DURABILITY AND PERFORMANCE OF CARBON FIBRE REINFORCED POLYMER-CONCRETE BONDING SYSTEM UNDER TROPICAL CLIMATES

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To my beloved parent,

HJ. MOHD HASHIM ISMAIL

and

HJH. CHE NAH BINTI HJ. MOHD YATIM

My beloved wife,

ROBIHA BINTI MD SABIRIN

And our children,

MOHD NAZHIF MOHD HISBANY

MOHD NAUFAL MOHD HISBANY

MOHD NUDZRAN MOHD HISBANY

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ABSTRACT

The existing reinforced concrete structures may require rehabilitation and strengthening to overcome defect and environmental deterioration. Fibre Reinforced Polymer (FRP)-concrete bonding systems can provide solution for the deficiencies, but the durability of the bonded joint needs to be investigated for structural reliability. This research studies the flexural performance of reinforced concrete beams strengthened with Carbon FRP and the interfacial bonding behaviour of CFRP-concrete system under tropical climate exposure. A 300 mm concrete prisms were bonded with CFRP plate and exposed for 3, 6, and 9 months to continuous natural weather, laboratory environment, and wet-dry exposure in 3.5% saltwater solution at room and 40 °C temperature. The prisms were subjected to tension and compression load under bonding test to determine the strain, stress distribution and shear stress transfer behaviour. The flexural performance was studied on 2400 mm length reinforced concrete beams strengthened with CFRP plate and fabric and exposed for six months to similar conditions as the concrete prisms without the higher temperature. The results of the bonding test showed that load transfer was fairly linear and uniform at lower load level and changed to non-linear and non-uniform at higher load level. The force transfers affected and shifted the shear stress distribution along the bonded length. The flexural capacity of the reinforced concrete beams increased between 32% and 37% and for CFRP plate and between 10% and 12% for CFRP fabrics. High interfacial stress developed near the cut-off point and decreased towards the centre of the beam. Plate-end debonding dominated the failure pattern of the beam. The combination of climate effects may have provided better curing of the bonded joints, but longer duration of exposure may be required to weaken the bond strength. Nevertheless, the tropical climate and salt solution did not yield significant bad effect on the CFRP-concrete bonding system.

ABSTRAK

Struktur konkrit sedia ada berkemungkinan memerlukan pemulihan dan pengukuhan bagi mengatasai kecacatan dan kemorosotan disebabkan persekitaran. Sistem ikatan Konkrit-Polimer Bertetulang Gentian boleh memberikan penyelesaian kepada kekurangan tersebut, tetapi ketahanan ikatannya perlu diselidiki untuk keutuhan struktur. Penyelidikan ini mengkaji prestasi lenturan bagi rasuk bertetulang konkrit yang diperkuat dengan Polimer Bertetulang Gentian Karbon dan kelakuan permukaan ikatan Konkrit-Polimer Bertetulang Gentian Karbon dalam iklim tropika. Prisma konkrit berukuran 300 mm diikat dengan plat dan didedahkan sepanjang masa di dalam cuaca semulajadi, persekitaran makmal, dan kitaran basah-kering di dalam 3.5% larutan garam di dalam suhu bilik dan 40 °C selama 3, 6, dan 9 bulan. Prisma tersebut dikenakan daya tegangan dan mampatan untuk ujian ikatan bagi mendapatkan terikan, pembahagian tegasan, dan kelakuan pemindahan tegasan ricih. Ujian prestasi lenturan dijalankan ke atas rasuk bertetulang konkrit sepanjang 2400 mm yang diperkuat dengan plat dan fabrik karbon dan didedahkan selama enam bulan sama seperti keadaan prisma tanpa suhu yang dinaikkan. Keputusan ujian ikatan menunjukkan bahawa pemindahan daya adalah bersifat hampir lelurus dan seragam pada peringkat beban rendah dan bertukar kepada tidak lelurus dan tidak seragam pada peringkat beban tinggi. Pemindahan daya telah mempengaruhi dan mengalihkan agihan tegasan ricih di sepanjang ikatan. Rasuk yang diperkuat telah mengalami pertambahan kapasiti lenturan diantara 32% sehingga 37% untuk plat dan 10% sehingga 12% untuk fabrik. Tegasan permukaan yang tinggi telah terbentuk berhampiran hujung ikatan dan berkurangan ke bahagian tengah rasuk. Ikatan yang tertanggal di hujung rasuk menguasai corak kegagalan rasuk. Kombinasi kesan iklim mungkin telah menghasilkan pembaikan pengawetan ikatan, tetapi tempoh dedahan yang lebih panjang mungkin diperlukan untuk melemahkan kekuatan ikatan. Namun, iklim tropika dan larutan garam tidak memberikan kesan buruk ketara kepada sistem ikatan Konkrit-Polimer Bertetulang Gentian Karbon.

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LIST OF SYMBOLS

A_{plate}	-	area of bonded CFRP plate
b	-	with of a CFRP plate
E_c	-	concrete modulus of elasticity
E_p	-	Modulus of Elasticity of CFRP plate
E_u	-	total area under load deflection curve
E_y	-	total area under load deflection curve until reinforcement yielding
g_i	-	strain measurement of CFRP plate
I_g	-	gross transformed section of moment of inertia including
L_{plate}	-	length of bonded CFRP plate
w_{plate}	-	width of bonded CFRP plate
t_p	-	CFRP plate thickness
ε_{frp}	-	rate of change of strain
ε_{max}	-	maximum strain
ΔF	-	longitudinal force in two consecutive points
Δl_i	-	distance between any two consecutive strain gauges
Δx	-	distance between any two consecutive strain gauges
Δ_u	-	ultimate deflection at mid-span of a beam
Δ_y	-	deflection of steel at yielding of steel reinforcement
$\mu\Delta$	-	deflection ductility factor
φ_u	-	ultimate curvature at mid span of a beam
φ_y	-	curvature of steel at yielding of steel reinforcement
μ_φ	-	curvature ductility factor
μ_E	-	energy ductility factor
μ_E	-	energy ductility factor
δ	-	mid-span deflection of a beam
τ	-	shear stress

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CHAPTER 1

INTRODUCTION

1.1 Background

A large numbers of bridges, building, and other structures require rehabilitation and strengthening due to continuous deterioration during its service life. Reinforced concrete made by an ideal combination of concrete and reinforcing bars has been used as the main structural material in the construction of these structures. Some of these structures may be subjected to increases in service loads, changes in the use of the structure, design or construction errors, degradation problem, changes in design codes regulation and seismic retrofits that can possibly lead to the need for rehabilitation of the existing structure.

An appreciable worldwide interest has been given to the use of Fibre Reinforced Polymer (FRP) in the rehabilitation of concrete structures to extend their service life. Fibre Reinforced Polymer system comprises of continuous fibres of high tensile strength within a polymer matrix. The matrix has two functions in which it enable the loads to be transferred among the fibres and the matrix also acts to protect the fibres against environmental attacks and mechanical damage during handling. These fibres have beneficial properties such as high stiffness to weight ratio, high strength to weight ratio, superior environmental durability, resistance to corrosion, high durability, ease of application and low maintenance [1, 2]. The properties have made them a competing alternative to the conventional strengthening and repair materials. External pre-stressing and bonding of steel plates to the tension face of the concrete beams are some of the methods applied in strengthening and repairing deteriorated concrete structures in order to improve the stiffness and strength.

1.2 Problem Statement

Strengthening of existing reinforced concrete structures may be necessary in order to overcome the increase in loading capacity and also due to the effect of environmental degradation. Over the years, reinforced concrete structures are subjected to deterioration due to, among others, alkali-aggregates reaction, chloride induced corrosion, and carbonation. The damaged structures need to be addressed with rehabilitation.

Since 1980s, the use of fibre reinforced polymers for the strengthening of reinforced concrete members has taken momentum and a significant number of studies on flexural and shear strengthening of beams, axial strengthening of columns and more recently, strengthening of joints have been conducted. FRP has been used and studied in different configurations, techniques and environment to utilize the material effectively and to prolong the service life of selected structural system [3-10].

This present research focuses on the effect of tropical climate exposure as well as salt solution on the flexural performance and bond durability of externally bonded Carbon Fibre Reinforced Polymer (CFRP) plate and fabric on reinforced concrete beams and concrete prisms. Durability and ductility are essential to the long-term sustainable service life of FRP material and concrete structural members with FRP reinforcement [11]. Structural reliability and durability imply good performance of material that is able to resist degradation and capable to avoid structural damage. The strengthening of concrete structures through the use of externally bonded FRP composite system raises a two-prong concern on the durability of the system. The first one is the durability of the FRP material itself and the other is the durability of bonding between the FRP material and concrete substrate. The latter concerns with the durability of the interface bond in the FRP-concrete bonding system [12-14].

There is an enormous concern with regards to the reduction in the performance of externally bonded FRP systems over long period of time. Tropical climate countries which experience high average annual temperature, humidity, rainfall and relatively constant ultra violet ray (UV) may have detrimental effect on the usage of FRP composite either externally or internally retrofitted. The amount of information on the durability of FRP subjected to environmental condition especially in the tropical climate environment is still very limited. The outcomes of the past researches show inconsistencies in the results on the degradation effect. Therefore, it is crucial to study the tropical climate effect on FRP and its matrix material in structural element in order to gain acceptance in a country which is experiencing tremendous wet and dry cycle through rain, moisture and dry season. This is essential because many of the applications of FRP as strengthening or repair materials are for outdoor exposure. However, there is another concern on the use of FRP as external strengthening material which is the interfacial fracture along the bonded joints that can limit the strengthening performance of FRP materials. A reinforced concrete beam strengthened with an external FRP plate or fabrics and subjected to flexural loading causes a development of a high tensile and bond shear stress in the concrete or near the adhesive layer. This high stress can possibly lead to the debonding of FRP plate from concrete. It is important for the long term behaviour of the structural bonded joints in civil engineering structures be guaranteed between 50 to 100 years for the acceptance of this bonded system in the construction industry [15].

1.3 Aim and Objectives of Research

The aim of the investigation is to study the flexural behaviour of reinforced concrete member strengthened with Carbon Fibre Reinforced Polymer (CFRP) plate and fabric and also the interfacial bonding of the CFRP-concrete system exposed to tropical climate. The shortcomings of the published literature in this field were the rationale behind the investigation.

Related objectives of the research investigation are as follows:

i) To examine the basic mechanical properties of concrete, CFRP plate, and adhesive in normal laboratory condition and climatic exposure as well as seawater solution.

ii) To determine the effect of tropical climate exposure and saltwater solution (at normal laboratory and higher temperature) on the bonding performance (interfacial bonding) of the concrete prism strengthened with CFRP plate.

iii) To investigate the short term flexural behaviour of reinforced concrete beam strengthened with externally bonded CFRP plate and fabric.

iv) To determine the effect of tropical climate exposure as well as saltwater solution on the flexural behaviour of RC beam strengthened externally with CFRP fabrics and plate.

v) To determine the effect of tropical climate exposure as well as saltwater solution on the interfacial bond of CFRP-reinforced-concrete bonding system using epoxy as adhesive for externally strengthened RC beams.

1.4 Scope of Research

The scope of research for this particular experimental study included:

i) Tests on basic properties of materials used for laboratory and exposure condition (tensile strength, modulus and strain for CFRP plate, adhesive, steel reinforcement; sieve analysis and moisture content for aggregates; compression for concrete).

ii) CFRP plate and fabrics were used as the external reinforcement for RC beam for flexural strengthening and only CFRP plate for bond load test with epoxy as adhesive.

iii) The environmental response parameters studied both for concrete prism and RC beams were exposure to tropical weather, saltwater solution and dual exposure of tropical weather and saltwater solution and subjected to continuous and cyclic exposure.

iv) Selected RC beam was pre-cracked before bonding the CFRP plate and fabrics to simulate in-service damage condition before being subjected to environmental exposure.

v) All beams were subjected to four point load test for flexural studies to determine the load carrying capacity, load deflection behaviour, strain, failure modes, cracking behaviour (inclusive micro-cracking) and interfacial stress behaviour.

1.5 Significant of Research

The results obtained from this research are expected to make contribution in understanding the behaviour and performance of concrete structures strengthened with FRP composite that is very much needed in tropical climate environment. As such, the significant of the current research may include the following outcomes:

i) The availability of new information in FRP strengthening system of reinforced concrete structures in the aspect of flexural can contribute to better understanding of the design and industrial application.

ii) Added information on the characteristics of FRP strengthened structures due to tropical environmental exposure will contribute significantly to the acceptance of this material in the relevant locality.

iii) Enhancing the understanding on interfacial stress behaviour between FRP and concrete using epoxy as adhesive due to tropical climate exposure and aggressive environment.

iv) As steel is susceptible to corrosion and higher weight, the introduction of better used and sustainable building material such as FRP is anticipated to help in improving the effect of environmental degradation as well as managing, handling and costing problem of steel as repair and strengthening materials.

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