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Behaviour of Bond Mechanism in Fibre Reinforced Polymer (FRP) Composites Externally Bonded to Timber

by Abbas Vahedian

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Doctor of Philosophy

under the supervision of
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Dedication

In memory of my mother

and

To my beloved father, and

To my dearest wife.

Declaration

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Abbas Vahedian declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technologies at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by an Australian Government Research Training Program Scholarship.

Signature: Production Note: Signature removed prior to publication. Date: 10.04.2019

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List of abbreviations and acronyms

ACI	American Concrete Institute
AFRP	Aramid Fibre Reinforced Polymer
AS/NZS	Standards Australia
ASTM	American Society for Testing and Materials
BSI	British Standards Institution
BS	British Standards
CFRP	Carbon Fibre Reinforced Polymer
CoV	Coefficient of Variation
EB	Externally bonded
FEA	Finite Element Analysis
FRP	Fibre reinforced polymer
GFRP	Glass Fibre Reinforced Polymer
AFRP	Aramid Fibre Reinforced Polymer
Glulam	Glued-laminated timber
IAE	Integral Absolute Error
ISO	International Organization for Standardisation
LVDT	Linear variable differential transformer
LVL	Laminated veneer lumber
MOE	Modulus of Elasticity
NSM	Near-surface mounted
SR	Stepwise Regression
UTM	Universal testing machine
W	Increment of strain

List of notations

A_{eff}	Effective bonded area
A_f	FRP cross section area
A_t	Timber cross section area
b_t	Width of timber block
b_c	Concrete width
b_f	Width of FRP
d_t	Timber depth
E_{adh}	Adhesive elastic modulus
E_f	Elastic modulus of FRP plate
$E_f t_f$	Bond stiffness
E_L	Elastic modulus of timber parallel to grain
E_R	Elastic modulus of timber perpendicular to the grain
E_t	Elastic modulus of timber
E_T	Elastic modulus of timber tangential to the growth rings
f'_c	Concrete compressive strength
$f_{c,0}$	Compressive strength of timber parallel to grain
$f_{c,90}$	Compressive strength of timber perpendicular to grain
F_{c1t}	Plastic compressive loads in timber
F_{c2t}	Plastic compressive loads in timber
F_{ct}	Compression force in timber
f_t	Tensile strength of timber parallel to grain
F_{tf}	Tension force in FRP
F_{tt}	Tension force in timber
f_{ut}	Ultimate tensile strength of timber parallel to grain
G_a	Adhesive shear modulus
G_f	Interfacial fracture energy of FRP-to-timber interface
G_t	Timber shear moduli
L_e	Effective bond length of FRP-to-timber joint
L_f	Length of bonded FRP plate
L_t	Timber length
m	Slop of the plastic zone
M_u	Ultimate bending capacity of the composite beam
P_u	Maximum load before failure of joint and beam
$P_{u\ Anal.}$	Analytical maximum load of joint

$P_{u\ Num.}$	Numerical maximum load
$P_{u\ Exp.}$	Experimental maximum load of joint
s	Slip of FRP-timber interface
s_0	Slip of FRP plate at free unloaded end
s_1	Initial slip
s_i	Slip between adjacent strain gauges
s_{max}	Maximum slip for bond stress-slip model
s_x	Slip of FRP plate at location x
t_f	Thickness of FRP plate
t_{pl}	Measured thickness of the plate (or coupon specimen)
x_0	Variable location along FRP plate
y_c	Neutral axis
α	Effective bond length factor
β	Width ratio factor
Δl	Distance between adjacent strain gauges
Δ_{max}	Deflection of beam corresponding to ultimate load
ε	Strain of FRP plate
ε_{ct}	Maximum strains in compression
ε_{cu}	Ultimate strain in the plastic limit compression
ε_{cy}	Strain in the elastic limit compression
ε_{FRP}	Ultimate strain of FRP
$\varepsilon_{FRP,x}$	Strain of the FRP at point x
ε_t	Maximum strains in tension
ε_f	Strain at the loaded end
σ_{ct}	Maximum timber compression stress
σ_{FRP}	Axial stresses in FRP
σ_t	Maximum timber tensile stress
τ_1	Initial shear stress
τ_i	Average shear stress between two consecutive strain gauges
τ_u	Maximum bond stress for bond-slip model
τ_x	Shear stress of interface at location x
τ_v	Adhesive shear resistance
υ	Poisson ratio
γ_t	Timber type factor

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Abstract

Timber has been extensively used in construction for many centuries due to a number of advantageous properties such as aesthetics, strength-to-weight ratio, fire performance and acoustic properties. Besides, timber is only one of few renewable construction materials that can be used in large quantities. There has been an increase in the use of timber in modern structures in recent times with the advent of engineered wood products and growing interest in the use of environmentally sustainable materials in construction. Timber structures may need to be repaired and/or strengthened due to a number of reasons, such as, degradation as a result of biological and/or physical hazards, loss of strength or damage due to overloading or to meet increased load demands due to change in functionality or to comply with new code requirements. Therefore, either entire structures or key components may require strengthening, rehabilitation or replacement to maintain or upgrade their structural integrity.

Whilst demolition and replacement of degraded structures is a straightforward solution, it is often costly and time-consuming. Recent studies and applications have demonstrated that Fibre Reinforced Polymer composites (FRP) can effectively and economically be used for new structures, as well as in the strengthening and retrofitting of existing civil infrastructure. FRP is a material with high stiffness and strength to weight ratio, high Young's modulus and high fatigue performance. Moreover, additional advantageous properties of FRP such as being light in weight with superior corrosion resistance and flexibility in application make it a viable alternative to steel in reinforcing and/or repairing timber, especially in aggressive and extreme environments.

One of the most common problems associated with the use the externally bonded FRP sheets is the premature failure due to debonding which limits the full utilisation of the material strength of the FRP. Whilst the debonding mechanism in FRP bonded to concrete is well understood based on several previous studies, only limited attempts have been made to investigate the debonding behaviour of FRP bonded to timber. It is important to mention that there are some fundamental differences in the failure mechanism when FRP is bonded to timber compared to when it is bonded to concrete. Concrete is weak in tension; whilst tensile strength of timber is much higher. Therefore, the models which work for FRP-to-concrete bond may not work for when FRP is bonded to timber. As such, a knowledge gap on potential parameters that influence bond behaviour of FRP-to-timber interface exists. Therefore, a sound understanding of the behaviour of FRP-to-timber interfaces needs to be developed and consequently, further understanding of the bond is essential.

The main goal of this research was to identify and investigate the potential parameters affecting the behaviour of the bond between timber and FRP. To achieve these outcomes, an extensive experimental program followed by analytical and numerical investigation was carried out. Through the experimental program, the influence of potential factors such as bond width, bond length, material properties and geometries on the bond strength was investigated. Investigation of the bond parameters showed that the bond strength significantly increases with increase in bond width and timber tensile strength. In addition, bond length has a major impact on the bond strength; however, bond strength cannot increase further once the bond length exceeds the effective bond length.

Whilst a number of analytical methods exist to predict the bond behaviour of FPR-to-concrete interface, analytical solutions to determine the interface behaviour of FRP-to-timber have not been fully investigated. Furthermore, existing analytical models for FRP-to-timber joints have been mostly derived based on the theoretical proposals where concrete had been used as a substrate and therefore, these models do not correlate particularly well with the experimental results. Novel theoretical models are proposed in this study to quantify the bond length, bond strength, the strain distribution profile, slip profile and shear stress relationships for FRP-timber joints. A good correlation could be obtained between the proposed models and experimental results.

Numerical simulation of FRP-to-timber joint is one of the most neglected fields of research. Numerical simulation has been undertaken to gain a better understanding about the interface behaviour of FRP-to-timber joints, and also to evaluate the feasibility of FRP application bonded to timber. It was found that by employment of proper constitutive behaviour for materials, the bond behaviour can be successfully predicted by FEA models.

The outcomes of FRP-to-timber joint tests and the models developed for the joints were then scaled up to FRP-strengthened timber beams. Finally, a design procedure for an FRP strengthened timber beam was developed to design and accurately predict the flexural capacity of strengthened timber beams.

The experimental, analytical and numerical works presented in this dissertation lead to a number of conclusions which are expected to make a significant contribution for understanding and modelling of FRP strengthened timber beams.