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SYNERGISTIC PERFORMANCE DEGRADATION OF MARINE STRUCTURAL ELEMENTS: CASE STUDY OF POLYMER-BASED COMPOSITE AND STEEL HYBRID DOUBLE LAP JOINTS

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ABSTRACT

The degradation of structures under the influence of a marine environment tends to be rapid and disruptive compared to that of structures that are far away from these influences. Efforts to consider these impacts in the design phase are increasing, with a view to the construction of more sustainable structures. However, experimental data from which designers and builders can benefit cannot be found in the relevant literature, especially when it comes to the effects of composite degradation. In this study, we experimentally investigate the combined effects of degradation factors such as a drying-wetting cycle, the shape of the structure, the variety of materials used in the structure, and the differences in the manufacturing of the materials . The structure chosen as an example is a hybrid structural double lap joint composed of epoxy resin, fibreglass composite, and steel, which is widely used in ship structures. The experiments considered four aging periods (zero, 30, 60 and 90 days) under a wet-dry cycle in a programmable corrosion chamber, two overlap lengths (short and long), two surface roughnesses of the steel parts (50 and 90 μm), and two surface preparation alternatives (uncoated and coated with epoxy primer). The synergistic effects of these parameters on the tensile strength, deformation and toughness of the joints were evaluated, and suggestions are made for ship designers. The attention of interested parties, and particularly ship designers, is drawn to the comparative effects of these degradation agents on performance.

Keywords: Wet-dry cycle; Double lap joint; Polymer composite-steel joints; Surface roughness; Aging in marine environment

INTRODUCTION

It is well-known that water, despite being the source of life and well-being for humans, is less kind to the materials and structures that come into contact with it or are located close to it. Water helps initiate and drive natural phenomena that lead to the weakening of mechanical properties established in the design phase, thereby increasing the need for repair and reconstruction, and shortening the expected life of related materials and structures. Material degradation is a global phenomenon that increases costs related to construction and operation, as well as the carbon footprint of a structure. For example, it has been estimated that the economic and ecological effects of corrosion reach 3–4% of the gross domestic product of industrialised countries, especially in regard to metallic structures [1]. In order to achieve more sustainable structures, the resistance of marine structures to degradation needs to be increased and their service life extended.

In a seawater environment, the water itself is not the only element that causes these irreversible effects on the materials and structures; other degrading factors include salt (which is composed of different minerals depending on the geography), wetting/drying and freezing/thawing cycles, moisture, weathering (including rain, sand erosion, etc.), UV radiation, microorganisms (e.g. fouling/boring organisms), and chemicals (acids, alkalis, solvents, oxygen, etc.) [2].

Although these factors often interact, research has focused on a single mechanism of degradation for a single material. In the design of ship structures, where designers tend to use the results of experimental studies, the synergistic effect of different combinations must be taken into account. It would be appropriate to refer to the total degradation effect, which occurs as a result of the action of many agents on the material according to many different mechanisms in the marine environment, as synergistic degradation.

As floating marine structures, ships are exposed to conditions that can be divided into three zones: underwater, the splash zone and the atmospheric zone (Figure 1). Degradation in the splash zone occurs more rapidly due to the high chloride and oxygen content and the cyclic wetting and drying action (WDA), which causes accumulation of chloride and increased intrusion and transfer of moisture into the structure [3].

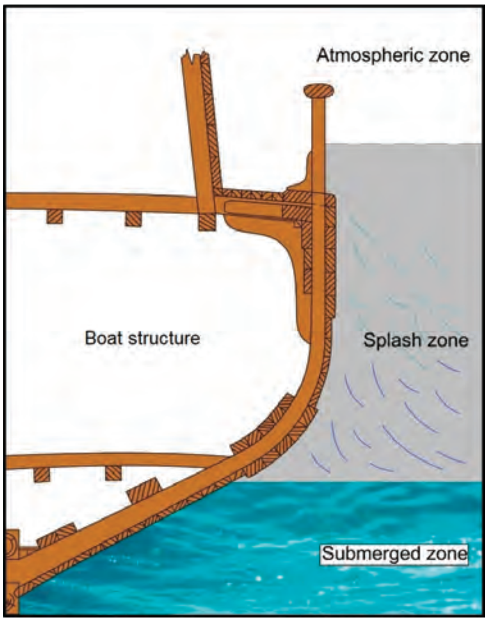

Fig. 1. Zones of the marine environment acting on a ship

As in other fields of engineering, the main aim of naval architecture is to achieve the lightest possible structure. To this end, naval architects tend to use lighter materials even for heavy floating metal structures, which mainly include composites based on fibre-reinforced polymers (FRP) [4]. These are used in a variety of industrial marine applications, including coastal structures, due to their high specific strength and stiffness. FRPs are also characterised by high corrosion resistance, good impact strength, and fatigue resistance, which make them attractive for use in marine applications such as propellers, boats, ships, turbine blades (wind and tidal turbines), and sails [5].

FRPs are also used to reinforce coastal structures such as ports and piers, either in the form of bars as a replacement for reinforcing steel, or as strips that are bonded to concrete for the external reinforcement of structural members or delineation of columns. The beneficial effects of their use in rehabilitation, which arise from their ease of installation, high chemical resistance and reduced architectural impact and/or increased mechanical or fatigue resistance, are well known and have been described in the literature.

The water around the glass fibres becomes an alkaline solution as alkali ions dissolve out of the glass, and the glass fibres gradually decompose [6]. In general, the moisture concentration initially increases with time and eventually approaches a saturation point (equilibrium) after several days of exposure. The time needed to reach the saturation point depends on the properties of the materials and the ambient temperature, and although drying can reverse the process it may not lead to full recovery of the original properties [7]. This degradation often leads to damage to the FRP, such as microcracking of the matrix, fibre/matrix interfacial debonding and delamination, plasticisation and swelling of the matrix materials (making the polymer more ductile and lowering its glass transition temperature), and hydrolysis, leading to the ultimate failure of the structure [8]. In particular, for epoxy resins, a decrease in the elasticity modulus of this material has been observed under wetting-drying action (WDA). It has been reported that in long-term tests on glass/epoxy composites, about half of the tested specimens failed at a sustained stress of only 50% of the ultimate load after about seven years [9].

In the absence of chemical interactions, salt crystallisation occurs in saline environments, which physically damages the materials. This damage is caused by internal stress resulting from the formation of salt crystals in the material pores when the solution inside the pores becomes supersaturated [10]. Salt crystallisation occurs under two circumstances: the evaporation of the pore solution with the capillary rise, which is the action of a liquid moving across a small space without the aid of, or even against, any external forces like gravity, and WDA [11].

In one of the first studies in this field, by Gellert and Turley [12], it was shown that the glass fibre-reinforced plastics (GFRP) used in marine applications, which are composed of various resins such as polyester, phenol, and two types of vinyl esters, lose 15–25% of their mechanical properties during aging. During the tests, specimens were immersed in seawater and unloaded and loaded at high service temperatures in the range 30–50°C, and continuous solar radiation increased the temperature of the structure [13, 14]. There was a greater loss of mechanical properties from immersion at 50°C, which was accompanied by signs of abnormal degradation. The researchers also included an oven drying phase in their experiment to account for this effect, at temperatures of 45–80°C. Higher temperatures were used to increase the rate of water evaporation and to significantly shorten the duration of the test. Alhozaimy et al. [15] found that the corrosion of steel became more severe when the temperature was increased from 28.5°C to 34.5°C. This was due to the catalytic effect of a higher temperature on chloride, which destroys the passivity of the steel.

However, it must be mentioned that there are some difficulties with joining polymer-based composites with metalelements of a marine structure, which are related to the large differences in mechanical properties (stiffness, coefficient of thermal expansion, etc.) between the adherents, and the strong anisotropy of composites.

Joints cause the local accumulation of stress, which can lead to discontinuities in the shape of the structure and the material properties. When designing and manufacturing a joint that is reliable over the long term, the effects of the marine environment in terms of degradation must be considered, as well as the elements of the joint and its shape, in order to minimise stress accumulation. The influence of the environment on materials significantly increases in the WDA zone. With a view to predicting potential degradation in the properties of materials, in situ data and data from accelerated aging simulations in materials laboratories have been used to overcome the difficulties of conducting long-term tests in natural environments. Studies of accelerated aging using distilled water and seawater have been reported in the literature, beginning in the early 1980s. In these studies, where the main corrosive element of the marine environment was salt from sea air, it was mentioned that aging leads to a reduction in the mechanical properties of materials, such as their stiffness and ultimate strength [16].

In addition to these effects, the steel parts of a hybrid joint may be roughened, which greatly complicates the prediction of its performance. The effects of surface roughness have not been extensively investigated in existing studies of composite-steel joints. Some type of surface pretreatment is required to achieve adequate bond strength and resistance to environmental degradation. Surface pretreatments are primarily used to remove contaminants and wear layers from surfaces, to increase the surface area, and to ensure that all mechanisms of adhesion are activated. The strength of bonded joints is increased if the surface is textured and made rougher before bonding, for example by mechanical abrasion, although the relationship between roughness and adhesion is not yet fully understood. This relationship may be explained by the large effective surface area or by some mechanical interlocking, and numerous studies have focused on the use of different metrics to describe roughness and its relationship to mechanical strength.

In composite shipbuilding, many types of adhesive joints are used, such as single and double lap joints, docking joints, bevel joints and trapezoidal joints, both to maintain the light weight of the structure and to improve its mechanical and physical properties [17]. Bonded and bolted double lap joints are prominently used for the connection of polymer-based composite–steel structures. It is well known that bonded joints have several advantages over conventional joints (bolted, welded, riveted, etc.), such as their ability to join dissimilar materials, better stress distributions, weight reduction, applicability to complex shapes, improved hydrodynamic surface resistance, and better corrosion and fatigue resistance [18]. In a study by Bohlman and Fogarty [19], bolted and bonded joints were compared in terms of joining a composite superstructure to the steel hull of a naval ship, and bolted joints were found to be more expensive to manufacture and maintain. The plates are not weakened or damaged during the joining process. The strength-to-weight ratio is also high for these joints [20]. Le Lan et al. [21], who studied both bolted and bonded joints, also developed bonded joints for French Lafayette frigates. Bonded double lap joints have been used in the study of metal-to-metal, metal-to-composite and composite ship elements, and have also been used to explore the interfacial fracture of the corresponding structure. In ship structures, double lap joints are preferable because they can resist transverse shear forces due to blast or sea pressure on a panel [22].

Damage to composite materials is one of the most important topics of current research, and numerical and experimental models have been developed specifically to study damage to composite joints. For example, Yang et al. [23] proposed an efficient model based on peridynamic theory to estimate the damage around a hole at the connection points of bolted composite joints. In addition, dynamic effects such as low-velocity impacts have been investigated due to their negative effects on the lifecycle of composite materials [24].

In a study by van Dam et al. [25], a shear test on a single lap joint showed that the dominant factor affecting the initial adhesion between the epoxy adhesive and the steel substrate was the roughness of the substrate. In addition, specimens with different surface morphologies but comparable average levels of roughness showed significant improvements in initial adhesion. The porous morphologies of etched and blasted surfaces gave superior adhesion performance, and appear to be key factors in the development of potential mechanical interlock. This occurs when the adhesive penetrates the pores of the surface and creates an area known as the microcomposite interphase zone.

In this study, experiments were conducted to predict the performance of double lap joints with lower and upper parts made of e-glass fibre-reinforced epoxy composites and a middle part made of ship-grade steel. We considered four aging periods (zero, 30, 60 and 90 days) under a wet-dry cycle in a programmable corrosion chamber, two overlap lengths (short and long), two surface roughnesses (50 and 90 μm) of the steel parts, and two surface preparation alternatives (uncoated and coated with epoxy primer). The synergistic effects of the above parameters on the joint performance were evaluated, and suggestions were drawn up for marine designers.

MATERIALS AND METHOD

SPECIMENS

Specimens of hybrid double overlap joints were fabricated, consisting of e-glass reinforced epoxy composite layers and a steel member between these layers, to comply with ASTM D3528-96 [26]. These specimens had two different lengths of overlap (short and long), which were used as a performance variable for the joint (Figure 2).

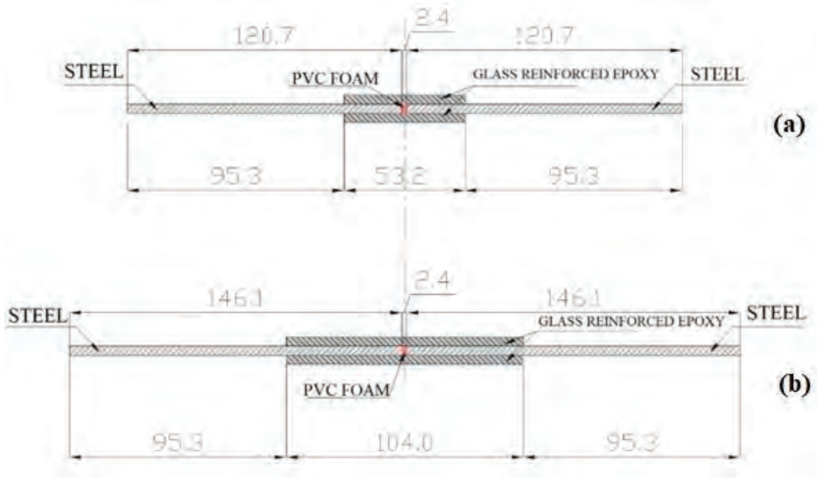

Fig. 2. Geometry (in mm) of the specimens for the hybrid double lap joints: (a) short overlap, (b) long overlap

The reinforcement of the composite part was a stitched multiaxial [0, −45°, 45°, 90°] e-glass fibre with an area weight of 850 g/m^2, manufactured by Metyx [27] under code Q850E10B. The resin used in this composite was an epoxy resin made by Duratek [28], code 1000, which was recommended by the manufacturer for vacuum bagging, and was used with a hardener from the same manufacturer. It is worth mentioning that the sides of the composite parts were coated with an epoxy paint to prevent water from being absorbed.

The steel layers were Grade A St37 marine steel manufactured by Erdemir Iron and Steel Mill Corp. of Turkey [29]. The specimens, consisting of the composite material and a steel layer, were vacuum-bagged in a serial manner using a system developed by the authors (Figure 3), since vacuum-assisted methods cause fewer manufacturing defects than conventional hand lay-up methods [30]. To ensure that the steel parts did not touch each other and were aligned correctly, strips of PVC foam material were placed between them. In this way, it was prevented that the epoxy fills the gap between the steel parts.

PREPARATION OF STEEL PARTS

The surface roughness of the steel part of the joint was considered as another performance variable in this study. To evaluate the effect of this parameter on the performance, the surface of some specimens was textured with two different roughness values, Rz (average distance between the highest peak and lowest valley in each sampling length of the measured surface), of 50 µm and 90 µm. To obtain these roughness values, the steel layers were blasted using steel balls with diameters of 1 and 2.5 mm, respectively. The resulting roughness values of the surfaces were measured with a Mitutoyo SJ-301 (Neuss) instrument.

Before the roughened steel parts were used to make the double lap joint, a primer was applied to the surface of some parts. The application of the primer was also considered as a performance variable for the joints.

AGING

In order to simulate the effect of wet-dry cycling in a marine environment, the specimens were stored in a programmable cyclic corrosion test chamber (salt spray booth) [Ascoot CC 1000 IP, Staffordshire, UK]. A daily cycle was programmed in which the specimens in the chamber were covered with salt fog (a 2.5% solution of sodium chloride, NaCl) during the first eight hours of the day under the conditions specified in the ASTM B 117 standard [31] and at a temperature in the range 45–60°C. The specimens were then exposed to a relative humidity of 100% at a constant temperature of 60°C for the second period of eight hours. These two eight-hour periods represented the wetting phase of aging. During the final eight hours of the day, the specimens were exposed to a temperature from 60°C to 45°C without humidity. This last period represented the drying phase of aging. The weekly wet-dry aging cycle is shown in Figure 4. Specimens were grouped and aged for 30, 60 and 90 days to investigate the effect of the duration of aging on the joint performance, and were weighed with a precision balance at the end of each

Fig. 3. Specimen fabrication with vacuum bagging technique

period to determine the degree of water absorption.

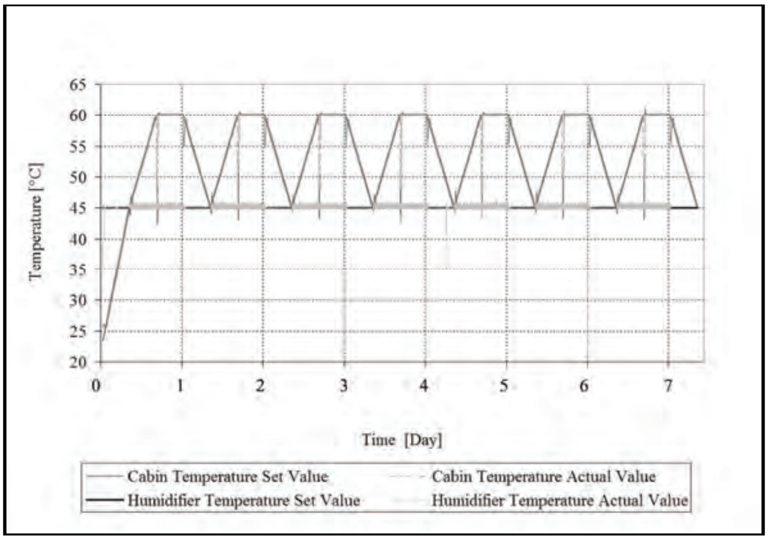

Fig. 4. Weekly aging cycle

TENSILE TESTS

To measure the strength of the joints (i.e. the maximum force that the joints could withstand), tensile tests were carried out in the Mechanics Laboratory of Dokuz Eylül University Engineering Faculty using a tester [Shimadzu Autogarph AG-IS, Kyoto, Japan] which complied with the ASTM D3528-96 standard [26], at a speed of 1.27 mm/min. The data were recorded and the equipment was controlled using Trapezium software.

SPECIMEN CODING

Specimens were coded as X-YY-ZZ, where X represented the overlap length (S indicated short and L long), YY was 50 or 90 (the values of the surface roughness), and ZZ represented the use of primer (where PN indicated without primer and PY with primer). For example, a specimen labelled L-90-PY had a long overlap, a surface roughness of 90 µm, and primer applied. For each condition (code), five specimens were tested in order to minimise the error rate, resulting in a total of 160 specimens tested.

RESULTS

The samples were weighed under ambient conditions to determine the water absorbed in the composite parts of the joints, and were then quickly returned to the exposure environment It was found that the amount of water absorbed was 1.3% of the total weight of the specimens after 30 days of aging, and and the same value was found for the materials at the second weighingafter 60 days of aging. At the last weighing, the amount of absorbed water decreased to the value of 1.1% of the total weight This deabsorption may have been due to the drying effect of the cycle. In addition, the water-repellent effect of salt crystals accumulating in the pores of the material should be noted. During the aging process, it was observed that the colour of the specimens changed from white to yellow, due to the time spent in the corrosion chamber.

The general results of the tensile tests are given below:

1. The tensile strength of the specimens increased with the aging time up to 60 days, and then started to decrease up to 90 days of aging. Samples with a longer overlap showed better performance (Figure 5). However, for S-50-PY and L-50-PY, the decrease in tensile strength started after the 30-day period. This indicates that the accumulation of salt crystals in the pores of the material, which led to a temporary increase in strength during the aging process, was prevented by the low surface roughness and the application of a primer coating.
2. Coating with primer resulted in better strength values for the specimens with a higher surface roughness than those with lower roughness. The strength of specimens with lower roughness coated with primer increased up to the end of the 30-day aging period, after which it began to decrease steadily. For the uncoated specimens, the strength of the joints increased steadily over the 90-day aging period. Uncoated joints with lower roughness showed a higher strength performance than those with higher roughness.
3. The length of the overlap had a positive effect on the performance of the joint. For uncoated joints, the ratio between the strength of specimens with lower roughness and those with higher roughness was almost 1.3 for shorter overlaps, but was 1.5 for longer ones. This ratio gradually decreased to 1.25 for longer joints at the end of the 90-day aging period, while it remained constant for shorter joints. It could be concluded that longer overlapped joints had higher strength due to the longer curing time at the relatively high temperature in the aging chamber. For coated joints, the shorter overlap/lower roughness or longer overlap/higher roughness required for desired performance. As with the uncoated joints, specimens coated with primer with higher roughness gradually became stronger than those with lower roughness during the aging process. However, the performance of the joints did not increase in proportion to the overlap length. It was found that the reason for this nonlinearity was due to the adhesive performance of the joints during vacuum bagging, especially those with higher roughness, where the interface between the composite and steel consisted of micro voids. Despite cleaning, the roughened surface also contained small particles. Joint failure was triggered by these voids/particles, and joint joints began to separate nonlinearly, if the tensile force was sustained.
4. Except for joints with low surface roughness/primer coating/short overlap, the shorter joints showed nearly

the same performance as the longer ones as aging progressed.

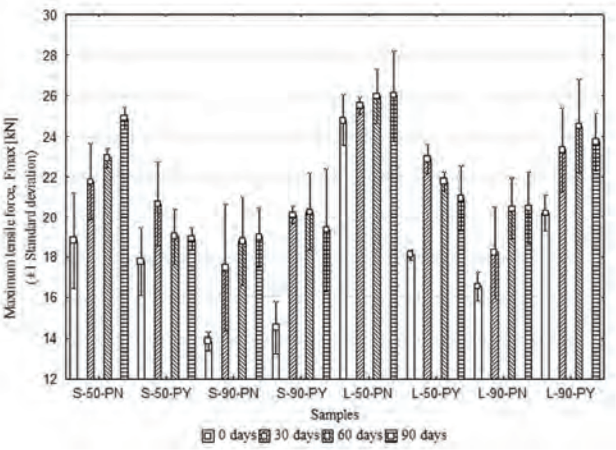

Fig. 5. Tensile strength of the specimens

5. The failure displacement increased throughout the aging process, indicating that aging made the joints much more ductile (Figure 6).

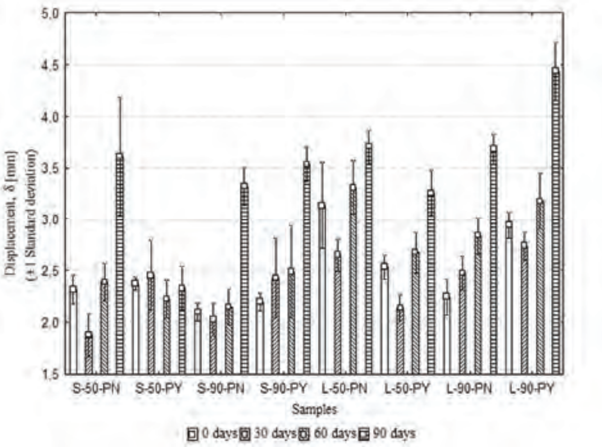

Fig.6. Maximum displacement of specimens

6. The failure energy (area under the force–displacement curve) increased with the aging time (Figure 7).

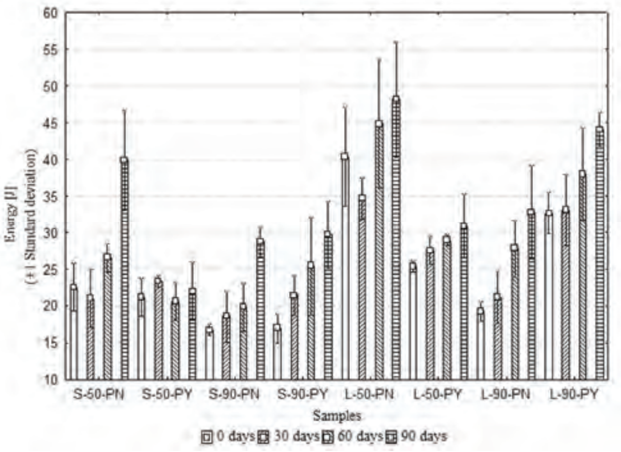

Fig. 7. Failure energy of the test specimens

CONCLUSIONS

In this study, bonded double lap joints consisting of glass fibre-reinforced epoxy composites and steel members were experimentally investigated with the aim of contributing to the design of marine structures in general and small marine craft in particular. For this purpose, a wet-dry cycle was used; the shape of the joints, the surface preparation of the steel part and the use of a primer were selected as performance parameters for the corresponding joints, and the effects of these parameters were discussed in detail.

This study provides deeper insight into the effects of WDA on the mechanical performance of the joints through experimental research. The following conclusions can be drawn from the study:

1. WDA exacerbates joint degradation depending on properties such as the duration, temperature and external loading. A combination of several mechanisms was investigated, and the results suggest that WDA makes the surfaces more susceptible to degradation.
2. Tests should be conducted in a real environment, which would allow the laboratory simulation of WDA to be further improved through the collection of extensive field data.

For designers of marine structures who wish to combine polymer composites with steel structures, the following points should be considered:

(1) It is advantageous to keep the overlaps of double lap joints short, for ease of fabrication. However, in this case, it is necessary to remove the roughness of the steel parts to enable effective bonding, and a primer may have to be used for this.

(2) When exposed to environmental agents for more than three months, the performance of structures such as the double lap joints in this study decreases. In general, measures should be applied (effective coatings, planned maintenance, etc.) to keep materials away from the exposure of the corrosive effects of the marine environment away from these effects.

(3) Although some experimental data are available for the study of the degrading effects of environmental factors on individual materials, further experimental tests are needed to understand the effects of more than one factor, as in this study. Conducting aging tests under real or simulated conditions during the design phase of structures operating under such synergistic effects is very important for the long-term reliability of the structure.

From this study, it can be concluded that the best solution for joining two different materials is to use an uncoated steel part with low surface roughness and composite parts with longer overlaps, which should be joined with a vacuum-assisted technique. In case of steel parts with higher surface roughness, the use of a primer coating is highly advisable. To produce a much stronger joint, an additional bolt could be placed in the location at which separation is initiated.

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