MULTIMATERIAL OFFSHORE WIND TURBINES STRUCTURES WITH HIGH CORROSION AND MECHANICAL REQUERIMENTS

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Abstract

The increasingly demanding requirements in offshore wind structures have led to new solutions in order to reduce operating and maintenance costs. The perspective of moving wind turbines further away from the coast, their large size, and high corrosion requirements are critical for structural parts. These structures, such as transition pieces, which are located in the splash zone, are traditionally made of steel, and especially designed with a corrosion allowance leading to an increasing of structure weight and costs.

The present work deals with the use of multi-material steel-composite systems, with composite as reinforcement of this type of structures, specifically on the transition part of an offshore windmill. The main interest of the multi-material structures is based on mechanical and corrosion resistance improvement.

Different combinations in terms of fibre type, orientations and thicknesses of composite manufactured by filament winding have been studied in order to obtain the optimal combination against corrosion, maintaining the mechanical performance. Laboratory-scale structures have shown the effect of reinforcement of the composite on the primary structure of steel subjected to bending and compression efforts and avoiding premature failure and local deformations. The composite reinforcement also acts as a barrier against corrosion, which has been monitored by FBG sensors with Fe and FeNi coating that act as corrosion sensors.

1. Introduction

Composite materials reveal several engaging characteristics for offshore service that have motivated the industry to introduce them into structural elements: high strength to weight ratio, good corrosion and fatigue resistance, good thermal insulation, and increased design flexibility.

Multimaterial structures, combining steel and FRP, are a great solution when composite structures can not fulfill the design requirements [1]. This approach is beneficial with regard to weight savings and structural integrity when compared to metallic or FRP structure independently. Several authors have successfully studied the strength, repair and reinforced of steel with FRP for marine aplications [2], [3] (i.e. ships [4], pipelines, offshore risers [5], [6]) or civil engineering [7], [8]. Studies refered to offshore or uderwater applications are based in circular hollow section (CHS) steel beams with FRP reinforcement looking for avoid buckling and increase flexural stiffness capacity [9] .

However, long-term damage mechanisms and in-service integrity monitoring are both significant challenges in marine aggressive environments. Structural health monitoring of composite, multimaterials and adhesive joints by FBG sensors have been studied in maritime structures [10] and recent developments leads to use them for corrosion monitoring [11] to achieve safer structures and anticipate failure.

In order to study the effect of multimaterial structures on the transition part of an offshore windmill, axial compression [12], [13] and bending forces [14] had been taken into consideration. Fatigue loads, cyclic temperatures and galvanic corrosion, wich may result due to direct contact between carbon fibers with steel parts, form the basis for additional considerations in this study. FBG coated sensors placed into composite layers will reveal the presence of electrolyte inside the reinforcement, and shows the adhesive joint degradation if they are placed into steel-composite interface.

2. Experimental Procedure

The objective of this work has been the study of multimaterial structures under conditions of corrosion and fatigue in order to reduce the steel corrosion allowance in offshore structures. Prior to the experimental work, a study of the main efforts in offshore structures, such as a transition piece, has been carried out. Compression and bending efforts on multi-material piece have been studied.
The materials used in the study were S355 J2 structural steel, with a module comprised between 325-335MPa, maximum strength of 470-630MPa and an elongation at break of 20-22%. In case of composite material: an EPOVIA optimum KRF 1001 TAS vinyl ester resin has been used for the manufacture by filament winding, with a tensile strength of 85MPa and a modulus of 3,9GPa and a Tg 110°C. Two rovings Sigrafil (SGL) carbon roving and Advantex glass roving from Owens Corning, have been used as reinforcement material.
The geometries of the bending and compression steel specimens are listed below in the following table (Table 1). The manufacturing process of the specimens has been the same for all cases: Steel surface treatment (blasting) until a roughness of Ra=8,2µm is obtanined, application of epoxy-Zn anticorrosive primer, manufaturing of the composite part by filament winding with embedded FBG sensors. Finally, in the case of corrosion tests, a self-finishing paint is applied.

Table 1. Specimen geometries for compression and three point bending test.

	Multimaterial compression specimen	Multimaterial bending specimen
Length	280mm	670mm
Diameter-Steel$_{out}$	102mm	102mm
Thickness-Steel	4,5mm	4,5mm

Steel specimen with same diameter and length but with 6mm thickness were used as reference.

In a first stage of the study, static tests (axial compression and 3 point bending) with different combinations of composite reinforcements have been carried out in order to obtain the best combination in therms of orientations, type of reinforcement, etc.

Compression tests have been carried out in a universal test machine MFL 1000kN with force controlled speed test rate of 500N/s. The specimens were monitored by an extensometer located on the outside of the specimen in the midle point in length specimen as can be seen in figure (Fig. 1). Four straing gauges were placed at the mid-heigh (140mm from the end of the specimen), at 0°, 90°, 180° and 270° in order to monitor any possible buckling of the specimen during the test.

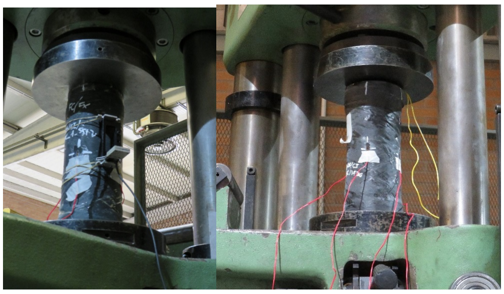

Figure 1. Compression test, extensometer and gauges.

Three point bending tests where carried out in a Shimadzu 250kN universal testing machine with force controlled speed test rate of 500N/s. Load was applied at the midpoint of the specimen, supports with 40mm were placed with a 500mm distance between them. The following figure (Fig. 2) shows schematically the test carried out.

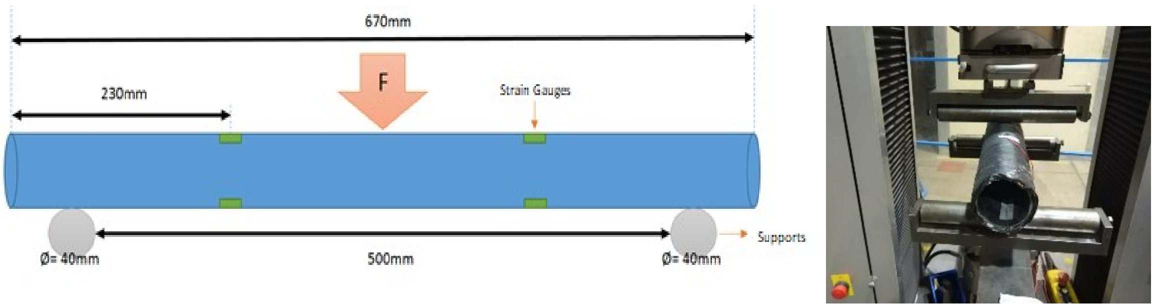

Figure 2. Compression test, extensometer and gauges.

Table 2 summarizes all the combinations tested in compression and bending tests.

Table 2. Combinations for compression and three point bending test.

Compression		
Number layers	Material	Orientation angle
1	CF	±55°
2	CF	±55°
3	CF	±55°
2	CF	±65°
2	GF	±55°
2	CF	90° and ±55°
2	GF-CF	±55°
2	CF-GF	±55°
3 Point Bending		
Number layers	Material	Orientation angle
1	CF	±55°
3	CF	±55°

4	CF	±55°
3	CF	±45°
3	CF	±65°
3	CF	90° ±55° 90°
3	CF	90° ±55° ±55°
3	GF	±55°
3	GF-CF-GF	±55°
3	GF-CF-CF	±55°
3	GF-GF-CF	±55°

In order to evaluate durability of multimaterial structures, some of the above combinations have been subjected to thermal fatigue and corrosion tests by immersion in seawater. Different FBG sensors coated with Fe and FeNi were embedded in immersed specimens for corrosion detection: on the steel-composite interface, between the layers of the composite and on the composite and the finishing paint used. Wavelength shift presents a marked change when the coating corrodes (Fig. 3). After 30 days of immersion, specimens were tested under compression test.

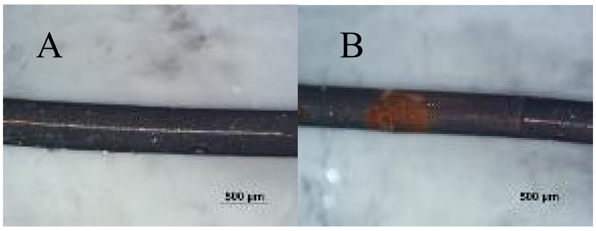

Figure 3. FBG sensor coated with FeNi (A) before corrosion (B) after corrosion

Finally, thermal tests where carried out in a climatic chamber (Fitoclima 300 Aralab) with temperature cycles (Table 3). In this case, only specimens with 2 layers of carbon fiber with ±55° angle and with two layers of fiberglass with ±55° have been tested, in order to appreciate the changes due to the different reinforcements. Compression test where carried out after 42, 84, 126 and 168 cycles in order to evaluate the loss of mechanical properties due to temperature cycles.

Table 3. Temperature cycles.

High Temperature	90°C±1°C 1 hour
Transitions	1,67°C/min ~60 minutes
Low Temperature	-10°C±1°C 1 hour

3. Results and Discussion

3.1. Static Tests

The following figure (Fig. 4) shows the average results of compression tests, as can be seen there are no significant differences between the different combinations evaluated. However, it can be said that the best results are obtained with layers oriented at ±55°. In addition, it is notable that the multimaterial specimens (jacketed with composite) exceed the load at break of the steel jacket with higher thikness (6mm). Figure 5 (Fig. 5) shows the change in failure mode of the steel without composite (barrelling), with one layer and with 2 layers, clearly appreciating the change in the failure mode when the reinforcement is increased. The composite acts as a boundary contention, reducing the effect of barreling and increasing the load at break.

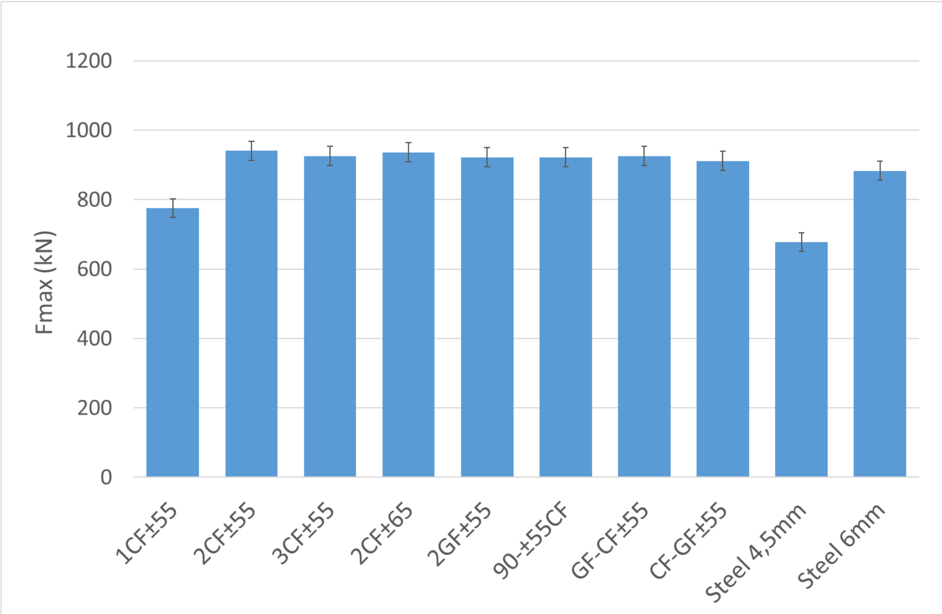

Figure 4. Compression test: Axial load at failure (kN) for different combinations

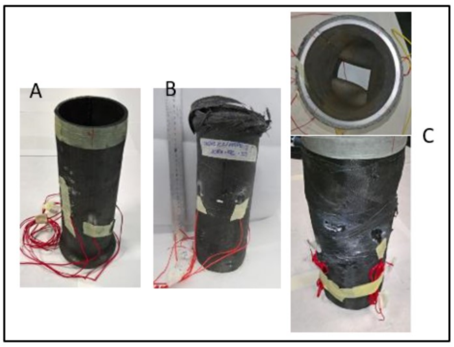

Figure 5. Failure modes: A) Steel structure with local elephant's foot buckling failure,B) Multimaterial structure (1 layer carbon fiber ±55°) with buckling failure and composite rupture, C) Multimaterial structure (2 layer carbon fiber ±55°) with central failure.

With regard to the 3-point bending tests, results show a great difference between steel and multimaterial structure. Figure 7 (Fig.7) shows the energy per kg absorbed by the structures, in other words, the area under the bending test curve (Fig. 6) according to the equation (Eq. 1).

$$E_t = \int_0^{u_f} F \cdot du \tag{1}$$

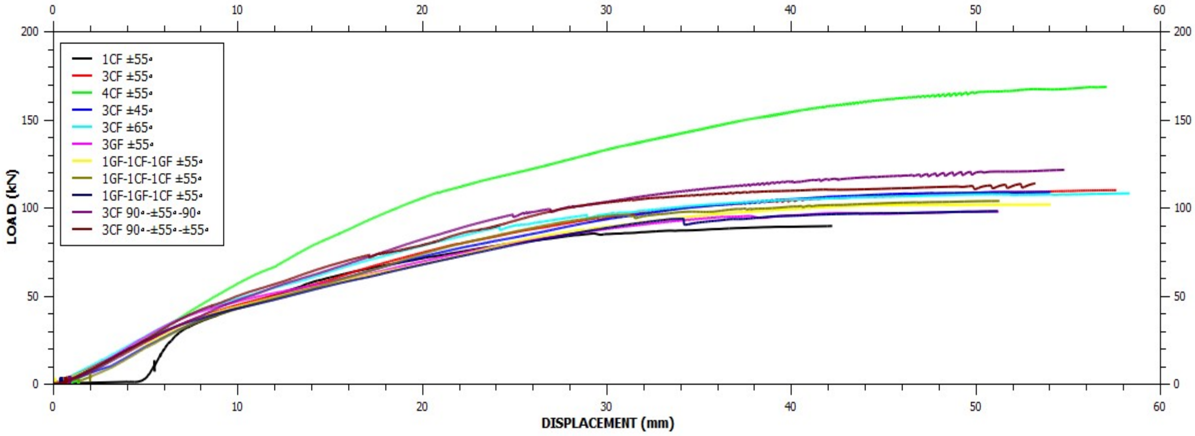

Figure 6. Load vs.displacement for 3 point bending tests.

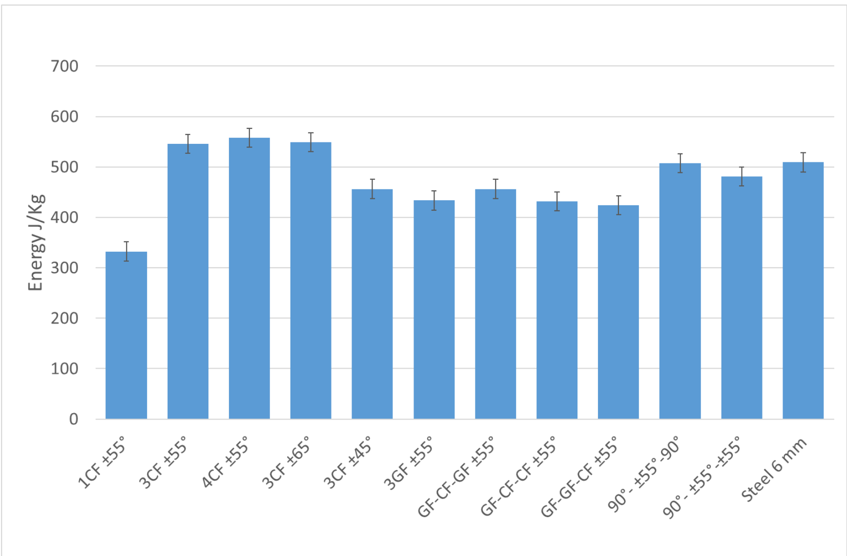

Figure 7. Multimaterial structures energy absorption (J/kg)

The results of the tests with 3 layers of carbon fiber at ± 55 ° and ± 65 ° show similar to the steel structure with a higher thickness.

3.2. Degradation, corrosion and thermal tests

The corrosion test specimens have been evaluated after immersion of one month. The values (Fig.8) reflect that the structure has not been affected. Low variations have been observed, which can be considered within the dispersion of the test.

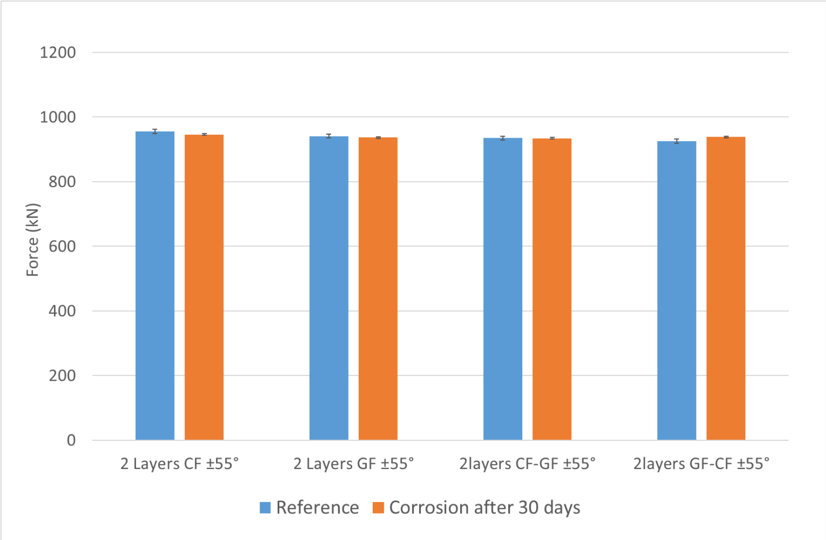

Figure 8. Comparative compression test after 30 days immersion

In addition, as shown in the following figure (Fig. 9 A), the coated FBGs do not show signs of corrosion and all follow the same trend as uncoated FBGs. Variations are related to environmental temperature changes.

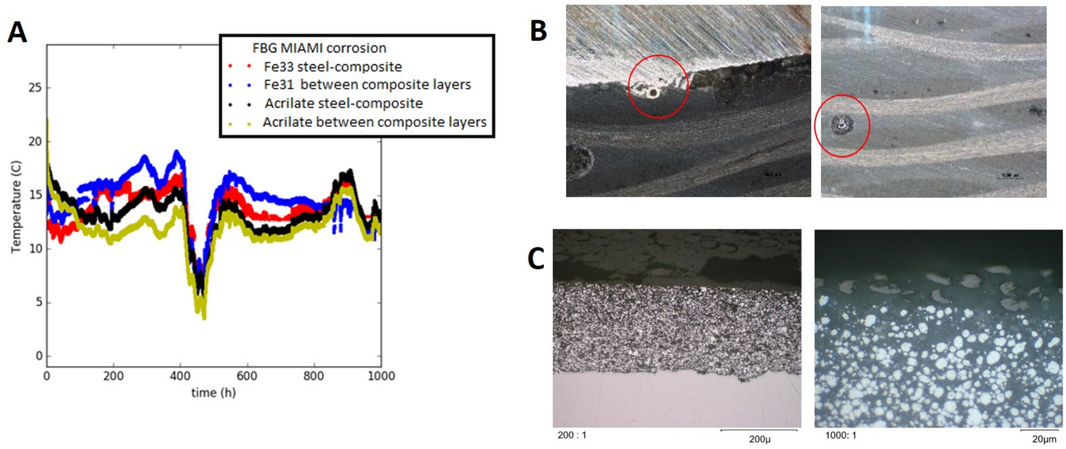

Figure 9. A) FBGs signal trend, B) optical micrographs cross sections with optical fiber embedded in steel-composite interface and between composite layers C) optical micrographs cross sections for corrosion evaluation in steel-composite interface.

To evaluate the presence of corrosion in the interface, cross section micrographs have been carried out. As can be seen in the upper images (Fig. 9 B and C), the interfaces steel-composite and the sensor do not show the presence of corrosion

Regarding to the compression tests of the specimens subjected to thermal cycles, results show a small variation in their maximum load. The specimens with fiberglass show a gradual decrease, however this effect is not seen in the carbon fiber specimen as is shown in Fig.10.

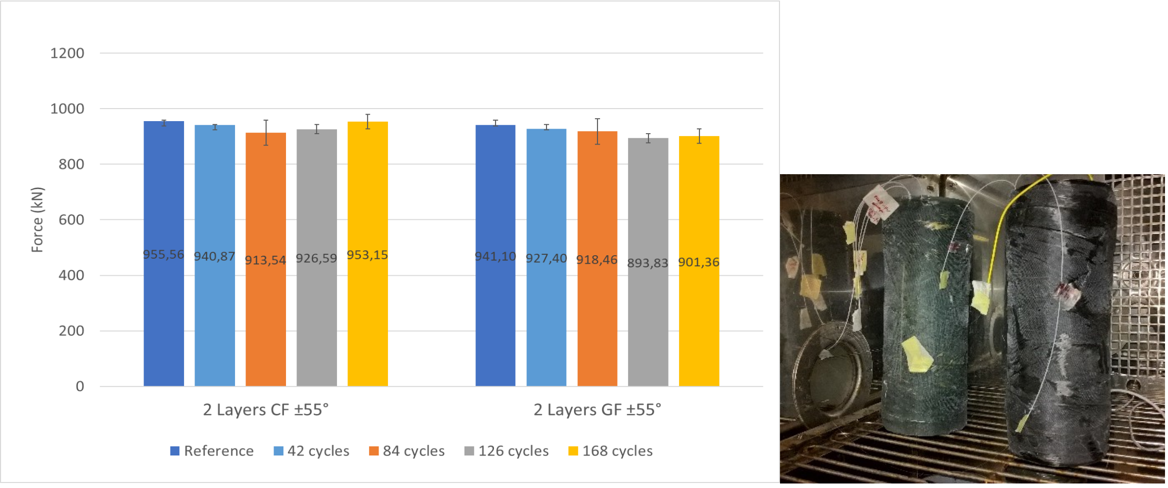

Figure 10. Maximun load for carbon fiber (CF) and fiberglas (GF) specimens and specimens inside test chamber.

4. Conclusions

The behavior of multimaterial structures under mechanical and corrosion demand for offshore structures has been studied in this work.
After the results of the compression tests it can be concluded that the best combination (carbon fiber with a winding angle at 55 degrees) results in an improvement of 5,10% compared to steel reference specimen (with a 33,33% greater thicknes).
In the case of bending tests, the results are more significant. An improvement in flexural capacity of 63,48% is obtained compared to steel steel structure with 6mm thickness. This results in an increase in the energy absorption efficiency (J/kg) of the piece of 28.99% compared to the steel structure used as a reference.
After the immersion tests it can be concluded that no corrosion is present in the interface, coinciding with the coated FBG sensors signals. Cyclic temperature tests show no significant variation, although the specimens with fiberglass composite have a slight decrease in their compression results.
Long-term tests are ongoing with the purpose of corroborating the results obtained in this study.

Acknowledgments

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