2/11	2/11	2/11

Appendix 2: Sustainable Development Goals

See Tables 7, 8, 9, and 10.

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Table 9 Boolean indicators of contribution of composite materials to SDGs 9 to 16, as per considered industries

Target	Aerospace	Civil	Wind	Naval
(a) SDG 9				
9.1	0	1	1	0
9.2	1	1	1	1
9.3	0	0	0	0
9.4	1	1	1	1
9.5	1	1	1	1
9.A	0	1	1	1
9.B	1	1	1	1
9.C	0	0	0	0
Total	4/8	6/8	6/8	5/8
(b) SDG 10				
10.1	0	0	0	0
10.2	0	0	0	0
10.3	0	0	0	0
10.4	0	0	0	0
10.5	0	0	0	0
10.6	0	0	0	0
10.7	0	0	0	0
10.A	0	0	0	0
10.B	0	0	0	0
10.C	0	0	0	0
Total	0/10	0/10	0/10	0/10
(c) SDG 11				
11.1	0	1	0	0
11.2	1	1	1	1
11.3	0	0	0	0
11.4	0	0	0	0
11.5	0	0	0	0
11.6	0	1	1	0
11.7	0	0	0	0
11.A	0	0	0	0
11.B	0	1	1	0
11.C	0	1	0	0
Total	1/10	5/10	3/10	1/10
(d) SDG 12				
12.1	0	0	0	0
12.2	1	1	1	1
12.3	0	0	0	0
12.4	0	0	0	0
12.5	1	1	1	1
12.6	1	1	1	0
12.7	0	0	0	0
12.8	0	0	0	0
12.A	0	0	0	0
12.B	0	0	0	0
12.C	0	0	0	0
Total	3/11	3/11	3/11	2/11
(e) SDG 13				
13.1	0	0	0	0
13.2	0	0	0	0
13.3	0	0	0	0
13.A	0	0	0	0
13.B	0	0	0	0
Total	0/5	0/5	0/5	0/5
(f) SDG 14				
14.1	0	0	0	1
14.2	0	0	0	0
14.3	0	0	0	0
14.4	0	0	0	0
14.5	0	0	0	0
14.6	0	0	0	0
14.7	0	0	0	0
14.A	0	0	0	0
14.B	0	0	0	0
14.C	0	0	0	0
Total	0/10	0/10	0/10	1/10
(g) SDG 15				
15.1	0	0	0	0
15.2	0	0	0	0
15.3	0	0	0	0
15.4	0	0	0	0
15.5	0	0	0	0
15.6	0	0	0	0
15.7	0	0	0	0
15.8	0	0	0	0
15.9	0	0	0	0
15.A	0	0	0	0
15.B	0	0	0	0
15.C	0	0	0	0
Total	0/12	0/12	0/12	0/12
(h) SDG 16				
16.1	0	0	0	0
16.2	0	0	0	0
16.3	0	0	0	0
16.4	0	0	0	0
16.5	0	0	0	0
16.6	0	0	0	0
16.7	0	0	0	0
16.8	0	0	0	0
16.9	0	0	0	0
16.10	0	0	0	0
16.A	0	0	0	0
16.B	0	0	0	0
Total	0/12	0/12	0/12	0/12

B 43(3):902–913. https://doi.org/10.1016/j.compositesb.2011.10.007

Table 10 Boolean indicators of contribution of composite materials to SDG 17, as per considered industries

Target	Aerospace	Civil	Wind	Naval
17.1	0	0	0	0
17.2	0	0	0	0
17.3	0	0	0	0
17.4	0	0	0	0
17.5	0	0	0	0
17.6	1	1	1	1
17.7	1	1	1	1
17.8	0	0	0	0
17.9	0	0	0	0
17.10	0	0	0	0
17.11	1	0	0	1
17.12	0	0	0	0
17.13	0	0	0	0
17.14	0	0	0	0
17.15	0	0	0	0
17.16	0	0	0	0
17.17	0	0	0	0
17.18	0	0	0	0
17.19	0	0	0	0
Total	3/19	2/19	2/19	3/19

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