QUANTIFYING CORROSION CAUSED BY EXTREME WEATHERING BETWEEN CARBON FIBRE REINFORCED POLYMERS (CFRP) AND STEEL

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ABSTRACT

Research into carbon fibre reinforced polymers (CFRP)’s application to steel as a retrofitting technique has shown very positive results for increasing mechanical properties. However, the limitation of these materials in a corrosion inducing environment has been widely overlooked. In this study, the possible interaction of CFRP and steel in extreme weather conditions in causing localized corrosion (e.g., pitting) was investigated, with the primary aim of quantifying the pit depth and density caused by the galvanic corrosion process between the two materials. Steel tiles patched in direct contact with different varieties of CFRP were exposed to 5% NaCl solutions at two temperatures for different durations. After removal, the pit depth and pit density were analysed to determine whether galvanic conditions could indeed generate pits, which are known to initiate fatigue cracks in steels. It was observed, in this initial work, that after 4 weeks of exposure to NaCl, the pits formed from the CFRP patched specimens were not exceedingly different or critical compared to that of the control steel tiles.

KEY WORDS

CFRP, fibre reinforced polymer, galvanic corrosion, steel, weathering, extreme environments.

INTRODUCTION

Large numbers of aging civil infrastructure such as marine structures, mining equipment and bridge decks are becoming severely degraded. Dynamic loading on these structures, especially when coupled with exposure to extreme weather, make them highly susceptible to corrosion and fatigue damage. Corrosion damage can cause progressive weakening of structural elements, but it may also be localised in the form of pits and crevices, causing stress concentrations that can result in crack initiation (Karbhari and Shulley 1995). When corrosion is combined with fatigue loading, the loss of strength and stiffness can be remarkably exaggerated (Masoud, Soudki, and Topper 2001), resulting in structural failure.

CFRP has great potential in strengthening steel structures subjected to fatigue loading (Zhao and Zhang 2007). However, fibres of materials such as carbon are highly cathodic, with considerable electrochemical potential difference when exposed to an electrolyte such as saline water. This means that although CFRP is generally corrosion resistant, if it comes in contact with metals, galvanic interaction between the two materials can take place (Hollaway and Cadei 2002). Steel structures that require patching are often located close to sea waters, or in the case of bridges, de-icing salts are washed over them to prevent icy roads. Sea water and salt solutions are electrolytes that are highly corrosive for common engineering metals and alloys such as steels. Hence it is highly likely that galvanic corrosion may occur when CFRP and steel are in contact with one another in the presence of a salt solution. There is limited research on this topic (Torres-Acosta 2002a; Torres-Acosta 2002b; Tavakkolizadeh and Saadatmanesh 2001).
Although it is understood that the CFRP, and steel, in contact and exposed to saline solutions (such as sea water) will create a favourable condition for galvanic corrosion over a relatively large area of steel, the localised galvanic corrosion levels when directly patched to steel are yet to be researched. Recent studies (Nguyen et al. 2013; Dawood and Rizkalla 2010) have witnessed levels of corrosion when patching steel with CFRP after exposure to extreme environments. However, no research has quantified the levels observed. Experiments outlined in this paper are the preliminary results of an ongoing study with the aim to find whether galvanic corrosion of CFRP-steel joints creates pits critical enough to initiate fracturing of loaded steel members. Therefore, pit density and pit geometry of CFRP patched steel tiles were characterized after samples of CFRP-steel in direct contact were exposed to harsh environmental conditions.

EXPERIMENTAL SET UP

Material Properties

Tiles (16x16x5mm) of 250 grade mild steel were cut for the purpose of testing steel with CFRP patching. Such small tiles were prepared because of the requirement to have sample sizes appropriate for scanning electron microscopy (SEM) analysis.

Two common CFRP materials were chosen for testing. The first being a ‘High Modulus’ CFRP sheeting reinforcement manufactured by MBRACE, comprising of exposed, unidirectional fibres. The second, a ‘Normal Modulus’ laminate made from unidirectional carbon fibres embedded into a resin matrix, also manufactured by MBRACE. It should be noted that the laminate remains rigid while the sheeting is flexible. The relevant physical properties of the CFRP materials are shown in Table 1.

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>CFRP Sheeting (MBRACE CF 530)</th>
<th>CFRP Laminate (MBRACE 210/3300)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Density</td>
<td>2.1 g/cm³</td>
<td>1.6 g/cm³</td>
</tr>
<tr>
<td>Fibre Content</td>
<td>≈ 100 %</td>
<td>70 %</td>
</tr>
<tr>
<td>Thickness</td>
<td>≈ 0.1-0.2 mm</td>
<td>1.4 mm</td>
</tr>
</tbody>
</table>

Specimen Preparation

The steel tiles were subjected to two types of surface preparation that are commonly used in research and industrial application for composites. Metals are generally prepared to have a uniformly rough surface to promote adhesion with composites. Four mechanisms have been proposed to explain adhesion: adsorption, mechanical interlocking, diffusion and electrostatic attraction (Mays and Hutchinson 1992) in which roughness plays a major role in the two most important mechanisms. Surface roughness or profile may vary from one adhesive to another (Sykes 1982), but it will always increase the surface area, which enhances adsorption and interlocking, thereby facilitating adhesion and bonding.

Sandblasting and grinding were the two surface preparation techniques employed to clean and roughen the surface of the steel tiles before patching. Sandblasting was performed using 16 grit sand particles holding the pressured gun approximately 3 cm away at an angle of 45 degrees to the tile. Grinding was initially performed using 80 grit sandpaper which is similar to the procedure of the reported studies (Tavakkolizadeh and Saadatmanesh 2001), although a comparison of SEM surface topography (Figure 1) would suggest the 36 grit sand paper provides an improved and more uniform surface roughness for adhesion than these due to higher grit papers.
SEM surface topography (Figure 1) suggested the sandblasting to produces a surface with uniform roughness. As also suggested in Figure 1, the grinding created regions with roughness that may be comparable to sandblasting; however, grinding generally also produced surface roughness with directional streaks (Figure 1a) which may not be desirable for adhesion. These streaks are inevitably hard to avoid because of the very directional nature of grinding process. These streaks in the surface inherently hinder the ability of CFRP and steel to bond effectively.

After surface sandblasting or grinding, the tiles were patched with the same surface sized CFRP materials that were cut to size. The CFRP laminate was mechanically abraded using 80-grit sand paper to expose embedded fibres, i.e., to mimic damage on the bonding surface that can occur in construction practice, handling, placing, and casting of the composite (Torres-Acosta 2002b).

Combinations of CFRP laminate and CFRP sheeting were placed with their fibres in direct contact with either sandblasted or grinded steel tiles. This paper details the sandblasted specimens only.

CFRP laminate or CFRP sheeting were finally held together with the steel tile, using pliable neoprene O-rings, as shown in Figure 2. The O-ring material was able to withstand the aggressive corrosive environments for prolonged time. As they are made out of a synthetic rubber, these O-rings themselves were not expected to play any active role in the galvanic interaction between the steel and CFRP.

**Experimental Procedure**

In order to replicate critical field application exposures, these CFRP-steel tiles were exposed to the test environment of NaCl solution (5%, by weight) in two tanks at different temperatures - one tank held at 22-23 °C the other at 50 °C. The temperatures were selected to represent likely temperatures witnessed during industrial scenarios, viz., the higher temperature was chosen for the structural surfaces exposed to direct sunlight in typical summer climates (Nguyen et al. 2013). Specimens were submerged in the corrosive environment for 4 and 12 weeks before they were removed. However this paper will detail the 4 week submerged specimens only.

After the 4-week exposure, specimens were removed from the test tank and immediately placed in a beaker containing a dilute acidic cleaning solution of 50 mL butynediol (C₄H₆O₂) and 30mL Hydrochloric Acid (HCl). The remaining solid corrosion products still sticking to the specimen surface were cleaned away by subjecting the specimens to ultrasonic cleaning. Lastly, specimens were washed with de-ionised water and ethanol and dried using pressurized air.
RESULTS AND DISCUSSION

Corrosion and Pit Morphology

As well as localised pitting, every exposed sample showed obvious signs of chloride induced surface corrosion. Surface corrosion occurred due to the aqueous chloride environment. This surface corrosion caused the exposed surfaces to be much smoother than the originally crystalline sandblasted tiles and was more noticeable at the edges of the sample. The edges provide greater surface energy, thereby making it more prone to corrosion. Pits, however, generally had sharp discontinuous openings at the surface as seen in Figure 3.

![Figure 3: Variety of pits at 2000x (left), 2200x (middle) and 1900x (right) magnification.](image)

It was noticed on a number of the corroded specimens that pits often collected in a unidirectional string, creating what looked like cracks on the surface. These strings often comprised of much deeper and wider pits. This type of pitting formation may be due to multiple contact points between the CFRP and steel, or possibly from a defect in the steel. This phenomenon of multiple pits becomes a potential sight for fracture initiation if load is applied perpendicular to the pitting direction.

![Figure 4: Arrays of multiple pits, forming in a unidirectional mode on corroded specimens.](image)

Pit Characteristics

For characterization of pits, the surface of the cleaned specimens was examined using SEM. In using SEM for pit characterization, two locations for a given pit were focused on, in order to find the pit depth, i.e., firstly, the steel surface around the pit, and secondly, the bottom of the pit. Thus, the distance between the two focal points gave a measurement of the depth of the visible pit. Using this method 10 pit depths from each specimen were measured, as presented in Table 2.
Table 2: Specimens with their average pit depths

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Type of CFRP</th>
<th>Temperature Exposure</th>
<th>Average Pit Depths (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBT23</td>
<td>NONE</td>
<td>23°C</td>
<td>0.055 ± 0.04</td>
</tr>
<tr>
<td>SBT50</td>
<td>Laminate</td>
<td>50°C</td>
<td>0.047 ± 0.03</td>
</tr>
<tr>
<td>SBLMT23</td>
<td>Laminate</td>
<td>23°C</td>
<td>0.057 ± 0.04</td>
</tr>
<tr>
<td>SBLMT50</td>
<td>Laminate</td>
<td>50°C</td>
<td>0.051 ± 0.03</td>
</tr>
<tr>
<td>SBSHT23</td>
<td>Sheeting</td>
<td>23°C</td>
<td>0.042 ± 0.02</td>
</tr>
<tr>
<td>SBSHT50</td>
<td>Sheeting</td>
<td>50°C</td>
<td>0.042 ± 0.02</td>
</tr>
</tbody>
</table>

These 10 pits per sample were identified while observing the surface of the steel at a relatively low magnification; hence the larger and more developed pits become obvious to the viewer first. Although not every surface pit is observed and analysed, the most critical pits are the deepest ones that are more likely to reduce the strength of the steel. Deepest pits generally incur the highest pit depth to diameter ratio. This ratio is referred to as the pit aspect ratio and is very important because the higher the aspect ratio the higher the stress concentration region at the base of the pit, in turn becoming a critical region for the fatigue initiation and fracture.

Though the pit depths varied considerably, the majority remained within 0.02 mm and 0.05 mm. Specimens with slightly higher averages generally had 1-2 statistically outlying depths of 0.08-0.1 mm. There were also regions of much deeper pits, with depths up to 0.16mm. These depths were often found in regions of multiple pits and probably occur because of a combination of an initial material defect, exaggerated then by the corrosion and surface preparation. Some geometrical properties may also cause an increase in corrosion rates. Regions with higher surface energy, such as specimen edges and ridges, suffer increased corrosion rates.

Initial results of 4 week tests have indicated that the pit depths have no obvious correlation to any particular experimental variables. The variations in pit characteristics are due more likely to the statistical scatter, and they do not show any conclusive trend from a particular influence. However, it is obvious that the regions of pit depths that exceed the average are regions of concern for the strength of the steel. It is anticipated that as exposure periods extend, a more definite trend or influence of a factor, if any, may emerge.

FUTURE WORK

Further analysis of samples submerged for longer periods of time are underway, for conclusively determining whether or not pit depth reaches a critical stage. Some more specific techniques will be employed for examining the entire surface, ensuring all pits are measured, reducing the statistical and human error. Also, for future pit characterization, a stronger cleaning solution may be employed to remove the small amounts of corrosion deposits, not visible to the naked eye, that were observed during SEM analysis. Such deposits may obscure some pits and prevent proper pit characterisation.

CONCLUSIONS

This preliminary study into pit formation due to the galvanic corrosion of environmentally exposed CFRP and steel suggested:

1) After 4 weeks of exposure to 5% NaCl solution, the average pit depths produced between galvanically corroded samples does not differ significantly from the control steel samples.
2) Arrays of pit lines formed on corroded steel samples. Such pits could create a problem of increased stress regions and potential fracture initiation.
3) Pit densities were observed to be relatively consistent over the described samples.
4) These results are part of an ongoing experimental process which will see further analysis of samples submerged for longer periods of time.
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REFERENCES


