Review Paper: Environmental factors affecting Composite Materials

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Abstract
One of the most trending ways for repairing and rehabilitation of engineering structures in civil is through Fibre Reinforced Polymers (FRPs) Polymer Matrix Composites (PMCs) are popular because of their ease of application to the outer surface structure and causing diminutive trouble during restoration/overhaul processes. An added advantage of the PMCs is that they are low-cost as well as long-lasting. Conversely, the continuing resilience of PMCs is not widely recognized. This review paper attempts to discuss and summarize much of the presently available study on PMC durability, highlighting the environmental factors' interaction and trending maintenance and inspection practices.

Keywords: Polymer Matrix Composites (PMCs), Fibre Reinforced Polymer (FRP)

1. Introduction

Fibre Reinforced Polymers (FRP) are in popular demand for restoration processes. Though, a lot of scientists and engineers have found various factors contributing to the damage of installed wraps which entail moisture, acidity, alkalinity, thermal effects, salts, freezing/thawing, pH, creep, fatigue, ultraviolet radiation, galvanic corrosion, humidity, fire, and underwater [8]. Oehlers [25] recognized the accompanying mechanical failure schemes for FRPs connected to slabs/beams (concrete) externally: (1) before debonding takes place, cracks resulting from flexural peeling always start at the plate's end, and propagate towards the centre of the plate. As the member bends, the plate tries to stay straight which hence causes crack formation (Fig. 1); (2) prior to the shear peeling onset, shear cracks form diagonally. The diagonal crack base is the starting point of these shear cracks (Fig. 2); (3) axial peeling that presents as debonding cracks and travel away from a flexural crack (Fig. 3). To attain maximum mechanical performance of the composite, the most important factor is the matrix health. In the situation of a degraded matrix, full stress transfer from the substrate to the Fibres or vice versa cannot be achieved within the composite. Matrices often fracture alongside the interface of the layers instead of cracking perpendicularly to the layer direction. Crack propagation is relatively easier in the transverse direction as the composite's tensile strength in the transverse direction is much poorer than its tensile strength in the longitudinal direction. For civil rehabilitation, employing PMCs is a relatively new application which is trending. Due to this, no comprehensive inspection and maintenance guide is available for PMCs, and hence there is a dire need for a guidelines' set regarding the inspection and maintenance of the previously-installed PMCs and their prospect installations.

These guidelines would require addressing factors such as wear sign identification and deterioration, ways to judge structural integrity, ways to shield installations from possible damage sources, ways of fixing damaged wraps, and ways to switch sections with permanent or high-priced damage.

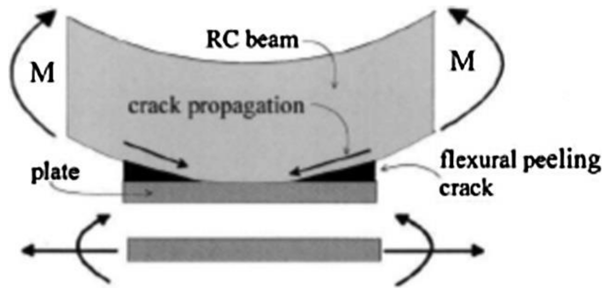

Fig. 1. Flexural peeling [25].

This work is an attempt to review the research, guidelines from the previous researchers, and procedures for the inspection and maintenance of PMCs. This study is an effort in response to the concerns regarding the deterioration factors contributing most to the wear of PMCs.

To investigate the cautionary signs of the aforesaid deterioration? The ways and means available to extend their life and performance.

2. Combined effects

In the introduction chapter, the exposure environments mentioned do not necessarily work independently. Quite a lot of these situations can occur concurrently in the field, also, frequently, they aggravate the damage done through one another. Because of this, much of research has tried to inspect the effects of numerous conditions of exposure on PMC samples, in the lab as well as the field. A small number of papers also propose overall academic work reviews on PMCs.

Weitsman [38] noticed that carbon Fibres independently are considerably hydrophobic, immune to acids, and alkalis, even though pre-stressed PMCs are more vulnerable to degradation which is solvent-related. Water plus saltwater have proven to be more harmful to PMCs strength than oils, and temperature effects damage related to moisture [38].

Salt can too intensify the damage by freezing-thawing as salt has the ability of collecting, expanding, and contracting [10]. In addition to this, creep in polymers and PMCs has been witnessed to upturn upon moisture exposure [37].

PMCs with Fibres that are unidirectional reveal increased creep phenomenon under shear loading (load that acts perpendicular to the fibre direction). Other researchers have also observed that moisture and elevated temperatures both upsurge the susceptibility to creep [10].

after it is dried at first and the greatest quantity of water after it is saturated and shifted to lesser temperatures.

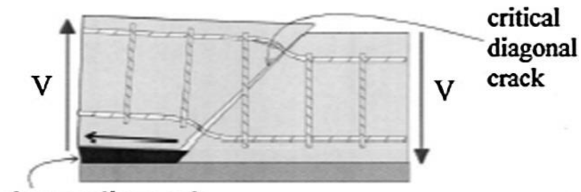

Fig. 2. Shear peeling [25].

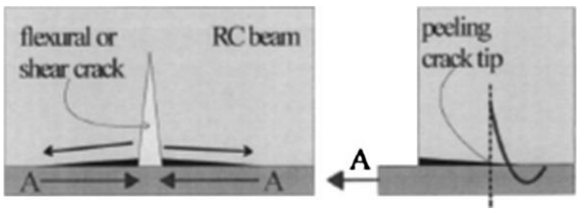

Fig. 3. Axial peeling [25].

Imani et al. [16] evaluated the durability of the bond between Carbon FRPs (CFRP) and concrete. Single shear test specimens were submerged in water at various temperatures ranging from 35 ºC to 60 ºC. The researchers investigated Mode-II (i.e., in-plane shear/sliding mode), because delamination of PMCs strips used to reinforce flexural members is dominated by Mode-II fracture. The researchers investigated moisture effects because understanding the interactions between moisture and PMCs is critical because many other environmental effects, such as freeze/thaw cycling, wet/dry cycling, acidity, and alkalinity, are all related to moisture. This study observed significant deterioration of the FRP–concrete bond with rising temperature and moisture. The researchers examined that temperature in past studies to speed up this wear. Interfacial fracture energy was seen to decrease with both rising immersion time and increasing temperature. Maximum number of samples failed cohesively; i.e., their failure was in concrete. Conversely, the extent of concrete that was stuck onto the FRP after failure reduced as duration of temperature and exposure was increased. This study revealed that temperature has a greater influence compared to moisture on the bond of FRP–concrete. The researchers estimated 60 ºC as the threshold temperature above which the bond behaves differently. Zheng and Morgan [40] published results from an examination of weight alterations in carbon/epoxy PMCs immersed in distilled water in temperatures between 0.5 ºC to 80 ºC. The researchers recognised the occurrence of ‘‘reverse thermal effect’’ in which the resin moisture absorption essentially increases with falling temperature. Though, this study established that resins undergoing this effect bear no permanent impairment. It rather is essential for resins to surpass a critical temperature to reveal this reverse thermal behaviour. The critical temperature in this case was roughly 60 ºC. This temperature is also mentioned by Imani et al. [16] by means of the estimated threshold beyond which the bond of FRP–concrete behaves in a different way. It was revealed by Zheng and Morgan [40] that resins retained the tiniest quantity of water

2.2. Sun exposure

Nishizaki et al. [24] carried out a ten-year long research on durability of the PMCs exposed and unstressed fronting the south direction. The materials tried comprise two types of CFRP sheets - CFRP protected by a coating and epoxy matrix plates. Samples were positioned at 2 locations in Japan and at 1 site in Canada. Sections were exposed to the sun for one, three, five, seven or ten years. After the 5 years exposure, the first type of FRP sheet exhibited an irregular surface, however, it did not display any below the surface damage. The second type displayed a noteworthy colour transition, turning to yellow from blue. Conversely, this colour shift was not related with any loss in strength of Fibres. Degradation was evident on the resin surface, but not below the Fibres, which is indicative of good resin shielding by the Fibres. The bending strength was witnessed to drop rapidly in the initial phases of exposure. The in-plane shear strength also decreased slightly. Nevertheless, there was no noteworthy loss of tensile strength after five years of exposure at any location.
These results designate a wear of the Fibres and the matrix bond. Roylance and Roylance [29] studied a glass/epoxy composite subjected to outdoor environments.

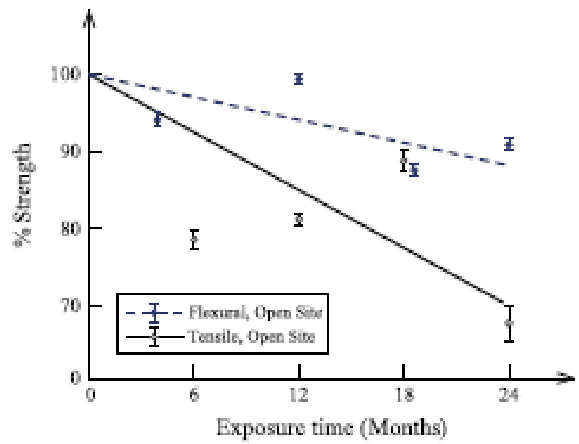

Fig. 4. Outdoor exposure influence on mechanical properties (courtesy: Roylance and Roylance [29]).

The samples were either exposed or unexposed in an open-air, field location at Ft. Sherman, Panama. Trial subjects were removed every 6 months for 2 years. The longer a sample was out in the atmosphere, the more the outer face was worsened (Fig. 4). What was noticed during this study entailed ‘‘a growing deterioration in the following order: unexposed, middle, bottom, & top layers.’’

2.3. Moisture and stress

Helbling et al. [13] studied applied stress, thermal, and moisture effects on PMCs, with glass FRP (GFRP) PMCs in particular. The effective lifespan of a PMC installation is determined by not only the health of the

PMC itself, but also the health of the in-between bond of the PMC and the substrate. Stress rupture and moisture degradation are well-known intimidations to E-glass Fibres. These effects are particularly powerful when they come about concurrently. Tensile & compressive stresses act to have stabilising effects on the moisture diffusion, which shows that bending stresses have a comparatively trivial effect on absorption of moisture at temperatures in the normal range (around 22 ºC). Though, tensile strains higher than 45% capacity have been perceived to increase moisture absorption, particularly instantly preceding failure. Progressive debonding and delamination permits more routes for further entrance of water that clarifies the heavier weight. Increasing the immersion time and also increasing the temperature increases strength losses. Likewise, increasing immersion time and overall rigorousness of the environment have been detected to alter the failure mode to central Fibre rupturing from a brush-like failure.

2.4. pH and temperature

Kshirsagar et al. [21] exposed 203 mm x 102 mm cylinders of concrete, enveloped with an E-glass composite of fabric/epoxy, to compression tests so as to regulate the effects of accelerated aging. Specimens were subjected for a thousand hours to either of the: solution with a temperature of 23 ºC and a pH of 9.4, solution with a temperature of 23 ºC and a pH of 12.4, solution with a temperature of 66 ºF and a pH of 12.4, water with a temperature of 66 ºF a neutral pH, a temperature of 66 ºF - dry heat, or seventeen freeze–thaw cycles and a comparative humidity of 100% from -30 ºF to 49 ºF. The researchers detected adverse effects only after the samples were exposed to both high temperatures and moisture. The solution pH did not quite appear to affect the results. The researchers hypothesise that the moistness was able to pierce through the PMC and chemically deteriorate the glass Fibres.

2.5. Freeze–thaw and salt

Banthia et al. [4] explained an experimental valuation of the bond amongst PMCs and concrete. In Canada, the researchers executed direct tensile pull-off experiments on numerous in-service installations (Fig. 5).

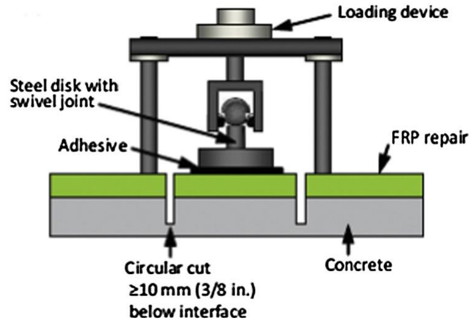

Fig. 5. Moderately destructive technique: The pull-off experiment [4].

Installations incorporated many types of carbon and glass FRPs. The first assembly was Safe Bridge that was reinforced in 2001 with sprayed GFRP, supports two traffic lanes and a footpath, and experiences daily temperatures going from -25 ºC all the way up to 18 ºC. Structure number two was the Bridge "St. Etienne de Bolton" that was reinforced in 1997 with both CFRP and GFRP column wraps experiences daily temperatures going from -18 ºC up to 24 ºC, noteworthy amounts of deicing salt, and bodily impact through snow-clearing. Structure three was the Bridge Leslie Street that was reinforced in 1996 with CFRP column wraps, upholds thirteen traffic lanes, experiencing temperatures in the range of -10 ºC and 27 ºC, noteworthy amounts of deicing salt, and numerous rounds of freezing - thawing. Structure four was Bridge Maryland which in 1999 was reinforced with girders comprising CFRP sheets, upholds ten traffic lanes, experiencing temperatures in the range of -23 ºC and 26 ºC. At the Safe Bridge, the researchers detected fairly low bond strengths, and proposed that the girder geometries might have enabled the water to surround the PMCs rather easily. Which then could have caused ice jacking and overall bond degradation. Multiple sites of the Leslie Bridge from a single column failed before testing, probably due to ice jacking. The GFRP showed greater bond strengths than CFRP at the St. Etienne Bridge. Though, the researchers pointed out the probable effects from exposure, location, surface finish, workmanship, and service conditions. The researchers established that, though most of the PMCs continued to be in a satisfactory condition after almost thirteen years of tough exposure, several installations were drawn off on the same project at below 5% strength of the comparable installations. The researchers highlighted the significance of accurate installation and the necessity for more research on the variance in bond strength and means for repairing it. The researchers also noticed that, often, the FRP–concrete bond is a weak link in the structure. Higgins et al. [14] observed the durability of CFRP reinforced concrete girders so as to raise shear strength. The researchers observed the freeze–thaw, fatigue, and moisture effects. The researchers also summarised and gathered results from various other studies. They observed that high moisture together with high temperature ominously influences the strength of the bond. Higgins et al. [14] witnessed a reduction in shear stiffness in addition to shear capacity for CFRP-strengthened T-sections when they were exposed to freeze–thaw cycling. This is probable because of the development of debonded regions. When joined, fatigue raised the properties of freeze–thaw cycling. Though, if protected countering moisture, less deterioration was likely to be experienced by the system. The researchers suggested that additional resin to the edges of an already set up FRP system must be applied to avoid moisture penetration. The researchers witnessed this treatment to avert strength drops in systems open to simultaneous fatigue loading and freeze–thaw cycling.

2.6. Humidity

Startsev et al. [33] presented a study entailing carbon, S-glass, and Kevlar- 49 Fibres comprising an epoxy matrix out in the open for 10 years to the hot, humid atmosphere on the Black Sea coast of Batumi, Georgia. On visual examination, the composite side exposed to Ultraviolet radiation displayed epoxy matrix weathering and destruction. The diffusion coefficient of moisture increased almost 2.5 times when it was exposed for 1 year, presumably since it is tremendously sensitive to the surface of the composite. Fatigue strength (tensile) was found to be susceptible as well to the surface flaws. Surface damage and post-curing were observed to occur concurrently in the glass/epoxy composite matrix, plus the adhesion in-between the Fibre and the matrix was decreased.

2.7. Underwater

Sen and Mullins [30] presented four tasks wherein PMCs were used to patch-up underwater piles. Fibreglass and carbon both were used, and both kinds of Fibres were employed with any one of a hydro-activated resin (urethane) or an epoxy resin. Any members or repairs to wet/dry cycling, high temperatures, high humidity, and ocean salts were exposed by this environment. The oldest restoration was four years old when this paper was published, and any visual inspections appeared to designate that all rework was still undamaged.

2.8. Multiple environmental factors

A methodical paper by Belarbi et al. [7] presented outcomes of an environmental experiment of GFRP- and CFRP-wrapped concrete reinforcement columns (Fig. 6). Environments encompassed cycles of freezing–thawing, cycles of high temperatures, cycles of high humidity, UV radiation, and saline water. The paper also presented evidence from several other researchers as a literature review. Glass fibre reinforced polymer was witnessed to be more sensitive than Carbon fibre reinforced polymer to high temperature cycle damaging with high humidity cycles and Ultraviolet radiation. The GFRP experienced an extraordinary reduction in failure load, but the CFRP seemed practically invulnerable to collective environmental cycles. Cycles of high temperature collectively with cycles of high humidity and Ultraviolet radiation was perceived as the succeeding worst scenario for the columns which were GFRP-wrapped.

Fig. 6. Damage sites post concentric axial-load analysis: (a) CFRP split devoid of accelerated corrosion (b) Lap joint debonding - CFRP sheets post accelerated corrosion [7].

The columns which were CFRP-wrapped had degradation which was much lesser than the degradation of the columns which were GFRP-wrapped. Moisture was yet again was the primary concern. Baiyasi and Harichandran [12] carried out trials to study the usefulness of employing GFRP and CFRP wraps to reorient corroding columns of concrete. The researchers studied effects of freeze/ thaw, wrapping on the rate of corrosion effects, effects of wet/ dry, effects of high temperature resistance to impact, and field employment on corroding sections of FRP wraps. PMCs were tested independently, not connected to concrete samples. There was no noteworthy reduction in mechanical properties under any conditions of exposure. Though, each condition of exposure was tried individually. They had not been cycled. Baiyasi and Harichandran [12] established that damage and minor vehicle impacts do not considerably affect the performance of GFRP or CFRP wraps.

3. Conclusions

This review proposes that the bond line and the PMC both be inspected. This is due to the fact that deterioration at the bond line could be more critical compared to the transmission of moisture all through the PMC. Damage as a result of moisture is usually exposed as whitening of Fibre, microcracking of matrix, surface blisters, and adhesion loss. The review recognised pitting of Fibre as an indication of damage due to an alkaline atmosphere. Inspectors must check for resin cracks, and should note widths of crack, resin flaking, and adhesion loss. The resin must stay uncracked, and must always envelop the Fibres. Preferably, the resin must be completely cured in advance to exposure. A tap test could be performed, in which delaminations are likely to sound muffled and of a low pitch, but knowledge is essential for active detection. Moreover, inspectors must make sure that only sizable problems are detected by the tap test. Small problems can frequently go undetected. In case of a disbond, the adhesive must be inserted inside the recognised area. Eventually, adequate preparation of surface at the stage of installation is important. This study proposes numerous things to find when reviewing installations which pertain (severity increasing order) damage to surface shine, resin flaking, chalking, microcracking, pitting, substantial resin loss, blistering, and visible Fibres. This review also recognised yellowing, spalling of resin, noteworthy cratering and cracking in isopolyester and vinylester as evidence of deterioration from Ultraviolet exposure.

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