Numerical and Experimental Investigations of Vibration-based Assessment of Timber Beams Rehabilitated by Fibre-Reinforced Polymer

By

Runhua Xiao

A thesis submitted for the degree of
Master of Engineering (Research)

Faculty of Engineering and Information Technology (FEIT)
University of Technology, Sydney (UTS)

February, 2014

UTS
University of Technology, Sydney

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student:

Date:

ABSTRACT

Timber has been traditionally used all over the world as a construction material. Built timber structures may require repair and/or strengthening because of a number of factors such as age-related deterioration, fungus or termite attacks and damage caused by overloading. In recent years, a great deal of research and development has been focused on utilizing vibration based methods to detect structural damage and use of fibre reinforce polymer (FRP) on timber for strengthening or repair damaged timber structural members in various types of structures. Although the application of FRP for repair and/or strengthening of structures has been researched for a decade, anon-destructive evaluation of the effectiveness and reliability of the FRP repaired or strengthened structure are yet to be investigated.

In this study, the damage index method, i.e. a robust vibration-based damage detection method, is proposed to localize and quantify damage in timber beams and to evaluate the effectiveness of repair for the damaged timber beams, in which the damaged timber beams are repaired by applying carbon fibre reinforced polymer (CFRP).

In addition to numerical investigation using Finite Element (FE) analysis, an experimental program comprising of static and dynamic testing was carried out on five laminated veneer lumber (LVL) beams. Different damage cases (severe, moderate, minor) are introduced on these beams. The experimental results indicate that the use of CFRP was effective in repairing the damaged timber beams. Both numerical and experimental investigations have also shown that the proposed damage index method is able to accurately detect damage location and severity, and evaluate the repair effectiveness for damaged timber beam after repairing with CFRP.

ACKNOWLEDGEMENT

This Master research could not have been possible without the assistance, understanding and guidance rendered by numerous people throughout the project. The author would very much like to express his appreciation and gratitude to his supervisors, Associate Professor Jianchun Li, and Docter Rijun Shrestha, for their support and guidance throughout this work and for their patience with proof-reading this thesis. The author would also like to thank Yunlong Luo, who had given the author invaluable advice and assistance in writing this thesis. Utmost gratitude is also due to Xiang Luo and Nin Yan who helped the author for familiar with the ANSYS and MATLAB.

Furthermore, the author would like to thank staff of the UTS Structures Laboratory for their help in the experimental work. Special thanks must also go to David Dicker and Peter for helping the author in setting up static test system and the acquisition system. I wish to sincerely thank Muhammad for helping author applying CFRP on damaged beams. The author also feels a deep sense of gratitude to all the academic and non-academic staff in the Faculty of Engineering and Information Technology for the help rendered.

Finally, the author wishes to thank for my family. For my parents, it is their altruistic and unimaginable support through my master research period. Thank to my aunt, Dr Linda Xiao for giving me a lot of support and guidance on my study and daily life.

LISTOFPUBLICATIONS BASED ON THIS RESEARCH

Refereed Journal Articles

1. Xiao, R., Li, J. & Shrestha, R. (2014), 'Investigations of Vibration Based Condition Assessment of Timber Beams Strengthened with Fibre Reinforced Polymer', *Advanced Materials Research Vol.831 (2014) pp 53-57.*
2. Xiao, R., Li, J. & Shrestha, R. (2014), 'A Novel Vibration Based Assessment Approach for Repair Effectiveness of Damaged Timber Beam Rehabilitated by Fibre Reinforced Polymer', *In Preparation.*

Refereed Conference Papers

1. Xiao, R., Li, J. & Shrestha, R. (2014), 'Investigations of Vibration Based Condition Assessment of Timber Beams Strengthened with Fibre Reinforced Polymer', *3rd International Conference on Civil Engineering and Building Materials, 2013.*
2. Xiao, R., Li, J. & Shrestha, R. (2014), 'A Novel Vibration Based Assessment Approach for Repair Effectiveness of Damaged Timber Beam Rehabilitated by Fibre Reinforced Polymer', *In Preparation.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF NOTATIONS

Δ	change in the flexibility
φ_i	eigenvector of mode I of undamaged model
φ_j	eigenvector of mode I of damaged model
$\emptyset$	mode shape vector
$\emptyset_i$	mode shape of mode *i*
$\emptyset_{ij}$	mode shape vector of the i^{th} mode and j^{th}element of undamaged beam
$\emptyset_{ij}^*$	mode shape vector of the i^{th} mode and j^{th}element of damaged beam
δ	deflection of the LVL beam
β	damage indicator
β_j	damage indicator of j^{th}member
α	severity estimator
α_j	severity estimator of j^{th}member
α_{cj}	calibrated severity estimator of j^{th}member
η	calibration factor
$\Delta\alpha_d$	indicator of effectiveness of the repair calculated from dynamic test results
$\Delta\alpha_s$	indicator of effectiveness of the repair calculated from static test results
α_s	severity estimation of damage
α_r	severity estimation of the repair
3-D	three-dimensional
9-nodes	9 measuring points taken from the VEMA
CFRP	carbon fibre reinforced polymer
COMAC	coordinate modal assurance criterion
DD	damage detection
Denom	denominator
DOF	degree of freedom
E	modulus of elasticity
E_j	j^{th}equivalent elemental modulus of elasticity of undamaged beam
E_j^*	j^{th}equivalent elemental modulus of elasticity of damaged beam
EI	flexural stiffness
EMA	experimental modal analysis
F	system force vector
FE	finite element
FEA	finite element analysis
FEM	finite element model

FFT	fast Fourier transform
FRF	frequency response function
I	moment of inertia
K	system stiffness matrix
L	light damage
LVDT	linear variable differential transformer
LVL	laminated veneer lumber
M	medium damage
MAC	modal assurance criterion
MSE	modal strain energy
NFerror	natural frequency difference between FE and experimental models
Num	numerator
VEMA	Virtual Experimental Modal Analysis
Z	system displacement vector
Z_j	damage location index