DEVELOPMENT OF PREFABRICATED COMPOSITE PATCHES FOR REPAIR OR STRENGTHEN MARINE STRUCTURES

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Abstract

The present work deals with different aspects of the technology transfer of an innovative technology widely used in the aeronautical sector for repair and reinforce aluminium structures. This technology is based on the application of composite patches across the critical region that if adequately performed, will provide an alternative load path for the stress leading to an improved fatigue resistance.

A broad range of composite laminates, surface treatments and adhesives had been considered in this study so to maximise the strength of the solution. Special emphasis was placed on the dissimilar composite- steel adhesive joint strength evaluation and performance over time. Different tests had been carried out to identify the combination of surface treatments (mechanical and chemical), adhesives and composites for different case scenarios. The optimum combination was scaled-up with the aid of numerical simulation based on the finite element method (FEM), and validated on large scale specimens in which artificial defects were performed.

1. Introduction

Weather conditions, operations and both sea and cargo loads are responsible for most of structural damages experienced by ships, with fatigue playing a predominant role. Present experience indicates that about 70% of the total structural damage in medium-sized ships and larger may be classified as fatigue damage. Thus, cyclic stresses arising from the above factors lead to stress concentration areas that can jeopardize the strength of the structure. In order to avoid structural failures, the designed ships need to have structural elements maintained, repaired and/or replaced during their whole designed life. Therefore, repair activities have historically grown parallel to ship construction ones. However they have remained virtually unchanged partly motivated by the conservatism of the sector. The techniques used are limited to several basic practices and generally it requires welding or bolting double plates or, in the worst case scenario, the replacement of the damaged part could be performed, depending on the particular case [1]. In any case, both methods have to some extent a number of drawbacks such as; deformations derived from welding processes, weight increase due to the inclusion of additional steel plates, introduction of localized stresses, need of rework operations, etc.

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Composites materials have emerged as a promising technology to overcome the previous limitations. And while the technology itself is not new, given its maturity in the aerospace sector, it is in a nascent stage of development in the maritime sector where it faces a clearly distinctly system and working conditions. The basic/operational principle relies in a well-known capability of composite materials. Thus, a laminated composite bonded across the critical region, if adequately performed, will provide an alternative load path for the stress. As a result the probability of fatigue failure of specific critical parts of the structure will diminish leading to a extended lifespan.

The repair procedure can be performed either by in-situ manufacturing of the composite, in which case the matrix of the composite itself acts as an adhesive or, instead, by assembling the composite with adhesives. The aim of PARCHE Project, under which the present work has been developed, is to demonstrate the effectiveness of the latter alternative for which the composites will have to be manufactured at a previous stage. In this regard it should be noted that even if a few preceding studies can be found in marine industry with the first methodology (i.e. in its application on naval ships) [2], the second approach would be new according to the authors' knowledge. PARCHE solution is the terminology adopted hereafter to refer to this type of approach.

2. Experimental procedure

2.1 Repair optimization

To adecuatly determine the effectiveness of PARCHE solution the optimization of the different members of the repair system has been necessary (i.e. steel, composite and adhesive bonding). As a starting point, the manufacture, characterization and selection of the most suitable composite laminate was accomplished. This was followed by the required studies on the surface finish of both adherents so to maximize the dissimilar joint strength. It should be noted that marine steel grade A was chosen as the subject material since this is one of the most widely used. As for the surface preparation techniques evaluated only grit blasting was considered due to the optimal characteristics that it confers. Thus, grit blasting allows a range of roughness to be obtained by tuning the process parameters or instead by changing the applied grit. Within this work the optimal process window was identified establishing pressure, optimium nozzle-surface distance and grit material and morphology. On the other hand, the properties of a primer developed ad-hoc for the purpose of this project was evaluated. This primer aims at improving the corrosion resistance of the joint, given its working conditions under marine environment, without compromising its mechanical strength. Finally, this optimization was completed with the selection of the most appropriate structural adhesive.

<u>Manufacturing and characterization of composites</u>

Three types of high performance composites were manufactured in order to achieve a different ratio of price- properties. Thus, a high performance monolithic composite and two hybrid composites were chosen as candidate laminates. The latter were designed to increase the efficieny of the patch. In this manner the fibers with higher performance are placed in contact with the steel, leaving the fibers of lower mechanical strength in the top region away from the steel. This responds to the stress distribution along the composite´s thickness taking into account stresses that come into play in the real application. The prepreg laminate was manufactured by hand lay-up and oven vaccumm bag cure, whereas the hybrid composites were manfucature by resin transfer moulding (RTM). In the first case carbon fiber was used while for the hybid laminates glass-carbon and aramid-glass fiber were selected. In all cases the matrix was epoxy resin due to its mechanical properties and also its degradation resistance. The normalized samples were manufactured and conveniently machined in order to characterize its tensile strength (ASTM D3039) and compression resistance (ISO 14126).

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Application and evaluation of surface treatments

Several parameters of the grit blasting process were evaluated. Firstly, different kinds of grits were selected, namely metallic angular grit from A.m.p.e.r.e (i.e. Decablast with G50 designation) and, two iron silicate ones from Mendiola Abrasives (i.e. references M25 and M50), also with an angular morphology. Likewise, in order to induce a range of roughness on the sustrate, different pressures were assessed. Thus, 2, 4 and 7 bar were identified as the most suitable parameters leading to a total amount of 9 samples. The resulting surfaces were subjected to the conventional tests needed prior a standard paint application process of shipbuiding industries, due to the resemblance of both applications [3]. This includes determining roughness parameters (ISO 8503-4), salt content (ISO 8502- 6 and 9) and dust content (ISO 8502-3). Immediately afterwards, and once passed the latter tests that allow to ensure to some extent the quality of the joint, the anticorrosive primer was manually applied with a paint roller onto the different samples. The most adequate surface was identified by perfoming a tensile strenght test (UNE-EN ISO 4624) of the zinc-enriched epoxy primer.

Finally, for the repair system optimization two different adhesives were considered among the most common structural adhesive families. Specifically, these references belong to the epoxy and modified acrylic families, commonly used for repair procedures comprising composites for aeronautical and civil applications (Resoltech 3350 and Crestomer 1152PA, respectively). The adhesives were applied following its corresponding technical datasheets and also considering the cure time of the primer. To evaluate the bond strength normalized single lap joint tests (ASTM D5868) were performed, since the adhesive joint will work under shear stresses during the real application.

2.2 Repair evaluation

After the separate optimization of the above parameters had been accomplished, the validation of the results were performed in larger specimens. In particular, a representative coupon of a typical fault on a ship detail was designed. In order to evaluate the effectiveness of the repair an artificial crack of 80mm long was EDM machined and located in the region specified in Fig. 1. Thus the behavior of the reference sample (no crack) was compared with the cracked and the cracked and repaired one. The specimens were subjected to a tensile test under speed control mode on a universal test equipment HOYTOM (DI-600/CPC). The load curve was recorded against total displacement and the deformation of the samples at specific points were also monitored. The latter was achieved by means of two different methods; one one hand by 5mm long standard strain gages (Kyowa) and on the other hand FBG fiber optic sensing systems. Their respective location depended on the specific sample under study.

In order to perform a more thorough analysis of the repaired system the study had been completed with its corresponding finite element analysis. A 3D finite element model was developed so to predict the stress and strain field of the component and also to determine its ultimate failure strength. Also, the adhesive joint was modelled with CZM (Cohesive Zone Modelling) techniques with the main purpose of getting an insight on the failure mechanisms of the system.

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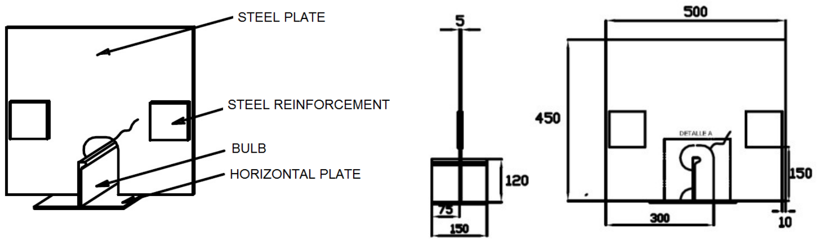

Figure 1. Drawing of the designed coupon corresponding to a stiffener clearance cut-out detail.

3. Results and discussion

3.1 Repair optimizacion

Manufacturing and characterization of composites

Table 1 clearly shows the superior properties that the prepreg laminate exhibits. This corresponds to the expected behavior bearing in mind the higher carbon fiber content. On the other hand, there are no major differences between both hybrid materials.

Table 1. Tensile and compression resistance for the different laminates under study.

Resistance	PREPREG	HYBRID-C	HYBRID-A
Compression, MPa	328	281	262
Tension, MPa	888	360	366

Application and evaluation of surface treatments

The analysis of the salt content of the different steel's surfaces indicates that all specimens present a similar content and located between 20-25 mg/m^2 which is substantially lower than the value of 80mg/m^2 recommended not to exceed [3]. Regarding the roughness values, the G50 grit lead to lower values followed by those obtained by the M25 one. Whereas M8 grit produce the highest surface roughness which are located around 140µm of Rz. These values are the expected ones according to the particle size distribution of each of the references. In Figure 2 the influence of different grit blasting parameters on the tensile strength of the primer- steer joint is displayed. This shows that the G50 grit, and specifically with low application pressures, lead to the optimum adhesion values.

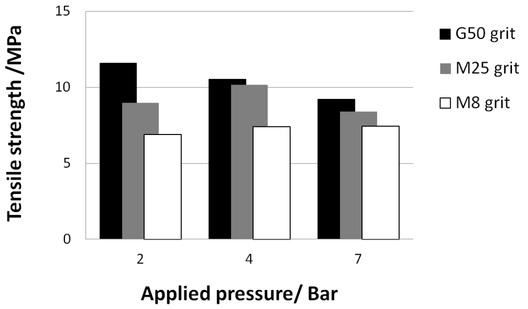

Figure 2. Tensile strength of the primer- steel joint as a function of both the grit nature and applied pressure.

Following the identification of the most appropriate surface treatment to maximize the adhesion of the primer to the steel, the dissimilar adhesive joints were studied. It should be noted that studies with and without primer were performed concluding that its presence does not interfere with the resistance of the adhesive bond. Once this was determined the shear strength of the dissimilar composite-steel joints mentioned earlier was tested. In this case only the optimum surface finish defined in the previous stage was contemplated. Fig. 3 shows that the hybrid C leads to a substantially superior results. Regarding

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the behavior of the two adhesives it should be noted that although the epoxy type achieves higher strength it also shows a limited strain to failure. Therefore the acrylic one seems to be more adequate for the purpose of this work. In this sense it should be noted that due to the particular needs of the present application a tougher adhesive capable of absorbing deformations seems to be essential. This deformation can be the consequence of the different coefficients of thermal expansion of both adherents, among other factors.

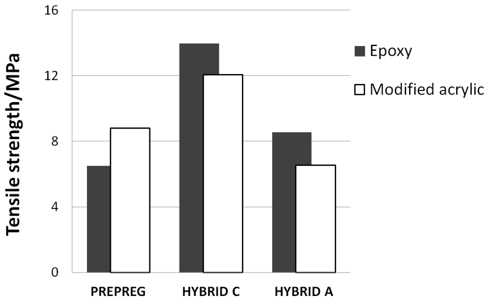

Figure 3. Tensile strength of the different single steel-composite lap joints as a function of the adhesive.

3.2 Repair evaluation

The test results of the tensile test of the three types of specimens are shown in Fig. 4 corresponding to the reference, crack and repaired ones. From these results it is derived that the composite patch increases the stiffness of the damaged sample and, as a consequence it delays the onset of plastic deformation arresting the crack growth. Similarly, it is observed that once the adhesive bond loses effectiveness the solution behaves as the damaged structure. This joint failure results in a drop in load during the tensile test, and it is clearly identified by the embedded FBGs sensors.

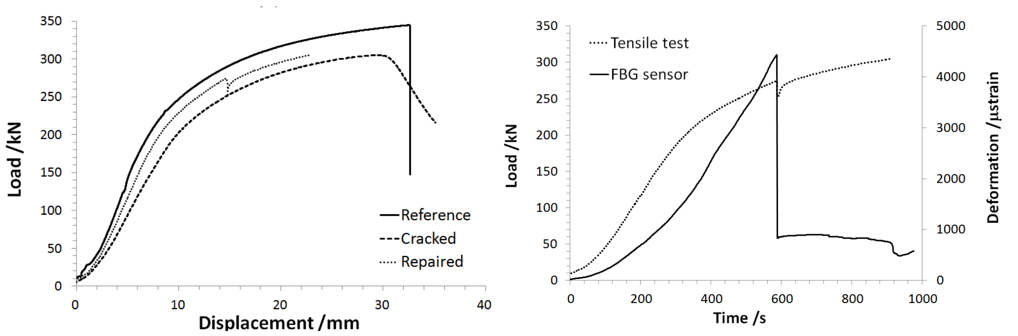

Figure 4. (Left) Load- displacement curve for the reference, craked and repair samples and, (right) FBG monitoring of the adhesive joint.

The same trend was observed in the simulation study. Thus, as shown in Fig. 5, the damaged sample starts to deform plastically at the local scale with a load of 78,80kN while the repair requires 99,1kN for reaching the same point, i.e. delaying the onset of plastic deformation in 25%.

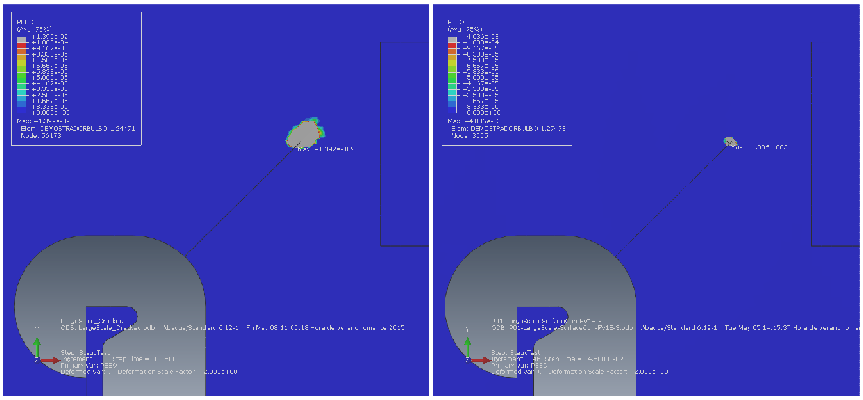

Figure 5. Comparative of the plastic deformation level at the same loading level (left) damaged sample and (derecha) repaired sample.

4. Conclusions

In this work it has been possible to develop prefabricated composite patches that allow to effectively arrest crack growth. For this purpose the adhesive bond has been optimized since it is the ultimate responsible of the system behaviour. On the other hand fiber optic sensors have proven to be effective on the idenfication of the onset of failure

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