



University of Technology, Sydney

School of Civil and Environmental Engineering

Faculty of Engineering and Information Technology

Investigation of a Proposed Long Span Timber Floor for Non-Residential Applications

By

Zhinus Zabihi

BEng, MEngSc (From BIHE)

Thesis submitted in fulfilment of
requirements for the degree of
Doctor of Philosophy

October 2014

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for any 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 and 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.

Production Note:
Signature removed
prior to publication.

Zhinus Zabihi
October 2014

ACKNOWLEDGMENTS

I would like to express my gratitude to those who have supported me throughout my study and helped make this PhD research possible.

Firstly I would like to thank my principal supervisor, Professor Keith Crews, without whose support, patience and understanding, this thesis would not have been completed. It was a valuable experience for me to work with him and be inspired by his guidance, supervision and knowledge throughout my study. I would also like to thank my co-supervisor Professor Bijan Samali for his constant encouragement and advice during my research, and for introducing me to my principal supervisor to start my PhD. His technical guidance while reviewing my papers and his helpful observations are highly acknowledged.

I gratefully acknowledge the Structural Timber Innovation Company for providing the financial support for this research project. Also, the financial assistance provided by University of Technology Sydney (UTS) as International Research Scholarship, and all administrative and technical support provided by the Faculty of Engineering and Information Technology at UTS is deeply appreciated.

The feedback from examiners is highly acknowledged, and the details of modifications related to their feedback are contained in the report of changes.

Many thanks to Dr. Rijun Shrestha, for his guidance, his constant and genuine encouragement, and for generously sharing his knowledge. I would also like to thank Dr. Christophe Gerber for his technical advice, and for providing his experience on experimental works. Dr. Hamid Valipour's invaluable technical guidance on numerical work is also gratefully acknowledged.

I am grateful to my friends and fellow workers on the STIC project, namely Nima, Rajendra, Mulugheta, Farzad, and Matthew, for providing generous help during this study and sharing their findings.

Special thanks to the UTS laboratory staff (Rami Haddad, Peter Brown, David Dicker, and other lab assistants) for their great efforts in providing technical support and assistance for all of my experimental tests. I would also like to thank Mr Laurence Stonard, Scott Graham and Mulughet Hailu from the Materials Testing Lab for their support in completing the tests.

I cannot thank my family enough (my parents, and my lovely brother and sisters) for their inspirational encouragement, love and support during my study. I would like to express my sincere gratitude to my beloved husband, Riaz, for his loving care and support throughout my research, and to my baby for being very patient and a great son while still very little (13 months old now!).

Lastly, I would like to dedicate this thesis to my lovely parents to whom I owe an endless depth of gratitude, as a small token of their genuine love in supporting me and preparing me for the journey of life. Their steadfastness and hardworking spirit was always a source of inspiration for me to aim high and to pursue my dreams. Thanks a lot and I always love you.

Zhinus Zabihi

October 2014

ABSTRACT

Design of floor systems for commercial and multi-residential buildings in many parts of the world is currently dominated by the use of structural materials other than timber, such as reinforced concrete systems. Recent research in Australia has shown that the major barriers to using timber in non-residential buildings are the fire performance and the lack of designer confidence in commercial and industrial timber-based constructions. In this regard, significant research initiatives have commenced in Australia and New Zealand with the aim of developing timber and timber hybrid systems for large span commercial and industrial applications. This PhD research provides a detailed procedure for designing and investigating the short term static behaviour of a proposed long span timber floor system for non-residential applications that meets serviceability and ultimate limit design criteria, with the use of timber as the only structural load bearing part of the system. The specimen's responses to long-term loading, in-plane loading, dynamic excitation, cyclic loading and loading history are outside the scope of this PhD research. Moreover, other aspects of performance such as assessment of acoustic performance, dynamic performance and the possible interconnection systems alongside floor modules are not covered in the scope of this research project.

In this study the behaviour of two types of LVL are investigated through a number of experimental and analytical tests. As a result of the tension and compression tests, a suitable constitutive law is developed which can accurately capture the stress-strain relationship and the failure behaviour of LVL, and it can also be incorporated into FE analysis of any LVL beam with similar structural features to the tested specimens. Further, the results of the full scale four point bending tests on LVL sections are used to identify the behaviour of LVL up to the failure point and to develop a finite element model to capture the behaviour and failure of LVL.

Moreover, after investigating the long span timber floors, one system is proposed to be fabricated for the extensive experimental and numerical investigation. The experimental investigation involved subjecting the full scale proposed floor modules (6m and 8m

clear span LVL modules) to both serviceability and ultimate limit state static loading to assess the strength and serviceability performance of the proposed system. A continuum-based finite element model is also developed to capture the behaviour and failure of the long span LVL modules and to adequately predict the serviceability and ultimate limit performance of the proposed floor system.

To evaluate the partially-composite strength and serviceable performance of LVL floor system, a series of push-out tests are conducted on the fabricated timber connections using normal screws as the shear connectors, and the stiffness of the connections are assessed at serviceability and ultimate limit state. A number of LVL beams (3.5m “T” shaped beams) were also fabricated using only normal screws as the load bearing shear connectors at the interfaces, and are tested under serviceability and ultimate limit state loads with different screw spacing. Furthermore, a closed-form prediction analysis is conducted to calculate the partially-composite ultimate load of the beams. A comparison between the experimental results and the closed-form predicted results is undertaken, and the results are used for predicting the partially-composite behaviour of long span 6m and 8m LVL modules.

The results of the full scale experimental tests together with the numerical investigation provide a robust model for predicting the performance of any timber beams with similar structural features to the proposed system while the dimensions and spans can be varied according to special requirements such as dynamic performance or fire resistance requirements.

TABLE OF CONTENTS

Certificate of Authorship/Originality	i
Acknowledgements	ii
Abstract	iv
Table of Contents	vi
List of Figures	x
List of Tables	xviii
List of Publications	xxi
List of Notations	xxii
1 INTRODUCTION.....	2
1.1 Background.....	2
1.2 Structural Timber Innovation Company (STIC).....	4
1.3 Scope of Research Topic	4
1.4 Research Objectives.....	7
1.5 Research Methodology	8
1.6 Research Significance.....	12
1.7 Layout of the Thesis	12
2 LITERATURE REVIEW.....	16
2.1 Introduction.....	16
2.2 Materials in Timber Structures	16
2.3 Performance Requirements of Timber Floors	18
2.4 An Overview of Various Types of Timber Floor Systems.....	21
2.4.1 Joist Floor Systems	25
2.4.2 Stressed Skin Panels	27
2.4.3 Plate Floor Systems.....	29
2.4.4 Timber Concrete Composite System	31
2.5 Structural Performance of Composite Floor Systems	33
2.5.1 Interaction between the Floor Members	33
2.5.2 Fully Composite Action.....	34
2.5.3 The Effects of Shear lag and plate buckling on Effective Flange Width..	35

2.5.4	Partially Composite Action.....	38
2.5.5	Verification of the Serviceability and Ultimate Limit State	40
2.6	Numerical Investigations on Timber Floor Systems	43
2.7	Long Span Timber Floors	48
3	THE PROPOSED TIMBER FLOOR SYSTEM	61
3.1	Introduction.....	61
3.2	The Proposed Long Span Timber Floor Modules	61
3.3	Serviceability and Ultimate Design Criteria.....	65
3.3.1	Design Requirement and Procedure.....	65
3.3.2	Serviceability – Deflection	70
3.3.3	Serviceability - Dynamic behaviour	71
3.3.4	Strength of the LVL floor modules.....	72
3.4	Analytically Predicted Response of the System	75
3.4.1	Material Properties Input	75
3.4.2	Effective Bending Stiffness and the Second Moment of Inertia.....	76
3.4.3	Loading Input.....	77
3.4.4	Serviceability Check	77
3.4.5	Strength Check.....	78
3.5	Conclusions	81
4	EXPERIMENTAL AND ANALYTICAL INVESTIGATION ON SHORT TERM BEHAVIOUR OF LVL	83
4.1	Introduction.....	83
4.2	Experimental Program	84
4.2.1	Tension and Compression Test Specimens.....	84
4.2.2	Proposed Constitutive Law for LVL.....	87
4.2.3	Four Point Bending Tests.....	97
4.2.4	Three Point Bending Tests (flexural shearing strength)	105
4.3	Comparison between the Experimental Results and Analytically Predicted Results	110
4.4	Conclusion	113

5 EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF PROPOSED LONG SPAN LVL FLOOR MODULES..... 116

5.1	Introduction.....	116
5.2	Predicting the Response of the System.....	116
5.2.1	6m and 8m modules	116
5.2.2	Floor System	123
5.3	Experimental Program	124
5.3.1	The Test Setup	125
5.3.2	Instrumentation	130
5.4	Experimental Results.....	136
5.4.1	Failure Modes	136
5.4.2	Stiffness and Strength of the Modules	141
5.4.3	Composite Behaviour of the Modules	148
5.5	Conclusions	154

6 EXPERIMENT AND ANALYTICAL INVESTIGATION ON PARTIALLY-COMPOSITE BEHAVIOUR OF LVL BEAMS 157

6.1	Introduction.....	157
6.2	Experimental Program - Push out Tests	158
6.2.1	Test Specimens	158
6.2.2	Test setup and loading procedure	161
6.2.3	Characteristic Behaviour of Connections	164
6.3	Push out Test Results	165
6.3.1	Strength and Stiffness of the Connections.....	165
6.3.2	Analytical Model for Shear-Slip Behaviour of the Connections	167
6.4	Experimental Investigation on Partially-Composite Behaviour of LVL Beams.....	171
6.4.1	Test Specimens and Experimental Program	171
6.4.2	Instrumentations and Test Set up.....	175
6.4.3	Analytically Predicted Responses.....	176
6.5	Experimental Results of LVL Beams.....	178
6.5.1	Failure Mode of the System.....	178

6.5.2	Flexural Stiffness of the LVL Beams	182
6.6	Partially-Composite Behaviour of 6m and 8m LVL Modules	188
6.6.1	Cross-section Characteristics	188
6.6.2	Serviceability Check	191
6.6.3	Strength of the LVL floor modules.....	192
6.7	Conclusions	196
7	NUMERICAL INVESTIGATION OF TIMBER FLOOR	
	MODULES.....	199
7.1	Introduction.....	199
7.2	Numerical Investigation.....	200
7.2.1	Geometric Properties of Model.....	200
7.2.2	Element Type	202
7.2.3	Material Properties	202
7.2.4	Material Model and Constitutive Law	203
7.2.5	Boundary Conditions	206
7.2.6	Mesh Size.....	206
7.2.7	FE Results and the Comparison between Analytically Predicted Results and the Experimental Results.....	208
7.2.8	FE Results of 6m and 8m modules, and the Comparison between Analytically Predicted Results and the Experimental Results	212
7.2.9	Comparison of the FE results with the FE results of 2D/3D ABAQUS model and Hashin damage model	219
7.3	Conclusions	221
8	CONCLUSIONS	224
8.1	The Proposed Floor System.....	224
8.2	LVL Properties, Test Results.....	225
8.3	Experimental Investigation of the Proposed System	226
8.4	Finite Element Results	230
8.5	Future Work and Recommendation.....	231
	REFERENCES.....	232
	APPENDICES.....	253

LIST OF FIGURES

Figure 1.1 Summary of STIC’s objectives.....	5
Figure 1.2 Research plan for experimental study.....	10
Figure 2.1 Engineered wood products (a) Glulam (BoiseCascade 2013), (b) CLT (APA 2013)	17
Figure 2.2 A typical timber flooring system (Kolb 2008)	21
Figure 2.3 “Timber only” flooring systems (Sigrist & Gerber 2002)	23
Figure 2.4 “Modern” plate floor systems (Jorissen 2006)	24
Figure 2.5 Plywood webbed box beams (EWPA 2008)(the thinckness of flanges and webs are schematic)	27
Figure 2.6 Stressed Skin Panels Systems (Kolb 2008)	29
Figure 2.7 Butt-jointed solid timber joists (Kolb 2008).....	30
Figure 2.8 Solid timber joists with double tongue and groove (Kolb 2008).	30
Figure 2.9 Edge-fixed floor elements, dowelled (Kolb 2008).	30
Figure 2.10 Edge-fixed floor elements, nailed (Kolb 2008).	30
Figure 2.11 Edge-fixed timber floors (glued, with loose tongue joints) (Kolb 2008). ...	30
Figure 2.12 The strain and stress distribution over the depth of section with no slip in the interlayers.....	34
Figure 2.13 The effect of shear lag on stress distribution.....	36
Figure 2.14 Strain and stress distribution across the floor section – free slip at the interfaces	38
Figure 2.15 Four point bending load.....	42
Figure 2.16 Interrelation between the values a and b taken from Eurocode 5 [3]: Direction 1 means better performance, direction 2 means poorer performance	43
Figure 2.17 Yield Surface for von Mises Yield Criterion.....	47
Figure 2.18:Finnjoist® Systems (a) I beams (Finnforest 2010a), (b) standard Finnjoist sizes(Finnforest 2010a)	49
Figure 2.19:Tecbeam system (<i>Tecbeam</i> 2010)	49
Figure 2.20 I joist systems (a) TECslab® (2013), (b) HyJoist® (2013), (C) SmartJoist (2013) and (d) Lumberworx® (2013)	50
Figure 2.21: Truss Systems (a) Gitterbjelker System (2013), (b) Pryda (2013)	51

Figure 2.22 Kerto-Ripa®, T section and Box section SSPs	52
Figure 2.23 Cross section of the floor elements (André Jorissen 2006)	53
Figure 2.24 Potius floor system (Potius™ 2010).....	53
Figure 2.25 Lignatur flooring systems, (a) box beam elements, (b) surface beam elements, (c) shell beam elements.....	54
Figure 2.26 (KLH) Cross-laminated timber panels.....	55
Figure 2.27 The proposed section for the experimental and analytical investigation.....	59
Figure 3.1 Dimensions of 8m modules	62
Figure 3.2 Dimensions of 6m modules	63
Figure 3.3 The Dimensions of the type 17 normal screws.....	63
Figure 3.4 Geometry of timber floor module (a) Cross-section geometry, (b) Transformed cross-section geometry	68
Figure 4.1 Dimensions and test set up for tension test.....	86
Figure 4.2 Dimensions and test set up for compression test.....	87
Figure 4.3 Stress-Strain graphs for tension tests for hySpan Cross-Banded LVL.....	88
Figure 4.4 The regression line for the tension tests for hySpan Cross-Banded LVL	89
Figure 4.5 The regression line for the tension tests for hySpan Project LVL.....	89
Figure 4.6 Stress-Strain graphs for compression tests of hySpan hySpan Project LVL.....	90
Figure 4.7 Stress-Strain graphs for compression tests for hySpan Project LVL	91
Figure 4.8 Stress-Strain relation according to Glos Model (Glos 1981)	91
Figure 4.9 The comparison between the experimental data and the modified Glos model for hySpan Cross-Banded LVL.....	94
Figure 4.10 The comparison between the experimental data and the modified Glos model for hySpan Project LVL	95
Figure 4.11 The adopted parabola model for hySpan Cross-Banded LVL.....	96
Figure 4.12 The adopted parabola model for hySpan Project LVL.....	97
Figure 4.13 Test set-up for measuring the bending strength and apparent modulus of elasticity (4063.1:2010).....	98
Figure 4.14 The test set up for edge-wise tests according to 4063.1:2010	98
Figure 4.15 The test set up for flat-wise tests according to 4063.1:2010	98
Figure 4.16 The test set up for flat-wise tests according to 4063.1:2010	99
Figure 4.17 The test set up for Edge-Wise tests	101

Figure 4.18 Failure pictures of a beam subjected to Edge-Wise four-point bending tests	102
Figure 4.19 Failure pictures of different beam subjected to Edge-Wise four-point bending.....	102
Figure 4.20 Load-deflection graphs for hySpan project LVL(45mm*90mm), Edge-Wise tests.....	103
Figure 4.21 Test set up for flat-wise four-point bending tests	103
Figure 4.22 Failure pictures in flat-wise four-point bending tests	104
Figure 4.23 Load-deflection graphs for cross-banded LVL (35mm*90mm), Flat-Wise tests.....	104
Figure 4.24 Load-deflection graphs for hySpan project LVL (35mm*90mm), Flat-Wise tests.....	105
Figure 4.25 Shear test configuration according to AS/NZS 4063.1:2010	106
Figure 4.26 Steel bearing plate.....	106
Figure 4.27 Shear test set up according to AS/NZS 4063.1:2010	106
Figure 4.28 The test set up for measuring the shearing strength	107
Figure 4.29 Failure picture of LVL under three-point bending test.....	108
Figure 4.30 Failure picture of LVL under three-point bending test.....	108
Figure 4.31 Load – Displacement of LVL under three-point bending load- test 1	109
Figure 4.32 Load – Displacement of LVL under three-point bending load- test 2.....	109
Figure 5.1 Dimensions of 6m modules	117
Figure 5.2 Dimensions of 8m modules	117
Figure 5.3 Four point bending loads	120
Figure 5.4 Floor System (by connecting three 8m modules side by side	123
Figure 5.5 Schematic diagram of test setup (a) 8 m module (b) 6 m module.....	126
Figure 5.6 Boundary conditions (a) pinned support (b) roller support (dimensions in mm)	127
Figure 5.7 Layout of the 8m LVL Modules.....	128
Figure 5.8 The Reaction frame.....	129
Figure 5.9 The hydraulic jacks and the load cells.....	129
Figure 5.10 Data processing system	130
Figure 5.11 Locations and numbers of LVDTs (dimensions in mm)	131
Figure 5.12 Third-span LVDTs.....	131

Figure 5.13 Mid-span LVDTs.....	132
Figure 5.14 Horizontal LVDTs for measuring any possible slip at interfaces.....	132
Figure 5.15 Type PL-60-11 Strain Gauges	133
Figure 5.16 Adopted names and locations of the Strain Gauges U8-01	134
Figure 5.17 Adopted names and locations of the Strain Gauges for U8-02 and U8-03	134
Figure 5.18 Adopted names and locations of the Strain Gauges for 6m modules	135
Figure 5.19 Strain gauges of U8-03 (a) at top flange, (b) over the depth of the section	136
Figure 5.20 Failure of U8-01, east side of Module	137
Figure 5.21 Failure of U8-01, west side of Module	137
Figure 5.22 Failure of U8-03	138
Figure 5.23 Failure of U8-02	139
Figure 5.24 Deformation of one of the screws after failure of U8-02	140
Figure 5.25 Failure of one of the screws after failure of U8-02	140
Figure 5.26 Notable slip at interfaces (East side web).....	140
Figure 5.27 Notable slip at interfaces (west side web)	141
Figure 5.28 Load –deflection graph for U8-01 at mid-span	143
Figure 5.29 Load –deflection graph for U8-01 at third-span	144
Figure 5.30 Load –deflection graph for U8-03 at mid-span	144
Figure 5.31 Load –deflection graph for U8-03 at third-span	145
Figure 5.32 Load –deflection graph for U8-02 at mid-span	145
Figure 5.33 A comparison of Load-Displacement for all modules (mid-span)	146
Figure 5.34 Strain gauges readings vs locations of the gauges for U8-03, west web (mid-span) at P=10kN	150
Figure 5.35 Strain gauges readings vs locations of the gauges for U8-03, west web (mid-span) at P=30kN	150
Figure 5.36 Strain gauges readings vs locations of the gauges for U8-03, west web (mid-span) at P=40kN	151
Figure 5.37 Strain gauges readings vs locations of the gauges for U8-03, west web (mid-span) at P=50kN	151
Figure 5.38 Strain gauges readings vs locations of the gauges for U8-03, west web (mid-span) at P=65kN	152

Figure 5.39 Location of N.A for at different load levels for U8-03.....	152
Figure 6.1 Dimensions and materials of the connection type 1 (mm)	159
Figure 6.2 Dimensions and materials of connection type 2 (mm)	160
Figure 6.3 Dimensions of type 17 the normal screws (mm)	161
Figure 6.4 Push out test set up, front view	162
Figure 6.5 Push out test set up, back view	162
Figure 6.6 Loading procedure based on European Standard	163
Figure 6.7 Idealized load-slip curves based on European Standard.....	163
Figure 6.8 Load-slip Response of connection type 1 for a single screw.....	166
Figure 6.9 Load-slip Response of connection type 2 for a single screw.....	166
Figure 6.10 Response of connection type 1 without the load cycle (the unloading stage eliminated).....	168
Figure 6.11 Response of connection type 2 without the load cycle (the unloading stage eliminated).....	169
Figure 6.12 Response of connections without the load cycle (the unloading stage eliminated).....	171
Figure 6.13 Cross-sectional dimensions of LVL beams	172
Figure 6.14 Cross section of LVL beams.....	173
Figure 6.15 The fabricated LVL beams with Different screw spacing.....	174
Figure 6.16 Test set up for LVL beams	175
Figure 6.17 LVDTs and Pin-Roller supports for LVL beams	175
Figure 6.18 Failure of LVL beam with 400mm screw spacing, (a) right side of beam, (b) left side of beam	179
Figure 6.19 Failure of LVL beam with 200mm screw spacing (a) right side of beam, (b) left side of beam	180
Figure 6.20 Failure of LVL beams with 100mm screw spacing (a) right side of beam, (b) left side of beam	181
Figure 6.21 Deformation of the screws after completing the test of LVL beam (with 100mm screw spacing).....	182
Figure 6.22 Load-deflection graphs for LVL beams with different screw spacing (serviceability tests)	184
Figure 6.23 Load-deflection graphs for LVL beams with different screw spacing (ultimate limit tests)	185

Figure 6.24 The bi-linear behaviour of LVL beams with different screw spacing.....	185
Figure 6.25 A comparison between all Load-deflection graphs for serviceability and destructive tests	186
Figure 6.26 Dimensions of the Components.....	188
Figure 7.1 Test setups for flat-wise and edge-wise tests according to 4063.1:2010, (a). The test set up for edge-wise tests, (b) The test set up for flat-wise tests, (c)The test set up for flat-wise tests	201
Figure 7.2 Geometric properties of SOLID185 (ANSYS 2011).....	202
Figure 7.3 Yield Surfaces for Compression and Tension	205
Figure 7.4 Pin and Roller supports.....	206
Figure 7.5 Continuum-Based ANSYS model for hySpan Project LVL, Edge-Wise tests with 9mm mesh size.....	207
Figure 7.6 Mesh sensitivity analysis for edge-wise tests of hySpan Project LVL.....	208
Figure 7.7 Compression between FE and experimental results, Edge-Wise tests	210
Figure 7.8 Compression between FE and experimental results, Flat-Wise tests	210
Figure 7.9 Compression between FE and experimental results, Flat-Wise tests	211
Figure 7.10 Cross sectional view of ANSYS model of 8m LVL modules	213
Figure 7.11 3D view of ANSYS model of 8m LVL modules	213
Figure 7.12 Load vs max deflection of modules for the SLS and ULS tests.....	214
Figure 7.13 Comparison between FE and experimental results for 6mm and 8m LVL modules	215
Figure 7.14 Ansys Model of the floor system (1.8m wise).....	216
Figure 7.15 The Comparison between the FE results and analytically predicted results of the Floor system (1.8m wide)	217
Figure 7.16 Possible interconnection system between LVL floor modules.....	218
Figure 7.17 A comparison between the FE modelling results and experimental results of U8-03	220
Figure 8. 8.1 Load –deflection graph for U8-01 at third-span.....	227
Figure 8.2 Load –deflection graph for U8-03 at third-span.....	228
Figure 8.3 Location of N.A for at different load levels for U8-03.....	228
Figure A.1 Dimensions for 8m span timber modules (mm)	253
Figure B.1 Load vs. strain gauge readings at mid-span, top flange, for U8-01	262
Figure B.2. Load vs. strain gauges reading at mid-span, west web, for U8-01	263

Figure B.3. Load vs. strain gauges reading at mid-span, east web, for U8-01	263
Figure B.4. Load vs. strain gauges reading at 0.5m off mid-span, top flange, for U8-01.....	264
Figure B.5. Load vs. strain gauges reading at 0.5m off mid-span, west web, for U8-01.....	264
Figure B.6. Strain gauge readings vs location of gauges on top flange at mid-span, for U8-01	265
Figure B.7. Strain gauge readings vs location of gauges on top flange at 0.5m off mid-span, for U8-01.....	265
Figure C.1. Strain gauges readings vs locations of the gauges for U8-01, west web (mid-span) at P=10kN.....	266
Figure C.2. Strain gauges readings vs locations of the gauges for U8-01, west web (mid-span) at P=30kN.....	267
Figure C.3. Strain gauges readings vs locations of the gauges for U8-01, west web (mid-span) at P=50kN.....	267
Figure C.4. Strain gauges readings vs locations of the gauges for U8-01, west web (mid-span) at P=75kN.....	268
Figure C.5. Location of N.A for at different load levels for U8-01.....	268
Figure C.6. Strain gauges readings vs locations of the gauges for U8-02, west web (mid-span) at P=10kN.....	269
Figure C.7. Strain gauges readings vs locations of the gauges for U8-02, west web (mid-span) at P=30kN.....	269
Figure C.8. Strain gauges readings vs locations of the gauges for U8-02, west web (mid-span) at P=40kN.....	270
Figure C.9. Strain gauges readings vs locations of the gauges for U8-02, west web (mid-span) at P=50kN.....	270
Figure C.10. Location of N.A for at different load levels for U8-02	271
Figure C.11. Strain gauges readings vs locations of the gauges for L6-01, west web (mid-span) at P=5kN.....	272
Figure C.12. Strain gauges readings vs locations of the gauges for L6-01, west web (mid-span) at P=12kN.....	272
Figure C.13. Strain gauges readings vs locations of the gauges for L6-02, west web (mid-span) at P=5kN.....	273

Figure C.14. Strain gauges readings vs locations of the gauges for L6-02, west web (mid-span) at P=12kN.....	273
Figure C.15. Strain gauges readings vs locations of the gauges for L6-03, west web (mid-span) at P=5kN.....	274
Figure C.16. Strain gauges readings vs locations of the gauges for L6-03, west web (mid-span) at P=20kN.....	274

LIST OF TABLES

Table 2.1 stress verification for I beams, double I beams or box beams	41
Table 2.2 Load bearing capacity of floor systems	56
Table 2.3 Comparison between timber floor systems	57
Table 3.1 The Properties of LVL provided by the manufacturer CHH	64
Table 3.2 Load combinations and deflection limit for serviceability limit state design ..	66
Table 3.3 Load combinations for ultimate limit state design	66
Table 3.4 Calculation of neutral axis in step by step procedure	69
Table 3.5 Calculation of the effective flexural stiffness in step by step procedure	69
Table 3.6 Recommended values of the creep factor j_2 according to AS 1720.1 (2010) ..	71
Table 3.7 Modification Factors	73
Table 3.8 Axial components of Equation 11	73
Table 3.9 Bending components of Equation 11	73
Table 3.10 Input loading of the LVL modules	77
Table 3.11 The maximum bending moment and shear force at ultimate limit state	78
Table 3.12. The modification factors	78
Table 3.13 k_1 modification factors	79
Table 3.14 Shear Stress ratios at the interfaces	79
Table 3.15 Stress ratio checks for 8m modules	80
Table 3.16 Stress ratio checks for 6m modules	80
Table 4.1 Dimensions and number of samples for tension test	85
Table 4.2 Dimensions and number of samples for compression test	85
Table 4.3 The compression and tension test results	87
Table 4.4 Edge-Wise four point bending test results	101
Table 4.5 Flat-Wise four point bending test results	101
Table 4.6 Shear test results	107
Table 4.7 Comparison between the closed-form solution and the experimental result of Edge-Wise four point bending for hySpan Project LVL	111
Table 4.8 Comparison between the experimental results and analytically predicted results of the ultimate load of LVL beam	112

Table 4.9 Comparison between the experimental results and analytically predicted results of the maximum deflection of LVL beams.....	112
Table 5.1 Material properties of LVL.....	118
Table 5.2 Calculation of the Neutral axis of 8m LVL modules.....	119
Table 5.3 Calculation of the flexural stiffness of 8m LVL modules	119
Table 5.4 Cross-sectional characteristic of the LVL modules based on the fully composite behaviour	120
Table 5.5 Ultimate loads and maximum deflections of 8m LVL modules.....	122
Table 5.6 Ultimate loads and maximum deflections of 6m LVL modules.....	122
Table 5.7 Analytically predicted response of 1.8*8m floor system.....	123
Table 5.8 Analytically predicted response of 1.8*6m floor system.....	124
Table 5.9 The experimental investigation plan	124
Table 5.10 A comparison between the global stiffness of the modules.....	147
Table 5.11 A comparison between the experimental and predicted flexural stiffness of the modules at mid-span.....	147
Table 5.12 Comparison between the experimental and analytical results for the location of N.A (U8-03, Mid-Span, West Web strain gauges).....	153
Table 5.13 Summary of the experimental and analytical results of the LVL modules.	153
Table 6.1 MOE of LVL.....	161
Table 6.2 Strength and Stiffness of Connections	167
Table 6.3 Constant values of the analytical model	170
Table 6.4 Plan for destructive tests	173
Table 6.5 $(EI)_{eff}$ and the Neutral Axis of the partially composite section.....	177
Table 6.6 Analytically predicted maximum deflection and ultimate design load of the LVL beams.....	178
Table 6.7 A Comparison between the analytically predicted yield point load and the experimental results	183
Table 6.8 A Comparison between the analytically predicted yield-point deflection and the experimental results.....	184
Table 6.9 Comparison between the analytically predicted flexural stiffness and the experimental results	187
Table 6.10 Comparison between the analytically predicted flexural stiffness and the experimental results	187

Table 6.11 Comparison between the analytically predicted maximum deflection and the experimental results	187
Table 6.12 The analytically predicted flexural stiffness and the neutral axis of 8m LVL modules	190
Table 6.13 The analytically predicted flexural stiffness and the neutral axis of 6m LVL modules	195
Table 7.1 A summary of the material properties of LVL	203
Table 7.2 Comparison between the experimental results, FE results and analytically predicted results of the ultimate load of LVL beam	211
Table 7.3 Comparison between the experimental results, FE results and analytically predicted results of the maximum deflection of LVL beams.....	212
Table 7.4 Comparison between the experimental, analytically predicted and FE results of the ultimate load of LVL beams	217
Table 7.5 Comparison between the experimental, analytically predicted and FE results of the ultimate load of LVL beams	218
Table 7.6 The FE results of ultimate loading capacity and corresponding deflection for U8-03	220
Table 8.1 Comparison between the experimental, analytically predicted and FE results of the ultimate load of LVL beams	231
Table D.1 k_s for 5TH PERCENTILE VALUE—75% CONFIDENCE.....	23175
Table D.2 The mean value (\bar{m}), 5th percentile value ($m_{05[75]}$) of the LVL material properties.....	276
Table E.1 The measurement accuracy of the experimental appliance is as follows....	277

LIST OF PUBLICATIONS BASED ON THIS THESIS

Zabihi, Z., Samali, B., and Crews, K. (2010), “Modern trends in long span timber flooring systems”, *Proceedings, 21st Australasian Conference on the Mechanics of Structures and Materials, ACMSM 21*, Melbourne, Australia, 7-10 December.

Zabihi, Z., Samali, B., Shrestha, R., Gerber, C. and Crews, K. (2012), “Serviceability and Ultimate Performance of Long Span Timber Floor Modules”, *Proceedings, Twelfth World Conference on Timber Engineering, WCTE 2012*, Auckland, New Zealand, 16-19 July.

Zabihi, Z., Samali, B., Shrestha, R., and Crews, K. (2012), “Ultimate Performance of Timber Connection with Normal Screws”, *Proceedings, 22nd Australasian Conference on the Mechanics of Structures and Materials, ACMSM 22*, Sydney, Australia, 11-14 December.

LIST OF NOTATIONS

α	modification factor in Glos model
α_{tf}	distance between point of zero bending moment to centroid of top flange
α_{bf}	distance between point of zero bending moment to centroid of bottom flange
α_{wf}	distance between point of zero bending moment to centroid of web
γ_{tf}	partial factor for material properties of the top flange
γ_{bf}	partial factor for material properties of the bottom flange
γ_{web}	partial factor for material properties of the web
δ_{max}	maximum mid span deflection
δ_{Mid}	measurements of LVDTs under mid-span
δ_{Trd}	measurements of LVDTs under third-span
ϵ_t	tensile strain
ϵ_c	compressive strain
ϵ_0	strain coefficient
ϕ	Capacity factor for imposed load as per AS1720.1 (2010)
ϕN	axial design capacity of the timber cross-section
ϕM	bending design capacity of the timber cross-section
ϕN_p	bearing design capacity of the timber cross-section
$\phi \sigma_{tf,axial}$	top flange axial stress design capacity
$\phi \sigma_{bf,axial}$	bottom flange axial stress design capacity
$\phi \sigma_{tf,bending}$	top flange bending stress design capacity
$\phi \sigma_{bf,bending}$	bottom flange bending stress design capacity
ρ	density
$\sigma^*_{tf,axial}$	axial stress in top flange due to design action
$\sigma^*_{bf,axial}$	axial stress in bottom flange due to design action

$\sigma_{tf,bending}^*$	bending stress in top flange due to design action
$\sigma_{bf,bending}^*$	bending stress in bottom flange due to design action
$\sigma_{f,t,max}$	tensile design stress of the extreme fiber of flange
$\sigma_{f,t}$	mean tensile design stress of the flange
ν	Poisson's ratio
ν	relative slip of timer connections
Ψ	coefficient for long term load combination
$\Delta F/\Delta e$	linear elastic slope of the load-displacement graph
Δ_{vib}	mid span deflection of the floor beams as a result of impact loading
Δ_b	mid span flexural deflection of the floor beams
1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
A_{tf}	top flange area
A_{bf}	bottom flange area
A_w	web area
b	width (breadth) of the timber cross section
b_{tf}	top flange width
b_{bf}	bottom flange width
b_w	web width
CoV	coefficient of variation
d	total depth of the timber cross section
d_{tf}	top flange depth
d_{bf}	bottom flange depth
d_w	web depth
E_{tf}	top flange modulus of elasticity
E_{bf}	bottom flange modulus of elasticity
E_w	web modulus of elasticity
E	modulus of elasticity
E_t	modulus of elasticity in tension
E_c	modulus of elasticity in compression

EI	flexural stiffness
$(EI)_{eff, LT}$	long term effective flexural stiffness
$(EI)_{eff}$	effective flexural stiffness
$(EI)_{Mid}$	flexural stiffness at mid-span
$(EI)_{Trd}$	Flexural stiffness at third-span
F, P	point load
F_{est}	peak load
F_{max}	Ultimate/failure load
F_{ave}	average reading of load cells 1 and 2
F_{bf}	shear load on a single screw in bottom flange
F_{tf}	shear load on a single screw in bottom flange
f'_b	characteristic strength in bending (bending design capacity)
f'_c	characteristic strength in compression (compression design capacity)
f'_s	characteristic strength in shear (shear design capacity)
$f'_{s, glue}$	shear strength (shear design capacity) of glue
f'_t	characteristic strength in tension (tensile design capacity)
$f'_{b, tf}$	top flange bending strength (design capacity)
$f'_{b, bf}$	bottom flange bending strength (design capacity)
$f'_{b, w}$	web bending strength (design capacity)
$f'_{t, tf}$	top flange tension strength (parallel to grain) (design capacity)
$f'_{t, bf}$	bottom flange tension strength (design capacity) parallel to grain
$f'_{t, w}$	web tension strength (design capacity) parallel to grain
$f'_{c, tf}$	top flange compression strength(design capacity) parallel to grain
$f'_{c, bf}$	bottom flange compression strength (design capacity) parallel to grain
$f'_{c, w}$	web compression strength (design capacity) parallel to grain
$f'_{s, tf}$	top flange shear strength(design capacity)
$f'_{s, bf}$	bottom flange shear strength (design capacity)
$f'_{s, w}$	web shear strength (design capacity)
f_1	fundamental frequency (first natural frequency of the structure)
f_s^*	shear stress due to loading (design action)
f_p	bearing strength of the bottom flange
f_b	mean bending strength
f_c	mean compression strength

f_t	mean tension strength
$f_{c,y}$	yielding compression strength
f_t	mean tensile strength
f_v	mean shear strength
G	self-weight & permanent loading
g	acceleration due to gravity (9.81 m/s ²)
G_s	shear modulus; Modulus of rigidity
h_{tf}	distance between the neutral axis of the cross section and the centroid of htop flange
h_w	distance between the neutral axis of the cross section and the centroid of webs
h_{bf}	distance between the neutral axis of the cross section and the centroid of botom flanges flange
I	moment of inertia
I_{eff}	effective moment of area
j_2	creep factor (stiffness modification factor)
K	stiffness
K_{Mid}	stiffness at third-span of the beam
K_{Trd}	stiffness at mid-span of the beam
K_i	initial stiffness of the connection
$K_{s,0.4}$	serviceability stiffness
$K_{s,0.6}$	ultimate stiffness
$K_{s,08}$	near collapse
K_p	the strain-hardening stiffness in Richard-Abbott model
K_0	initial stiffness in Richard-Abbott model
k_1	duration of load (timber)
k_{12}	stability factor (timber)
k_4	moisture condition factor (timber)
k_6	temperature factor (timber)
k_7	length and position of bearing factor (timber)
k_9	strength sharing between parallel members factor (timber)
$K_{(11)}$	coefficient factor in Glos model

$K_{(22)}$	coefficient factor in Glos model
$K_{(33)}$	coefficient factor in Glos model
$K_{(44)}$	coefficient factor in Glos model
$(K_{(11)})_{mod}$	modified coefficient factor in Glos model
L	span of the floor modules or length of the timber beams
LL	live Load
LVDT	Linear Variable Differential Transformers
m	mass of the floor ; mass per unit area (kg/m^2)
M^*	maximum bending moment due to design action
MC	moisture content
M_0	oven dried mass
M_i	initial mass
N.A.	neutral axis
N	power in Glos model (chapter 4)
N^*	maximum axial force due to design action
N_p^*	bearing load due to design action
n	a parameter associated with the sharpness of the curve in Richard-Abbott
n_w	modular ratios for web of the LVL modules (Chapter 3)
n_{bf}	modular ratios for bottom flange of the LVL models (Chapter 3)
P_0	reference shear force in in Richard-Abbott model
Q_{tf}	first moment of area of top flange about the neutral axis
Q_{bf}	first moment of area of bottom flange about the neutral axis
Q_{max}	maximum first moment of area
Q	imposed loading
R^2	coefficient of determination
S	joist spacing
SDL	superimposed permanent load
S_s	screw spacing
S_{tf}	screw spacing in top flange interface
S_{bf}	screw spacing in bottom flange interface
V^*	maximum acting shear force (shear force due to design action)

\bar{y}_c, y_c	neutral axis of the LVL floor module
\bar{y}_{tf}	location of centroid of top flange from the base of the cross section
\bar{y}_w	location of centroid of web from the base of the cross section
y_{bf}, \bar{y}_{bf}	location of centroid of bottom flange from the base of the cross section
$y_{bf/2}$	the distance between the half of the depth of bottom flange and the centroid of the section