Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognize the author's right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form and Deposit Licence.
Behaviour of natural fibre reinforced concrete composite under impact loadings

Wenjie Wang

A thesis submitted in fulfilment of the requirements for
the Degree of Doctor of Philosophy

Supervised by Associate Professor Nawawi Chouw
Co-supervised by Associate Professor Krishnan Jayaraman

Department of Civil and Environmental Engineering
The University of Auckland
June, 2018
Abstract

Natural fibres are environmentally-friendly, economical, lightweight, renewable, and have excellent thermal and acoustic insulating properties. Although the history of the applications of natural fibres in civil construction goes back thousands of years, few studies have been conducted to investigate the behaviour of natural fibre reinforced concrete composites until recent decades, especially in regard to impact loads.

This research aims to study the impact behaviour of a natural fibre reinforced concrete composite. Flax fibre reinforced polymer strengthened coconut fibre reinforced concrete (FFRP-CFRC) was first developed at the University of Auckland. To study its impact behaviour, experiments were carried out on various types of specimens, i.e. FFRP laminates, CFRC cylinders, FFRP-CFRC beams and slabs. Initially, the impact behaviour of FFRP laminates was studied using both an instrumented drop weight machine and a Charpy testing machine. The dynamic tensile properties of FFRP under various strain rates were studied using a high-speed servo-hydraulic machine. Then, to study the effect of coconut fibre length, single and repeated drop weight impacts were carried out on CFRC cylinders. Impact loads were also applied to FFRP wrapped CFRC beams to investigate the influence of coconut fibre content on composites behaviour. The results indicated that 3% of coconut fibre content in specimens was best in resisting impact compared with 1% and 5% specimens. Furthermore, the effect of FFRP thickness (2-, 4- and 6-layers) on impact behaviour of FFRP laminated CFRC beams was also studied. In addition, impact experiments were conducted to compare CFRC slabs with three different FFRP wrapping configurations. A theoretical model was applied to predict the maximum impact force and maximum deflection. The last experiment was a study on FFRP renovated cracked CFRC slabs with two configurations.

The outcomes of this research will contribute to a comprehensive understanding of the impact characterization of FFRP-CFRC composite, which is helpful in designing impact resistant natural fibre reinforced concrete composites. It also provides an assessment of this FFRP-CFRC material for construction or retrofitting residential buildings.
Dedication

To my family with love
Acknowledgement

I would like to express my sincere appreciation and thanks to my supervisor Associate Professor Nawawi Chouw, for his invaluable guidance, supervision and encouragement throughout my entire doctoral research. His suggestions and support helped me a lot to overcome many difficulties. This work would not have been able to come this far without his guidance and involvement. He dedicates his life to teach us, and lead us to become a person who is strong in both professions and personalities.

I would also like to express my sincere appreciation to my co-supervisor Associate Professor Krishnan Jayaraman. He has provided a lot of important and insightful advices in this study. He has always been supportive and professional. He always encouraged and cheered me up when I have difficulties. I am lucky to be supervised by him, and I learned a lot from him. I sincerely thank him from bottom of my heart and will be truly indebted to him throughout my life time.

I am grateful to my co-supervisor Dr. Thomas Larkin. His consistent support and technical guidance made me think and learn more. His passion and attitude has always inspired me towards the graduation. I also appreciate Dr. Wei Yuen Loo. He gave me a lot of help in my writing. Without his guidance, I cannot improve my writing so quickly. I am also very thankful Dr. Libo Yan, Dr. Sushil Khatiwada and Zhenghao Tang who provided me lots of help when I started my work at the Civil Materials Lab on City Campus and the Centre for Advanced Composite Materials on Tamaki Campus.

In addition, I would like to thank the China Scholarship Council (CSC) for providing the scholarship to enable me to pursue my PhD study. The experimental materials donation from companies, Cement Bay and Winstone Aggregate is gratefully acknowledged.

I would like to acknowledge technical staff Ross Reichardt and Mark Byrami, from the Department of Civil and Environmental Engineering, who provided me a lot of help when I work at the Materials Laboratory. They also gave much valuable experimental guidance along my research. Especially, I would like to express my sincere gratitude to Shane Smith, the technical staff from the Department of Civil and Environmental Engineering. He provided me technical support and labour work throughout my study, including
constructing impact machine and other help. Without his support and involvement, I would have faced much more difficulties.

My sincere appreciation is given to the staff from the Department of Civil and Environmental Engineering for their helpful assistance: Magdalene Woo (Mags), Pervin Suntoke, Santha Pollayah, Olga Beliakina, Cathrine Taylor, Sujith Padiyara, Dan Ripley, Dr. Sherif Beskhyroun, Mark Twiname, Geoff Kirby, Jay Naidoo, Andrew Virtue, Dr. Felix Scheibmair, Jeffrey Melster, Jerome Quenneville, Peter Oneill and Mark Liew.

I am also very thankful to staff at Centre for Advanced Composite Materials: Jos Geurts, Callum Turnbull and Stephen Cawley from the Department of Mechanical Engineering at the University of Auckland, who provided me a lot of help when I started my work at the Centre for Advanced Composite Materials at Tamaki Campus.

My sincere gratitude is also extended to my friends and colleagues: Dr. Bo Li, Dr. Majid Ali, Dr. Xiaoyang Qin, Dr. Miguel Ormeno Godoy, Dr. Nurul Fazita Mohammad Rawi, Dr. Yuanzhi Chen, Tongyue Zhang, Dr. Ellys Lim, Jiaxin Chen, Chern Kun, Gonzalo Barrios Parga, Diego Hernandez, Saeed Eyvazinejad Firouzsalari, Aina Milson, Jing Lu, Mario Vedanayagam, and Febelyn Reguyal.

My deepest gratitude goes to my family for their love and unconditional support. My parents did whatever they can do for me. I express my deepest gratitude to Mr. Mo. He made great sacrifice to help me to finish my degree. He is always with me when I need him. Without your love and support, I could not have made this happen. I love you all.
List of publications

Journal articles:

Under review:


Published:


Conference papers:


Co-Authorship Form

This form is to accompany the submission of any PhD that contains published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements. Co-authored works may be included in a thesis if the candidate has written all or the majority of the text and had their contribution confirmed by all co-authors as not less than 65%.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 4 contains materials of the following journal article:


<table>
<thead>
<tr>
<th>Nature of contribution by PhD candidate</th>
<th>Design and conduct experiment, data analysis and manuscript writing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patent of contribution by PhD candidate (%)</td>
<td>60</td>
</tr>
</tbody>
</table>

**CO-AUTHORS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Nature of Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nawawi Chouw</td>
<td>Guidance in planning, testing and analysis; Advice during writing; Editing manuscript</td>
</tr>
<tr>
<td>Krishnan Jayaraman</td>
<td>Guidance in planning, testing and analysis; Advice during writing; Editing manuscript</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Certification by Co-Authors**

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- that the candidate wrote all or the majority of the text.

<table>
<thead>
<tr>
<th>Name</th>
<th>Signature</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nawawi Chouw</td>
<td></td>
<td>18/08/2017</td>
</tr>
<tr>
<td>Krishnan Jayaraman</td>
<td></td>
<td>18 August 2017</td>
</tr>
<tr>
<td>Wenjie Wang</td>
<td></td>
<td>18/08/2017</td>
</tr>
</tbody>
</table>

Last updated: 19 October 2015
Co-Authorship Form

This form is to accompany the submission of any PhD that contains published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements. Co-authored works may be included in a thesis if the candidate has written all or the majority of the text and had their contribution confirmed by all co-authors as not less than 65%.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 5 is extracted from the following journal article:


<table>
<thead>
<tr>
<th>Nature of contribution by PhD candidate</th>
<th>Design and conduct experiment, data analysis and manuscript writing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent of contribution by PhD candidate (%)</td>
<td>90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO-AUTHORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Nawawi Chouw</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Certification by Co-Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>The undersigned hereby certify that:</td>
</tr>
<tr>
<td>• the above statement correctly reflects the nature and extent of the PhD candidate’s contribution to this work, and the nature of the contribution of each of the co-authors; and</td>
</tr>
<tr>
<td>• that the candidate wrote all or the majority of the text.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Signature</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nawawi Chouw</td>
<td>(Signature)</td>
<td>18/08/2017</td>
</tr>
<tr>
<td>Wenjie Wang</td>
<td>(Signature)</td>
<td>18/08/2017</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Last updated: 19 October 2015
Co-Authorship Form

This form is to accompany the submission of any PhD that contains published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements. Co-authored works may be included in a thesis if the candidate has written all or the majority of the text and had their contribution confirmed by all co-authors as not less than 65%.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 6 is extracted from the following unpublished journal article:

<table>
<thead>
<tr>
<th>Nature of contribution by PhD candidate</th>
<th>Design and conduct experiment, data analysis and manuscript writing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent of contribution by PhD candidate (%)</td>
<td>90</td>
</tr>
</tbody>
</table>
This form is to accompany the submission of any PhD that contains published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements. Co-authored works may be included in a thesis if the candidate has written all or the majority of the text and had their contribution confirmed by all co-authors as not less than 65%.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 7 is extracted from the following unpublished journal article:

| Nature of contribution by PhD candidate | Design and conduct experiment, data analysis and manuscript writing |
| Extent of contribution by PhD candidate (%) | 90 |

### CO-AUTHORS

<table>
<thead>
<tr>
<th>Name</th>
<th>Nature of Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nawawi Chouw</td>
<td>Guidance in planning, testing and analysis; Advice during writing; Editing manuscript</td>
</tr>
</tbody>
</table>

### Certification by Co-Authors

The undersigned hereby certify that:
- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- that the candidate wrote all or the majority of the text.

<table>
<thead>
<tr>
<th>Name</th>
<th>Signature</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nawawi Chouw</td>
<td>[Signature]</td>
<td>16/08/2017</td>
</tr>
<tr>
<td>Wenjie Wang</td>
<td>[Signature]</td>
<td>18/08/2017</td>
</tr>
</tbody>
</table>

Last updated: 19 October 2015
Co-Authorship Form

This form is to accompany the submission of any PhD that contains published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements. Co-authored works may be included in a thesis if the candidate has written all or the majority of the text and had their contribution confirmed by all co-authors as not less than 65%.

<table>
<thead>
<tr>
<th>Nature of contribution by PhD candidate</th>
<th>Design and conduct experiment, data analysis and manuscript writing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent of contribution by PhD candidate (%)</td>
<td>90</td>
</tr>
</tbody>
</table>
# Table of Contents

Copyright Statement ........................................................................................................ i
General copyright and disclaimer .................................................................................. i
Abstract .......................................................................................................................... i
Acknowledgement .......................................................................................................... v
List of publications ......................................................................................................... vii
Table of Contents ......................................................................................................... xiv
List of Figures ............................................................................................................... xviii
List of Tables .................................................................................................................. xxii
Symbols and notations ................................................................................................. xxiii

## Chapter 1

Introduction ..................................................................................................................... 1
  1.1 Motivation .............................................................................................................. 1
  1.2 Objectives ............................................................................................................. 3
  1.3 Thesis outline ...................................................................................................... 3

## Chapter 2

Literature review .......................................................................................................... 6
  2.1 Fibre reinforced polymer (FRP) composites ...................................................... 6
  2.2 Fibre reinforced concrete (FRC) and FRP concrete composites ...................... 8
    2.2.1 Fibre reinforced concrete (FRC) ................................................................. 8
    2.2.2 FRP strengthened concrete ....................................................................... 9
  2.3 Impact behaviour of FRC and FRP strengthened concrete .............................. 10
    2.3.1 Impact behaviour of FRC ........................................................................ 10
    2.3.2 Impact behaviour of FRP strengthened concrete .................................... 12
  2.4 Strain rate effect on concrete ............................................................................ 13
  2.5 Research methods for fibre reinforced concrete composites under impact ..... 15
    2.5.1 Experimental method .............................................................................. 15
    2.5.2 Analytical method ...................................................................................... 18
    2.5.3 Numerical method .................................................................................... 19
2.6 Concrete structure failure modes......................................................... 19
2.7 Summary .......................................................................................... 21

Chapter 3 ............................................................................................. 23
Development of a drop weight impact machine........................................... 23
3.1 Introduction ......................................................................................... 23
3.2 Description of the drop weight impact machine ................................... 27
   3.2.1 Mechanical structure of the impact test rig .................................... 27
   3.2.2 Instrumentation ............................................................................ 29
3.3 Summary .......................................................................................... 31

Chapter 4 ............................................................................................. 32
Mechanical properties of flax fibre reinforced polymer under dynamic loadings.. 32
4.1 Flax fibre and flax fibre reinforced polymer composites ..................... 32
   4.1.1 Flax fabric and epoxy system ....................................................... 32
   4.1.2 Tensile properties of FFRP ......................................................... 33
4.2 Impact properties of FFRP ................................................................ 36
   4.2.1 Introduction ................................................................................ 36
   4.2.2 Specimens ................................................................................ 37
   4.2.3 Drop weight impact test setup .................................................... 38
   4.2.4 Drop weight impact tests results and discussion ......................... 39
   4.2.5 Charpy impact tests of FFRP ....................................................... 53
4.3 Dynamic tensile properties of FFRP .................................................. 55
   4.3.1 Specimens ................................................................................ 56
   4.3.2 Testing apparatus ...................................................................... 57
   4.3.3 Dynamic tensile test results and discussions ............................... 58
4.4 Summary .......................................................................................... 65

Chapter 5 ............................................................................................. 67
Impact properties of coconut fibre reinforced concrete .............................. 67
5.1 Coconut fibre and coconut fibre reinforced concrete composite .......... 67
   5.1.1 Coconut fibre ............................................................................. 67
   5.1.2 Coconut fibre reinforced concrete (CFRC) ................................. 68
### Chapter 5

5.2 Experimental work ................................................................. 70
  5.2.1 Specimens preparation ......................................................... 70
  5.2.2 Testing procedure .............................................................. 71
5.3 Results and Discussion ............................................................ 72
  5.3.1 Static compressive test ....................................................... 72
  5.3.2 Test results of single impact ................................................ 73
  5.3.3 Dynamic Increase Factor (DIF) of CFRC ............................... 76
  5.3.4 Test results of repeated impact ............................................ 78
5.4 Summary ................................................................................. 84

### Chapter 6

Effect of coconut fibre content on the impact behaviour of W-FFRP-CFRC beams ......................................................... 85
  6.1 Experimental work ................................................................. 86
    6.1.1 Specimen preparation ....................................................... 86
    6.1.2 Test setup and procedure .................................................. 87
  6.2 Results and Discussion ............................................................ 89
    6.2.1 Static flexural tests ......................................................... 89
    6.2.2 Impact tests ..................................................................... 91
  6.3 Summary ................................................................................. 97

### Chapter 7

Effect of flax thickness on the impact behaviour of L-FFRP-CFRC beams ................................................................. 99
  7.1 Experimental works ............................................................... 100
    7.1.1 Specimen preparation ...................................................... 100
    7.1.2 Testing procedure ............................................................ 101
  7.2 Results and discussion ............................................................ 103
    7.2.1 Static tests ...................................................................... 103
    7.2.2 Impact tests ..................................................................... 104
  7.3 Summary ................................................................................. 112

### Chapter 8

Impact behaviour of FFRP-CFRC slabs .................................................. 114
8.1 Impact behaviour of PC, CFRC and CFRC slabs with three different FFRP wrapping configurations
........................................................................................................................................... 114
   8.1.1 Experimental works ............................................................................................................ 115
   8.1.2 Results and Discussion ..................................................................................................... 118
   8.1.3 Theoretical analysis of maximum impact force and maximum deflection
.............................................................................................................................................. 127
8.2 Impact behaviour of renovated CFRC slabs using FFRP laminates ............................. 131
   8.2.1 Specimen preparation ...................................................................................................... 131
   8.2.2 Impact test ......................................................................................................................... 133
   8.2.3 Results and discussion ..................................................................................................... 134
8.3 Summary ................................................................................................................................... 139

Chapter 9 ...................................................................................................................................... 141

Conclusions and recommendations for future research ...................................................... 141

9.1 Conclusions ........................................................................................................................... 141
   9.1.1 Dynamic properties of FFRP ......................................................................................... 141
   9.1.2 Impact properties of CFRC – The effect of fibre length ............................................. 142
   9.1.3 Behaviour of FFRP wrapped CFRC beams (W-FFRP-CFRC) – The effect of fibre content
................................................................................................................................................. 143
   9.1.4 Properties of CFRC beams laminated with FFRP (L-FFRP-CFRC) – The effect of thickness of FFRP
.................................................................................................................................................... 144
   9.1.5 Strengthening of CFRC slabs using FFRP lamination ..................................................... 145
9.2 Future work for FFRP-CFRC composites .......................................................................... 146

References ..................................................................................................................................... 147
List of Figures

Figure 1.1 Contemporary residential natural fibre reinforced house in south-western China .......................................................... 1
Figure 2.1 Strain rate according to loading types ....................................................... 14
Figure 2.2 Missile impact phenomena on concrete targets (Li et al. 2005) ................. 20
Figure 3.1 Schematic diagram of the drop weight impact machine (Kaweewunruen 2007) ........................................................................ 24
Figure 3.2 Drop weight impact system by Chen and May (2009) .............................. 25
Figure 3.3 Schematic diagram of the drop weight impact machine by Zhang et al. (2010) ........................................................................ 26
Figure 3.4 Schematic diagram of the drop weight impact machine ............................ 27
Figure 3.5 View of the drop weight test rig column ................................................. 28
Figure 3.6 Dynamic load cells Model 200C50 ......................................................... 29
Figure 3.7 Accelerometer Model 305B21 ............................................................... 30
Figure 3.8 Displacement laser sensor .................................................................... 31
Figure 3.9 Signal model 482C05 by PCB Piezotronics conditioner ......................... 31
Figure 4.1 Flax fabric and FFRP laminates ............................................................. 33
Figure 4.2 FFRP samples for static tensile tests ...................................................... 33
Figure 4.3 Static tensile test machine and set up ..................................................... 34
Figure 4.4 Stress-strain curves of 2-layer-FFRP under static tensile loading .......... 35
Figure 4.5 Fracture of FFRP under tensile loading ............................................... 36
Figure 4.6 FFRP specimens for drop weight impact test ........................................ 37
Figure 4.7 Sketch of a FFRP specimen with impact location ................................. 38
Figure 4.8 Impact test set up .................................................................................. 38
Figure 4.9 Impact force time history of 2-layer FFRP specimens ............................ 39
Figure 4.10 Impact force time history of 4-layer FFRP specimens ......................... 40
Figure 4.11 Impact force time history of 6-layer FFRP specimens ......................... 40
Figure 4.12 Force-deflection curves and damage at impact zones of 2-layer FFRP specimens .................................................................. 42
Figure 4.13 Force-deflection curves and damage at impact zones of 4-layer FFRP specimens .................................................................. 43
Figure 4.14 Force-deflection curves and damage at impact zones of 6-layer FFRP specimens .................................................................. 45
Figure 4.15 Typical force-deflection history for a 2-layer FFRP composite ......... 47
Figure 4.16 Energy profile of 2-layer composite ..................................................... 48
Figure 4.17 Energy profile of 4-layer composite ..................................................... 48
Figure 4.18 Energy profile of 6-layer composite ..................................................... 49
Figure 4.19 Energy dissipation during the impact test ............................................. 50
Figure 4.20 Force-deflection curves with and without perforation ....................... 52
Figure 4.21 Damage of 2-layer FFRP composite at 15 J impact energy with different striker diameters .................................................. 53
Figure 4.22 Charpy impact test instrument and specimen ....................................... 54
Figure 4.23 Relation between energy absorbed and composite thickness ............ 55
Figure 4.24 Schematic view of FFRP samples for dynamic tensile tests .............. 56
Figure 7.5  Effect of the number of FFRP layers on the flexural response of FFRP-CFRC beams under static load ................................................................. 103
Figure 7.6  Effect of FFRP thickness on flexural strengths ................................................................. 104
Figure 7.7  Effect of loading rate on the force histories of 2L-FFRP-CFRC beam ........................... 105
Figure 7.8  Effect of loading rate on the force histories of 4L-FFRP-CFRC beam ........................... 105
Figure 7.9  Effect of loading rate on the force histories of 6L-FFRP-CFRC beam ........................... 106
Figure 7.10  The flexural response of 2L-FFRP-CFRC beams under various impact loadings. (a) Without and (b) with fracture ......................................................... 107
Figure 7.11  The flexural response of 4L-FFRP-CFRC beams under various impact loadings. (a) Without and (b) with fracture ......................................................... 107
Figure 7.12  The flexural response of 6L-FFRP-CFRC beams under various impact loadings. (a) Without and (b) with fracture ......................................................... 108
Figure 7.13  Failure modes of L-FFRP-CFRC beams: (a), (c), (e) static loading; (b), (d), (f) impact loading ......................................................................................... 109
Figure 7.14  De-bonding failure mechanism of L-FFRP-CFRC ....................................................... 109
Figure 7.15  Schematic description of maximum impact force due to different loading rates .................................................................................................................. 111
Figure 7.16  Effect of FFRP thickness on accumulated absorbed energy ........................................ 112
Figure 8.1  Configurations of FFRP-CFRC slabs ............................................................................ 116
Figure 8.2  Fabrication of FFRP-CFRC slabs ................................................................................. 117
Figure 8.3  Impact test set up ........................................................................................................... 118
Figure 8.4  Time history of the impact force of PC and CFRC slabs ................................................ 118
Figure 8.5  Force-time, deflection-time curves for PC and CFRC at the damaged state ................. 119
Figure 8.6  Comparison of failure modes for PC and CFRC slabs .................................................. 119
Figure 8.7  Force time histories for C1 slab ....................................................................................... 120
Figure 8.8  Force time histories for C2 slab ....................................................................................... 121
Figure 8.9  Force time histories for C3 slab ....................................................................................... 121
Figure 8.10  Force, deflection time histories of C1 slab ................................................................. 123
Figure 8.11  Force-deflection curves of the damaged slabs .......................................................... 124
Figure 8.12  Relationship between impact height and the absorbed energy ................................... 125
Figure 8.13  Total energy absorbed for different specimen configuration ..................................... 126
Figure 8.14  Observable damage to C1, C2 and C3 ....................................................................... 127
Figure 8.15  (a) Mass-slab impact sketch, and (b) its equivalent system ........................................ 127
Figure 8.16  Sketch of a cylindrical striker impacting an elastic surface ..................................... 128
Figure 8.17  Sketch of a plate under point loading ....................................................................... 129
Figure 8.18  Stiffness of the specimens at different impact heights ................................................ 130
Figure 8.19  Maximum impact force comparison between experimental and analytical results ........................................................................................................ 130
Figure 8.20  Maximum deflection comparison between experimental and analytical results ........................................................................................................ 130
Figure 8.21  Deflection-time curves of CFRC slabs under impact load (5 mm drop height) ........................................................................................................ 132
Figure 8.22  Crack patterns of CFRC slabs under impact load (5 mm of drop height) 132
Figure 8.23  Sketches of renovated FFRP-CFRC slabs: (a) D1 and (b) D2 ................................. 133
Figure 8.24  Force-time histories of D1 slab ............................................................................... 134
Figure 8.25  Force-time histories of D2 slab ............................................................................... 134
Figure 8.26 Deflection-time curves of D1 and D2 ....................................................... 137
Figure 8.27 Damage patterns of D1 and D2 ................................................................. 138
Figure 8.28 FFRP strain curves of D1 and D2 slabs ..................................................... 138
List of Tables

Table 2.1  Manufacturing methods for FRP composites (Thomas et al. 2015) .......... 6
Table 4.1  Properties of the flax yarn, epoxy and flax/epoxy composites .......... 33
Table 4.2  Tensile properties of FFRP ................................................. 35
Table 4.3  Properties of FFRP specimens ............................................. 37
Table 4.4  Total energy dissipation of FFRP of different thickness .......... 50
Table 4.5  Ductility of FFRP of different thicknesses ......................... 51
Table 4.6  Summary of impact property of 2-layer FFRP composite under impact ...... 52
Table 4.7  Charpy test: Effect of specimen thicknesses and impact energies on the energy absorbed and impact resistance. a ................................................. 54
Table 4.8  Specimen configurations during the dynamic test .......... 56
Table 4.9  Summary of results in the dynamic tensile tests .................. 59
Table 5.1  Physical and mechanical properties of coconut fibre .................. 68
Table 5.2  Properties of gravel and sand ............................................. 70
Table 5.3  Mix ratio of the compositions ............................................. 70
Table 5.4  Static test results of PC and CFRC ....................................... 72
Table 5.5  Comparison of Young’s moduli before and after impact loading .... 75
Table 5.6  Experimental and calculated DIF values for CFRC ..................... 78
Table 5.7  Summary of repeated impact test results .................................. 80
Table 5.8  Summary of results in the dynamic tensile tests .................... 86
Table 5.9  Influence of coconut fibre content on MOR of W-FFRP-CFRC beams .... 91
Table 5.10  Experimental results of impact tests under different heights .......... 94
Table 5.11  Dynamic increase factor of W-FFRP-CFRC beams .................... 96
Table 7.1  Test matrix of the specimens .............................................. 101
Table 7.2  Summary of quasi-static flexure test results ........................ 104
Table 7.3  Effect of impact velocities on experimental results ................. 110
Table 8.1  Nomenclature of concrete slab specimens .............................. 115
Table 8.2  Summary of the impact force for all results ......................... 122
Table 8.3  Nomenclature and explanations of the two renovation approaches .... 133
Table 8.4  Summary of the impact force for all results for D1 and D2 slabs ....... 135
Symbols and notations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>Plain concrete</td>
</tr>
<tr>
<td>CFRC</td>
<td>Coconut fibre reinforced concrete</td>
</tr>
<tr>
<td>FFRP</td>
<td>Flax fibre reinforced polymer</td>
</tr>
<tr>
<td>CFRC-25</td>
<td>CFRC with 25 mm length of coconut fibre</td>
</tr>
<tr>
<td>CFRC-50</td>
<td>CFRC with 50 mm length of coconut fibre</td>
</tr>
<tr>
<td>CFRC-75</td>
<td>CFRC with 75 mm length of coconut fibre</td>
</tr>
<tr>
<td>W-FFRP-CFRC</td>
<td>FFRP wrapped CFRC</td>
</tr>
<tr>
<td>L-FFRP-CFRC</td>
<td>FFRP laminated CFRC</td>
</tr>
<tr>
<td>FFRP-CFRC-1%</td>
<td>FFRP-CFRC with 1% of coconut fibre</td>
</tr>
<tr>
<td>FFRP-CFRC-3%</td>
<td>FFRP-CFRC with 3% of coconut fibre</td>
</tr>
<tr>
<td>FFRP-CFRC-5%</td>
<td>FFRP-CFRC with 5% of coconut fibre</td>
</tr>
<tr>
<td>( \varsigma )</td>
<td>Nesting coefficient</td>
</tr>
<tr>
<td>T(N)</td>
<td>Thickness of laminates</td>
</tr>
<tr>
<td>N</td>
<td>Number of laminate layers</td>
</tr>
<tr>
<td>T(1)</td>
<td>Thickness of one layer laminate</td>
</tr>
<tr>
<td>( E_i )</td>
<td>Impact energy</td>
</tr>
<tr>
<td>( E_{ab} )</td>
<td>Absorbed energy</td>
</tr>
<tr>
<td>( E_p )</td>
<td>Perforation energy</td>
</tr>
<tr>
<td>( E_t )</td>
<td>Total energy calculated from the force-deflection curve</td>
</tr>
<tr>
<td>( W_f )</td>
<td>Energy dissipated by friction force at the stage of post-perforation</td>
</tr>
<tr>
<td>DI</td>
<td>Ductility index</td>
</tr>
<tr>
<td>( E_{prop} )</td>
<td>Propagation energy</td>
</tr>
<tr>
<td>( E_{init} )</td>
<td>Initiation energy</td>
</tr>
<tr>
<td>( E_{Charpy} )</td>
<td>Absorbed energy in Charpy test</td>
</tr>
<tr>
<td>( E_{Drop} )</td>
<td>Absorbed energy in the drop weight test</td>
</tr>
<tr>
<td>DIF</td>
<td>Dynamic increase factor</td>
</tr>
<tr>
<td>( D )</td>
<td>Damage index</td>
</tr>
<tr>
<td>( E_0 )</td>
<td>Original elasticity moduli</td>
</tr>
</tbody>
</table>
Elastic moduli of concrete cylinder after impact

Dynamic compressive strength at $\dot{\varepsilon}$

Static compressive strength at $\dot{\varepsilon}_s$

Strain rate in the range of $30 \times 10^{-6} \text{s}^{-1}$ to $300 \text{s}^{-1}$

Static strain rate, $30 \times 10^{-6} \text{s}^{-1}$

Impact failure energy

The first drop height

The last drop height

The maximum stress of CFRC-25 and CFRC-50

The maximum stress of CFRC-75

Energy absorption at ultimate value

Energy absorption at limiting curvature

Deformability factor

Maximum force under impact loading

Maximum force under static loading

Impact fracture energy

Static fracture energy

The area under the force-deflection curve

The mass, span, length, width and depth of the beam specimen, respectively.

Gravitational acceleration

Specified deflection of the specimen

The notch of the specimen

Total energy absorbed

The largest impact force

Peak contact force between mass-spring system and a rigid slab

The peak damper force

Damper viscosity
$k$ Contact stiffness

$r_0$ Insert radius at the centre of the impacted specimen

$w(x, y)$ Displacement of the slab

$D$ Bending stiffness of the slab

$\nu_i$ Poisson ratio of the slab

$E_i$ Young modulus of the slab
Chapter 1

Introduction

1.1 Motivation

The application of natural fibres for civil construction can be traced back 3000 years, when straw was mixed with clay (Brouwer 2001). Since natural fibres are environmentally-friendly, economical, lightweight, renewable, and excellent in terms of their thermal and acoustic insulating properties, they are still used in residential buildings today. For example, many residential two-level houses in the south-western China (Figure 1.1) use straw and tree needle fibres, obtained from wheat and pine trees in their construction. In practice, most buildings in rural areas in developing countries are steel-free due to the expense of steel.

(a) Straw fibre reinforced house

(b) Needle fibre block

(c) Straw fibre block

Figure 1.1 Contemporary residential natural fibre reinforced house in south-western China

Natural fibre reinforced concretes have higher tensile strength and ductility compared to plain concrete. They rarely have corrosion problems unlike steel reinforced construction. Furthermore, when damaged, natural fibre reinforced concretes are easy to dispose and create less danger to human beings and environment compared with current steel bar
reinforced buildings. Therefore, natural fibre reinforced concretes, with high specification construction properties, have great potential in civil structure applications.

Although natural fibres have been widely used as construction materials for thousands of years, until recently their mechanical properties had not been studied, with the first investigations appearing only in the late 1960s (Balaguru and Shah 1985). Mwangi (2001) experimentally studied the properties of sisal fibre reinforced concrete and found that the performance of sisal fibre in high-strength concrete was better than that of steel and polypropylene fibres. Ali (2013) studied the properties of coconut fibre reinforced concrete and developed a new construction technology using coconut ropes for economical seismic-resistant houses. Cervantes et al. (2014) compared flexural strength of concrete beams reinforced with hemp fibre reinforced polymer (HFRP) and carbon fibre reinforced polymer (CFRP). The study determined the number of HFRP layers needed to match the strength of concrete beams reinforced with one layer of CFRP. The study also found that manufacturing HFRP was 28% cheaper than CFRP. Yan (2014) developed a flax fibre reinforced polymer (FFRP) tube encased coconut fibre reinforced concrete composite and experimentally studied its static properties.

Nevertheless, from the perspective of the impact behaviour of natural fibre reinforced concrete composites, few studies have been conducted. Impact loads from strong earthquakes, resulting from falling weight for example, can significantly damage the surrounding structures. The 1996 Yunnan Lijiang earthquake (magnitude 6.6 on the Richter scale) spread over an area of approximately 1225 km² and damaged more than 950,000 houses (Wikipedia 2016), which were mainly natural fibre reinforced clay buildings in rural areas such as in Figure 1.1. Therefore, to develop natural fibre reinforced concrete composites, it is essential to investigate their impact properties.

With this motivation, two kinds of natural fibres, coconut and flax fibres, were selected for this research. Coconut fibre has higher toughness compared to other natural fibres (Munawar et al. 2007; Ramakrishna and Sundararajan 2005; Satyanarayana et al. 1990). Flax fibre reinforced polymer encased concrete was first developed by Yan (2014) at the University of Auckland. Combining the above materials, a flax fibre reinforced polymer strengthened coconut fibre reinforced concrete (FFRP-CFRC) composite was designed and fabricated, and its impact behaviour was investigated in this research using a drop weight test rig. The outcomes of this research will contribute to a comprehensive
understanding of impact characteristics of FFRP-CFRC, which will be helpful in
designing impact resistant natural fibre reinforced concrete composites. This study also
provides an assessment of this FFRP-CFRC material for construction or retrofitting
residential buildings.

1.2 Objectives

The overall aim of the research is to investigate the impact characteristics of FFRP-CFRC
composites. The research objectives are:

- To quantify the impact strength and dynamic tensile strength of FFRP composite
- To discover the impact strength and dynamic increase factor of CFRC
- To optimise the length and content of coconut fibre in CFRC to obtain the best
  impact properties
- To investigate the behaviour of FFRP-CFRC beams and slabs under impact
  loadings
- To explore the effects of FFRP wrapping configurations on the impact behaviour
  of FFRP-CFRC composites.
- To explore the application of FFRP composites as retrofitting materials

1.3 Thesis outline

The thesis consists of nine chapters and the following gives a brief description of the
content of the thesis:

Chapter 1 gives the motivation and objectives of this research, followed by the structures
of the thesis.

Chapter 2 presents the literature review on the impact behaviour of fibre reinforced
polymer and fibre reinforced concrete composites. It addresses why flax fabric and
coconut fibre was selected as the reinforcement material for this study.

Chapter 3 presents the design and construction procedure of the drop weight impact test
rig.

Chapter 4 presents the materials used, i.e. the properties of coconut fibre and flax fibre
reinforced polymer (FFRP). The static tensile properties of FFRP were studied. Besides,
dynamic properties, i.e. impact behaviour and dynamic tensile behaviour of FFRP were
experimentally investigated. Drop weight impact tests were performed to determine the perforation energy of the FFRP specimens. The effect of specimen thickness on impact behaviour was analysed through the damage mechanism, energy absorption and ductility index. Charpy impact tests were also carried out to determine the impact resistance. In addition, dynamic tensile tests were performed using a high-speed servo-hydraulic testing machine from the strain rate 0.764 s^{-1} to 135.68 s^{-1}. High-speed camera images were used to study the failure modes of FFRP.

Chapter 5 focuses on the response of CFRC cylinders under single and repeated drop weight impact loadings. In the single impact test, the impact force-time curves, change of Young’s moduli and the dynamic increase factor (DIF) of CFRC were investigated. The damage pattern of both PC and CFRC was compared. In the repeated tests, the effect of impact height on the maximum compressive stress and the damage pattern was evaluated. The relationship between impact height and maximum impact stress was examined, and an empirically derived equation was proposed.

Chapter 6 investigates the flexural behaviour of FFRP wrapped CFRC (W-FFRP-CFRC) beams under static and impact loads. The effect of coconut fibre content on static and impact behaviour, i.e. 1%, 3% and 5% of cement mass was considered. In the static tests, ASTM C78 standards were applied, and a comparison between CFRC and W-FFRP-CFRC was undertaken in regard to the flexural behaviour. Both single and repeated impact tests were performed using a drop weight impact machine. The parameters, i.e., impact force, deflection, energy absorption and DIF were analysed in order to understand the composites’ impact behaviour.

Chapter 7 investigates the behaviour of FFRP laminated CFRC (L-FFRP-CFRC) beams under static and impact loadings. The ASTM C1609 standard and a drop weight impact test machine were applied in quasi-static bending tests, and impact tests, respectively. During the experiments, parameters of the L-FFRP-CFRC specimens, i.e. impact force, displacement, energy absorption, dynamic increase factor, and damage pattern were studied. Moreover, the effects of FFRP thicknesses (2-, 4- and 6-layer) were investigated regarding (1) flexural strength and toughness under static loading, (2) flexural behaviour under impact loading, and (3) failure mode.

Chapter 8 presents the impact behaviour of FFRP strengthened CFRC (FFRP-CFRC) slabs using experimental and theoretical methods. Impact tests were carried out to find an
effective wrapping configuration of three different designs of FFRP-CFRC slabs, and their parameters, i.e. impact force, deflection, energy absorption and damage pattern were discussed to evaluate impact resistance. Following the experimental study, a theoretical analysis method was used to predict maximum impact force as well as maximum deflection, the results of which showed high level agreement with the experimental data. Besides, a preliminarily investigation of the effectiveness of FFRP composites as a potential retrofitting material was also conducted. CFRC rectangular slabs were cracked using small impact energy, resulting in small damage to the slabs. Then, two types of FFRP configurations were applied to renovate these crack slabs. Repeated impact tests were then conducted on them, and the effectiveness of the configurations was evaluated. The outcome of the research recommended that this natural FFRP composite has the potential to be applied as a protective material for residential buildings.

Chapter 9 comprises the conclusion and recommendations for future research.
Chapter 2

Literature review

2.1 Fibre reinforced polymer (FRP) composites

FRP is a composite material made of a polymer matrix reinforced with fibres. The fibres may be carbon, glass, aramid, basalt and natural fibres. The polymer used usually includes epoxy, vinylester, or polyester thermosetting plastic. Several manufacturing methods for FRP composites are used in the industry depending on its application. Some common manufacturing methods are listed in Table 2.1.

Table 2.1 Manufacturing methods for FRP composites (Thomas et al. 2015)

<table>
<thead>
<tr>
<th>Manufacturing method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Hand lay-up                | • Widely used for many years 
  • Higher fibre content 
  • Simple principle 
  • Economical | • Quality depends on skill 
  • Resin needs to be low viscosity |
| Spray up method            | • Continuous process 
  • Error can be corrected by re-spraying 
  • Any material can be used as spray | • Slow 
  • Only one side finished 
  • No control of fibre orientation 
  • Inconsistency 
  • Environmentally unfriendly |
| Pultrusion                 | • Fast 
  • Resin content can be accurately controlled 
  • Resin impregnation area can be enclosed | • Limited to constant cross-section component |
| Resin transfer moulding    | • Has good surface finish on both sides 
  • Combination of reinforced materials in any fibre orientation can be achieved 
  • Composite thickness is uniform 
  • Fast cycle time can be achieved | • Mould cavity limits component size 
  • High cooling cost 
  • Limited as to reinforcing materials |
Carbon and glass fibre reinforced composites have been the most studied in regard to impact loading (Strait et al. 1992; Naik et al. 2000a; Naik et al. 2000b; Hosseinzadeh et al. 2006; Minak and Ghelli 2008; Wang et al. 2010). Of these, Naik et al. (2000) carried out studies on the impact behaviour of E-glass/epoxy and T300/5208 carbon/epoxy composites using a finite element analysis (FEA) method. The results indicated that both carbon and glass woven fabric laminated composites showed a similar trend as to composite thickness, i.e. a linear relationship had been assumed between peak contact force and composite thickness, with maximum plate displacement and duration of impact increasing as thickness decreases. Minak and Ghelli (2008) performed both experimental and numerical studies on T300 carbon/epoxy composites. The authors concluded that both dimensions and boundary conditions of carbon fibre reinforced polymer (CFRP) plates could affect impact response. Different boundary conditions, i.e. clamped or supported, can result in varied maximum displacement, absorbed energy and maximum contact force.

Recently developed approaches can be used to improve the properties of composites, e.g. hybridization of different fibre materials. Sarasini et al. (2014) investigated the impact properties of woven hybrid basalt/carbon/epoxy composites. The results indicate that hybrid laminates provided better impact energy absorption capabilities and enhanced damage tolerance compared to CFRP laminates. Nisini et al. (2016) studied hybrid carbon/basalt/flax/epoxy composites. Impact properties of the composites with two different stacking sequences were compared, and little performance difference was found.
In recent decades studies have addressed the performance of natural fibre reinforced polymer composites under impact. Pavithran et al. (1987) applied the Charpy test to explore the fracture energy of different natural fibre reinforced composites, i.e. sisal, pineapple, banana and coir/polyester composites. Pothan et al. (1997) studied the impact strength of short banana fibre/polyester composites with different fibre lengths and content percentages. Singleton et al. (2003) applied Charpy tests to flax/recycled HDPE (high-density polyethylene) composites. The impact toughness and failure mechanisms were studied using SEM photomicrographs. Garkhail et al. (2000) performed Charpy tests to analyse the effect of natural fibre length and volume on the impact strength of flax/polypropylene composites.

Some studies applied biodegradable polyester to reinforce fabrics. The effect of fibre mass fraction on impact strength of flax/PLA (polylactic acid) and Cordenka rayon/PLA composites was studied by Bax and Müssig (2008). Ray et al. (2002) performed both single and repeated impact tests to examine the fatigue behaviour of alkali treated/untreated jute/vinylester composites. Scarponi et al. (2009) measured the mechanical properties of hemp/epoxy composites. Damage to hemp fibre reinforced composites under varied impact energy was studied by evaluating the damaged area. Caprino et al. (2015) compared the impact behaviour of unidirectional hemp/epoxy, bi-directional hemp/epoxy, unidirectional hemp/PLA and bi-directional hemp/PLA. It concluded that no sizeable differences were found in terms of indentation depth values between the configurations of unidirectional and bi-directional reinforcement, while the resin type led to differences in Hertzian contact law and exponential indentation law. An ultrasonic technique was used by Papa et al. (2017) to investigate the delamination of woven jute/PLA composite under low velocity impact tests. The results showed that the delaminated area had a linear relationship with energy and indentation depth.

2.2 Fibre reinforced concrete (FRC) and FRP concrete composites

2.2.1 Fibre reinforced concrete (FRC)

A fibre reinforced concrete (FRC) composite consists of cement, mortar or concrete and fibres. The fibres are discontinuous and randomly distributed in the composite. Fibre materials include steel, synthetics and natural fibres. There are different types of FRC, depending on the fibre material, geometry, distribution, orientation and density. FRC
shows higher tensile strength, durability and creep resistance compared to plain concrete. It is generally agreed that the static and dynamic properties of FRC can be improved by the addition of a suitable amount of uniformly distributed fibres as they act impede crack development (The constructor civil engineering home, n.d.).

2.2.2 FRP strengthened concrete

FRP strengthened concrete is concrete externally bonded with fabrics using resins. Fabric provides the main reinforcing element, while the resins act as a binder. FRP reinforcement has been used not only on steel reinforced concrete flexural members but also in other applications. In the book “Reinforced concrete design with FRP composites” (Page 103-104), GangaRao et al. (2006) provide the other applications of FRP composites:

```
1. Repairing damage/deteriorated beams and slabs to restore their strength and stiffness, assuming that de-bonded FRP wrap would not cause member failure;
2. Limiting crack width under increased (design/service) loads or sustained loads;
3. Retrofitting concrete members to enhance the flexural strength and strain-to-failure of concrete elements necessitated by increased loading conditions such as earthquakes or traffic loads;
4. Designing new concrete members with depth limitations or demanded for high ductility;
5. Rectifying design and construction errors;
6. Enhancing the service life of concrete members;
7. Increasing the shear strength of in-service concrete members;
8. Providing confinement for concrete members, such as concrete columns, as an alternative to steel jacketing;
9. Restoring or retrofiting structures built with masonry and wood;
10. Repairing old or historic structures.
```

Carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) have been extensively studied and applied in infrastructure construction since the 1980s (Alkhrdaji and Thomas 2001; Dolan 1993; Marshall et al. 1999; Plevris et al. 1995).
However, natural FRP composites have rarely been applied in construction. Natural FRP composites are considered green materials, being both environmentally-friendly and economical. The study by Cervantes et al. (2014) suggested that natural FRP is a feasible option for retrofitting concrete structures.

2.3 Impact behaviour of FRC and FRP strengthened concrete

2.3.1 Impact behaviour of FRC

As to fibre type, various FRCs have been investigated, the most common being steel, polypropylene and natural fibres. The following is a review of the impact behaviour of concretes reinforced by these fibres.

*Steel fibre reinforced concrete (SFRC)*

Steel fibre is one of the most popular fibres studied in civil engineering in recent decades due to its good impact and fatigue resistance. Mindess and Bentur (1985) compared the fracture toughness of SFRC, glass fibre reinforced concrete (GFRC) and plain concrete using a photographic record. Their results indicated that the cracking process under impact loading was not substantially different from that which occurs under static loading. Rao et al. (2010) compared the impact behaviour of slurry-infiltrated fibrous concrete (SIFCON) slabs of different steel fibre volumes. The results indicated that 12% fibre volume in the slabs exhibited the best performance in respect of energy absorption capacity and impact resistance.

Ong et al. (1999) compared the impact energy absorption of straight polyolefin, polyvinyl alcohol and hooked-end steel FRC plates. The results showed that hooked-end steel FRC has the highest energy absorption. Xu et al. (2012) conducted drop weight impact tests on SFRC of different steel shapes, i.e. hooked-end, flattened, cold rolled, undulated, synthetic and spiral. The spiral SFRC provided better impact resistance and energy absorption than the other kinds of SFRC. The study by Hao et al. (2016) also concluded that spiral SFRC was better than hooked-end SFRC in dissipating impact energy. Steel fibres are sometimes applied in ultra-high performance concrete (UHPC) to improve its properties. For example, Yu et al. (2016) compared the impact resistance of UHPC with and without steel fibres using both a Charpy and a modified pendulum test devices. It is suggested that steel fibre can improve energy dissipation capacity. Mao and Barnett (2017)
concluded that an increase in steel fibre volume can effectively improve the specimen impact resistance of ultra-high performance fibre reinforced concrete.

**Polypropylene fibre reinforced concrete**

Polypropylene fibre has the ability to control shrinkage induced cracking in concrete (Alhozaimy et al., 1996). Bindiganavile and Banthia (2001) investigated the bond-slip response, flexural toughness of polymeric and steel FRCs under impact loading. Polymeric FRC can absorb fracture energies similar to that of steel FRC. Nili and Afroughsabet (2010) studied the effect of polypropylene fibre on the impact resistance of concrete. Ductile failure can be observed, and polypropylene fibre can considerably improve absorption of energy. Tsesarsky et al. (2013) compared the impact resistance among three types of fibre reinforced concrete, i.e. carbon, alkali-resistant glass and polyethylene. The results indicated that carbon fibre reinforced concrete has the higher capacity to resist impact loading.

**Natural fibre reinforced concrete**

Natural fibres have become increasingly popular in construction due to economic, environmental and sustainability advantages. Studies of natural FRC under impact loading have not yet been thoroughly investigated.

Ramakrishna and Sundararajan (2005) compared four different natural fibres (coir, sisal, jute and hibiscus cannabinus) reinforced concrete under impact loading. In the study repeated impacts were performed on the specimens with an impact height of 200 mm and the weight being a 0.475 kg metallic ball. The number of blows required to initiate the first crack and the ultimate failure was recorded. The results suggested that among these four types of natural fibre coir performed best in resisting impact.

Wang et al. (2013) compared the impact resistance of hybrid steel/bamboo fibre reinforced concrete slabs using repeated impacts. Different fibre volume ratios of steel/bamboo were considered, i.e. 0/0, 0/0.5, 0/1, 0/2, 0.5/0.5 and 1/0. By comparing the number of impacts required for causing damage, it was concluded that the specimens of 0.5/0.5 provided the best impact strength as well as the best resistance against crack propagation through the whole specimen. Muda et al. (2013) experimentally discussed the diameter effect of the bamboo fibre on the impact resistance of lightweight oil palm shells reinforced bamboo concrete slab. Mo et al. (2014) carried out repeated impacts
with a height of 600 mm and a weight of 10 kg to find out the impact resistance of hybrid fibre reinforced oil palm shell concrete (FROPSC). The addition of different contents of steel (0.75%, 0.9%, 1%) and polypropylene fibres (0.1%, 0.25%, 1%) were considered. The results concluded that the specimen with 0.9% steel and 0.1% polypropylene (PP) hybrid-FROPSC had the greatest impact resistance compared with the specimens of other configurations. Yahaghi et al. (2016) investigated the impact resistance of oil palm shells (OPS) concrete considering the effects of polypropylene fibre content and the slab thickness. The experiments showed that an increase in slab thickness and polypropylene fibre content led to an increase in energy absorption and impact resistance but a decrease in the impact residual strength. Muda et al. (2016) focused on the impact properties of kenaf fibre reinforced concrete. The relationship between the impact resistance and the slab thickness was investigated, and the results indicated a clear linear relationship between them.

2.3.2 Impact behaviour of FRP strengthened concrete

Synthetic fibre (e.g. carbon and glass) reinforced polymers have been intensively studied to enhance the impact resistance of concrete structural members. Erki and Meier (1999) conducted drop weight impact tests on concrete beams strengthened with carbon fibre reinforced polymer (CFRP) laminates. It was found that the beams externally strengthened by CFRP laminates performed well under impact loading. Tang and Saadatmanesh (2005) conducted both experimental and analytical research on the concrete beams strengthened with carbon and Kevlar fibre reinforced polymer laminates. It was concluded that composite laminates increased both the initial and residual stiffness. Kevlar laminate reinforced beams were found to show higher residual stiffness than that of the CFRP beams. Soleimani (2006) studied impact behaviour of reinforced concrete strengthened with spray glass fibre reinforced polymer (GFRP) and concluded that this reinforcement improved the flexural strength. Teng et al. (2003) summarised a review of FRP concrete structures and indicated that FRP could enhance the flexural and shear strength of RC beams under static and seismic loads.

Many studies on the CFRP reinforced concrete composites were conducted to understand different types of FRP reinforcement configuration. For example, Min et al. (2010) studied the flexural performance of FRP reinforced concrete beams both under static and impact loadings. Three ways of retrofitting were considered, i.e. beams were retrofitted
at the bottom surface, with a U-strip at the centre, and both surface and U-strip reinforcement. The results indicated that beams reinforced by both bottom surface and U-strips absorbed the highest energy. Pham and Hao (2016) studied the contribution of CFRP reinforcement to shear strength and the response of RC beams under drop weight loadings. The beams were strengthened with different wrapping schemes, i.e. CFRP U-wraps and 45°-angle wraps. The results showed that with regard to the load bearing capacity and displacement, using the 45°-angle wraps provided better performance than the U-wraps. Fully wrapped RC beam with CFRP was found to be more efficient than wrapping with distributed FRP strips. Pham and Hao (2016) further investigated both the static and impact properties of RC beams reinforced by CFRP. It was recommended that de-bonding of CFRP and shear dominance in impact tests should be taken into account.

Studies of natural FRP concretes are scarce and mainly conducted on static behaviour. Yinh et al. (2016) experimentally studied the flexural behaviour of concrete beams reinforced with hemp fibre reinforced polymer (HFRP), and concluded that HFRP increased the load carrying capacity and stiffness. Zhang et al. (2016) applied hybrid basalt-carbon fibre reinforced polymer (HFRP) to reinforce concrete T-beams. The results showed that HFRP beams had an obvious post-yield stiffness, which could be used to control structural deformation. Yan (2014) developed the mechanical properties of coconut fibre reinforced concrete (CFRC) encased by a flax fibre reinforced polymer (FFRP), and recommended that the composite could be an alternative for future steel-free constructions. There are hardly any studies which consider the impact behaviour of natural FRP concretes. To fill this knowledge gap, this PhD research focuses on the behaviour of FFRP-CFRC composites under impact loadings.

2.4 Strain rate effect on concrete

The behaviour of concrete structures differs under static and dynamic loads. The difference is due to the fact that the static loadings are long-term applications with negligible variation in intensity over time, while dynamic loadings vary in both duration and intensity and generate inertial forces. The effect of dynamic loads was categorised within a time domain in relation to the strain rate (Macaulay 2012), which describes the rate of deformation of the material under dynamic loads. Different types of dynamic loading (Malgorzata 2011) can result in various strain rates, as shown in Figure 2.1.
Impact loads can cause extreme stress to structural members and thus cause damage to structures due to a sudden generation of high-intensity force (Fujikake et al. 2009). Impact testing techniques influence the strain rate sensitivity (Malgorzata 2011). The strain rates obtained from hydraulic machines/drop hammer machines and Split Hopkinson Pressure Bar (SHPB) are different, with the value usually being lower than $10^{-1}$ and for the latter being up to more than $10^{3}$ s$^{-1}$, respectively.

Bischoff and Perry (1995) made a review concerning the uniaxial compressive strength of plain concrete at a strain rate greater than $10^{-5}$ s$^{-1}$. The study fully discussed difficulties which could occur during high strain rate impact. For example, testing method, measurement approach and concrete quality may directly influence the test results. In addition, the strain rate effect on elastic modulus, critical compressive strain, Poisson’s ratio and energy absorption capacity were considered. It was concluded that compressive strength and modulus increased with strain rate. It was also suggested that numerical computational analysis should be applied to assist in predicting the behaviour of concrete under impact.

Wang et al. (2008) investigated the stress-strain relationship of SFRC using a SHPB with strain rates up to 99 s$^{-1}$. The results showed that SFRC is a strain rate sensitive brittle material. A high strain rate would lead to large compression strength.

Cusatis (2011) extended a meso-scale model, the Confinement-Shear Lattice (CSL) model, to study the effect of strain rate on concrete behaviour. The results showed that both compressive and tensile strength of concrete depend on strain rate. Fracture behaviour was also influenced by strain rate.
Moustafa and El Gawady (2016) studied the behaviour of rubberized concrete confined by glass fibre reinforced polymer tubes under various strain rates. With one layer of confinement, an increase in strain rate resulted in an increment of compressive strength, ductility and modulus elasticity. However, in the case of three layers of confinement the effect of strain rate was not obvious.

FRC is a strain rate sensitive material (Mindness and Zhang 2009). Its behaviour under high strain rates is more complex than under static load. Damage modes and impact behaviour may be quite different depending on factors, such as fibre material, structure dimension and configuration. Hence, study of impact performance on FRC composites, for new fibre materials is essential.

2.5 Research methods for fibre reinforced concrete composites under impact

Existing research methods include experimental, theoretical and numerical analysis. As for experimental methods, tests can be divided into two different types, i.e. single test and repeated test (e.g. Clifton and Knab 1983). In the theoretical method, various theories are used based on hypotheses. Many numerical methods have also been applied to assess the impact properties of FRC. Different commercial software, such as ANSYS and ABAQUS, are applied to simulate structural impact responses.

2.5.1 Experimental method

Cantwell and Morton (1991) gave a detailed introduction of impact tests. Impact tests normally include: Charpy pendulum impact, Izod impact, drop weight impact, hydraulic test machine, Split Hopkinson Pressure Bar technique and gas gun impact.

2.5.1.1 Charpy test

Gopalaratnam et al. (1984) modified a conventional Charpy tester, Tinius Olsen Model 64, and used it to study the impact behaviour of cement-based composites using four different impact velocities, ranging from 0.7 m/s to 2.4 m/s. The specimens had a dimension of 229 x 76 x 25 mm. The midpoint deflections of the specimens were measured using a Schaevitz LVDT, and the signal conditioner had a nominal frequency of 20 kHz. The load, deflection and strain information was monitored by a digital oscilloscope.
Yu et al. (2016) applied both the “Charpy Impact Device” and the “Modified Pendulum Impact Device” to study the impact resistance of ultra-high performance steel fibre reinforced concrete (UHPFRC) members. For the Charpy impact test, all specimens were broken at single impact due to the concrete specimens being relatively small. In this case, the concrete was broken immediately and more energy was consumed as fibres pulled out. On the other hand, the specimen dimensions were relatively large for the “Modified Pendulum Impact Device”, resulting in the specimen breaking after repeated impacts. Hence, the formation of cracks played an important role in resisting the impact loadings. The results indicated that the impact results of UHPFRC were highly dependent on test set-up and specimen dimensions. This would imply that it is important to develop a systematic standard for evaluating the impact resistance of UHPFRC.

2.5.1.2 Drop weight test

Drop weight impact tests were applied by many researchers even though each test method was different. Using the drop weight machine, researchers conducted single or repeated impacts on concrete specimens.

In the tests of the single impact, a detailed description of the instrumented drop weight impact machine was presented by Banthia et al. (1989). The machine has a frame with the height of 3.5 m. The instrumentation (the striker, support anvil, accelerometers and photocell assembly), the calibration, the inertial loading correction and the dynamic analysis of a concrete specimen under impact loading were described in detail, which provided very helpful guidance for other researchers.

An instrumented drop weight machine was used by Mindess and Zhang (2009). The impact mass was 578 kg and the height range is up to 2.5 m. Single impact tests were conducted by changing the impact height to study the impact resistance of fibre reinforced concrete. Chen et al. (2011) improved the impact test device using a magnetic positioning switch to release drop mass.

In many studies repeated impacts were considered according to the ACI Committee 544 impact standard (e.g. Nataraja et al. 2005, Mohammadi et al. 2009, Nili et al. 2010, Wang et al. 2013, Mo et al. 2014). Myers and Tinsley (2013) modified the ACI drop weight test to evaluate the effectiveness of a high-volume fly ash-wood fibre material. There are many other studies using self-built drop weight devices. Rao et al. (2011) chose a steel
drop hammer of 50 mm diameter and 5 kg mass to induce impact effect on beams to study the dynamic behaviour of recycled aggregate concrete.

Rokugo et al. (2001) presented a study of repeated drop weight tests on plain concrete and SFRC beams (3000 mm x 200 mm x 200 mm). The drop height was initially set at 100 mm, with an increment of 100 mm for each subsequent impact. Global response and local damage zone were discussed. The study also suggested that the relationship between the steel fibre content and the pre-stress of beams was important in improving the impact resistance.

Yazıcı et al. (2013) conducted repeated impact tests on cylindrical specimens (150 mm x 50 mm) to study the effect of steel fibre volumes (0.5%, 1% and 1.5%) on the impact resistance of SFRC. The impact height started from 30 mm, with an increment of 30 mm in each subsequent strike. The results found that SFRC with a 1.5% of steel content performed best in resisting impact loadings.

Anil et al. (2016) experimentally and numerically investigated the impact behaviour of concrete composites with polyvinyl alcohol (PVA) fibres. Two beam dimensions were studied, i.e. 750 mm x 100 mm x 150 mm and 750 mm x 50 mm x 50 mm. The test used a 9 kg of drop weight and varied heights between 0.5 m and 1.5 m. The specimens were subjected to multiple impacts during the tests. The experimental results illustrated that PVA efficiently decreased the crack development under impact loading. The results of the finite element study provided the stress distributions of concrete under impact loading, which aligned well with the experimental crack distributions.

2.5.1.3 Split Hopkinson Pressure Bar (SHPB)

The SHPB test is based on the propagation theory of an elastic stress wave in the thin and long bars (Wang 2011), which is normally used for high strain rate tests. Two assumptions are needed for SHPB (Ravichandran and Subhash 1994): (1) during the propagation process, every cross section of the elastic bar is kept in a plane and (2) stresses are the same in the bar after two or three incoming and outgoing propagating waves. Li and Xu (2009) used the SHPB test to study the impact property of basalt fibre. Wang et al. (2013) conducted repeated impact tests using the SHPB device, obtaining impact failure modes on ultra-short steel fibre reinforced cylinders.
2.5.2 Analytical method

A methodology is suggested for analysis and design of barrier-type structures by Yang and Qiao (2010) including several theoretical models of an elastic and elastic-plastic impact as well as an energy method. The result can be applied to the design of cushioning structures for bridge protection from collisions of overweight vehicles.

Wave theory is an important method to analyse impact properties. Martin and Forde (1995) used three types of waves (compressive wave, shear wave and surface wave) to discuss the influence of output from impact-echo tests on concrete. Olsson (2000) demonstrated that impact response is related to both impact energy and duration. In his work, the author discussed the effect of duration on impact response using the wave theory.

The mass-spring model was applied to analyse the impact behaviour of concrete components. Analysis of one-way slabs under severe dynamic loads was studied by Krauthammer et al. (1990). The structural resistance function was employed in single-degree-of-freedom system analyses to compute the parameters. Manolis et al. (1997) applied a single degree-of-freedom system to simulate the fibre reinforced concrete slab. The natural frequency and damping coefficient were determined.

Fujikake et al. (2009) applied a two degree-of-freedom model to determine the maximum mid-span deflection. The mid-span deflection results obtained from the model were in good agreement with the experimental values when RC beams exhibited flexure failure. Tang and Saadatmanesh (2005) applied the mass-spring model to examine the impact behaviour of a beam subjected to a drop weight. Habel and Gauvreau (2008) investigated the impact and static responses of ultra-high performance fibre reinforced concrete (UHPFRC) using a two degree-of-freedom model, and the results showed a good agreement with the impact test results.

The energy balance model was applied in some research to predict the amount of energy absorbed by the specimens. Mousa and Uddin (2014) concluded that impact peak forces and energy absorption of autoclaved aerated concrete (AAC) sandwich panels were greatly influenced by carbon fibre reinforced polymer (CFRP) laminates. Additionally, they used energy balance model to predict the amount of energy absorbed, and the results well aligned with the experimental values.
2.5.3 Numerical method

The numerical simulation method is a very popular way to assess the impact behaviour of a structure. Impact resistance of lightweight aggregate concrete (LWAC) was analysed using both experimental and numerical methods (Farnam et al. 2008). Yang et al. (2013) investigated domestic aramid fibre reinforced laminates through experiments and modelling, discussing the effect of low-velocity impact on the composite. The numerical result exhibited good validity. The impact resistance of SFRC slabs was investigated using the finite element code LS-DYNA (Teng et al. 2008). The “Elastic-Plastic Hydrodynamics” material model was employed to model the non-linear softening behaviour of SFRC through a tabulated stress-strain curve. Nia et al. (2012) applied both experimental and numerical methods to study SFRC and polypropylene fibre reinforced concrete. The LS-DYNA fibre concrete cylinder model was established to study the fibre volume effect on impact strength and impact failure. Modelling results were in good agreement with the experimental data. Su and Xu (2013) proposed a continuous numerical model to investigate impact properties of ceramic fibre reinforced concrete (CRFRC).

Richardson et al. (2016) created finite element analysis models of the synthetic fibre reinforced concrete slabs under shotgun fire tests, and successfully predicted the slab damage. Kezmane et al. (2017) provided a finite element model to investigate the local and global behaviour of reinforced concrete slabs subjected to low-velocity impact loading.

Although the numerical method cannot simulate real impact events, it can help in assessing the impact behaviour of a real structure and reduce the costs of a full-scale test. Additionally, results of a numerical simulation are very important in optimising the impact property of structures through experimental case studies.

2.6 Concrete structure failure modes

Kennedy (1976) described overall missile impact phenomena for concrete structures. In the research by Li et al. (2005) seven phenomena were suggested to clarify the impact effects on concrete targets, as shown in Figure 2.2: (a) penetration, (b) cone cracking, (c) spalling, (d) radial cracks (e) scabbing, (f) perforation, and (g) overall structural responses and failures.
With regard to FRC, Chen et al. (2011) compared the damage patterns of SFRC with different reinforcements, i.e. steel bar and steel fibre. It was concluded that a combination of steel fibre and steel rebar provided more even stress distribution, and thus resulting in the best impact resistance. Yu et al. (2016) discussed crack development in UHPFRC after each impact, and described the damage phenomena by recording cracks at each impact. Mastali et al. (2016) studied the impact resistance of concrete beams reinforced with recycled glass fibres. Scanning Electron Microscope (SEM) images were used to reveal the failure mechanism of recycled glass fibre in the concrete matrix. It indicated that the formation of multiple cracks on the specimen surface was due to the bridging action of the glass fibres. The SEM images also showed a tendency of long fibre rupture in the surface.

Hrynyk and Vecchio (2014) studied the crack and damage patterns of SFRC slabs under static and impact loadings. Under static loadings, the slabs were governed by flexural failure modes, while under impact the slabs were controlled by shear failures. The results also showed that an addition of hooked-end steel fibres reduced crack spacing and widths. Mitigation of mass penetration and concrete scabbing were observed. Under high-mass low-velocity impact loadings, the behaviour of the slabs was mainly deformed globally.
For FRP strengthened steel RC beams subjected to flexure, some failure modes were summarised by GangaRao et al. (2006): (1) rupture of FRP after tension steel yield; (2) secondary concrete crushing after tensile steel yield; (3) primary concrete crushing in compression before steel yield; (4) shear/tension delamination of FRP from concrete cover and (5) de-bonding of FRP from concrete substrate.

Some studies on the impact behaviour of FRP strengthened concrete also mentioned failure modes (e.g. White et al. 2001; Soleimani et al. 2007; Tang and Saadatmnesh 2003). Pham and Hao (2016) provided a review of concrete strengthened with FRP against impact loadings. The single impact test is close to a real impact situation, but it is difficult to examine failure progress due to the fact that the impact duration is only a few milliseconds. On the other hand, repeated impact tests can provide more detailed understanding of energy absorption and the failure progress of the specimens. The failure of FRP concrete beams could consist initially of either flexural cracks or shear cracks, and they induced peeling stress on the interface between the concrete and the FRP laminates. Finally, the specimens fractured mainly through de-bonding or rupture of the FRP. They also mentioned that the bonding between FRP and concrete in impact tests might react differently from static tests as impact loading is a force of great intensity over a very short time. Concrete structures may suffer both local response and overall response under impact loadings, which could result in a double impact on structures and led to a decrease in bond strength. The stress wave of a local response induced during impact tests may result in FRP de-bonding (Erki and Meier 1999; Tang and Saadatmnesh 2003).

2.7 Summary

A review of existing studies on the impact properties of FRP, FRC and FRP concrete composites was conducted. It is concluded that:

1. FRP strengthened concretes have attracted many researchers due to their wide application and convenient construction methods. Of all FRP composites, CFRP and GFRP have been studied and applied in real world civil construction. However, studies on the natural FRP concrete composites have rarely been reported. It is, therefore, necessary to investigate the impact behaviour of natural fibre reinforced concrete for its further development and application.
2. Various impact tests were designed and conducted. However, differences of specimen size, test procedure, test equipment and test parameters make impact tests complex and incomparable. Moreover, the impact duration is so short that dynamic response data is difficult to record using general equipment. It is important to obtain reliable impact signal within a very short time.

3. Parameters, such as fibre properties (content, length, and water absorption), deflection, maximum bearable impact force, energy absorption and fracture energy, are important when studying the impact behaviour of FRC. Failure modes of FRP strengthened concrete are important in assessing the impact resistance. Hence, failure mechanism under impact loadings has to be thoroughly studied.
Chapter 3
Development of a drop weight impact machine

3.1 Introduction

To carry out impact tests on FFRP-CFRC composites, a drop weight test rig was designed and constructed in the Civil Test Hall at the University of Auckland. This chapter presents the procedure for developing the drop weight impact test rig.

To design the drop weight impact machine, several similar prior studies were investigated first:

*Kawewunruen and Remennikov (2011)*

The drop weight impact testing machine at the University of Wollongong was used to evaluate the resistance of pre-stressed concrete sleepers under impact loadings. The impact testing facility (Figure 3.1) has a drop mass of 592 kg and variable drop heights. The drop height is up to 6 m, with an equivalent velocity of 10 m/s. The test rig is a free-fall hammer which is monitored by a motor and chain system.

In their study, the dynamic load cell (Type Interface Model 1200) with a capacity of 1200 kN and the piezoelectric accelerometer (Dytran Series 3200B) with an amplitude of up to 10,000 g were used to measure impact force and acceleration, respectively. They also used a magnifying glass telescope with a resolution of 0.1 mm to measure interfacial crack width. The foiled strain gauges were applied to measure strain on the concrete sleeper. The data acquisition system was from National Instruments, with 10 kHz low-pass filtering and the frequency ban filtering between 45 Hz and 55 Hz was used.
The research described a drop weight impact system (Figure 3.2), with a maximum height of 4 m. The impact machine was used to test large scale concrete beams and slabs. The striker consists of a drop mass, a load cell and an impact head. Two types of impact head were used, i.e. spherical and flat. A magnet system was used to control the release of the striker. The striker was lifted using a winch with a steel wire rope attached to the striker by an electromagnet.

For the instrumentation, the research applied a high-speed video camera with a sampling rate of 4500 fps to record the impact process. Both a load cell and an accelerometer were used to record impact force. When analysing acceleration data, a Butterworth filter with a cut-off frequency of 2000 Hz was used to reduce noise. A sampling rate of 500 kHz was used in an A/D data acquisition system during tests.
Zhang et al. (2010)

The research developed a new drop weight machine (Figure 3.3) to investigate the impact properties of SFRC components. The machine is a two-column structure system which is located on the strong floor of the Laboratory of Materials and Structures of ETSI Caminos, which can provide a height of 2.595 m. In order to uniformly distribute stress to the strong floor, a thin layer of neoprene was applied between the steel plate and concrete floor. Two types of strikers were designed for tests on different kinds of specimens, i.e. an aluminium hammer of 18.60 kg, and a steel hammer which ranges from 60.55 kg to 315.55 kg with increments of 15 kg.

In their study, force sensors, Model 204C and Model 203B, made by the PCB Company were applied, with a capacity of 177.92 kN and 89 kN, respectively. They were installed on the hammer tup and specimen support, respectively. The accelerometers with 1000 g of amplitude were mounted along the beam specimen to record data. In addition, an optical fibre photoelectric sensor was used to trigger the data acquisition system, with a sampling rate of 1.25 GHz.
Figure 3.3 Schematic diagram of the drop weight impact machine by Zhang et al. (2010)

**Gunawan et al. (2011)**

The research presents the development of a drop weight impact testing machine for crash boxes. The whole system was based on a foundation consisting of a 2 m x 1 m x 1 m concrete block. Columns were designed as a guide system for the striker. The frame was made of 6 m long stainless steel pipe with a thickness of 6 mm and an outer diameter of 11.4 mm. The clamp mechanism was designed to clamp and release the impactor assembly with a maximum weight of 150 kg. A load cell and a speed sensor were used as instrumentation, and a data acquisition system with a sampling rate of more than 10 kHz was used.

Based on the previous research, in this study a drop weight test rig was designed and assembled for conducting impact experiments on natural fibre reinforced concrete composite specimens. The construction procedures are described in the next section.
3.2 Description of the drop weight impact machine

3.2.1 Mechanical structure of the impact test rig

A schematic diagram of the drop weight impact test rig is displayed in Figure 3.4. The machine is located on the strong floor of the Civil Test Hall at the University of Auckland. The impact device includes a mechanical structure and a data acquisition system.

![Schematic diagram of the drop weight impact machine](image)

**Figure 3.4 Schematic diagram of the drop weight impact machine**

The mechanical structure consists of a steel frame, guiding system, chain hoist, and magnetic system.

(1) Steel frame

A two-column frame design (Figure 3.5) was selected from the alternatives: two columns or four columns, as the two-column design satisfied safety requirements, price and ease of operation. The steel frames were made of 3.5 m of stainless steel I-section with dimensions of 150 mm x 14 mm x 6 mm. They were pre-stressed on the one-meter thick concrete strong floor. The system has the capability to provide a 2.6 m drop height. Impact velocity can be varied by changing drop height. A rubber layer was placed on the strong
floor around the impact machine, so as to distribute the stresses transmitted to the floor as uniformly as possible. In addition, a plastic cage was produced to avoid splashing of concrete fragments during test.

Figure 3.5 View of the drop weight test rig column

(2) Striker
The striker was assembled from a steel beam, drop masses, an impact head and rollers. The rollers were used to connect the steel frame and the steel beam. This mechanism ensured that the striker always moved along the steel columns during experiments. Four steel wires were designed to act as guides for the moving drop mass assembly, which also helps to minimise drop mass jumping. The drop mass consists of assembled steel plates and a flat-head impactor. The drop weight ranges from 30 kg to 200 kg, with increments of 10 kg.

(3) Chain hoist and magnet control system

A chain hoist with a load capacity of one tonne was used to raise the drop mass to various impact heights. A remotely controlled magnetic system was applied to release the drop weight, and the drop weight is held in position until the user triggers its release. The electromagnet has a capacity of 500 kg, which can release the drop mass freely within 2 seconds. In addition to the magnet system, two steel clamps were applied to hold the drop mass, ensuring a safer impact test environment.

3.2.2 Instrumentation

(1) Load cells

Impact force was measured by a piezoelectric force sensor Model 200C50 made by PCB Company. The ceiling of the measurement range is 333 kN. Calibrations of the sensors were carried out by PCB Piezotronics, and accuracy of the sensors is ±0.7N. Figure 3.6 gives a view of the load cell.

![Figure 3.6 Dynamic load cells Model 200C50](image)

Checking the natural frequency of the load cell is essential in impact tests to make sure a reliable data is recorded. The rise time of the load cell should be faster than the rise time
of the force, and enough to record the true force history. Generally, the force sensor rise time can be estimated as one half of the natural period of the sensor:

\[ T_p = 0.5 \times \frac{1}{f_n} \]

(3.1)

where \( T_p \) is force sensor rise time, \( f_n \) is natural frequency of load cell, \( f_n = 30 \) kHz. Hence, \( T_p = 16.7 \mu s \).

The rise time for the force is about 600-800 \( \mu s \) in this study, which is much longer than the rise time of the load cell. Therefore, the load cell can record a valid data of the tested specimens.

(2) Accelerometer

To measure the acceleration of the specimens and the impactor, the PCB shock sensor 350B21 was applied. The sensor has a measurement range of up to 10,000 g, and a frequency range between 1 and 35 kHz. It is a very light sensor with a weight of about 4.4 gm and the sensitivity is 0.05 mV/g. Figure 3.7 provides a view of the accelerometer.

![Accelerometer Model 305B21](image)

Figure 3.7 Accelerometer Model 305B21

(3) Displacement laser sensor

To measure displacement of the specimens under impact loading, a laser sensor was used. It is a compact laser displacement sensor, with a resolution of 2.5 \( \mu m \). The measurement range is 85 ± 20 mm. Figure 3.8 shows a view of the laser sensor.
(4) Data acquisition system

Matlab based data acquisition tool box (Compact DAQ V2) software was used to record experimental data. The data acquisition system consists of a signal conditioner (Model: 482C05 by PCB Piezotronics) for dynamic load cells, an accelerometer signal conditioner (assembled on-site by Mark Twiname, a technician of the Civil Engineering Department at the University of Auckland) and a computer. The data acquisition system has a maximum sampling rate of 50 kHz.

The load cell signal conditioner has four channels (Figure 3.9), which are line-powered for sensor systems. It provides four individual channels for collecting data. Both the input and output connections use BNC connectors. The constant current output is from 2 to 20 mA.

3.3 Summary

A qualified drop weight test rig was developed in this study. With it, impact tests were carried out and the impact force, acceleration and displacement were recorded for analysis.
Chapter 4
Mechanical properties of flax fibre reinforced polymer under dynamic loadings

Related papers:


4.1 Flax fibre and flax fibre reinforced polymer composites

Flax fibre is also called linen, and is obtained from the plant Linum Usitatissimum. Flax fibre is the oldest fibre crop in the world and its application in textile goes back to 5000 BC (Yan 2014). Canada, France, Belgium and Netherlands are the main exporters of flax fibres. According to the study by Yan (2014), flax offers the best potential combination of economy, low weight, high strength and stiffness as a material for structural engineering applications, relative to other natural fibres. It has also been suggested that flax fibres have the potential to replace glass fibres. Previously in his research, a very detailed investigation of the mechanical properties of flax fibre and its reinforced polymer composite were described. Here, the impact behaviour and dynamic tensile behaviour of FFRP will be discussed.

4.1.1 Flax fabric and epoxy system

The plain-woven flax fabric (Figure 4.1 (a)) was sourcing from Libeco, Belgium. The fabric (550 g/m²) consists of 47.9% of weft and 52.1% of warp yarns for a proper weight
distribution. The epoxy system used was SP High Modulus Prime 20LV, sourced from Gurit in New Zealand. The mechanical properties of the flax yarns, fabric and flax/epoxy composites are given in Table 4.1.

Flax fibre reinforced polymer (FFRP) laminates (Figure 4.1 (b)) were fabricated by a hand lay-up technique. The preparation and curing were carried out at room temperature.

![Flax fabric and FFRP laminate](image)

Figure 4.1 Flax fabric and FFRP laminates

<table>
<thead>
<tr>
<th>Material</th>
<th>Flax yarns</th>
<th>Epoxy system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Resin</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.43</td>
<td>1.123</td>
</tr>
<tr>
<td>Mix ratio by weight (%)</td>
<td>--</td>
<td>100</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

### 4.1.2 Tensile properties of FFRP

#### 4.1.2.1 Specimens

For the static tensile tests, the configuration of 2-layer FFRP specimens was prepared according to ASTM D638 (2010). The gauge length of the specimen is 50 mm, as shown in Figure 4.2.

![FFRP samples for static tensile tests](image)

Figure 4.2 FFRP samples for static tensile tests
4.1.2.2 Testing apparatus

The static test was performed using an Instron 5567 hydraulic machine (Figure 4.3 (a)). The machine has a load capacity of 30 kN. An inbuilt load cell and extensometer were used to measure the force. A clip gauge was attached to the gauge length of the specimen to monitor the displacement (Figure 4.3 (b)). Room temperature during the test was around 25 °C. For the current study, the actuator extension speed was controlled at about 5 mm/min, which corresponded to an estimated strain rate of 0.0005 s⁻¹.

![Image of testing apparatus](image)

(a) Intron 5567 hydraulic machine (b) Tensile test set up

Figure 4.3 Static tensile test machine and set up

4.1.2.3 Tensile strength and failure mode

Figure 4.4 shows the stress-strain curves of 2-layer-FFRP under static tensile loading. The tensile strength was about 28.5 MPa, and the failure strain was about 0.022 mm/mm. Table 4.2 lists the static tensile test results of FFRP composites of different thicknesses.
Figure 4.4 Stress-strain curves of 2-layer-FFRP under static tensile loading

Table 4.2 Tensile properties of FFRP

<table>
<thead>
<tr>
<th>FFRP specimens</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Modulus (GPa)</th>
<th>Tensile stress (MPa)</th>
<th>Tensile strain at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Layer</td>
<td>13.7 (0.09)</td>
<td>2.82 (0.05)</td>
<td>3.66 (0.47)</td>
<td>28.5 (1.10)</td>
<td>2.22 (0.33)</td>
</tr>
<tr>
<td>4-Layer</td>
<td>13.75 (0.05)</td>
<td>5.29 (0.13)</td>
<td>3.92 (0.36)</td>
<td>30.1 (1.28)</td>
<td>2.34 (0.26)</td>
</tr>
<tr>
<td>6-Layer</td>
<td>13.88 (0.11)</td>
<td>7.53 (0.07)</td>
<td>3.67 (0.63)</td>
<td>32.0 (2.35)</td>
<td>2.28 (0.41)</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are standard deviations.

Figure 4.5 displays the damage pattern of FFRP coupons under a static tensile load. It is observed that the damage to the specimen was due to fibre pull-out. The fracture line is perpendicular to the direction of the applied loading, and the failure is almost a straight line. This damage pattern in tension was mainly due to failure of the fibres in the load direction, de-bonding and pull-out, and brittle fracture of the matrix (Yan et al. 2012).
4.2 Impact properties of FFRP

4.2.1 Introduction

The impact behaviour of flax/epoxy composites has been rarely studied. Therefore, the impact behaviour of FFRP is discussed in the following sections. An energy profiling method was applied to analyse the relationship between impact energy (kinetic energy of striker before contact) and energy absorbed, which has been well used in many studies to explore the impact behaviour of fabric reinforced polymer composites. For example, Aktas et al. (2009) applied the energy profiling method to study the impact resistance of glass/epoxy composites. Liu (2004) also investigated the impact response of glass/epoxy composites. Sayer et al. (2010) assessed the damage mode and process of glass-carbon/epoxy hybrid composites. Evci and Gülgeç (2012) studied the perforation limit for both unidirectional and plain woven E-glass/polyester composites. The results showed that woven composites performed better than unidirectional composites under low-velocity impact. Taraghi et al. (2014) applied the energy profile diagrams to determine the penetration threshold of Kevlar/epoxy composites enhanced with different weight percentages of carbon nanotubes.

Low impact strength has been considered one of the disadvantages of natural fibre composites (Pickering et al. 2016) and an understanding of the impact behaviour of these composites would be useful for future applications. Hence, the impact behaviour of flax fibre reinforced polymer (FFRP) was studied experimentally. Drop weight impact tests were performed to determine the perforation energy of FFRP. The effect of FFRP thickness on impact behaviour was analysed through the damage mechanism, energy
absorption and ductility index. Charpy impact tests were also carried out to determine the impact resistance of FFRP.

### 4.2.2 Specimens

FFRP specimens of 150 mm x 100 mm (Figure 4.6) were fabricated using the hand lay-up technique. Preparation and curing were carried out at room temperature. Three types of specimens were prepared: 2-, 4- and 6-layer FFRP composites. The corresponding flax fibre fractions with reference to the total mass of the specimens were 35.33%, 36.6% and 37.1%, respectively. Table 4.3 gives the properties of the FFRP specimens.

![Figure 4.6 FFRP specimens for drop weight impact test](image)

**Table 4.3 Properties of FFRP specimens**

<table>
<thead>
<tr>
<th>Layers of flax fabric</th>
<th>Thickness (mm)</th>
<th>Mass (g)</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.97</td>
<td>46.7</td>
<td>1.05</td>
</tr>
<tr>
<td>4</td>
<td>5.35</td>
<td>90.2</td>
<td>1.12</td>
</tr>
<tr>
<td>6</td>
<td>7.66</td>
<td>133.4</td>
<td>1.16</td>
</tr>
</tbody>
</table>

FFRP laminate thickness is not linear with the number of flax fabric layers, which can be explained by the effect of nesting. In general, nesting affects laminate thickness, fibre volume fraction and pore pattern. Many studies have mentioned that the thickness per layer decreases due to nesting, which could help explain why the composite thickness is not linear with the number of layers used in this study. The nesting coefficient was calculated using the following equation (Lomov 2011),

$$
\zeta = \frac{T(N)}{N \cdot T(l)}
$$

(4.1)

where $T(N)$ is the laminate thickness, $N$ is the number of fabric layers in the laminate, $T(l)$ is the thickness of one layer. The nesting coefficients of 2-, 4- and 6-layer FFRP composites were 0.92, 0.83 and 0.79, respectively. The coefficients decreased, indicating that the thickness per layer decreased due to nesting.
4.2.3 Drop weight impact test setup

Impact tests were performed according to the ASTM Standard D7136/D7136M (2012) using the Imatek fully instrumented drop weight impact tester IM10-20. Figure 4.7 displays a sketch of FFRP specimen with impact location and Figure 4.8 shows the test setup. The impactor is a smooth hemispherical striker tip with a total impact mass of 9.745 kg and a dimension of 16 mm. The specimen was fixed at all corners using four clamps. A number of impact tests were conducted each time with increasing impact energy until perforation of a specimen.

![Figure 4.7 Sketch of a FFRP specimen with impact location](image1)

![Figure 4.8 Impact test set up](image2)
4.2.4 Drop weight impact tests results and discussion

4.2.4.1 Impact force time history

Figure 4.9 shows the impact force time history of the 2-layer FFRP specimen. The impact energy increased from 10 J to 30 J. With 10 J impact, the impact force first increased to the maximum value, then decreased gradually to zero with a total duration of about 45 ms. For 15 J impact, however, the impact force dropped sharply from the maximum value to zero with a shorter impact period of 14 ms. As a consequence of 10 J impact, the specimen experienced only cracks and dent damage, with 15 J impact the specimen was perforated. The force time history of 20 J showed a similar trend. Two different patterns of impact force time history can be observed, corresponding to the specimen with and without perforation. Without perforation, the impact force increased to peak value and gradually decreased to zero. The impact force dropped sharply to zero when perforation took place as the striker passed through the specimen rather than rebounding.

![Impact force time history of 2-layer FFRP specimens](image)

Figure 4.9 Impact force time history of 2-layer FFRP specimens

Figure 4.10 shows the impact force time histories of the 4-layer specimens. Impact energy increased from 20 J to 40 J for the 4-layer specimens. Impact energies from 30 J to 70 J were applied (30 J, 50 J, 55 J, 60 J, 65 J and 70 J, respectively) for the 6-layer ones, and selected cases are shown in Figure 4.11. The impact force time histories of the 4- and 6-layer FFRP show a similar development to that of the 2-layer composite. The 4-layer
specimen perforated at 30 J impact, while the 6-layer specimen perforated under an impact of 70 J.

Figure 4.10  Impact force time history of 4-layer FFRP specimens

Figure 4.11  Impact force time history of 6-layer FFRP specimens

Hertzian force is the main reason for initial damage in the composites (Evci and Gülgeç, 2012). This initial damage is called Hertzian failure, which is defined as the first sudden drop in the force time curve. Damage develops through delamination within the composite structure, matrix cracking and local indentation (Sutherland and Soares 2003; Sutherland and Soares 2005). Force at the point of Hertzian failure is called the Hertzian force. Hertzian failure, highlighted in the Figures 4.9-4.11, is recognised as the first
change point of the force curve slope. The Hertzian forces are about 0.18 kN, 0.34 kN and 0.83 kN for 2-, 4- and 6-layer of FFRP composites, respectively.

For 2-, 4- and 6-layer specimens, peak impact forces are about 1 kN, 2.7 kN and 4.7 kN, respectively. With the same thickness, peak impact force and Hertzian force did not vary much with impact energy for a specimen. This is because the impact force was not dependent on the initial input energy, but on composite thickness. A larger thickness composite led to higher stiffness, resulting in larger impact force.

### 4.2.4.2 Damage mechanism

Figures 4.12, 4.13 and 4.14 display the damage development of respectively 2-, 4- and 6-layer composites with increasing impact energy. The corresponding force-deflection and energy-deflection curves are provided as well. In all cases considered, both the impact side and the reverse side show cracks.

As for the 2-layer specimen (see Figure 4.12), cases of 10 J and 15 J are shown. With 10 J impact, a visible cross-shaped crack occurred on the impact side with annular micro-cracks around the impact centre. A dent area was observed with a depth of about 5 mm and a diameter of 40 mm. On the reverse side, a cross-shaped crack occurred with a length of about 40 mm. A 12 J impact produced similar damage except the area of damage was larger with an apparent cross-shaped crack. Perforation occurred when the impact energy increased to 15 J, failure was extended across the cross-shaped crack. Almost symmetrical fracture can be observed. Damage caused at 20 J impact was similar to that of 15 J impact.

10 J
Figure 4.12 Force-deflection curves and damage at impact zones of 2-layer FFRP specimens

The damage development of the 4-layer specimen is shown in Figure 4.13. With 20 J of impact, there was no apparent damage on the impact side. Similar damage was observed at 25 J and 28 J. On the impact side, micro-cracks were produced around the impact location, while the lengths of crack on the reverse side were different. Perforation occurred at 30 J impact. The perforation hole can be observed on the impact side and an almost symmetrical fracture occurred along the crossed cracks at the back, as seen in the case of the 2-layer specimen. Damage from 40 J impact was almost the same as that found in the case of 30 J.
Concerning the 6-layer sample (Figure 4.14), the extent of damage was slight for low energy impact, i.e. 10 J and 30 J. As the impact energy increased to 50 J, a crack along the y-axis (about 40 mm) appeared on the impact side. Crossed cracks were found on the
reverse side, with a length of 90 mm along the y-axis and 35 mm along the x-axis. The damage due to the impact energy of 60 J was similar to that in the case of 50 J. There was a crack along the y-axis (about 50 mm) on the impact side. The crack lengths on the reverse side were about 110 mm along the y-axis and about 40 mm along the x-axis. Perforation occurred with impact energy of 70 J. On the reverse side, an almost symmetrical fracture was observed similar to those in the cases of 2- and 4-layer specimens. However, a much longer crack extension was found at the back along the y-axis, which was different from damage to the reverse side of 2- and 4-layer specimens.
Figures 4.12-4.14 respectively provide the force-deflection and energy-deflection curves of 2-, 4- and 6-layer FFRP. For the 2-layer FFRP specimens, it was observed that the maximum deflection reached a value of about 20 mm for the perforated specimens (15 J and 20 J). In comparison, the 4- and 6-layer FFRP composites had a maximum deflection of 15 mm when perforated.

Energy-deflection curves provide information about energy transformation during an impact test. The curves show different trends for the specimens with or without perforation. In the case of a non-perforated specimen, impact energy was dissipated mainly through two ways, i.e. part of the energy is absorbed by the specimen and the rest of the energy was used to make the striker rebound. From Figures 4.12 - 4.14, an obvious knee point can be found. In the case of perforation, there was also a knee point between the perforation phase and post-perforation phase. This showed that the impact energy was dissipated mainly by two means. One part was used to perforate the specimen, which happened before the knee point. The other part of the energy was consumed at the post-perforation phase (Sayer et al. 2010). In this stage, the energy was dissipated by friction between the striker and the specimen.

The damage to composites with different thickness can be concluded in the following way:

(1) A dent was only observed in the case of the 2-layer specimen. In comparison, 4-layer and 6-layer FFRP composites showed crossed cracks as initial damage. This can be explained by the difference between thin (2-layer FFRP) and thick (4-layer and 6-layer
FFRP) laminates. Bending was the primary activity for initial damage in thin laminates while shear stress dominates the damage initiation on thick laminates (Abrate et al. 2013). A dent was caused due to bending under impact loading. This confirmed the initial damage of 2-layer FFRP as caused by bending, while matrix cracks were the main reason for Hertzian failure in 4- and 6-layer composites.

(2) Damage to the impact side varied with thickness. Crossed cracks as well as annular cracks were observed in the 2-layer FFRP composite. Micro-cracks were observed in the 4-layer composite, while cracks along the y-axis occurred in the 6-layer composite. Damage to the reverse side was also thickness dependent. Almost the same length of crossed cracks was produced in the cases of 2- and 4-layer composites, while crack lengths along x- and y-axes were different in 6-layer composites. The length of y-axis cracks in the 6-layer samples were double that of these on the x-axis. The differences in damage on the impact side and the reverse side of the specimens can be explained using the fibre failure modes (Richardson and Wisheart 1996). On the impact side, fibre failures occur because of local high stresses and indentation effects, which were mainly governed by the impact forces. On the reverse side, failure occurs due to high bending stresses resulting in the fibres failing in tension. Therefore, the damage patterns were different on the impact and reverse sides of the specimens.

4.2.4.3 Impact resistance

The energy profile method (Sayer et al. 2010) was used to study the impact resistance of FFRP. It describes the relationship between impact energy and absorbed energy. Impact energy ($E_i$) was assumed equal to the kinetic energy prior to contact. An equal-energy line was defined at where the impact energy is fully absorbed, for providing comparison with the practical impact-absorbed energy. The absorbed energy ($E_{ab}$) of a composite can be obtained from the area under the force-deflection curve. Figure 4.15 shows a typical force-deflection relationship for a 2-layer FFRP specimen.
Figure 4.15 Typical force-deflection history for a 2-layer FFRP composite

The FFRP composite without perforation presented a closed force-deflection curve, while the specimen with perforation showed an open curve. In the closed curve, the absorbed energy equals the enclosed area. In the open curve, the curve includes friction that occurred at the end of the impact between the striker and the specimen. This part should not be included in the energy absorbed by the specimen. Therefore, absorbed energy is the area bounded by the curve, the x-axis and an extending line (shown in Figure 4.15).

The energy profiles of 2-, 4- and 6-layer composites are presented in Figures 4.16, 4.17 and 4.18, respectively. The relationship between the impact energy and absorbed energy was always under the equal energy line, which indicates that impact energy cannot be fully absorbed by the FFRP specimen. For the 2-layer composite (Figure 4.16), samples 1, 2 and 3 experienced respectively 10 J, 12 J and 15 J impact. The corresponding energies absorbed were 8 J, 9.25 J and 12.96 J. Of these three specimens, the 3rd specimen experienced perforation. Consequently, when 20 J impact was applied to the 4th specimen, energy absorbed was similar to the 3rd specimen. This indicated that in the cases considered, no more than 15 J of energy was required to perforate the specimen. The results of the experiments also showed that in the first three specimens, the absorbed energy increased with the impact energy from 8 J to 12.96 J. However, the energy absorbed by the 4th specimen was about 13 J, which was almost the same as 3rd specimen. This indicated that, the ability of the FFRP composite to absorb energy did not change when perforation occurred.
Figure 4.16 Energy profile of 2-layer composite

Figure 4.17 shows the relationship between impact energy and absorbed energy for the 4-layer FFRP composite. The impact energy increased from 10 J to 40 J. Specimens 1, 2, 3 and 4 produced non-perforation damage with the rebound of the impact striker. When 30 J impact was applied, specimen 5 was perforated. The absorbed energy for sample 6 was almost the same as that of the 5th specimen.

Figure 4.17 Energy profile of 4-layer composite
Concerning the 6-layer composite (Figure 4.18), the impact energy increased from 10 J to 70 J. For the first six specimens, no perforation was occurred. The 70 J impact on specimen 7 caused perforation, with nearly 60 J of energy absorbed.

![Figure 4.18 Energy profile of 6-layer composite](image)

Perforation energy is a significant parameter that represents the impact resistance of composites. Higher perforation energy indicates higher impact resistance.

As mentioned by Evci and Gülgeç (2012), perforation energy is expressed as:

\[ E_p = E_t - W_f \]  

(4.2)

where \( E_p \) is perforation energy, \( E_t \) is the total energy calculated from the force-deflection curve, \( W_f \) is the energy dissipated by friction force at post-perforation stage (see Figure 4.19).
According to the definition, perforation energy is equivalent to absorbed energy in this study. The perforation energies of the 2-, 4- and 6-layer FFRP composites were calculated to be 12.96 J, 24.13 J and 60.3 J, respectively. Table 4.4 gives the composites perforation energy and the energy dissipated by friction force. Impact resistance of the FFRP composites increases with the thickness as predicted, which was similar to other composites such as carbon or glass.

Table 4.4 Total energy dissipation of FFRP of different thickness

<table>
<thead>
<tr>
<th>Fabric layer</th>
<th>Thickness (mm)</th>
<th>$E_i$ (J)</th>
<th>$E_p$ (J)</th>
<th>$W_f$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.9</td>
<td>15</td>
<td>12.96</td>
<td>1.49</td>
</tr>
<tr>
<td>4</td>
<td>5.3</td>
<td>30</td>
<td>24.13</td>
<td>2.34</td>
</tr>
<tr>
<td>6</td>
<td>7.6</td>
<td>70</td>
<td>60.3</td>
<td>3.90</td>
</tr>
</tbody>
</table>

**4.2.4.4 Discussion of thickness effect on impact behaviour**

From the data analysis in the above sections, the effect of thickness on the impact behaviour of FFRP composites is summarised as follows:

(1) Damage initiation was different due to different composite thicknesses. Dent damage of thin composites (2-layer FFRP) was due to plastic deformation, while in thick composites (4- and 6-layer FFRP) this type of damage was not obvious as they had higher stiffness compared with the 2L-FFRP.

(2) It is observed that the final failure status of 2- and 4-layer composites was similar, i.e. similar perforated area and shape. However, for all 6-layer specimens, the crack along the
warp was much longer than those occurring on the 2- and 4-layer samples. This could be attributed to the influence of nesting during the hand lay-up procedure. The 6-layer FFRP also had a larger damage area, which indicated higher energy absorption ability.

(3) Another parameter discussed here is the ductility index of FFRP composites. The ductility index is defined as (Reid and Zhou 2000):

\[ DI = \frac{E_{\text{prop}}}{E_{\text{init}}}. \]  

(4.3)

where \( E_{\text{prop}} \) is propagation energy, which equals to the energy absorbed in the damage propagation phase. It is calculated from the area under the force-deflection curve, noting the point starts from maximum force till the specimen is perforated (see Figure 4.19). \( E_{\text{init}} \) is the initiation energy calculated from the force-deflection curve, taking note that the point starts from zero till maximum force (see Figure 4.19).

Table 4.5 gives the ductility index of FFRP. It was found that the ductility decreases with thickness. The 2-layer specimens had the highest ductility among these three composites, which produced the largest deflection compared with 4- and 6-layer composites.

<table>
<thead>
<tr>
<th>Fabric layer</th>
<th>Thickness (mm)</th>
<th>( E_{\text{init}} ) (J)</th>
<th>( E_{\text{prop}} ) (J)</th>
<th>Ductility Index (ID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.9</td>
<td>4.94</td>
<td>8.02</td>
<td>1.623</td>
</tr>
<tr>
<td>4</td>
<td>5.3</td>
<td>16.62</td>
<td>7.51</td>
<td>0.452</td>
</tr>
<tr>
<td>6</td>
<td>7.6</td>
<td>42.3</td>
<td>18.0</td>
<td>0.425</td>
</tr>
</tbody>
</table>

**4.2.4.5 Effect of striker diameter on FFRP impact behaviour**

Two different diameters of strikers were applied, i.e. 16 mm and 25 mm, to compare the impact behaviour of FFRP. A number of impact tests were considered to determine perforation impact energy.

Figure 4.20 shows the force-deflection curves of the 2-layer FFRP composite under impact loading with two different strikers. The curves showed a similar trend. Without perforation, the curve is closed (Figure 4.20 (a)), while the curve is open when the specimen is perforated (Figure 4.20 (b)).
Table 4.6 summarizes the test results of 2-layer FFRP composites under different impact energies using two different strikers. The impact energy was 15 J when the 16 mm impact striker perforated the specimen, while 20 J of impact was required to perforate the specimen when the 25 mm impact striker was applied.

Table 4.6 Summary of impact property of 2-layer FFRP composite under impact

<table>
<thead>
<tr>
<th>FFRP thickness (mm)</th>
<th>Striker diameter (mm)</th>
<th>Impact energy (J)</th>
<th>Energy absorbed (J)</th>
<th>Damage observed</th>
<th>Maximum length of crossed crack (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.99</td>
<td>16</td>
<td>12</td>
<td>9.85</td>
<td>Cracks</td>
<td>40</td>
</tr>
<tr>
<td>2.96</td>
<td>16</td>
<td>15</td>
<td>12.96</td>
<td>Perforation</td>
<td>--</td>
</tr>
<tr>
<td>2.90</td>
<td>25</td>
<td>12</td>
<td>7.10</td>
<td>Cracks</td>
<td>47</td>
</tr>
<tr>
<td>2.95</td>
<td>25</td>
<td>15</td>
<td>12.10</td>
<td>Cracks</td>
<td>65</td>
</tr>
<tr>
<td>2.95</td>
<td>25</td>
<td>18</td>
<td>13.48</td>
<td>Cracks</td>
<td>68</td>
</tr>
<tr>
<td>2.97</td>
<td>25</td>
<td>20</td>
<td>16.5</td>
<td>Perforation</td>
<td>--</td>
</tr>
</tbody>
</table>

Damage observed on the FFRP specimens with different striker diameter is shown in Table 4.6. For both strikers, crossed cracks and tiny annular cracks were observed on the specimens in the cases of non-perforation. In the case of the 16 mm diameter striker, the maximum crossed crack length was 40 mm. As for the 25 mm diameter striker, the maximum crossed crack length of specimen was 68 mm. Figure 4.21 shows the damage to 2-layer FFRP composites with 15 J of impact with different striker diameters. It was observed that the specimen perforated when using a 16 mm striker, while it only produced cracks using the 25 mm diameter striker.
Comparing the impact tests using two different sized strikers, the following conclusions can be drawn:

(1) The force-deflection curves were similar induced by the 16 mm and 25 mm diameter strikers;

(2) The impact energy required to perforate the FFRP composite was different depending on the diameter of the striker. The 25 mm striker required larger impact energy (20 J) to punch through the 2-layer specimen compared to the 16 mm diameter striker (15 J);

(3) The energy absorption ability of FFRP was higher when using a 25 mm impact striker compared with that of the 16 mm striker. This is because the larger diameter striker had more contact area with the specimen, where was activated to absorb the impact energy. This can also be proved by the crack development. The crack length was longer when a larger striker was used, which required higher impact energy to punch through the composite.

### 4.2.5 Charpy impact tests of FFRP

#### 4.2.5.1 Charpy impact test

The notched specimens were prepared following the ASTM D6110-10 standard (2010), as shown in Figure 4.22. The dimensions of the 2-, 4- and 6-layer specimens were 125 mm × 12.7 mm with the respective thicknesses of 2.9 mm, 5.2 mm and 7.6 mm. The
Impact resistance is reported in terms of energy absorbed (recorded by the electronic indicator on the Charpy machine) per unit width of the specimen according to the standard. Two different hammers, i.e. 1 J hammer and 5.5 J hammer, were used to investigate impact resistance.

![Charpy impact test instrument and specimen](image)

**Figure 4.22** Charpy impact test instrument and specimen

### 4.2.5.2 Charpy impact test results and discussions

Table 4.7 summarises Charpy test results, i.e. energy absorbed by the specimen and impact resistance. Impact resistance is defined as energy absorbed per unit of specimen width. The results show that both the energy absorbed and impact resistance increased with composite thickness, which was also observed in the drop weight impact results. With fracture the 2-layer specimen absorbed 0.319 J of impact energy. The 4- and 6-layer specimens dissipate 0.625 J and 0.942 J energy, respectively.

<table>
<thead>
<tr>
<th>Fabric layers</th>
<th>Thickness (mm)</th>
<th>Impact energy (J)</th>
<th>Absorbed energy (J)</th>
<th>Impact resistance (J/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.9</td>
<td>1</td>
<td>0.319</td>
<td>110 (7.92)</td>
</tr>
<tr>
<td>2</td>
<td>2.92</td>
<td>5.5</td>
<td>0.328</td>
<td>112 (7.66)</td>
</tr>
<tr>
<td>4</td>
<td>5.3</td>
<td>1</td>
<td>0.625</td>
<td>118 (6.07)</td>
</tr>
<tr>
<td>4</td>
<td>5.35</td>
<td>5.5</td>
<td>0.638</td>
<td>119 (3.73)</td>
</tr>
<tr>
<td>6</td>
<td>7.6</td>
<td>1</td>
<td>0.942</td>
<td>124 (2.02)</td>
</tr>
<tr>
<td>6</td>
<td>7.55</td>
<td>5.5</td>
<td>0.935</td>
<td>123 (7.83)</td>
</tr>
</tbody>
</table>

Table 4.7 Charpy test: Effect of specimen thicknesses and impact energies on the energy absorbed and impact resistance.
Two fitting formulae displayed in Figure 4.23 were used to describe the relationship between $E_{Drop}$ and $t$, $E_{Charpy}$ and $t$, respectively. $E_{Drop}$ is the energy absorbed observed in the drop weight test. $E_{Charpy}$ is the energy absorbed observed in the Charpy test and $t$ is the thickness of the composite. In the drop weight test, the absorbed energy shows an exponential increase with the thickness. The energy absorption of the specimen was influenced by thickness and damage pattern. The damage pattern of the 6-layer specimen was different from that of the 2- and 4-layer specimens, with much longer cracks which lead to a much more energy absorption and a non-linear relationship. In the Charpy test, because of the nature of the test only one damage pattern was found for different thicknesses. The thickness was the only factor that influenced the energy absorption. Consequently, a linear relationship between absorbed energy and thickness was observed.

![Figure 4.23 Relation between energy absorbed and composite thickness](image)

4.3 Dynamic tensile properties of FFRP

Dynamic tensile tests were performed using a high-speed servo-hydraulic testing machine with strain rates of $0.764 \text{ s}^{-1}$ to $135.68 \text{ s}^{-1}$. High-speed camera images were used to study the failure modes of the FFRP. Empirical formulas of dynamic increase factor (DIF) were derived at various strain rates.
4.3.1 Specimens

The 2-layer FFRP laminates were cut into 25 mm by 450 mm coupons. Mild steel tabs were bonded to both sides of the FFRP coupons, as shown in Figure 4.24 a detailed dimension. The gauge length of the specimen for the dynamic tests was 50 mm. As shown in Figure 4.24, the tab on one side was longer than the other, which was grabbed by the fast jaw of the Instron machine during the dynamic testing. The width and the thickness of the gauges were measured at their centres and quarter spans after each FFRP coupon was made. Average width and laminate thickness of the FFRP are listed in Table 4.8.

![Figure 4.24 Schematic view of FFRP samples for dynamic tensile tests](image)

<table>
<thead>
<tr>
<th>Specimen NO.</th>
<th>Actuator speed (m/s)</th>
<th>Gauge length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Strain rate (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_01</td>
<td>0.1</td>
<td>50</td>
<td>25.2</td>
<td>2.92</td>
<td>0.90</td>
</tr>
<tr>
<td>1_02</td>
<td>0.1</td>
<td>50</td>
<td>25.0</td>
<td>2.87</td>
<td>0.87</td>
</tr>
<tr>
<td>1_03</td>
<td>0.1</td>
<td>50</td>
<td>25.4</td>
<td>2.92</td>
<td>0.58</td>
</tr>
<tr>
<td>1_04</td>
<td>0.1</td>
<td>50</td>
<td>24.9</td>
<td>2.96</td>
<td>0.69</td>
</tr>
<tr>
<td>1_05</td>
<td>0.1</td>
<td>50</td>
<td>24.6</td>
<td>2.89</td>
<td>0.78</td>
</tr>
<tr>
<td>2_01</td>
<td>1.0</td>
<td>50</td>
<td>25.4</td>
<td>2.91</td>
<td>8.82</td>
</tr>
<tr>
<td>2_02</td>
<td>1.0</td>
<td>50</td>
<td>25.1</td>
<td>2.88</td>
<td>7.91</td>
</tr>
<tr>
<td>2_03</td>
<td>1.0</td>
<td>50</td>
<td>25.4</td>
<td>2.95</td>
<td>7.37</td>
</tr>
<tr>
<td>2_04</td>
<td>1.0</td>
<td>50</td>
<td>24.7</td>
<td>2.96</td>
<td>5.13</td>
</tr>
<tr>
<td>2_05</td>
<td>1.0</td>
<td>50</td>
<td>25.3</td>
<td>2.85</td>
<td>7.33</td>
</tr>
<tr>
<td>3_01</td>
<td>2.5</td>
<td>50</td>
<td>25.0</td>
<td>2.93</td>
<td>14.38</td>
</tr>
<tr>
<td>3_02</td>
<td>2.5</td>
<td>50</td>
<td>24.8</td>
<td>2.97</td>
<td>20.11</td>
</tr>
<tr>
<td>3_03</td>
<td>2.5</td>
<td>50</td>
<td>25.4</td>
<td>2.82</td>
<td>13.75</td>
</tr>
<tr>
<td>3_04</td>
<td>2.5</td>
<td>50</td>
<td>24.6</td>
<td>2.86</td>
<td>27.50</td>
</tr>
<tr>
<td>3_05</td>
<td>2.5</td>
<td>50</td>
<td>25.6</td>
<td>2.85</td>
<td>18.41</td>
</tr>
<tr>
<td>4_01</td>
<td>5.0</td>
<td>50</td>
<td>25.2</td>
<td>2.92</td>
<td>45.21</td>
</tr>
<tr>
<td>4_02</td>
<td>5.0</td>
<td>50</td>
<td>25.0</td>
<td>2.87</td>
<td>44.60</td>
</tr>
<tr>
<td>4_03</td>
<td>5.0</td>
<td>50</td>
<td>25.4</td>
<td>2.92</td>
<td>58.82</td>
</tr>
<tr>
<td>4_04</td>
<td>5.0</td>
<td>50</td>
<td>24.9</td>
<td>2.96</td>
<td>42.64</td>
</tr>
<tr>
<td>4_05</td>
<td>5.0</td>
<td>50</td>
<td>24.6</td>
<td>2.89</td>
<td>66.66</td>
</tr>
<tr>
<td>5_01</td>
<td>7.5</td>
<td>50</td>
<td>25.1</td>
<td>2.95</td>
<td>78.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>5_02</td>
<td>7.5</td>
<td>50</td>
<td>25.0</td>
<td>2.89</td>
<td>82.86</td>
</tr>
<tr>
<td>5_03</td>
<td>7.5</td>
<td>50</td>
<td>24.8</td>
<td>3.00</td>
<td>85.82</td>
</tr>
<tr>
<td>5_04</td>
<td>7.5</td>
<td>50</td>
<td>25.6</td>
<td>3.10</td>
<td>78.90</td>
</tr>
<tr>
<td>5_05</td>
<td>7.5</td>
<td>50</td>
<td>24.9</td>
<td>2.98</td>
<td>69.52</td>
</tr>
<tr>
<td>6_01</td>
<td>10</td>
<td>50</td>
<td>25.4</td>
<td>2.96</td>
<td>106.70</td>
</tr>
<tr>
<td>6_02</td>
<td>10</td>
<td>50</td>
<td>25.1</td>
<td>2.90</td>
<td>115.80</td>
</tr>
<tr>
<td>6_03</td>
<td>10</td>
<td>50</td>
<td>25.2</td>
<td>2.97</td>
<td>110.00</td>
</tr>
<tr>
<td>6_04</td>
<td>10</td>
<td>50</td>
<td>25.0</td>
<td>3.01</td>
<td>100.30</td>
</tr>
<tr>
<td>6_05</td>
<td>10</td>
<td>50</td>
<td>24.8</td>
<td>2.89</td>
<td>118.00</td>
</tr>
<tr>
<td>7_01</td>
<td>15</td>
<td>50</td>
<td>25.0</td>
<td>2.88</td>
<td>132.50</td>
</tr>
<tr>
<td>7_02</td>
<td>15</td>
<td>50</td>
<td>25.0</td>
<td>2.91</td>
<td>137.20</td>
</tr>
<tr>
<td>7_03</td>
<td>15</td>
<td>50</td>
<td>24.8</td>
<td>3.00</td>
<td>135.70</td>
</tr>
<tr>
<td>7_04</td>
<td>15</td>
<td>50</td>
<td>25.3</td>
<td>2.96</td>
<td>128.00</td>
</tr>
<tr>
<td>7_05</td>
<td>15</td>
<td>50</td>
<td>24.8</td>
<td>3.02</td>
<td>145.00</td>
</tr>
</tbody>
</table>

**4.3.2 Testing apparatus**

The dynamic tensile test was carried out using an Instron VHS 160-20 testing system. The machine applies servo-hydraulic technology, which is capable of providing a controlled testing velocity of up to 25 m/s and a maximum impact load of 100 kN. The room temperature during the test was about 20 ± 5°C.

Figure 4.25 shows the Instron VHS system and specimen set up. The fast jaw can accelerate in the tensile direction until the required velocity is achieved. The wedge is kicked out to release the spring grips which can grab the upper tap and pull the specimen at the required velocity until its fracture. A piezo load cell is installed below the bottom grip head to measure the force. An accelerometer was built on the fast jaw to measure its acceleration. A strain gauge was glued to the centre of each specimen to measure its strain. A data acquisition system with a sampling frequency of 65 kHz was used in the tests. A high-speed camera (Fastcam SA1.1 by Photron) was applied to record the failure process of the specimens with a frequency of 30,000 fps. In the dynamic tests, actuator speeds were set as 0.1 m/s, 1 m/s, 2.5 m/s, 5 m/s, 7.5 m/s, 10 m/s and 15 m/s, with the corresponding strain rates of about 0.764 s⁻¹, 7.312 s⁻¹, 18.33 s⁻¹, 51.586 s⁻¹, 79.12 s⁻¹, 110.16 s⁻¹ and 135.68 s⁻¹.
4.3.3 Dynamic tensile test results and discussions

4.3.3.1 Force-time history under various strain rates

Figure 4.26 presents the force-time histories under various tensile loading speeds. Figure 4.26 (a) shows the force-time curve of the static test, with a total response time of about 57 s. Figure 4.26 (b) displays the force-time history with 0.1 m/s tensile speed, over a period of about 28 ms. The force-time curves of 1 m/s, 2.5 m/s, 5 m/s, 7.5 m/s, 10 m/s and 15 m/s are displayed in Figure 4.26 (c) and (d), respectively. It can be observed that duration shortened significantly with an increase in tensile speed. With the speed of 15 m/s, the force duration was less than 0.2 ms. This indicates that the tensile force duration of 2-layer FFRP specimens is obviously strain rate sensitive.
4.3.3.2 Tensile results at various strain rates

Table 4.9 summarises the results obtained from the tensile tests of FFRP at various strain rates, showing the tensile strength increased with strain rate. The strength was 24.96 MPa at the strain rate of 0.764 s\(^{-1}\). The value increased to about 34.19 MPa at the strain rate of 79.12 s\(^{-1}\). When the strain rate increased to 135.68 s\(^{-1}\), the tensile strength reached up to 46.35 MPa.

Table 4.9 Summary of results in the dynamic tensile tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Strain rate (s(^{-1}))</th>
<th>Failure strain (mm/mm)</th>
<th>Peak force (kN)</th>
<th>Tensile strength (MPa)</th>
<th>Dynamic increase factor (DIF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_01</td>
<td>0.900</td>
<td>0.020</td>
<td>1.746</td>
<td>23.73</td>
<td>0.88</td>
</tr>
<tr>
<td>1_02</td>
<td>0.870</td>
<td>0.021</td>
<td>1.849</td>
<td>25.77</td>
<td>0.95</td>
</tr>
<tr>
<td>1_03</td>
<td>0.580</td>
<td>0.023</td>
<td>1.879</td>
<td>25.33</td>
<td>0.94</td>
</tr>
<tr>
<td>1_04</td>
<td>0.690</td>
<td>0.017</td>
<td>2.010</td>
<td>27.27</td>
<td>1.01</td>
</tr>
<tr>
<td>1_05</td>
<td>0.781</td>
<td>0.018</td>
<td>1.615</td>
<td>22.72</td>
<td>0.84</td>
</tr>
<tr>
<td>Average</td>
<td>0.764</td>
<td>0.020</td>
<td>1.820</td>
<td>24.96</td>
<td>0.92</td>
</tr>
<tr>
<td>2_01</td>
<td>8.821</td>
<td>0.020</td>
<td>2.077</td>
<td>28.10</td>
<td>1.04</td>
</tr>
<tr>
<td>2_02</td>
<td>7.910</td>
<td>0.022</td>
<td>1.879</td>
<td>25.99</td>
<td>0.96</td>
</tr>
<tr>
<td>2_03</td>
<td>7.371</td>
<td>0.017</td>
<td>1.904</td>
<td>25.41</td>
<td>0.94</td>
</tr>
<tr>
<td>2_04</td>
<td>5.130</td>
<td>0.022</td>
<td>2.257</td>
<td>30.87</td>
<td>1.14</td>
</tr>
<tr>
<td>2_05</td>
<td>7.330</td>
<td>0.017</td>
<td>1.835</td>
<td>25.45</td>
<td>0.94</td>
</tr>
<tr>
<td>Average</td>
<td>7.312</td>
<td>0.020</td>
<td>1.990</td>
<td>27.16</td>
<td>1.00</td>
</tr>
<tr>
<td>3_01</td>
<td>14.38</td>
<td>0.017</td>
<td>1.867</td>
<td>25.49</td>
<td>0.94</td>
</tr>
<tr>
<td>3_02</td>
<td>20.11</td>
<td>0.020</td>
<td>2.296</td>
<td>31.17</td>
<td>1.15</td>
</tr>
<tr>
<td>3_03</td>
<td>13.75</td>
<td>0.027</td>
<td>2.142</td>
<td>29.90</td>
<td>1.11</td>
</tr>
<tr>
<td>3_04</td>
<td>27.50</td>
<td>0.022</td>
<td>2.208</td>
<td>31.38</td>
<td>1.16</td>
</tr>
<tr>
<td>3_05</td>
<td>18.41</td>
<td>0.019</td>
<td>2.790</td>
<td>38.24</td>
<td>1.42</td>
</tr>
<tr>
<td>Average</td>
<td>18.33</td>
<td>0.021</td>
<td>2.261</td>
<td>31.24</td>
<td>1.16</td>
</tr>
<tr>
<td>4_01</td>
<td>45.21</td>
<td>0.026</td>
<td>2.060</td>
<td>27.95</td>
<td>1.03</td>
</tr>
<tr>
<td>4_02</td>
<td>44.60</td>
<td>0.019</td>
<td>2.340</td>
<td>32.61</td>
<td>1.21</td>
</tr>
</tbody>
</table>

Figure 4.26 Force-time histories of FFRP under various strain rates
### 4.3.3.3 Strain rate effect on tensile strength, failure strain and dynamic increase factor

The tensile strength of 2-layer FFRP at various strain rates are plotted in Figure 4.27 (a). Strength did not show much variation at low strain rates. A significant increase in strength was observed when the strain rate was over 79.12 s\(^{-1}\). Similar to carbon fibre reinforced polymer (Zhang et al. 2016), tensile strength was highly dependent on the strain rate, which had a significant increment with high strain rates.

![Figure 4.27 (a)](image1.png)  
![Figure 4.27 (b)](image2.png)
Figure 4.27 (b) shows the effect of strain rate on failure strains. The failure strains in the low strain rate range, i.e. less than 79.12 s\(^{-1}\), were around 0.02. Similar to the relationship between the strength and strain rate as described in Figure 4.27 (a), apparent higher failure strain can be observed, which increased with strain rate when it exceeded 79.12 s\(^{-1}\). The failure strain increased to about 0.026 when the strain rate reached 110.16 s\(^{-1}\). The value was about 0.027 when the strain rate was 135.68 s\(^{-1}\).

Dynamic increase factor (DIF), a ratio of dynamic strength over static strength, is used to distinguish a material’s behaviour at various strain rates. Figure 4.27 (c) shows the relationship between DIFs and strain rates, which can be expressed by the following empirical equations:

\[
DIF = 0.01 \log_{10} (\dot{\varepsilon}) + 1.125, \quad \dot{\varepsilon} < 79.12 \text{s}^{-1} \tag{4.4}
\]

\[
DIF = 1.08 \log_{10} (\dot{\varepsilon}) - 0.6, \quad \dot{\varepsilon} \geq 79.12 \text{s}^{-1} \tag{4.5}
\]

where \(\dot{\varepsilon}\) is the strain rate.

**4.3.3.4 Failure process**

Figure 4.28 shows the dynamic failure process of 2-layer FFRP at the strain rates of 0.764 s\(^{-1}\), 51.59 s\(^{-1}\) and 110.16 s\(^{-1}\), respectively. For the strain rate 0.764 s\(^{-1}\) (Figure 4.28 (a)), apparent tension of the specimen was observed at 10 ms, with the stretch of the flax fabric and epoxy. At 13.6 ms cracks were starting to be generated. A critical crack was formed at about 16.3 ms when the specimen split into two pieces. As for the case of the 51.59 s\(^{-1}\)
strain rate (Figure 4.28 (b)), obvious tension damage started to occur at 1.0 ms, and the failure was occurred at 1.57 ms, with damage occurring faster than the case of 0.764 s\(^{-1}\). Figure 4.28 (c) depicts the failure process of FFRP at the high strain rate of 110.16 s\(^{-1}\). Different from the low strain rate tensile tests as shown in Figure 4.28 (a-b), fracture of the specimens occurred in a shorter time, i.e. less than 1 ms.
Figure 4.28 High-speed camera images of FFRP specimen failure process at strain rates of 0.764 s\(^{-1}\), 51.59 s\(^{-1}\) and 110.16 s\(^{-1}\).

Figure 4.29 displays the failure modes of FFRP at various strain rates to investigate their differences. In all cases, cross-sectional fracture was observed. Single critical fracture perpendicular to the loading direction was generated by strain rates less than 79.12 s\(^{-1}\). FFRP specimens were fractured by tensile failure of fibre close to the centre of the specimen gauge length. However, at high strain rates, i.e. 110.16 s\(^{-1}\) and 135.68 s\(^{-1}\), multiple cross-sectional fractures were formed. The specimen eventually split into three segments at the two cracks, which can be clearly observed at the strain rate 135.68 s\(^{-1}\).

Compared to the single cross-sectional fracture mode at low strain rates, the multiple fractures consumed more energy, leading to higher tensile strength. The failure mode for FFRP was different to that of CFRP at high strain rates. The study by Zhang et al. (2016) demonstrated the failure mode of CFRP also being mainly diagonal cracks and multiple failure planes.
Fracture

Crack
The properties of flax fibre reinforced polymer (FFRP) composites under static, impact loading and dynamic tensile loading have been investigated experimentally. The study reveals that:

1. The damage to the FFRP was due to the fibre pull-out for tensile tests.

2. Impact force and Hertzian force increased significantly with composite thickness. However, in the cases considered, the impact force and the Hertzian force for a particular thickness have similar values independent of impact energy.

3. FFRP composites of greater thickness require higher perforation energy.

4. Damage to FFRP composites differs with thickness. Rebounding of the impactor, dented surfaces and perforations were observed on the 2-layer specimen, while only cracks and perforation were observed on the 4-layer and 6-layer specimens. Damage area increases with thickness. Longer cracks occur in 6-layer composites, associated with a higher impact resistance than those of 2-layer and 4-layer composites.

5. Striker diameter has a significant effect on the impact resistance of FFRP composite. The larger diameter of striker resulted in larger impact energies required to perforate and greater energy absorbed. In the case of the 2-layer FFRP composite under the impact, about 20J of impact energy is required with the 25 mm diameter striker, while 15J of impact energy is required with the 16 mm diameter striker.

6. The tensile properties of FFRP were strain rate dependent. The tensile strength, failure strain and DIF were found to increase significantly when the strain rate exceeded 135.68 s\(^{-1}\).

Figure 4.29 High-speed camera images of 2-layer FFRP specimen failure process at strain rates from 0.764 s\(^{-1}\) to 135.68 s\(^{-1}\)
79.12 s\(^{-1}\). However, under static and low strain rates, there was not much noticeable increase in the mechanical properties. Empirical formulas for DIF for FFRP laminates were derived based on testing results. Single critical fracture perpendicular to the loading direction was generated for the strain rates less than 79.12 s\(^{-1}\). While at the high strain rates, i.e. 110.16 s\(^{-1}\) and 135.68 s\(^{-1}\), multiple cross-sectional fractures formed. The specimen split into three segments through two cracks, which was clearly observed at the strain rate of 135.68 s\(^{-1}\).
Chapter 5

Impact properties of coconut fibre reinforced concrete

Related paper:


Natural fibres have been considered as potential construction materials due to their advantages of costless, environmental-friendly and good performance. However, the study on the impact behaviour of natural fibre reinforced concrete composites has not been conducted thoroughly.

This chapter presents the response of coconut fibre reinforced concrete (CFRC) cylinders under single and repeated drop weight impact loadings. The effect of coconut fibre length on the impact properties was investigated. In the single impact test, the history of impact force, change of Young’s moduli and the dynamic increase factor (DIF) of CFRC were investigated. The damage pattern of PC and CFRC was compared. In the repeated drop weight tests, the effect of impact height on the maximum compressive stress and damage pattern was evaluated. The relationship between impact height and maximum impact stress was examined and an empirically derived equation was proposed.

5.1 Coconut fibre and coconut fibre reinforced concrete composite

5.1.1 Coconut fibre

Coconut fibre, or coir, is a natural fibre extracted from coconut fruit husks. It is abundantly available in tropical areas. India and Sri Lanka are the main exporters of coconut fibres (Baruah and Talukdar 2007). Coconut fibres come in two varieties, i.e. brown and white coir. Brown fibre is extracted from ripe coconuts, and is thick and strong.
While white fibre is extracted from immature coconuts, and is smoother and finer. In engineering brown fibres are mostly commonly used (Gu 2009). Coconut fibre has many advantages, e.g. moth-proof, fungi and rots resistant, flame-retardant, provides excellent insulation against temperature and sound, amenable to chemical modification (Hemsri et al. 2012). Moreover, it has the highest ductility of all natural fibres (Rout et al. 2001).

Based on previous studies, the physical and mechanical properties of coconut fibres are summarised in Table 5.1.

![Table 5.1 Physical and mechanical properties of coconut fibre](image)

<table>
<thead>
<tr>
<th>References</th>
<th>Diameter (mm)</th>
<th>Density (kg/m³)</th>
<th>Elastic modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggarwal (1992)</td>
<td>0.1-0.4</td>
<td>145-280</td>
<td>19-26</td>
<td>100-130</td>
<td>130-180</td>
</tr>
<tr>
<td>Reis (2006)</td>
<td>0.1-0.4</td>
<td>-</td>
<td>16-26</td>
<td>174</td>
<td>-</td>
</tr>
<tr>
<td>Fernandez (2002)</td>
<td>-</td>
<td>1200</td>
<td>4-6</td>
<td>175</td>
<td>-</td>
</tr>
<tr>
<td>Dittenber and GangaRao (2012)</td>
<td>0.1-0.46</td>
<td>1150-1460</td>
<td>2.8-6</td>
<td>95-230</td>
<td>-</td>
</tr>
<tr>
<td>Ali (2013)</td>
<td>0.15-0.35</td>
<td>1120</td>
<td>0.58-1.24</td>
<td>47.3-106</td>
<td>-</td>
</tr>
<tr>
<td>Yan and Chouw (2013)</td>
<td>0.25</td>
<td>1200</td>
<td>2.74</td>
<td>286</td>
<td>-</td>
</tr>
</tbody>
</table>

5.1.2 Coconut fibre reinforced concrete (CFRC)

CFRC is a new natural fibre reinforced concrete composite which has been studied in recent years (Ali et al. 2012; Ramli et al. 2013; Dhandhania and Sawant 2014; Ali 2016). The use of coconut fibre in concrete materials offers many advantages, i.e. economical compared with other fibres such as carbon, glass and steel, lightweight, enhances tensile strength and is crack resistant. It has been suggested that CFRC be used in earthquake prone areas where frequent damage to infrastructure takes place (Dhandhania and Sawant 2014).

In this research the CFRC composite consists of ordinary cement, sand, gravel, water, and brown coconut fibres imported from Indonesia (Figure 5.1).
The sand used was sourced from the Winstone Aggregates Helensville Plant, New Zealand. The diameter range of the gravel was 7-13 mm. The coconut fibres were from the same source as those adopted by Yan and Chouw (2013), the properties of which can be found in Table 5.1. During the fibre preparation, cutting to intended fibre length and dust removal was undertaken. Details of preparation of the coconut fibres are shown in the flowchart in Figure 5.2, and were similar from the description in previous work by Ali et al. (2012). The physical properties of the gravel and sand are displayed in Table 5.2.

![Coconut fibre](image1.png)

![Micrograph of a coconut fibre](image2.png)

**Figure 5.1 Coconut fibres**

**Figure 5.2 Preparation of the coconut fibres**
Studies on impact properties of CFRC are not easily found in existing research. Therefore, this research will explore the impact properties of CFRC.

### 5.2 Experimental work

#### 5.2.1 Specimens preparation

The experimental specimens were plain concrete (PC) and coconut fibre reinforced concrete (CFRC) cylinders, with a design compressive strength of 30 MPa. For PC, the mix ratio by mass was 1:0.48:2:2 for cement: water: sand: gravel, respectively. The cement used was Golden Bay Cement’s premium Portland cement. The coconut fibre content with 1.5% of the cement mass was selected as an example, corresponding to an approximate fibre volume content of 0.6%. Three lengths of the fibres were used, i.e. 25 mm, 50 mm an 75 mm. The CFRC was designed the same as that of plain concrete, except that the fibres were added to the mixture, and the same amount of aggregate by mass was deducted from the total weight of the aggregate. The detailed mix ratio of CFRC was listed in Table 5.3. All the specimens were cured in a concrete curing room for 28 days before testing.

### Table 5.3 Mix ratio of the compositions

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>Water/cement ratio</th>
<th>Cement content (kg/m³)</th>
<th>Gravel (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>0.48</td>
<td>432.5</td>
<td>865</td>
<td>865</td>
<td>40</td>
</tr>
<tr>
<td>CFRC-25</td>
<td>0.52</td>
<td>423.9</td>
<td>835.3</td>
<td>835.3</td>
<td>37</td>
</tr>
<tr>
<td>CFRC-50</td>
<td>0.52</td>
<td>423.9</td>
<td>835.3</td>
<td>835.3</td>
<td>35</td>
</tr>
<tr>
<td>CFRC-75</td>
<td>0.52</td>
<td>423.9</td>
<td>835.3</td>
<td>835.3</td>
<td>35</td>
</tr>
</tbody>
</table>

A concrete mixer was used to prepare both PC and CFRC. For PC, all materials were put into the drum and rotated for three minutes. A slump test was carried out and the measured slump was about 40 mm.
For casting CFRC composites, the hand lay-up method was applied to separate the coconut fibres uniformly. Firstly, a layer of gravel was spread in the container, followed by a layer of sand, fibres, and cement. This process was repeated until all the materials are placed into the mix pan. Secondly, the mixture was rotated for 90 seconds. Then half of water was added to the mix, and the mixture was rotated for another 2 minutes. At this stage, the CFRC was not workable. Finally, the rest of the water was added to the mix in the pan, and the mixture was rotated for another 90 seconds to ensure the material was thoroughly mixed and the components distributed evenly through the mix. The average slump test was about 35 mm.

Cylinders with the size of 200 mm x 100 mm were prepared for both PC and CFRC. A set of at least three samples for each particular test was prepared.

5.2.2 Testing procedure

5.2.2.1 Static test

In total, 12 cylinders were tested. Of these, three were PC cylinders, three of CFRC specimens with 25 mm of coconut fibre (CFRC-25), three of CFRC specimens with 50 mm of coconut fibre (CFRC-50) and three of CFRC specimens with 75 mm of coconut fibre (CFRC-75). These specimens were tested using a compressive test machine to obtain their respective compressive strengths and static moduli of elasticity (Figure 5.3). Before testing, each cylinder was capped with plaster to ensure the compressive load was uniformly distributed over the end surfaces. The testing was carried out using the ASTM C39/C39M Standard test method (2004).

![Compressive test set up](image-url)
5.2.2.2 Impact test

Drop weight tests on CFRC cylinders (Figure 5.4) were carried out as follows. The specimen was prepared, and strain gauges were attached to the specimen. The dynamic load cell on the strong floor, was then set up, and the specimen placed on top of the load cell. The load cell and strain gauges were then linked to the data logger system. The 40 kg impact mass is raised to the desired height, and released to fall and strike the specimen. In the single impact test, only one drop was conducted on the specimen, while several drops were carried out on the same specimen in the repeated testing.

Figure 5.4 Drop weight impact test set up for CFRC cylinders

5.3 Results and Discussion

5.3.1 Static compressive test

Table 5.4 lists the compressive strengths as well as the elasticity moduli of PC and CFRC.

Table 5.4 Static test results of PC and CFRC

<table>
<thead>
<tr>
<th>Concrete type</th>
<th>Fibre length (mm)</th>
<th>Moduli of elasticity (GPa)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>--</td>
<td>32.6</td>
<td>34.07</td>
</tr>
<tr>
<td>CFRC-25</td>
<td>25</td>
<td>31.1</td>
<td>33.98</td>
</tr>
<tr>
<td>CFRC-50</td>
<td>50</td>
<td>31.9</td>
<td>32.18</td>
</tr>
<tr>
<td>CFRC-75</td>
<td>75</td>
<td>31.02</td>
<td>32.07</td>
</tr>
</tbody>
</table>
5.3.2 Test results of single impact

5.3.2.1 Impact force-time curves

This section investigated the change of the Young’s moduli before and after impact loading. PC and CFRC with a fibre length of 50 mm (CFRC-50) were tested. Three different heights, i.e. 40 cm, 60 cm and 80 cm, were considered in this series of tests. As the specimens started to occur large non-elastic deformation when the drop height was larger than 80 cm, less than 80 cm of drop height has only been considered.

The force recorded from the load cell is defined as the impact force. The maximum impact stress is calculated from the maximum impact force divided by the cross-sectional area. Figures 5.5 and 5.6 present the impact force history of the PC and CFRC-50, respectively. The impact duration was about 0.003 s for both types of cylinders. The maximum impact force typically occurred at around 0.001 s from the first moment of impact. Considering the speed of wave in concrete (about 3500 m/s) and the height of the specimen (200 mm), it should take about $6 \times 10^{-5}$ s for the first stress wave to reach the load cell. This could be attributed that there were some small reflections or reverberations before the peak was reached. These reflections have not been able to be recorded due to the sensitivity of the measurement system. For both PC and CFRC-50, the peak impact force increased with the increment of the drop height. With the same impact height, the impact force showed a similar value for both specimens. With the height of 40 cm, the impact force was about 80 kN. The values were about 110 kN and 140 kN for the 60 cm and 80 cm impact, respectively.
5.2.2 Calculation of Young’s Moduli of PC and CFRC cylinders from impact loading

Material properties, such as the moduli of elasticity and strength, are usually used to identify damage in materials. Here, moduli of elasticity were used to discuss the damage situation under drop weight loading. Damage index $D$ was defined:

$$D = \frac{\Delta E}{E_0}$$  \hspace{1cm} (5.1)
where \( \Delta E = E_0 - E_1 \) is the change of elasticity moduli due to impact, \( E_0 \) is the original elasticity moduli of the intact concrete cylinder, obtained from static compressive testing, and \( E_1 \) is the elastic moduli of the cylinder which has been impacted by the free falling mass. Young’s moduli are defined as the secant moduli at one-third of the failure stress.

Table 5.5 shows the damage index of the PC and CFRC-50 specimens under impact loads of associated with falls of 40 cm and 60 cm. The results indicated that both types of specimens experienced reductions of their respective elastic moduli. For the PC specimens, reductions of 8.3% and 13.8% in elastic moduli occurred, corresponding to 40 cm and 60 cm of drop weight. The CFRC-50 specimens had similar reductions in Young’s moduli, with 6% (under 40 cm of drop height) and 14% (under 60 cm of drop height), respectively.

Table 5.5 Comparison of Young’s moduli before and after impact loading

<table>
<thead>
<tr>
<th>Concrete type</th>
<th>Impact Height (cm)</th>
<th>Young’s moduli before impact ((E_0, \text{GPa}))</th>
<th>Young’s moduli after impact ((E_1, \text{GPa}))</th>
<th>Damage index ((\frac{(E_0-E_1)}{E_0} %))</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>40</td>
<td>32.6 (1.57)</td>
<td>29.88 (1.67)</td>
<td>8.3</td>
</tr>
<tr>
<td>PC</td>
<td>60</td>
<td>32.6 (1.57)</td>
<td>28.08 (2.71)</td>
<td>13.8</td>
</tr>
<tr>
<td>CFRC-50</td>
<td>40</td>
<td>31.9 (2.07)</td>
<td>30 (2.41)</td>
<td>6</td>
</tr>
<tr>
<td>CFRC-50</td>
<td>60</td>
<td>31.9 (2.07)</td>
<td>27.46 (0.82)</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are standard deviations.

However, the damage pattern was found to be distinctly different between these two materials. There was no apparent damage to both the PC and CFRC specimens when 40 cm impact was applied. However, visible damage to the exterior of the specimens was noticed when larger impact heights, such as 60 cm and 80 cm, were applied. Figure 5.7 shows the damage to PC and CFRC-50 specimens under impacts with heights of 60 cm and 80 cm, respectively. The PC specimen developed cracks and small-scale of spalling under the drop height of 60 cm. In comparison, the damage to the CFRC-50 specimen was minor. Facial cracks with lengths of around 3 cm were observed and several concrete fragments peeled under impact from the height of 60 cm. For the 80 cm of impact, the CFRC-50 specimen incurred less severe damage compared with that of the PC specimen. The PC cylinder presented large sized cracks and large scale spalling, resulting in a reduction of the contact area. However, for the CFRC-50 cylinder from the 80 cm impact, a single long facial crack of about 10 cm and minor spalling was observed. The reason
for the reduced damage to the PC specimens is attributed to the presence of coconut fibre in the CFRC-50. Coconut fibres were distributed in the CFRC-50 specimens, with the intention that both the development of cracks and damage from spalling would be reduced.

![PC and CFRC specimens](image)

Figure 5.7 Influence of the impact heights on the damage patterns of PC and CFRC specimens

### 5.3.3 Dynamic Increase Factor (DIF) of CFRC

The compressive strength of concrete under impact loading is different from that under static loading. Previous studies have used DIF as a parameter to quantify the change in compressive strength under impact loading. This section discussed the DIF of CFRC to find out the effect of impact on the strength of the CFRC composites. A drop weight of 50 kg and a height of 2 m were adopted. The DIF is defined as the ratio of the compressive strength under impact loading to the corresponding static compressive strength. In addition to the DIF obtained from experiments, the Euro-International Committee for Concrete (CEB) model (1993) was used to predict the DIF of CFRC.
The determination of DIF for compressive testing in the CEB model is given as follows:

\[
DIF = \frac{f_{cd}}{f_{cs}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1.026a}, \text{ for } \dot{\varepsilon} \leq 30s^{-1} \tag{5.2}
\]

\[
DIF = \frac{f_{cd}}{f_{cs}} = \gamma_s \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3}, \text{ for } \dot{\varepsilon} > 30s^{-1} \tag{5.3}
\]

where:

- \(f_{cd}\) is dynamic compressive strength at \(\dot{\varepsilon}\)
- \(f_{cs}\) is static compressive strength at \(\dot{\varepsilon}_s\)
- \(\frac{f_{cd}}{f_{cs}}\) is compressive strength dynamic increase factor (DIF)
- \(\dot{\varepsilon}\) is strain rate in the range of \(30 \times 10^{-6} \text{s}^{-1}\) to \(300\text{s}^{-1}\)
- \(\dot{\varepsilon}_s\) is static strain rate, \(30 \times 10^{-6} \text{s}^{-1}\)
- \(\gamma_s = 10^{(6.156a_1 - 2)}\)
- \(a_s = 1/(5 + 9f_{cd}/f_{co})\)
- \(f_{co} = 10\text{MPa} = 1450\text{psi}\)

Here, the strain rate \(\dot{\varepsilon}\) is defined as the axial strain at the maximum strength divided by the time taken to reach this value (Bischoff and Perry 1995). Table 5.6 displays DIF values obtained from the experiments, compared with those calculated from Equations (5.2) and (5.3). It can be seen that the concrete compressive strength is significantly different under static force and impact force. From the experiments the DIF was found to be around 1.2. Thus concrete strength under impact loading is observably higher than that under static loading. This is due to strain rate considerations. The strain rate is about \(6 \times 10^{-5}\text{ s}^{-1}\) under the condition of static loading, while it is about \(2\text{ s}^{-1}\) in the case of impact loading. This result aligns well with the results obtained in most of the previous research. Malgorzata (2011) summarised the strain rate effect on compressive strength of concrete, in which it was found that the DIF varies between 1 and 2 if the strain rate is \(1\text{~}10\text{ s}^{-1}\).
Table 5.6 Experimental and calculated DIF values for CFRC

<table>
<thead>
<tr>
<th></th>
<th>CFRC-25</th>
<th>CFRC-50</th>
<th>CFRC-75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static compressive strength (MPa)</td>
<td>33.98 (1.88)</td>
<td>32.18 (2.38)</td>
<td>32.07 (3.30)</td>
</tr>
<tr>
<td>Strain rate for static test (10^{-5} s^{-1})</td>
<td>5.66</td>
<td>6.1</td>
<td>5.95</td>
</tr>
<tr>
<td>Dynamic compressive strength (MPa)</td>
<td>40.44 (2.40)</td>
<td>40.54 (3.05)</td>
<td>37.84 (1.61)</td>
</tr>
<tr>
<td>Strain rate for impact test (s^{-1})</td>
<td>1.73</td>
<td>2</td>
<td>1.35</td>
</tr>
<tr>
<td>DIF (Experimental)</td>
<td>1.19 (0.07)</td>
<td>1.26 (0.09)</td>
<td>1.18 (0.05)</td>
</tr>
<tr>
<td>DIF (Calculated using CEB Model)</td>
<td>1.36</td>
<td>1.39</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are standard deviations.

This natural fibre reinforced concrete has similar impact behaviour as normal concrete (Bischoff and Perry 1995), i.e. the compressive strength increasing with the strain rate. A comparison of the results of all the CFRC specimens with similar compressive strength indicated that the length of the coconut fibres had minimal influence on the behaviour of CFRC composites under drop weight loading.

5.3.4 Test results of repeated impact

In this section, repeated impact tests on CFRC-25, CFRC-50 and CFRC-75 specimens are described.

The repeated tests were carried out using a drop weight of 40 kg. However, different drop heights were adopted, and the heights were increased until significant crushing damage to the specimens took place. The value of the impact failure energy is obtained from the following expression:

\[ W = P(h_1 + h_2 + \cdots + h_n) \]  

(5.4)

where \( W \) is the impact failure energy, \( P \) is the drop weight of 392 N, \( h_1 \) the first drop height (50 cm), \( h_2 = 2h_1 \), and \( h_n = nh_1 \), where \( h_n \) is the drop height associated with the final strike.

5.3.4.1 Time history of impact force

Figures 5.8-5.10 respectively show the impact force history of CFRC-25, CFRC-50, CFRC-75 specimens under repeated loadings. The impact duration was about 0.004 s, and the maximum impact force occurred between 0.001 s and 0.002 s. The reason of the
time to peak value was similar as that of Figure 5.5-5.6, which has been explained in section 5.3.2.1.

For the different types of specimens, the number of blows required to cause crushing was different. As for the CFRC-25 and CFRC-50 specimens, four blows of the drop weight were applied. Crushing appears when the impact height was 200 cm. On the other hand, only three blows were needed to crush the CFRC-75 specimens which mean the last impact was up to 150 cm.

Figure 5.8 Effect of impact height on force time history of CFRC-25 under repeated test

Figure 5.9 Effect of impact height on force time history of CFRC-50 under repeated test
Table 5.7 summarises the maximum values of impact forces, stresses, and strains under different drop heights. The maximum impact forces were 158.8 kN, 170 kN and 141.8 kN for CFRC-25, CFRC-50 and CFRC-75, respectively. For the CFRC-25 and CFRC-50, the impact force increased with the drop height increment when drop heights are less than 150 cm. The impact forces resulting from 150 cm and 200 cm of drop weight were found to be close to one another. This can be explained by the way in which damage was observed to develop in the specimens (refer next section for a detailed discussion of damage development).

Table 5.7 Summary of repeated impact test results

<table>
<thead>
<tr>
<th>Fibre length (mm)</th>
<th>Height (cm)</th>
<th>Impact energy (Nm)</th>
<th>Impact Force (kN)</th>
<th>Maximum Stress (MPa)</th>
<th>Maximum Strain (µε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>50</td>
<td>196.2</td>
<td>96.6</td>
<td>12.30 (1.18)</td>
<td>274</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>392.4</td>
<td>116.3</td>
<td>15.82 (1.87)</td>
<td>656</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>588.6</td>
<td>158.8</td>
<td>20.23 (2.71)</td>
<td>986</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>784.8</td>
<td>158.7</td>
<td>20.22 (2.12)</td>
<td>--</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>196.2</td>
<td>79.2</td>
<td>10.90 (1.51)</td>
<td>371</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>392.4</td>
<td>139.5</td>
<td>17.80 (2.98)</td>
<td>581</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>588.6</td>
<td>162.9</td>
<td>20.75 (2.31)</td>
<td>829</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>784.8</td>
<td>170</td>
<td>21.66 (2.41)</td>
<td>1219</td>
</tr>
<tr>
<td>75</td>
<td>50</td>
<td>196.2</td>
<td>88.1</td>
<td>11.75 (1.72)</td>
<td>785</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>392.4</td>
<td>118.1</td>
<td>15.04 (2.21)</td>
<td>912</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>588.6</td>
<td>141.8</td>
<td>18.06 (1.80)</td>
<td>1572</td>
</tr>
</tbody>
</table>

[Note] Values in parentheses are standard deviations.
For the CFRC-25 mm and CFRC-50 specimens, the relationship between compressive stress and drop height was similar. For the first three impacts, at drop heights of 50 cm, 100 cm and 150 cm, the maximum stress increased with the height, going from 11 MPa for 50 cm, to 21 MPa for 150 cm. The maximum stress at the fourth impact (h=200 cm) was close to that of the third impact, with the specimen crushed under this stress. In contrast, CFRC-75 experienced crushing at the third impact.

From the results, an equation to estimate relationship between impact height and maximum impact stress of CFRC-25 and CFRC-50, was proposed.

$$\sigma_{efrc_{-s}} = 2.14h^{0.4484}$$  \hspace{1cm} (5.5)

where \( \sigma_{efrc_{-s}} \) is the maximum stress, and \( h \) is the impact height.

Figure 5.11 displays the relationship between maximum impact stress and drop height. It is found that the maximum stress for CFRC-75 was smaller than other the two types.

For the relationship of CFRC-75 a reduction factor (0.95) was applied.

$$\sigma_{efrc_{-l}} = 0.95 \times 2.14h^{0.4484}$$  \hspace{1cm} (5.6)

where \( \sigma_{efrc_{-l}} \) is the maximum stress, \( h \) is the impact height. It is noting that the already damaged samples were not further crushed in the repeated tests in developing the empirical equations (5.5) and (5.6).
5.3.4.2 Damage mechanism

The damage pattern was similar for the three types of specimens (see Figure 5.12). All specimens were crushed into two pieces. The angle of the crushing plane was around 70°. The similarity of observed damage suggested that the coconut fibre length did not affect the damage pattern of CFRC.

![Image](image1)

Figure 5.12 Views of failure of CFRC with different fibre lengths

The damage to CFRC-50 specimen is presented in Figure 5.13. With the first impact of 50 cm drop height (Figure 5.13 (a)), only two small cracks of about 1.5 cm long occurred at the upper part of the specimen. With the second impact of 100 cm drop height (Figure 5.13 (b)), the length of the cracks developed to about 2.7 cm, and a small part of the specimen started to spall. The cracks continued to grow in length with the third impact (Figure 5.13 (c)), and part of the specimens experienced crushing. At the last impact (Figure 5.13 (d)), the failure was observed, where the specimen was crushed into two halves along the diagonal crack.

![Image](image2)

Figure 5.13 Consequences of impact height for the damage to CFRC-50 specimens
There were three damage levels for the specimen, i.e. light damage stage with facial crack, severe damage stage with long crack or large-scale spalling damage, and structural failure stage. The specimen experienced light damage when the impact height under 100 cm, as shown in Figure 5.13 (a) and Figure 5.13 (b). In this stage, it still had ability to resist larger impact force. The specimen reached the load bearing limitation in severe damage stage, like Figure 5.13 (c). After this stage, the impact force did not increase. This can help to explain the phenomenon of the increasing trend in impact force in Table 5.5, i.e. the impact force showed increase trend when the impact height increased from 50 cm to 150 cm, while the impact force of the 200 cm was close to the case of 150 cm.

The failure pattern of CFRC was different under static and impact loadings. Bishop and Perry (1993) mentioned two types of failure, i.e. bulking-type failure and slant-shear-failure. Bulking-type failure was the main failure pattern observed under static testing, while the slant-shear-failure mode was observed more for impact loading. Figure 5.14 displays the failure pattern of CFRC under different loading conditions. A similar phenomenon was found in this study, with bulking-type failure occurring during the static tests, and the slant mode failure occurring in the impact tests. This difference in modes of failure could be attributed to the effect of the strain rate. For the static test, the strain rate was very slow, while for the impact tests the sharp load increases led to more severe damage and quicker development of damage along the existing weaker parts of the material (such as along cracks and where the material cohesion was relatively weak).

![Figure 5.14 Failure pattern of CFRC-50 under static and impact loadings](image_url)
5.4 Summary

The behaviour of coconut fibre reinforced concrete (CFRC) cylinders under single and repeated drop weight impacts was investigated experimentally. In total, about 60 specimens were investigated. The study reveals:

Single impact tests:

- The CFRC specimens produced interior damage induced by a relatively low height (40 cm) of impact, which was deduced by the reduction of the elastic modulus.
- The experiments showed that the length of coconut fibres had little influence on the DIF of CFRC.
- The addition of coconut fibres performed the similar behaviour as the plain concrete in the compressive dynamic strength. However, CFRC had better performance in resisting spalling and fragmentation, which was due to the bridge function of coconut fibre distribution. It would be useful to protect people from damaged constructions.

Repeated impact tests:

- The maximum compressive stresses of CFRC-25, CFRC-50 and CFRC-75 specimens increased with impact height, the relationship of which was proposed through an empirical equation.
- Damage to the CFRC specimens due to repeated impact loading originated from tiny cracks close to the impact area. The cracks became longer and the impact contact area became smaller with increasing drop height. The final mode of failure involves the specimen experiencing brittle failure, through the sudden formation of a diagonal crack penetrating across most of the length of the specimen.
- The failure mode of CFRC due to static loading and impact loading, was shown to be significantly different. This is likely to be due to the dependence on damage development with the strain rate.
- The coconut fibre length had an influence on the behaviour of the CFRC specimens under repeated impact. Fibres with a length of 25 cm and 50 mm had better impact resistance compared with that of 75 mm.
Chapter 6

Effect of coconut fibre content on the impact behaviour of W-FFRP-CFRC beams

Related paper:


This chapter presents the performance of flax fibre reinforced polymer wrapped coconut fibre reinforced concrete (W-FFRP-CFRC) beams under static and impact loadings. The coconut fibre was mixed with the concrete internally and the concrete beams were wrapped externally by FFRP laminates. Static tests, followed by single and repeated impact tests were performed. Three different fibre contents, i.e. 1%, 3% and 5% of cement mass, corresponding to fibre volumes of respectively 0.4%, 1.2% and 2%, were considered. The effect of the coconut fibre content on the dynamic flexural load, deflection, energy absorption and dynamic increase factor (DIF) were analysed to discover the composites impact properties. The test results indicated that the flexural strength of W-FFRP-CFRC beams was almost three times higher than that of CFRC beams. Dynamic increase factors (DIFs) of the W-FFRP-CFRC beams were found not very sensitive to the coconut fibre content but influenced by strain rate. The beams with 3% coconut fibre content were the best in resisting impact when compared with that of W-FFRP-CFRC beams with 1% and 5% coconut fibre content.
6.1 Experimental work

6.1.1 Specimen preparation

6.1.1.1 CFRC specimens

For plain concrete, the proportions of the cement, water, sand and gravel were 1 : 0.5 : 2 : 2, respectively. For the CFRC, three percentages of fibre content, i.e. 1%, 3% and 5% of the cement mass were considered. The mix ratio of the specimens is listed in Table 6.1. All specimens were cured in a concrete curing room at a stable temperature of 23.0 ± 2.0°C and a relative humidity level of 95% for 28 days.

Table 6.1 Mix ratio of the composites

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>Coconut fibre content</th>
<th>Water/cement ratio</th>
<th>Cement content (kg/m³)</th>
<th>Gravel (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRC-3%</td>
<td>3%</td>
<td>0.56</td>
<td>421.9</td>
<td>831.1</td>
<td>843.7</td>
<td>38</td>
</tr>
<tr>
<td>FFRP-CFRC-1%</td>
<td>1%</td>
<td>0.53</td>
<td>428.1</td>
<td>851.9</td>
<td>856.2</td>
<td>35</td>
</tr>
<tr>
<td>FFRP-CFRC-3%</td>
<td>3%</td>
<td>0.56</td>
<td>421.9</td>
<td>831.1</td>
<td>843.7</td>
<td>38</td>
</tr>
<tr>
<td>FFRP-CFRC-5%</td>
<td>5%</td>
<td>0.6</td>
<td>414.4</td>
<td>808.1</td>
<td>828.8</td>
<td>40</td>
</tr>
</tbody>
</table>

6.1.1.2 Fabrication of W-FFRP-CFRC specimens

Two layers of FFRP laminates were wrapped over the CFRC specimens (Figure 6.1). The FFRP laminate was fabricated from plain-woven flax fabric and epoxy using the hand lay-up method. Preparation of the W-FFRP-CFRC specimens is given in Figure 6.2.

Figure 6.1 Flax fabric, fibre yarn, FFRP laminate and FFRP-CFRC specimens
6.1.2 Test setup and procedure

6.1.2.1 Static tests

The W-FFRP-CFRC beams, with a dimension of 500 mm x 100 mm x 100 mm concrete beams wrapped by two layers of FFRP, were tested according to ASTM C78/C78M-10 (2010). To measure the mid-span deflection of the beams, a linear variable differential transformer (LVDT) was installed in midway between the ground and the beam, as shown in Figure 6.3. Strain gauges were attached to the centre of the tensile side of the beams. The load was monotonically applied using a Universal Instron Compressive Testing Machine with a maximum load capacity of 100 kN.

Figure 6.3 Static flexural test setting up
6.1.2.2 Impact tests

An instrumented drop weight machine was used, as shown in Figure 6.4, to conduct impact tests on the W-FFRP-CFRC specimens. For each test, a total of 5 samples were employed to obtain reliable average results. To investigate the effects of strain rate on flexural behaviour, a flat-face drop hammer with a mass of 50 kg and a diameter of 100 mm was released from various heights to strike the mid-length of the beams. The pinned supports were used to constrain both vertical and horizontal movement, seeing in Figure 6.4 (b). Load cells were installed at each support of the beam to measure the reaction forces. A strain gauge was attached to the centre of the beam. A high-frequency laser displacement transducer was used to measure mid-span deflection. Data acquisition for the test was set at a rate of 50 kHz.

Figure 6.4 Drop weight impact testing set up (a) Drop weight test rig; (b) Specimen boundary condition before and after impact and (c) Sketch of the test set up
6.2 Results and Discussion

6.2.1 Static flexural tests

Figure 6.5 presents the force-deflection curves of the W-FFRP-CFRC beams with 1%, 3% and 5% of fibre content.

![Figure 6.5 Influence of coconut fibre content and FFRP wrapping on the force-deflection relationship of W-FFRP-CFRC beams](image_url)

The difference of the flexural behaviour between CFRC and W-FFRP-CFRC can be clearly seen. It shows that the flexural strength of W-FFRP-CFRC-3% was much higher than that of CFRC-3%. The maximum force of W-FFRP-CFRC-3% was about 26 kN, which was about 2.5 times larger than that of CFRC-3%.

The development of the force-deflection curves of CFRC-3% and W-FFRP-CFRC-3% was also different. The former specimens generated as a smooth curve, i.e. the force increased to the maximum value and then decreased until the fracture of the specimen occurred, whereas W-FFRP-CFRC specimens clearly showed two stages of behaviour. The first stage started at zero until the load was about 15 kN at a deflection of less than 4 mm, where a turning point occurred (see the location indicated by a circle), which was followed by the second stage. This indicated that during the flexural test approximate bilinear curves were generated in the case of W-FFRP-CFRC-3% specimens.

The difference between CFRC-3% and W-FFRP-CFRC-3% specimens was due to the contribution of FFRP during the second stage. In the first stage, the FFRP wraps were not
fully activated as the load was mainly taken over by the CFRC core. When the load exceeded the load capacity of the CFRC, the FFRP wraps started to reinforce the specimen, resulting in a higher load bearing capacity as well as larger deflection.

Figure 6.6 shows the failure modes of CFRC-3% and W-FFRP-CFRC-3%. The CFRC-3% beams suffered a fibre pull-out failure and broke into two pieces. The coconut fibre functioned as a connection to postpone the crack development, which showed some ductility. This was confirmed by the smooth force-deflection curve in Figure 6.5, which was different from the sudden drop curves of W-FFRP-CFRC specimens, although they showed lower load carrying capacity compared to W-FFRP-CFRC-3% specimens. However, W-FFRP-CFRC-3% beams produced a brittle failure close to the middle of the beam. They kept an integrated shape with the bending failure at the middle part, and less fibre pull-out was observed. The load carrying capacity of W-FFRP-CFRC-3% was increased significantly by adding external FFRP laminate. When the external layer failed, the load was far superior to the pull-out capacity of fibres. This type of load resulted in a brittle failure with ruptured fibres, as confirmed by Figure 6.5.

Figure 6.6 Damage patterns of CFRC-3% and W-FFRP-CFRC-3% beams

To study the effect of the coconut fibre content on the static flexural behaviour, the results of W-FFRP-CFRC beams with various coconut fibre contents are summarised in Table 6.2. The modulus of rupture (MOR), as described in Equation 6.1 according to Standard ASTM C78/C78M-10 (2010), was used to evaluate the flexural strength. The MORs of W-FFRP-CFRC beams were all about 13 MPa, showing that the coconut fibre content had little influence on bending strength.

\[ \text{MOR} = \frac{PL}{bd^2} \]  

where \( P \) = maximum applied load; \( L \) = Span length of specimen; \( b \) = Average width of specimen; \( d \) = Average depth of specimen.
Table 6.2 Influence of coconut fibre content on MOR of W-FFRP-CFRC beams

<table>
<thead>
<tr>
<th>Specimen</th>
<th>MOR (MPa)</th>
<th>Maximum deflection (mm)</th>
<th>Maximum strain of FFRP (µε)</th>
<th>DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRC-3%</td>
<td>4.92 (0.32)</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>W-FFRP-CFRC-1%</td>
<td>13.7 (0.69)</td>
<td>10.2 (1)</td>
<td>2392 (166.6)</td>
<td>11.9</td>
</tr>
<tr>
<td>W-FFRP-CFRC-3%</td>
<td>13.22 (0.71)</td>
<td>11.2 (1)</td>
<td>2244 (305.1)</td>
<td>12.1</td>
</tr>
<tr>
<td>W-FFRP-CFRC-5%</td>
<td>13.2 (0.31)</td>
<td>10.7 (1)</td>
<td>2222 (434.4)</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are standard deviations.

For the FRP-concrete materials, the deformability factor (DF) was used to evaluate ductility. The DF is defined as (GangaRao et al. 2006):

\[
DF = \frac{E_u}{E_l}
\]

where \( E_u \) is energy absorption at ultimate value, \( E_l \) is energy absorption at a limiting deflection of about 2.5 mm, which is defined by standard ACI 318 (2008). Energy absorption was obtained from the area of force-deflection curves. Table 6.2 shows that the deformability factor of W-FFRP-CFRC beams increased with the coconut fibre content.

6.2.2 Impact tests

In this section the results of repeated impact tests are presented, with a drop height starting from 200 mm and increasing by 100 mm in subsequent impacts until the specimens fractured.

6.2.2.1 Force-time history

The dynamic flexural force during the impact can be determined by adding the reaction forces at the two supports (Soleimani and Banthia 2014).

Figure 6.7 demonstrates the influence of coconut fibre content and drop height on the development of the dynamic flexural force. Coconut fibre content affected the number of blows required to break the specimen. Specimens with 1% coconut fibre underwent three impacts before fracture, i.e. with drop heights of 200 mm, 300 mm and 400 mm. As for the W-FFRP-CFRC-3% and W-FFRP-CFRC-5% specimens, three blows and two blows
were required respectively to cause breakage. This indicated that the specimens with 1% and 3% coconut fibre were better in resisting repeated impact than that of 5% specimens.

Figure 6.7 Effect of fibre content and drop heights on the dynamic flexural force of various specimens: (a) W-FFRP-CFRC-1% (b) W-FFRP-CFRC-3% and (c) W-FFRP-CFRC-5%
Fig. 6.7(a) shows the dynamic flexural force time history of the W-FFRP-CFRC-1% specimen. Three impacts with drop heights of 200 mm, 300 mm and 400 mm were applied to the same specimen, corresponding to the time durations of about 0.006 s, 0.005 s and 0.002 s, respectively. The W-FFRP-CFRC-3% and W-FFRP-CFRC-5% also showed a similar trend. The response duration difference could be caused by damage status of specimens and drop height during impacts. Before the specimen break, vibrations and the strike rebounds occurred due to lower drop heights. In contrast, in high drop heights (e.g. 400 mm in the W-FFRP-CFRC-1%), the specimen broke under fast loading rates, leading to a sudden damage.

6.2.2.2 Energy absorption

Figure 6.8 shows the force-deflection curves of the specimens under different drop heights, from which energy absorption can be calculated. Figure 6.8 (a) shows the force-deflection curves of the specimens with a drop height of 200 mm. At this stage the specimens did not fracture, and exhibited a deflection less than 1 mm. In contrast, the deflection reached up to around 4 mm as the specimen was broken with the last strikes, the heights of which were 400 mm for the 1% and 3% specimens, and 300 mm for the 5% specimens, as shown in Figure 6.8 (b).

![Figure 6.8](image)

Figure 6.8  Force-deflection curves of the W-FFRP-CFRC beams under impact loadings: (a) Non-fracture specimen and (b) fracture specimen

Table 6.3 summarises the experimental results of various drop weight impacts. The maximum strain of FFRP was about 0.0208, 0.0310 and 0.0245 for W-FFRP-CFRC-1%,

93
W-FFRP-CFRC-3% and W-FFRP-CFRC-5% specimens, respectively. Compared with the maximum static strain values in Table 6.2, the values increased by about 117%, 138% and 110% for the three specimen types, respectively. The increase in the maximum strain was due to the strain rates induced by various impact heights.

Table 6.3 Experimental results of impact tests under different heights

<table>
<thead>
<tr>
<th>W-FFRP-CFRC specimen</th>
<th>Drop height (mm)</th>
<th>Absorbed energy (J)</th>
<th>Maximum strain of FFRP (mm/mm)</th>
<th>Damage status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>200</td>
<td>5.21 (1.55)</td>
<td>0.0189 (0.002)</td>
<td>V</td>
</tr>
<tr>
<td>3%</td>
<td>200</td>
<td>5.53 (1.35)</td>
<td>0.0179 (0.001)</td>
<td>V</td>
</tr>
<tr>
<td>5%</td>
<td>200</td>
<td>6.21 (0.61)</td>
<td>0.0198 (0.002)</td>
<td>V</td>
</tr>
<tr>
<td>1%</td>
<td>300</td>
<td>8.01 (1.3)</td>
<td>0.0238 (0.004)</td>
<td>V</td>
</tr>
<tr>
<td>3%</td>
<td>300</td>
<td>8.90 (1.46)</td>
<td>0.0249 (0.004)</td>
<td>V</td>
</tr>
<tr>
<td>5%</td>
<td>300</td>
<td>55.4 (4.69)</td>
<td>0.0245 (0.003)</td>
<td>F</td>
</tr>
<tr>
<td>1%</td>
<td>400</td>
<td>62.69 (5.0)</td>
<td>0.0280 (0.005)</td>
<td>F</td>
</tr>
<tr>
<td>3%</td>
<td>400</td>
<td>71.8 (4.96)</td>
<td>0.0310 (0.004)</td>
<td>F</td>
</tr>
<tr>
<td>5%</td>
<td>400</td>
<td>62.69 (5.0)</td>
<td>0.0280 (0.005)</td>
<td>F</td>
</tr>
</tbody>
</table>

Note: N=Non-visible damage, V=Visible damage, F= Failure and values in parentheses are standard deviations.

The total energy absorption, accumulated from all impact blows, was used to evaluate impact resistance. The total energy absorption of W-FFRP-CFRC-1%, W-FFRP-CFRC-3% and W-FFRP-CFRC-5% specimens were about 75.91 J, 83.23 J and 61.61 J, respectively. The relationship between coconut fibre content and total absorbed energy was explored, as expressed in Figure 6.9, and indicated the optimum fibre content among the three types for resisting impacts. The total energy absorption increased with the fibre content from 1% to 3%, while it decreased when the fibre content increased from 3% to 5%. This is because an excessive percentage of fibre in concrete reduces its workability and consequently affects the quality of CFRC.
6.2.2.3 DIF at various strain rates

DIF is an important parameter to evaluate the enhancement in material impact properties from the static response. It is defined by the ratios of maximum impact forces and fracture energies to their corresponding static values (Zhang et al. 2014), as described in the Equations (6.3) and (6.4), respectively:

\[
DIF_{p} = \frac{P_i}{P_s} \quad (6.3)
\]

\[
DIF_{G} = \frac{G_f}{G^s} \quad (6.4)
\]

where \( P_i \) is the maximum impact force, \( P_s \) is the maximum force under static loading.

where \( G_f \) is the impact fracture energy, \( G^s \) is the static fracture energy.

The fracture energy \( G_f \) was defined by RILEM 50-FMC Technical Committee (1985) as:

\[
G_f = \frac{W_0 + mg \frac{S}{L} \delta_s}{B(D - a)} \quad (6.5)
\]

where \( W_0 \) is the area under the force-deflection curve; \( m, S, L, B, D \) are the mass, span, length, width and depth of the specimen, respectively; \( g \) is gravitational acceleration; \( \delta_s \)
is the specified deflection at the time of failure, which was 4 mm; \( a \) is the notch of the specimen. In this study, no notches were considered, i.e. \( a = 0 \).

Table 6.4 summarises the DIF of W-FFRP-CFRC beams with various coconut fibre contents and strain rates. In this study, strain rate was calculated by differentiating the maximum strain with respect to time (Dey et al. 2014; Yoo et al. 2015), as expressed:

\[
\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{6hv}{L^2}
\]

where \( h \) is width of the beam specimen, \( L \) is the beam span, and \( v \) is the specimen velocity which was calculated using deflection time response.

### Table 6.4 Dynamic increase factor of W-FFRP-CFRC beams

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Drop height (mm)</th>
<th>Impact velocity (m/s)</th>
<th>Strain rate (s(^{-1}))</th>
<th>( P_i ) (kN)</th>
<th>DIF(_p)</th>
<th>( G_i ) (N/m)</th>
<th>DIF(_G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-FFRP-CFRC-1%</td>
<td>200</td>
<td>1.98</td>
<td>1.09 (0.56)</td>
<td>31.1 (3.12)</td>
<td>1.14</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>3.43</td>
<td>7.05 (1.61)</td>
<td>34.81 (5.01)</td>
<td>1.27</td>
<td>5846 (504)</td>
<td>1.57</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>4.42</td>
<td>11.13 (2.37)</td>
<td>47.85 (4.5)</td>
<td>1.74</td>
<td>6314 (776)</td>
<td>1.69</td>
</tr>
<tr>
<td>W-FFRP-CFRC-3%</td>
<td>200</td>
<td>1.98</td>
<td>1.12 (0.47)</td>
<td>36.62 (3.95)</td>
<td>1.36</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>3.43</td>
<td>6.66 (1.63)</td>
<td>43 (3.71)</td>
<td>1.59</td>
<td>5598 (313)</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>4.42</td>
<td>10.02 (2.33)</td>
<td>52.3 (4.16)</td>
<td>1.94</td>
<td>7225 (563)</td>
<td>2.17</td>
</tr>
<tr>
<td>W-FFRP-CFRC-5%</td>
<td>200</td>
<td>1.98</td>
<td>0.95 (0.39)</td>
<td>31.92 (4.35)</td>
<td>1.20</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>3.43</td>
<td>6.10 (0.87)</td>
<td>37.2 (3.80)</td>
<td>1.40</td>
<td>4985 (1068)</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>4.42</td>
<td>9.76 (1.07)</td>
<td>46.90 (6.42)</td>
<td>1.76</td>
<td>6666 (847)</td>
<td>2.19</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are standard deviations.

DIFs of the W-FFRP-CFRC beams were not very sensitive to the coconut fibre content but influenced by strain rate. DIFs ranged from 1.14-1.74 for W-FFRP-CFRC-1%, 1.21-1.94 for W-FFRP-CFRC-3% and 1.20-1.76 for W-FFRP-CFRC-5%, as listed in Table 6.4. For all three strain rates considered, higher strain rate exhibited higher DIF value. An empirical equation was proposed to describe the relationship between strain rate and DIF, as shown in Figure 6.10.
6.3 Summary

The study experimentally investigated the flexural behaviour of FFRP wrapped CFRC beams under static and drop weight impact loadings. The findings of the study are:

In the static tests:

- The flexural strength of W-FFRP-CFRC beams was much higher than that of CFRC beams, about 4.92 MPa and 13 MPa for CFRC and W-FFRP-CFRC, respectively.

- The force-deflection curves of the W-FFRP-CFRC beams showed a bi-linear trend, while CFRC specimens performed as a smooth curve. Failure pattern of CFRC and W-FFRP-CFRC was different. For the CFRC specimens, the coconut fibre functioned as a connection to postpone the crack development, which showed some ductility. However, W-FFRP-CFRC beams produced a brittle failure close to the middle of the beam.

- The coconut fibre content had little influence on the flexural strength, while it increased the ductility of the W-FFRP-CFRC beams.
In the impact tests:

- In the repeated test, coconut fibre content affected the number of blows required to break the specimen. For the W-FFRP-CFRC specimens with 1%, 3% and 5% coconut fibre content, 3, 3 and 2 blows were required respectively to cause breakage.

- The W-FFRP-CFRC specimens with 3% coconut fibre content absorbed highest energy of about 83.23 J compared with that of 1% and 5% specimens.

- In the single impact test, the DIFs of the W-FFRP-CFRC beams were not sensitive to coconut fibre content, but influenced by strain rate. Higher strain rate led to a higher DIF value. An empirical equation was proposed to better describe the relationship between strain rate and DIF.

Based on the single and repeated impact test results, it was concluded that W-FFRP-CFRC specimens with 3% of coconut fibre content was the best at resisting impact compared with that of 1% and 5% specimens, i.e. the number of blows required to break the specimen and total energy absorption.
Chapter 7

Effect of flax thickness on the impact behaviour of L-FFRP-CFRC beams

Related paper:


Reinforced concrete flexural members, such as beams and slabs with procured FRP strips and laid-up FRP sheets, have been studied extensively in recent decades. Based on these researches, America Concrete Institute (ACI) committee developed the guiding specifications ACI 440.2R-02 for design and construction of FRP reinforced concrete under static loadings. However, it is evident that performance of FRP concrete composites subjected to impact loading differs from that of the static loading. Concrete structures can suffer from severe impact loadings in many situations, such as earthquake induced pounding between structural members, vehicle impacts, explosion generated impact. Many researchers have carried out studies on the impact behaviour of FRP concrete composites, e.g. mainly with carbon and glass fibre reinforcement.

This chapter presents the behaviour of flax fibre reinforced polymer laminates strengthened coconut fibre reinforced concrete (L-FFRP-CFRC) beams under static and impact loadings through a series of static and impact tests. Three FFRP thicknesses, i.e. 2-, 4- and 6-layer was considered. The ASTM C1609 standard was applied in static flexural tests and a drop weight machine was used in impact tests. In the experiments, parameters of the L-FFRP-CFRC specimens, i.e. impact force, deflection, energy absorption, dynamic increase factor, and damage pattern were studied. The effect of FFRP
thickness was investigated in terms of (1) flexural strength and toughness under static loading, (2) flexural behaviour under impact loading, and (3) failure mode.

7.1 Experimental works

7.1.1 Specimen preparation

The proportion of materials used in the coconut fibre reinforced concrete (CFRC) was 1: 0.5: 2: 2 for Portland cement, water, and sand and gravel, respectively. All specimens were cured in a concrete curing room at a stable temperature of 23.0 ± 2.0°C and a relative humidity level of 95% for 28 days.

To investigate the effect of the FFRP thickness on the flexural behaviour induced by static and impact load, three different thicknesses of 2-, 4- and 6-layer of FFRP were considered. The flax fabric was bonded to the tensile surface of the beam, using SP High Modulus Prime 20LV epoxy, as shown in Figure 7.1. A detailed specimen preparation chart is shown in Figure 7.2. The test matrix of the specimens is listed in Table 7.1.

![Figure 7.1 FFRP-CFRC beams](image-url)
Table 7.1 Test matrix of the specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>No. of specimens</th>
<th>No. of fabric layers</th>
<th>Concrete core dimension (mm)</th>
<th>FFRP thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRC cylinder</td>
<td>5</td>
<td>--</td>
<td>200 × 100</td>
<td>--</td>
</tr>
<tr>
<td>CFRC beam</td>
<td>6</td>
<td>--</td>
<td>500 × 100 × 500</td>
<td>--</td>
</tr>
<tr>
<td>2L-FFRP-CFRC beam</td>
<td>8</td>
<td>2</td>
<td>500 × 100 × 500</td>
<td>2.82</td>
</tr>
<tr>
<td>4L-FFRP-CFRC beam</td>
<td>8</td>
<td>4</td>
<td>500 × 100 × 500</td>
<td>5.29</td>
</tr>
<tr>
<td>6L-FFRP-CFRC beam</td>
<td>8</td>
<td>6</td>
<td>500 × 100 × 500</td>
<td>7.53</td>
</tr>
</tbody>
</table>

7.1.2 Testing procedure

7.1.2.1 Static test

The CFRC cylinders (200 mm x 100 mm) were used to determine compressive strength following the standard ASTM C39/C39M (2004), with an average strength of 29.84 MPa. The beam specimens (500 mm x 100 mm x 100 mm) were tested under the third-point flexure principle according to ASTM C1609 (2005). To measure the average mid-span deflection, two linear variable differential transformers (LVDTs) were fixed on both sides of the beam at mid-span (see Figure 7.3). The compressive load was monotonically applied by an Instron machine with a maximum load capacity of 100 kN. Toughness was
calculated at the net deflection of $L/150$ and $L/75$ (as recommended by ASTM C1609), where $L$ is span length.

![Figure 7.3 Third-point flexural test](image)

**7.1.2.2 Impact test**

An instrumented rig for drop weight impact testing was used, as shown in Figure 7.4. It has a maximum drop height of 2600 mm and an impact mass capacity between 30 kg and 200 kg. The impact mass was set to 40 kg, with drop heights ranging from 200 to 600 mm, which led to potential impact velocities from 1.98 m/s to 3.43 m/s. The third-point loading was also adopted for the impact tests.

![Figure 7.4 Impact test. (a) Test rig and (b) experimental setup](image)

The drop weight hammer had a flat striking face and a diameter of 100 mm, as shown in Figure 7.4. Load cells were installed at each support of the beam to measure the
transmitted forces. A displacement laser sensor was used to measure mid-span deflection, with a set acquisition rate of 50 kHz.

7.2 Results and discussion

7.2.1 Static tests

Figure 7.5 shows the influence of the number of FFRP layers on the force-deflection curves. Two stages were observed in the curves of the L-FFRP-CFRC beams when compared to that of CFRC beams. The first stage started from zero to around 0.7 mm of deflection, which was similar to the curve of CFRC beams. This indicates that the CFRC was mainly bearing the load and the FFRP laminates had not been fully activated. The second stage started at the inflection points with deflection values of 0.5 ± 0.2 mm, indicated by the vertical dashed line in Figure 7.5. The force exceeded the load capacity of the CFRC at this stage. Thus the FFRP laminates were fully activated to reinforce the tensile part of the specimen, achieving a higher load bearing capacity as well as larger deflection.

![Figure 7.5 Effect of the number of FFRP layers on the flexural response of FFRP-CFRC beams under static load](image_url)

The results of the static flexure tests are summarised in Table 7.2, which provided average values of strength, deflection at the peak, and toughness at net deflection at L/150 and L/75. The flexural strength increased with FFRP thickness, as shown in Figure 7.6. The flexural strengths of L-FFRP-CFRC beams with 2-, 4- and 6- were almost 1.7, 3 and 4 times higher than that of CFRC beams, respectively. This significant increase in the
strength was due to the reinforcement by FFRP laminates at the tensile surface. This led to a higher bending resistance. Besides, the L-FFRP-CFRC specimens showed high toughness even at large deflections. This owes to the improvement of tensile strength of the composite, which could impede the development of cracks. It can be seen that the toughness increased almost linearly with FFRP thicknesses.

Table 7.2 Summary of quasi-static flexure test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. load (kN)</th>
<th>Flexural strength (MPa)</th>
<th>Deflection at maximum Load (mm)</th>
<th>Toughness at L/150 (kN mm)</th>
<th>Toughness at L/75 (kN mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRC</td>
<td>8.9</td>
<td>4.45</td>
<td>0.67</td>
<td>6.36</td>
<td>33.04</td>
</tr>
<tr>
<td>2L-FFRP-CFRC</td>
<td>14.86</td>
<td>7.43</td>
<td>9.08</td>
<td>32.05</td>
<td>67.22</td>
</tr>
<tr>
<td>4L-FFRP-CFRC</td>
<td>31.2</td>
<td>15.56</td>
<td>12.65</td>
<td>48.02</td>
<td>112.31</td>
</tr>
<tr>
<td>6L-FFRP-CFRC</td>
<td>38.24</td>
<td>19.12</td>
<td>11.96</td>
<td>60.8</td>
<td>156.5</td>
</tr>
</tbody>
</table>

Figure 7.6 Effect of FFRP thickness on flexural strengths

7.2.2 Impact tests

7.2.2.1 Force-time histories

During impact tests, repeated strikes were applied to specimens until fracture. The impact height started from 200 mm, with an increment of 100 mm for each subsequent strike. Figures 7.7-7.9 respectively display the development of the dynamic flexural force in the cases of 2-, 4- and 6-layer of L-FFRP-CFRC beams under various impact heights. The 2-layer specimens experienced two impacts before fracture, with a drop height of 200 mm (equivalent to an impact velocity of 1.98 m/s) and a subsequent drop height of 300 mm.
(equivalent to an impact velocity of 2.42 m/s). As for the 4-layer and 6-layer FFRP-CFRC specimens, four and five strikes were respectively required to cause breakage.

The impact duration of each strike was less than 0.01 s for all specimens. The first peak impact force occurred at around 0.001 s and the maximum impact force appeared between 0.003 s and 0.005 s, as shown in Figures 7.7-7.9. The maximum impact force in the specimens with 2-, 4- and 6-layer of FFRP were about 32 kN, 65 kN and 75 kN, respectively.

Figure 7.7 Effect of loading rate on the force histories of 2L-FFRP-CFRC beam

Figure 7.8 Effect of loading rate on the force histories of 4L-FFRP-CFRC beam
7.2.2.2 Deflection-force curves

The force-deflection responses of all test beams are shown in Figures 7.10-7.12, under impact velocities from 1.98 m/s to 3.43 m/s.

The deflection development of L-FFRP-CFRC specimens depends on damage level in relation to impact velocity. Prior to fracture, the L-FFRP-CFRC beams exhibited a low deflection, i.e. less than 1 mm and it increased gradually with the impact velocity. However, in the last strike, the deformation increased to a large deflection value, resulting in fracture. For example, as shown in Figure 7.11 (a), the deflection for the 4-layer specimen increased from about 0.12 mm under the impact velocity of 1.98 m/s to about 0.3 mm under the impact velocity of 2.42 m/s and then developed to 0.4 mm under the loading rate of 2.80 m/s. On the other hand, the deflection surged to a 6 mm of deformation under the velocity of 3.13 m/s, resulting in specimen rupture. The deflection development of the 6-layer specimen (Figure 7.12 (a)) was similar, except that the fracture occurred under the impact velocity of 3.43 m/s. A bounce-back deflection was observed in the 6-layer specimen (indicated in Figure 7.12 (b)), which could be due to the remaining elasticity of the damaged beam.
Figure 7.10 The flexural response of 2L-FFRP-CFRC beams under various impact loadings. (a) Without and (b) with fracture.

Figure 7.11 The flexural response of 4L-FFRP-CFRC beams under various impact loadings. (a) Without and (b) with fracture.
Figure 7.12 The flexural response of 6L-FFRP-CFRC beams under various impact loadings. (a) Without and (b) with fracture.

Damage to the beams under static and impact loadings are shown in Figure 7.13.
More distributed cracks under static loading were observed compared with the impact loading, which aligns well with the results obtained by Hwang et al. (2017). This phenomenon can be attributed to the effect of the loading rate. For the static test, the loading rate was very slow, and all weaker positions had a chance to develop cracks, leading to distributed cracks. However, for the impact tests the sharp increase in the loading rate led to the fast development of damage, focused mainly on the weakest part of the specimens.

The failure pattern differed between specimens with different thicknesses of FFRP. For the 2L-FFRP-CFRC specimens, both the concrete and the FFRP laminate fractured under static and impact loadings. In contrast, both the 4- and 6-layer beams showed de-bonding failure on the FFRP laminates as shown in Figure 7.13 (c)-(f). According to the fundamental de-bonding mechanisms by Gunes (2004), the failure of 4- and 6-layer L-FFRP-CFRC beams belonged to the case named FRP de-bonding from flexure-shear crack of concrete (Figure 7.14), which may occur when laminate ends are constrained. In this study, the FFRP laminates were constrained by the two pinned supports, which initiated the de-bonding at the largest crack of CFRC and then propagated towards beam ends.

7.2.2.3 Effect of impact velocity on the behaviour of L-FFRP-CFRC beams

The DIF of concrete was defined by the ratios of the maximum force ($P_{\text{max}}$) under impact to that under static loading (Zhang et al. 2014). In this study, the DIF values of the 2-layer, 4-layer and 6-layer specimens ranged 1-1.78, 1-2.15 and 0.99-1.91, respectively (see Table 7.3).
Table 7.3 Effect of impact velocities on experimental results

<table>
<thead>
<tr>
<th>FFRP-CFRC specimen</th>
<th>Drop height (mm)</th>
<th>Impact velocities (m/s)</th>
<th>Maximum force (kN)</th>
<th>DIF</th>
<th>Absorbed energy (J)</th>
<th>Damage status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRC (Reference)</td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>8.90</td>
<td>1.0</td>
<td>19.36</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>14.86</td>
<td>1.0</td>
<td>2.84</td>
<td>F</td>
</tr>
<tr>
<td>2L</td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>26.40</td>
<td>1.78</td>
<td>61.22</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>31.20</td>
<td>1.77</td>
<td>90.96</td>
<td>F</td>
</tr>
<tr>
<td>4L</td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>40.40</td>
<td>1.30</td>
<td>5.61</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>60.48</td>
<td>1.95</td>
<td>9.36</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>66.76</td>
<td>2.15</td>
<td>11.58</td>
<td>V</td>
</tr>
<tr>
<td>6L</td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>40.15</td>
<td>1.05</td>
<td>6.16</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>52.60</td>
<td>1.38</td>
<td>9.36</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>61.27</td>
<td>1.60</td>
<td>9.36</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>72.90</td>
<td>1.91</td>
<td>11.58</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Static 200</td>
<td>3.33x10^{-6}</td>
<td>73.75</td>
<td>0.99</td>
<td>108.6</td>
<td>F</td>
</tr>
</tbody>
</table>

Note: N=Non-visible damage, V=Visible damage, F= Failure

Table 7.3 shows the effect of impact velocity on the maximum force. The force increased with the impact velocity before the beam fracture. However, the maximum forces showed no obvious pattern with different FFRP thicknesses during the beam fracture. For example, the 2L-FFRP-CFRC beams fractured with the maximum impact force of about 26.13 kN, which was close to its previous impact force value. However, the 4- and 6-layer specimens had larger and smaller maximum forces, respectively, at the last impact than that of penultimate impact. Based on these test results, the behaviour of L-FFRP-CFRC under impact loadings can be summarised as follows:

Prior to the occurrence of cracking, the first stage was called the non-visible damage stage as shown in the curve “A-B” shown in Figure 7.15, where maximum force increased slowly. The subsequent curve “B-C” was called visible damage, during which, maximum force increased remarkably. Damage started with tiny cracks, developing quickly with increasing loading rates. At point C, the specimens showed severe damage, e.g. cracks almost through total the beam depth. The last stage was called the fracture stage, maximum force in this stage was not predictable. This was attributed to the failure mode of the corresponding specimen and in the accumulated damage due to previous impacts.
Energy absorption was calculated from the area of the force-deflection curves. The results indicated that at the fracture stage the specimen absorbed much more energy than at other stages. For example, the energy absorbed by the 2L-FFRP-CFRC specimen with the impact velocity of 1.98 m/s was only about 2.84 J, while it was 61.22 J under the 2.42 m/s impact velocity. With regard to the 4-layer specimen, energy absorbed by the specimen ranged from 2 J to 5 J with impact velocities from 1.98 m/s to 2.80 m/s, respectively. With the impact velocity of 3.13 m/s, the specimen absorbed about 91 J, and a similar trend was observed with the 6-layer specimen. This phenomenon was due to the fact that before fracture the impact energy was mainly spent as a source of specimen vibration.

As the beams were subjected to repeated impact loadings with ranging impact velocities, the total energy absorbed was calculated by adding the energy absorption from all impact blows for each specimen. The accumulated energy absorption was calculated to evaluate the impact resistance of the specimen, with values of about 64.1 J, 102.3 J and 160.9 J for the 2-, 4- and 6-layer beams, respectively. The results of accumulated energy absorption
indicated that the impact resistance of the L-FFRP-CFRC beams linearly increased with the FFRP thickness, as shown in Figure 7.16.

![Figure 7.16 Effect of FFRP thickness on accumulated absorbed energy](image)

**7.3 Summary**

The behaviour of L-FFRP-CFRC beams under static and impact loadings was investigated experimentally, with 30 specimens tested in total. The loading rate varied from 1.98 m/s to 3.43 m/s. The result revealed:

In the static test:

- FFRP was very effective in enhancing flexure strength. The flexural strengths of L-FFRP-CFRC beams with 2-, 4- and 6-layer were respectively almost 1.7, 3 and 4 times higher than that of CFRC, respectively.

- The toughness of L-FFRP-CFRC beams increased almost linearly with the increment of the FFRP thicknesses.

In the impact test:

- Deflection development of L-FFRP-CFRC specimens depended to a great degree on the damage stages as well as the loading rates. The DIF for 2-, 4- and 6-layer of L-FFRP-CFRC beams were 1-1.78, 1-2.15 and 0.99-1.91, respectively.

- More widely distributed cracks were observed under static loading compared with
the case of impact loading. The failure pattern was influenced by the thickness of FFRP. For 2-layer L-FFRP-CFRC, both concrete and FFRP laminate fractured, while 4- and 6-layer beams showed de-bonding failure on the FFRP laminates.

- At the fracture stage the specimen absorbed much more energy than at the other stages. The impact resistance of the L-FFRP-CFRC beams showed a linear relationship with FFRP thickness.
Chapter 8
Impact behaviour of FFRP-CFRC slabs

Related papers:


The impact behaviour of FFRP strengthened CFRC slabs were investigated through experimental and theoretical studies. This chapter comprises two experiments.

In the first experiment, impact tests were carried out to find the most effective FFRP wrapping configuration of three different wrapping designs for CFRC slabs. A theoretical model was also used to predict maximum impact force and maximum deflection.

In the second experiment, a preliminarily investigation of the effectiveness of FFRP composite as a retrofitting material was conducted. Firstly, CFRC rectangular slabs were cracked using low impact energy, resulting in minimal damage to the slabs. Secondly, two FFRP wrapping configuration methods were applied to retrofit these cracked CFRC slabs. Repeated impact tests were then conducted on these FFRP-CFRC slabs, and the effectiveness of the two FFRP configuration types was evaluated. The results indicated that FFRP could be an option for retrofitting materials for future civil construction.

8.1 Impact behaviour of PC, CFRC and CFRC slabs with three different FFRP wrapping configurations

The impact behaviour of FFRP strengthened CFRC slabs was investigated through experimental and theoretical studies. PC, CFRC and FFRP-CFRC slabs were constructed
and tested under impact loadings. Impact results showed that FFRP-CFRC slabs had better performance in aspects of energy absorption and keeping the integrity of the concrete, comparing with PC and CFRC specimens.

Impact tests were also carried to find an effective wrapping configuration of three different FFRP wrapping designs for CFRC slab, and their parameters, i.e. the impact force, deflection, energy absorption and damage pattern were discussed to evaluate impact resistance. After the experimental study, a theoretical analysis method was used to predict maximum impact force as well as maximum deflection.

8.1.1 Experimental works

The experimental works included casting and testing of concrete slab specimens, of which 5 were PC slabs, 6 were CFRC slabs, and 15 were CFRC slabs with three different FFRP reinforcement configurations. All slabs were rectangular with dimensions of 600 x 300 x 50 mm. The nomenclature and explanations of the various specimens is presented in Table 8.1. Sketches of the three configurations of FFRP-CFRC slabs are presented in detail in Figure 8.1.

Table 8.1 Nomenclature of concrete slab specimens

<table>
<thead>
<tr>
<th>Slab designation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>Plain concrete</td>
</tr>
<tr>
<td>CFRC</td>
<td>Coconut fibre reinforced concrete, with 3% of coconut fibre content</td>
</tr>
<tr>
<td>C1</td>
<td>CFRC fully wrapped by FFRP along the long axis with an additional 100 mm width central FFRP strip</td>
</tr>
<tr>
<td>C2</td>
<td>CFRC wrapped by FFRP along the long and short axis including the side faces with a 10 mm width top edge overhang</td>
</tr>
<tr>
<td>C3</td>
<td>CFRC wrapped by FFRP along the long axis and the side faces with an additional 100 mm width central FFRP strip</td>
</tr>
</tbody>
</table>
8.1.1.1 Materials and specimen preparation

(1) Materials

Ordinary 60 Grade Portland cement manufactured by the Golden Bay Company was used and the relative density of the cement was 3.11 t/m$^3$. Local sea sand passing through a 2.36 mm sieve was used. The fineness modulus of the sand is found to be 2.75. Crushed aggregate available from local sources was used, with a diameter range of 7-13 mm and a fineness modulus of 3.48. The coconut fibre content was 3% of the cement mass in the CFRC.

(2) Casting of CFRC slabs

The slab specimens were cast to the required size using wooden moulds. Two frames with a depth of 50 mm were connected to a flat plate at the bottom with dimensions of 600 mm x 300 mm. Initially the wood mould was coated with engine oil so that the slab specimens could be de-moulded. Next, PC and CFRC were cast. For PC the mix ratio of 1:0.48:2:2 for cement, water, sand, aggregate, respectively. The CFRC mix the same as that of the
PC, except that the coconut fibres were added to the mixture by replacing the same amount of the aggregate. The slump test was then performed and the results for the PC and CFRC were about 42 mm and 35 mm, respectively.

The specimens were de-moulded after 24 hours and cured for 28 days in a fog room ensuring temperature and humidity.

(3) Fabrication of FFRP-CFRC slabs

After curing the CFRC for 28 days, FFRP laminates with a thickness of 3 mm were prepared and wrapped over the CFRC slabs. A total of about 0.5 m² of flax fabric was applied to each slab specimen. A detailed specimen preparation chart is shown in Figure 8.2.

![Fabrication of FFRP-CFRC slabs](chart)

**Cut flax fabric**

Mix epoxy system thoroughly for 3 minutes (Resin : Slow Hardener = 100 : 26 by mass)

Impregnate the flax fabric with the epoxy using a brush

Clean the CFRC slab surface well to remove the dust

Wrap the epoxy-impregnated fabric tightly to the slabs in configurations C1, C2 and C3

Cure the specimens at room temperature for at least 48 hours

**Figure 8.2 Fabrication of FFRP-CFRC slabs**

### 8.1.1.2 Test setup

Impact tests were performed using a drop weight test rig, with a maximum impact height of 2600 mm. The impact mass could be set from 30 kg to 200 kg, with an increment of 10 kg. The PCB dynamic load cell was used to record the impact force. The PCB accelerometer was used to record the acceleration of the specimens during impacts. The laser displacement sensor was placed beneath the slab centre to measure the net deflection and the data acquisition was set to 50 kHz. A number of impact tests were conducted with increasing impact heights until breakage of the specimen. The test setup for the impact
8.1.2 Results and Discussion

8.1.2.1 Test results for PC and CFRC slabs

Repeated impact tests were carried out on PC and CFRC slabs. The impact height was initially set to 10 mm, with then increased 10 mm for each subsequent strike until the specimen broke.

Figure 8.4 shows the impact force curves of PC and CFRC. The PC slabs fractured at the first strike, while the CFRC slabs experienced two impacts, and broke on the 20 mm impact. At the failure state, the PC and CFRC slabs had similar maximum impact forces of 6.23 kN and 5.75 kN. For PC and CFRC slabs, the numbers of strikes were 1 and 2, respectively, indicating that CFRC displayed higher impact resistance ability than PC. This can be attributed to the addition of coconut fibres which enhanced the ductility.
Figure 8.5 displays the force-time and deflection-time histories of PC and CFRC specimens when breaking on their last impact. The maximum deflection was about 0.82 mm and 2.6 mm for PC and CFRC specimens, respectively. The greater deflection of CFRC compared to PC was due to improved flexibility by the addition of coconut fibres. To confirm the effectiveness of coconut fibres, the absorbed energy was calculated from the deflection-force curves to quantify the impact resistance (refer to Section 8.1.3 for a detailed discussion).

![Force-time, deflection-time curves for PC and CFRC at the damaged state](image)

(a) PC  (b) CFRC

Figure 8.5  Force-time, deflection-time curves for PC and CFRC at the damaged state

The failure modes of PC and CFRC are shown in Figure 8.6. Breakage was defined as a crack spreading through the whole thickness of the specimen, resulting in the loss of load bearing capacity (see Fig. 8.6 (a) and (b)). It was observed that the PC slab broke into two pieces under impact, while the CFRC slab stayed whole due to the bridging function of the coconut fibres even where there was a sizeable crack (see Fig. 8.6 (c) and (d)).

![Comparison of failure modes for PC and CFRC slabs](image)

(a) PC_Failure mode  (b) PC_Crack pattern
(c) CFRC_Failure mode  (d) CFRC_Crack pattern

Figure 8.6  Comparison of failure modes for PC and CFRC slabs
8.1.2.2 Test results for FFRP-CFRC slabs: Configurations C1, C2 and C3

Repeated impact tests were carried out on the C1, C2 and C3 specimens. The impact height started from 30 mm, followed by the height at 50 mm, 70 mm, 100 mm, 150 mm, 200 mm, 300 mm and 400 mm, until the specimen was broken.

(1) Impact force histories of slabs C1, C2 and C3

Figures 8.7-8.9 respectively present the impact force histories of C1, C2 and C3. The whole impact force duration for all slabs was about 0.015 s. The first peak of force occurred at the very first stage of impact, i.e. before 0.003 s. In addition to the first peak, multiple smaller peaks were observed, which was due to the multiple contacts between the slabs and the projectile during the impact. The peaks were referred to as “secondary peaks” in the force history, these being observed by Tabatabaei et al. (2014) in their study on the impact behaviour of carbon fibre reinforced concrete slabs.

![Figure 8.7 Force time histories for C1 slab](image-url)
With regard to the total number of blows required for failure, specimen C1, C2 and C3 respectively experienced 7, 8 and 6 strikes. The maximum force and the damage status of all tested specimens are presented in Table 8.2. The maximum impact force for C1, C2 and C3 slabs was greater than for CFRC slab, indicating that FFRP greatly enhanced the load bearing capacity. The maximum impact force in the C2 slabs (58.39 kN) was found to be largest compared with C1 (46.24 kN) and C3 (46.75 kN).
Table 8.2 Summary of the impact force for all results

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Drop height (mm)</th>
<th>Peak impact force (kN)</th>
<th>Time to peak force (ms)</th>
<th>Damage status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRC</td>
<td>30</td>
<td>8.39</td>
<td>0.8</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>24.82</td>
<td>0.4</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>28.25</td>
<td>0.4</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>35.24</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>40.61</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>46.02</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>46.24</td>
<td>0.4</td>
<td>F</td>
</tr>
<tr>
<td>C1</td>
<td>30</td>
<td>17.12</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>24.18</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>29.33</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>31.88</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>42.03</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>44.52</td>
<td>0.8</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>53.59</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>58.39</td>
<td>0.6</td>
<td>F</td>
</tr>
<tr>
<td>C2</td>
<td>30</td>
<td>19.15</td>
<td>0.8</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>27.29</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>31.93</td>
<td>0.8</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>36.77</td>
<td>0.8</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>46.75</td>
<td>0.8</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>41.94</td>
<td>0.8</td>
<td>F</td>
</tr>
<tr>
<td>C3</td>
<td>30</td>
<td>17.12</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>24.18</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>29.33</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>31.88</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>42.03</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>44.52</td>
<td>0.8</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>53.59</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>58.39</td>
<td>0.6</td>
<td>F</td>
</tr>
</tbody>
</table>

Note: N=Non-visible damage, V=Visible damage, F=Failure.

(2) Damage development

To investigate the damage development of the FFRP-CFRC slabs, force-time and deflection-time histories were considered. Figure 8.10 shows the force-time and deflection-time histories under different impact heights for C1 slabs.
The deflection curves at the impact heights of 30 mm, 50 mm, 70 mm and 100 mm (Figures 8.10 (a), (b), (c) and (d)) increased to the peak and then decreased to almost zero, indicating that the deflection was mainly developed as elastic deformation. While the deflection curves at the heights of 150 mm and 200 mm in Figures 8.10 (e) and (f) showed that the specimens experienced irreversible displacement, which can be regarded as plastic deformation. As for the case of last impact of 300 mm (Figure 8.10 (g)), the deflection increased during the entire impact period, corresponding to the fracture of the slab. This also showed that maximum deflection increased with impact height. As for specimen types of C2 and C3, the deflection-time histories showed similar developments.
to that of C1.

(3) Energy absorption

The energy absorption developed in the slabs is one of the most important parameters in evaluating the impact behaviour. This energy was calculated by the integration of the force-deflection curves (see Figure 8.11) as shown in Equation (8.1).

\[ E_{ab} = \int F \delta \]  

\hspace{1cm} (8.1)

Figure 8.11  Force-deflection curves of the damaged slabs

Figure 8.12 describes the relationship between the energy absorbed and the impact height. For all three slab types, the energy absorption increased exponentially with the impact height, which can be described by the curve fitting Equations (8.2), (8.3) and (8.4). Additionally, the results showed that the energy absorbed at the last impact was much higher than that of the other impacts, as on the last strike the specimen fractured with great deformation, meaning higher energy was required.

C1: \[ E_{ab} = 0.2746e^{0.0137h} \]  

\hspace{1cm} (8.2)

C2: \[ E_{ab} = 0.5331e^{0.0085h} \]  

\hspace{1cm} (8.3)

C3: \[ E_{ab} = 0.3006e^{0.0191h} \]  

\hspace{1cm} (8.4)
Figure 8.12 Relationship between impact height and the absorbed energy

For repeated impact, the total energy absorption was calculated by totalling the strain energy in each individual impact, using Equation (8.5).

\[ E_{total} = \sum_{n=1}^{n} E_{ab} \]  

(8.5)

where \( n \) presents the strike numbers until failure.

The total energy absorbed was used to evaluate the impact resistance of the slabs. Figure 8.13 compares the total energy absorbed for all types of concrete slabs. The total energy absorbed was accumulated from all impact tests. The values were about 0.93 J and 2.19 J for PC and CFRC, respectively, which showed that the proper addition of coconut fibres to the concrete slabs could enhance flexural behaviour under impact loadings. Compared with PC and CFRC, the three FFRP-CFRC configuration slabs absorbed much more energy. The energy absorption capacity of CFRC slabs is 135% higher than PC slabs. Energy absorption capacity of FFRP-CFRC slabs, i.e. C1, C2 and C3, are respectively 987%, 1316% and 960% higher than CFRC. Considering the effectiveness of the configurations C1, C2 and C3, the total energy absorbed by C2 was highest among the three types, followed by C1, and then C3. From the analysis above, the C2 showed the best impact resistance.
(4) Failure mode

A comparison of the damage to C1, C2 and C3 specimens under impact loadings is presented in Figure 8.14. The damage in the case of C1 and C2 slabs was similar, with both a long crack at the tensile part (Figures 8.14 (a), (c)), and fracture was also observed at the edge of the specimen (Figures 8.14 (b), (d)). Compared with C1 and C2, the C3 specimens showed more severe damage, with fracture in the middle of the specimen (Figure 8.14 (e)). In addition, the FFRP laminate reinforcement separated from the concrete surface (Figure 8.14 (f)). The reason for the lower impact resistance of C3 slabs compared with C1 and C2 can be attributed to the de-bonding failure of FFRP laminates.

![Figure 8.14](image1)

(a) C1_bottom surface

(b) C1_edge of the specimen

(c) C2_bottom surface

(d) C2_edge of the specimen

Figure 8.13 Total energy absorbed for different specimen configuration
The experimental results showed different FFRP reinforcement configurations led to different impact behaviour and failure modes and that the FFRP reinforcement significantly improved the impact resistance of the CFRC slabs compared with the failure modes of CFRC in Figure 8.6.

8.1.3 Theoretical analysis of maximum impact force and maximum deflection

8.1.3.1 Theoretical model of impact on a slab

The Mass-slab impact was modelled as a single-degree-system (Szuladzinski 2008) which is shown in Figure 8.15 (a) and 8.15 (b), respectively.

![Figure 8.15](image)

The impact was considered as a sudden attachment to the slab. The problem can be simplified as an impact mass $M$ against a spring (contact stiffness) $k$ and a damper viscosity $C$. The largest impact force $P_m$ can be estimated according to Equations (8.6)-(8.8) (Szuladzinski 2008):

$$P_m \approx (P_{ms}^{-0.95} + P_{md}^{-0.95})^{-1.053}$$  \hspace{1cm} (8.6)
where $P_{ms}$ is the peak contact force between the mass-spring system and a rigid slab, $P_{md}$ is the peak damper force. $\nu_0$ is initial velocity of the striker.

The damper viscosity $C$ is derived from:

$$C = 2\pi r_0 \sqrt{Gh_m}$$  (8.9)

where $r_0$ is the insert radius at the centre of the impacted slab, $G$ is the shear modulus of the plate, $h_i$ is the shear thickness of solid slab $h$ thick, $h_i = h/1.2$, $m$ is the mass per unit surface of the slab.

The contact stiffness $k$ in Equation (8.7) was calculated by Equation (8.10), which was the model of a cylindrical striker impacting an elastic surface (Szuladzinski 2009), as shown in Figure 8.16:

$$\frac{1}{k} = \frac{1}{2r_i E_i} \left(1 - \nu_i^2 + \frac{E_i H}{\pi E_i r_i} \right)$$  (8.10)

where $\nu_i$ is the Poisson ratio of the slab, and $E_i$ is the Young modulus of the slab.

Figure 8.16 Sketch of a cylindrical striker impacting an elastic surface

The calculation of deflection was according to the theory of plate (Chennamsetti 2008). The small displacement $w$ of a thin plate can be obtained by the following classical plate equation:
where $w = w(x, y)$ is the vertical deflection, and $q = q(x, y)$ is external loading as shown in Figure 8.17, $D$ is the bending stiffness of the plate.

For a simple supported plate, the final solution of the deflection can be described as:

$$w(x, y) = \frac{4P}{\pi^4 abD} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\sin \frac{m\pi x_0}{a} \sin \frac{n\pi y_0}{b} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}}{\left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\right]}$$  \hspace{1cm} (8.12)

where $P$ is the point load which was obtained from the equation (8.6), $x_0$ and $y_0$ are the loading coordinates of axis $x$ and $y$, respectively; $a$ and $b$ are the width and length of the plate, respectively. In the calculation of maximum deflection in Equation (8.12), two terms were used for summary, i.e. $m=2$, $n=2$.

The stiffness $D$ in Equation (8.12) was obtained from the experimental results. Figure 8.18 displays the estimated stiffness of C1, C2 and C3 slabs. To estimate the stiffness at each impact, the equation $F_i = D_i w_i$ was used, where $D_i$ is the stiffness of the specimen and $w_i$ is the maximum deflection of the specimen at the $i$th impact, respectively. In this procedure, five samples in each configuration were considered to obtain an average value of stiffness.
8.1.3.2 Analytical results

Figures 8.19-8.20 showed the experimental and analytical predicted maximum force and deflection of the specimens at various impact heights. The results showed that the theoretical results aligned well with the experimental results.
8.2 Impact behaviour of renovated CFRC slabs using FFRP laminates

FRP composite has been considered an important method in civil construction engineering for repairing structure components. Carbon fibre reinforced polymer (CFRP), as an example, has been applied in buildings and bridges. Based on the research results of previous chapters, FFRP, a novel and natural composite, has the potential to be applied as a protective material for civil infrastructure. This section preliminarily investigates the effectiveness of FFRP composite as a renovating material.

Firstly, six CFRC rectangular slabs were cracked using low impact energy, resulting in minimal damage to the slabs. Secondly, two FFRP configuration methods were applied to renovate the cracked slabs. In the next stage, the repeated impact tests were conducted on these renovated FFRP-CFRC slabs, and the effectiveness of the two FFRP wrapping configurations was evaluated.

8.2.1 Specimen preparation

Specimen preparation included casting, cracking and renovating CFRC rectangular slab specimens, with a total of six samples prepared. All slabs were with dimensions of 600 x 300 x 50 mm. The casting procedure and concrete mixture was the same as described in Section 8.1.1.

All six specimens were cracked under a same drop weight of 40 kg and a 5 mm of height. This was to make sure all specimens had the same loading condition, which would be comparable. The deflection-time curves of the specimens are displayed in Figure 8.21. The maximum deflection ranged between 0.89 mm and 1.65 mm.
The crack patterns of these six specimens were similar, as shown in Figure 8.22. The cracks occurred on the tensile side of the slab, located close to the specimen centre line and their width was less than 0.5 mm.
In the renovating procedure, specimens 1-3 were reinforced by adhering FFRP laminates to the tensile surface, and specimens 4-6 were reinforced by adhering both FFRP laminates and strips. The nomenclature and explanations of the two renovation approaches are presented in Table 8.3. Sketches of the two renovated FFRP-CFRC slab types are displayed in detail in Figure 8.23. FFRP fabrication procedures were the same as in the Section 8.1.1.

Table 8.3  Nomenclature and explanations of the two renovation approaches

<table>
<thead>
<tr>
<th>Name of FFRP renovation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>FFRP laminates were attached to the tensile side of cracked slabs</td>
</tr>
<tr>
<td>D2</td>
<td>Both FFRP laminates and U-shape strips were attached to the tensile side of cracked slabs</td>
</tr>
</tbody>
</table>

![Sketches of renovated FFRP-CFRC slabs: (a) D1 and (b) D2](image)

Figure 8.23  Sketches of renovated FFRP-CFRC slabs: (a) D1 and (b) D2

8.2.2 Impact test

Repeated impact tests were performed on the specimens D1 and D2 as described above. The impact height started from 30 mm, followed by heights at 50 mm, 70 mm, 100 mm, 150 mm, 200 mm and 250 mm, until the specimen was broken. A dynamic load cell and a laser sensor were used to measure the impact force and deflection, respectively. Besides, strain gauges were also attached to the centre of the slabs tensile surface to measure the strain of FFRP laminates.
8.2.3 Results and discussion

8.2.3.1 Force-time histories

Figures 8.24 and 8.25 display the impact force histories of D1 and D2, respectively. The entire impact force duration for slabs D1 and D2 were respectively about 0.01 s and 0.015 s. The maximum impact force occurred at the very first stage of impact before 0.002 s. In addition, a “secondary peaks” phenomenon was also observed in this test.

![Figure 8.24 Force-time histories of D1 slab](image1)

![Figure 8.25 Force-time histories of D2 slab](image2)
With regard to the total number of blows required for failure, slab D1 withstood 6 impacts while slab D2 damaged on the 7th strike. The maximum forces and the damage status of D1 and D2 are presented in Table 8.4. Maximum impact force increased with impact height, with the value being slightly different among the specimen types. The maximum impact forces of D1 and D2 slabs were found to be about 54.79 kN and 50.26 kN, respectively.

Table 8.4 Summary of the impact force for all results for D1 and D2 slabs

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Drop height (mm)</th>
<th>Peak impact force (kN)</th>
<th>Time to peak force (ms)</th>
<th>Damage status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRC (reference)</td>
<td>30</td>
<td>8.39</td>
<td>0.8</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>18.57</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>27.37</td>
<td>0.4</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>32.51</td>
<td>0.8</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>40.78</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>51.56</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>54.79</td>
<td>0.4</td>
<td>F</td>
</tr>
<tr>
<td>D1</td>
<td>30</td>
<td>17.01</td>
<td>1</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>23.15</td>
<td>1.2</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>29.08</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>30.24</td>
<td>0.8</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>33.26</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>40.67</td>
<td>0.8</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>50.26</td>
<td>0.6</td>
<td>F</td>
</tr>
<tr>
<td>D2</td>
<td>30</td>
<td>18.57</td>
<td>0.6</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>27.37</td>
<td>0.4</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>32.51</td>
<td>0.8</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>40.78</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>51.56</td>
<td>0.6</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>54.79</td>
<td>0.4</td>
<td>F</td>
</tr>
</tbody>
</table>

Note: N=Non-visible damage, V=Visible damage, F= Failure.

The impact behaviour of the CFRC slab discussed in section 8.1.2 was used as a reference in this test. It is evident that CFRC slabs fractured at a drop height of 30 mm, while the renovated FFRP-CFRC slabs had greatly enhanced load bearing capacity.

8.2.3.2 Deflection curves and damage development

Figure 8.26 provides the deflection-time curves of D1 and D2 specimens, of which Figure 8.26 (a)-(b) show undamaged cases, and Figure 8.26 (c) provides the deflection-time curves at the final impact with specimen fracture. Maximum deflection increased with drop height. For the D1 slab, the maximum value increased from about 0.03 mm (30 mm of impact height) to 0.13 mm (150 mm of impact height). Deflection increased significantly on the last impact (200 mm of impact height), with a maximum value of about 1.5 mm. Slab D2 showed a similar development of maximum deflection, while the
values were larger than that of slab D1. For the case of slab D2, the maximum deflection increased from 0.07 mm to 0.35 mm, and the fracture deflection was about 3 mm, with the drop height of 250 mm.

(a) Deflection-time curves of D1 (30 mm to 150 mm)

(b) Deflection-time curves of D2 (30 mm to 200 mm)
The deflection difference between D1 and D2 could be due to the difference in their damage patterns. Figure 8.27 shows the damage patterns. D1 exhibited de-bonding failure when the drop height was 200 mm, hence the test was stopped at this impact. On the other hand, slab D2 did not fail until FFRP laminate fracture occurred. This phenomenon can also be observed through the strain changes of FFRP laminates, shown in Figure 8.28. The strain in the case of D1 decreased suddenly to 2500 με at a 200 mm impact height, due to the FFRP laminates de-bonding from concrete core. On the other hand, FFRP strain in the D2 slab increased gradually with increments of drop height until damage occurred.
Figure 8.27 Damage patterns of D1 and D2

Figure 8.28 FFRP strain curves of D1 and D2 slabs
Comparing the above renovation methods corresponding to slabs D1 and D2 respectively, it can be concluded that the D2 renovation method performed better than D1. This recommendation is based on the fact that a de-bonding problem should be avoided when using FFRP laminates for renovation. The FFRP laminate combined with u-strips could be an effective approach for retrofitting structural components.

8.3 Summary

In the first part of this chapter, the impact behaviour of PC, CFRC and three configurations of FFRP-CFRC slabs were investigated. A total of 26 specimens were considered. From the results obtained, the following conclusions are given:

• The superiority of FFRP-CFRC slabs over CFRC and PC slabs in terms of the impact resistance was demonstrated by experimental results. The FFRP-CFRC slabs showed higher capability to maintain integrity of the specimens compared with that of PC and CFRC slabs.

• FFRP-CFRC slabs absorbed more impact energy than CFRC and PC slabs. The energy absorption capacity of the CFRC was 135% higher than that of PC. The energy absorption capacity of FFRP-CFRC slabs, i.e. C1, C2 and C3, were respectively 987%, 1316% and 960% higher than that of CFRC.

• Empirical formulas were proposed to describe the relationship between energy absorption and impact height for the FFRP-CFRC slabs.

• Of all FFRP-CFRC slabs, configuration C2 had the best impact resistance compared with that of C1 and C3 in terms of energy absorption and the number of strikes required to cause the breakage of slabs.

• The maximum impact force and maximum deflection of FFRP-CFRC slabs obtained from a theoretical model showed a good agreement with the experimental results. The results showed that the theoretical model can be used to estimate the impact response of FFRP-CFRC slabs.
In the second experiment, the effectiveness of FFRP composites as a renovation material was preliminarily investigated. Repeated impact tests were conducted on two different FFRP renovating configurations, i.e. D1 and D2. Comparing these renovation methods, it was found that the D2 renovation method performed better than D1. FFRP laminates combined with u-strips could be an effective approach to retrofit structural components.
Chapter 9

Conclusions and recommendations for future research

This study provides a comprehensive understanding of the characteristics of steel-free FFRP-CFRC composites structural components under impact loadings, the results of which could make them candidates for development and design in infrastructure construction, e.g. constructing or retrofitting residential buildings in rural areas and temporary construction materials in earthquake zone as they are economical.

9.1 Conclusions

The overall outcomes of this research are: (1) The dynamic behaviour of FFRP composite, i.e. impact properties and dynamic tensile properties, were studied experimentally; (2) A drop weight impact test device was designed and built to conduct impact tests on concrete specimens; (3) The impact properties of CFRC cylinders were studied under single and repeated drop weight tests, and an optimised coconut fibre length was recommended; (4) The flexural behaviour of FFRP-CFRC beams were explored under static and impact loads, and an optimised coconut fibre content and FFRP thickness was recommended; (5) Performance of CFRC slabs with three different FFRP wrapping configurations were compared under impact loadings; (6) The effectiveness of FFRP composites as a retrofitting material was preliminarily investigated. The results are expected to be helpful in developing FFRP for retrofitting residential construction materials in rural areas. Conclusions from the work performed during this doctoral research are explained in the following sub-sections.

9.1.1 Dynamic properties of FFRP

The properties of flax fibre reinforced polymer (FFRP) composites were experimentally investigated under impact and dynamic tensile loadings. The study reveals that:

- Impact force and Hertzian force increased significantly with composite thickness.
  However, in the cases considered, the impact force and the Hertzian force for a
particular thickness had similar values independent of the impact energy. Higher thickness of FFRP composites can lead to greater impact resistance.

- Damage to the FFRP composite differed with thickness. Rebounding of the impactor, dented surfaces and perforations were observed for the 2-layer specimen, while only cracks and perforations were observed for the 4-layer and 6-layer specimens. The damage area increases with thickness. Longer cracks occurred in the 6-layer composites, which are associated with a higher impact resistance than those of the 2-layer and 4-layer composites.

- Striker diameter has a significant effect on the impact resistance of FFRP composites. A large diameter of the striker resulted in large impact energies required to perforate.

- The tensile strength was about 28 MPa under static loading. The tensile properties of FFRP were strain rate dependent. The tensile strength, failure strain and DIF were found to increase significantly when strain rate exceeded $79.12 \text{ s}^{-1}$. Empirical formulas of DIF for FFRP laminates were derived based on testing results. A single critical fracture perpendicular to the loading direction was generated for the strain rates less than $79.12 \text{ s}^{-1}$, while at the high strain rates, i.e. $110.16 \text{ s}^{-1}$ and $135.68 \text{ s}^{-1}$, multiple cross-sectional fractures were formed. The specimen split into three segments through the two cracks, were most clearly observed at the strain rate of $135.68 \text{ s}^{-1}$.

### 9.1.2 Impact properties of CFRC – The effect of fibre length

The behaviour of coconut fibre reinforced concrete (CFRC) cylinders under single and repeated drop weight impacts was investigated. Impact performance of PC and CFRC cylinders were compared under single impact tests. The results indicated that concrete with an addition of coconut fibres performed similarly to the plain concrete in compressive dynamic strength. However, CFRC had better performance in resisting spalling and fragmentation, which was due to the bridging function of the coconut fibre. This would be useful in protecting people from falling pieces of damaged structures, e.g. in strong earthquakes.
Various coconut fibre lengths were considered to study its effect on CFRC impact behaviour. The results showed that the length of coconut fibres had little influence on the dynamic increase factor (DIF) of CFRC under single impact. Under repeated impacts, the fibres with a length of 25 mm and 50 mm had better impact resistance compared with those of 75 mm. Considering the ease of experiment execution, 50 mm of fibre length is recommended as an optimized design for CFRC.

Damage to the CFRC cylinders due to repeated impact loading originated from tiny cracks close to the impact area. The cracks became longer and the impact contact area became smaller with increasing drop height. The final mode of failure involved the specimen experiencing brittle failure, through the sudden formation of a diagonal crack penetrating across most of the length of the specimen. The failure mode of CFRC under static and impact loadings was different. This is likely to be due to the dependence on damage development with the strain rate.

9.1.3 Behaviour of FFRP wrapped CFRC beams (W-FFRP-CFRC) – The effect of fibre content

Behaviour of W-FFRP-CFRC beams under static and drop weight impact loadings were experimentally investigated. The effect of coconut fibre content was considered.

In the static tests, the flexural strength of the W-FFRP-CFRC beams was much higher than that of CFRC beams. The coconut fibre content had little influence on the flexural strength, while it increased the ductility of the W-FFRP-CFRC beams. The force-deflection curves of the W-FFRP-CFRC beams showed a bi-linear trend, while CFRC specimens performed as a smooth curve. Failure pattern of CFRC and W-FFRP-CFRC was different. In the case of the CFRC beams, the coconut fibre functioned as a connection to postpone the crack development, which showed some ductility. However, W-FFRP-CFRC beams produced a brittle failure close to the middle of the beam.

In the repeated impact tests, the coconut fibre content affected the number of blows required to break the specimen. For the W-FFRP-CFRC specimens with 1%, 3% and 5% coconut fibre content, 3, 3 and 2 blows were required respectively to cause breakage. The W-FFRP-CFRC beams with 3% coconut fibre content absorbed highest energy of about 83.23 J compared with that of 1% and 5% specimens.
In the single impact test, the DIFs of the W-FFRP-CFRC beams were not sensitive to coconut fibre content, but influenced by strain rate. Higher strain rate led to a higher DIF value. An empirical equation was proposed to describe the relationship between strain rate and DIF.

Based on the single and repeated impact test results, it is suggested that 3% of coconut fibre W-FFRP-CFRC beams were recommended as being the best at resisting impact compared with 1% and 5% specimens, i.e. the number of blows required to break the specimen and total energy absorption.

9.1.4 Properties of CFRC beams laminated with FFRP (L-FFRP-CFRC) – The effect of thickness of FFRP

The behaviour of L-FFRP-CFRC beams under static and impact loadings were investigated experimentally. The effect of FFRP thickness was studied and the results revealed:

In the static test, FFRP was very effective in enhancing the flexural strength. The flexural strengths of L-FFRP-CFRC beams with 2-, 4- and 6-layer were almost 1.7, 3 and 4 times higher than that of CFRC, respectively. The toughness of L-FFRP-CFRC beams increased almost linearly with increments in FFRP thicknesses. The failure pattern of L-FFRP-CFRC beams was also influenced by the thickness of the FFRP laminates.

In the impact test, the deflection development of L-FFRP-CFRC specimens highly depended on the damage stages as well as loading rates. The DIFs for 2-, 4- and 6-layer L-FFRP-CFRC beams were 1-1.78, 1-2.15 and 0.99-1.91, respectively. More distributed cracks were observed under static loading compared with impact loading. The failure pattern was influenced by the thicknesses of FFRP. The 2-layer L-FFRP-CFRC beams fractured both at in the concrete and the FFRP laminate, while the damage occurred on the 4 and 6 layers specimens were evaluated as FRP de-bonding from CFRC surface.

The impact resistance of the L-FFRP-CFRC beams showed a linear relationship with the FFRP thickness. Based on the test results, 4- and 6-layer FFRP were recommended to enhance CFRC beams with 30 MPa design strength.
9.1.5 Strengthening of CFRC slabs using FFRP lamination

In the first experiment, impact behaviour of PC, CFRC and FFRP strengthened CFRC slabs were investigated. From the results obtained, the following conclusions were obtained:

- The superiority of FFRP-CFRC slabs over CFRC and PC slabs in terms of the impact resistance was demonstrated by experimental results. The FFRP-CFRC slabs showed higher capability to maintain integrity of the specimens compared with that of PC and CFRC slabs.

- FFRP-CFRC slab specimens absorbed more impact energy than CFRC and PC slab specimens. The energy absorption capacity of the CFRC slabs was 135% higher than the PC slabs. The energy absorption capacity of FFRP-CFRC slabs, i.e. C1, C2 and C3, were respectively 987%, 1316% and 960% higher than that of CFRC.

- Of all FFRP-CFRC slabs, configuration C2 (CFRC wrapped by FFRP along the long and short axis including the side faces with a 10 mm width top edge overhang) had the best impact resistance compared with that of C1 and C3 in terms of energy absorption and the number of strikes required to cause the breakage of slabs.

- The values of impact parameters, i.e. the maximum impact force and the deflection, were theoretically calculated, and agreed well with the experimental results.

In the second experiment, the effectiveness of FFRP composites as a retrofitting material was preliminarily investigated. Repeat tests were conducted on two different FFRP renovating configurations of slabs, i.e. D1 and D2. Comparing the above renovation methods, it is advised that the D2 renovation method (both FFRP laminates and U-shape strips were attached to the tensile side of cracked slabs) performed better than D1. The FFRP laminates combined with u-strips could be an effective approach to retrofit structural components.
9.2 Future work for FFRP-CFRC composites

Since research will never end, there are always many horizons to explore at the end of a particular research step. Many things are worth to be done to develop this novel steel-free FFRP-CFRC composite and make it applicable.

- Impact tests on small scale and large scale FFRP-CFRC beams and slabs serving as secondary structures.
- Consideration of the bonding relationship between FFRP and CFRC under impact loadings.
- The effect of strain rate on the FFRP-CFRC composites under high velocity impact is essential.
- Numerical and theoretical studies will help better understanding the impact behaviour of FFRP-CFRC composite structures, and the results can help predict the ultimate values during impact.
- As a new natural FRP composite, its retrofitting application potential should be further experimentally and theoretically investigated based on real structures, e.g. as wallpapers.
- Developing guidelines for this steel-free FFRP-CFRC composite in construction.
References


ACI Committee (2008), American Concrete Institute and International Organization for Standardization. Building code requirements for structural concrete (ACI 318-08) and commentary. American Concrete Institute.


This Agreement between Wenjie Wang ("You") and Elsevier ("Elsevier") consists of your license details and the terms and conditions provided by Elsevier and Copyright Clearance Center.

<table>
<thead>
<tr>
<th>License Number</th>
<th>4362540503172</th>
</tr>
</thead>
<tbody>
<tr>
<td>License date</td>
<td>Jun 05, 2018</td>
</tr>
<tr>
<td>Licensed Content Publisher</td>
<td>Elsevier</td>
</tr>
<tr>
<td>Licensed Content Publication</td>
<td>International Journal of Impact Engineering</td>
</tr>
<tr>
<td>Licensed Content Title</td>
<td>Local impact effects of hard missiles on concrete targets</td>
</tr>
<tr>
<td>Licensed Content Author</td>
<td>Q.M. Li, S.A. Reid, H.M. Wen, A.R. Telford</td>
</tr>
<tr>
<td>Licensed Content Date</td>
<td>Dec 1, 2005</td>
</tr>
<tr>
<td>Licensed Content Volume</td>
<td>32</td>
</tr>
<tr>
<td>Licensed Content Issue</td>
<td>1-4</td>
</tr>
<tr>
<td>Licensed Content Pages</td>
<td>61</td>
</tr>
<tr>
<td>Start Page</td>
<td>224</td>
</tr>
<tr>
<td>End Page</td>
<td>284</td>
</tr>
<tr>
<td>Type of Use</td>
<td>reuse in a thesis/dissertation</td>
</tr>
<tr>
<td>Portion</td>
<td>figures/tables/illustrations</td>
</tr>
<tr>
<td>Number of figures/tables/illustrations</td>
<td>1</td>
</tr>
<tr>
<td>Format</td>
<td>both print and electronic</td>
</tr>
<tr>
<td>Are you the author of this Elsevier article?</td>
<td>No</td>
</tr>
<tr>
<td>Will you be translating?</td>
<td>No</td>
</tr>
<tr>
<td>Original figure numbers</td>
<td>Fig. 1</td>
</tr>
<tr>
<td>Title of your thesis/dissertation</td>
<td>Behaviour of natural fibre reinforced concrete composite under impact loadings</td>
</tr>
<tr>
<td>Expected completion date</td>
<td>Jun 2018</td>
</tr>
<tr>
<td>Estimated size (number of pages)</td>
<td>185</td>
</tr>
<tr>
<td>Requestor Location</td>
<td>Wenjie Wang</td>
</tr>
<tr>
<td>Civil and Environmental Engineering</td>
<td></td>
</tr>
<tr>
<td>the University of Auckland</td>
<td></td>
</tr>
<tr>
<td>22 Symonds Street, Auckland 1001</td>
<td></td>
</tr>
<tr>
<td>Auckland, Auckland 1023</td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td></td>
</tr>
<tr>
<td>Attn: Wenjie Wang</td>
<td></td>
</tr>
</tbody>
</table>

## Introduction

The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your

https://s100.copyright.com/Customers/AdminPLF.jsp?ref=2a10be86f-90c7-4170-a71a-570eb8007d05
This Agreement between Wonjie Wang ("You") and Elsevier ("Elsevier")
consists of your license details and the terms and conditions provided by
Elsevier and Copyright Clearance Center.

License Number  45125/14/8UY9
License date       Jun 05, 2018
Licensed Content Publisher Elsevier
Licensed Content Publication Engineering Failure Analysis
Licensed Content Title  Experiments into impact behaviour of railway prestressed concrete sleepers
Licensed Content Author Sakdinat Kaewunruen, Alex M. Remennikov
Licensed Content Date Dec 1, 2011
Licensed Content Volume 18
Licensed Content Issue 8
Licensed Content Pages 11
Start Page          2305
End Page            2315
Type of Use         reuse in a thesis/dissertation
Intended publisher of new work other
Portion             figures/tables/illustrations
Number of
figures/tables/illustrations 1
Format              both print and electronic
Are you the author of this Elsevier article? No
Will you be translating? No
Original figure numbers Fig. 3
Title of your thesis/dissertation Behaviour of natural fibre reinforced concrete composite under impact loadings
Expected completion date Jun 2018
Estimated size (number of pages) 185

Requested Location
Wonjie Wang
Civil and Environmental Engineering
the University of Auckland
20 Symonds Street, Auckland 1001
Auckland, Auckland 1023
New Zealand
Attn: Wonjie Wang

Publisher Tax ID GB 494 6272 12
Total 0.00 USD

Terms and Conditions

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you

https://s100.copyright.com/CustomerAdminPLF.jsp?ref=a2d686b8-962a-4753-9c9c-31132145629
**Confirmation Number:** 11722012  
**Order Date:** 06/05/2018  
**Customer Information**  
- **Customer:** Wenjie Wang  
- **Account Number:** 3000844825  
- **Organization:** Wenjie Wang  
- **Email:** wwan586@aucklanduni.ac.nz  
- **Phone:** +64 223881422  
- **Payment Method:** Invoice

---

**This is not an invoice**

---

**Order Details:**

- **Proceedings of the Institution of Civil Engineers. Structures and Buildings**
  - **Billing Status:** N/A

<table>
<thead>
<tr>
<th>Order detail ID</th>
<th>71231282</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Journal</td>
</tr>
<tr>
<td>Type</td>
<td>Republish in thesis/dissertation</td>
</tr>
<tr>
<td>Volume</td>
<td>162</td>
</tr>
<tr>
<td>Issue</td>
<td>1</td>
</tr>
<tr>
<td>Start page</td>
<td>45-56</td>
</tr>
<tr>
<td>Publisher</td>
<td>THOMAS/TFI PUBLISHING LTD (GREAT BRITAIN)</td>
</tr>
<tr>
<td>Author/Editor</td>
<td>Y. Chen, I. M. May</td>
</tr>
</tbody>
</table>

**Permsision Status:** Granted

- **Permission:** Republish or display content
- **Type:** Republish in a thesis/dissertation
- **Order License ID:** 4362551372233

- **Requestor type:** Academic institution
- **Format:** Print, Electronic
- **Portion:** 1
- **Number of images/photos requested:** 1
- **The requesting person/organization:** University of Auckland
- **Title or numeric reference of the portion(s):** Chapter 3, Figure 3.2
- **Title of the article or chapter the portion is from:** N/A
- **Editor of portion(s):** N/A
- **Author of portion(s):** N/A
- **Volume of serial or monograph:** 162
- **Issue, if republishing an article from a serial:** N/A
- **Page range of portion:** 45-56
- **Publication date of portion:** February 2009
- **Rights for:** Main product
- **Duration of use:** Current edition and up to 5 years
- **Creation of copies for the disabled:** No
- **With minor editing privileges:** No
- **For distribution to:** Worldwide
- **In the following language(s):** Original language of publication

---

https://www.copyright.com/printOrder.do?id=11722012
This Agreement between Wenjie Wang ("You") and John Wiley and Sons ("John Wiley and Sons") consists of your license details and the terms and conditions provided by John Wiley and Sons and Copyright Clearance Center.

<table>
<thead>
<tr>
<th>License Number</th>
<th>4826007151</th>
</tr>
</thead>
<tbody>
<tr>
<td>License date</td>
<td>Jun 05, 2018</td>
</tr>
<tr>
<td>Licensed Content Publisher</td>
<td>John Wiley and Sons</td>
</tr>
<tr>
<td>License Content Publication</td>
<td>Strain</td>
</tr>
<tr>
<td>Licensed Content Title</td>
<td>A New Drop-weight Impact Machine for Studying Fracture Processes in Structural Concrete</td>
</tr>
<tr>
<td>Licensed Content Author</td>
<td>X. X. Zhang, G. Ruiz, R. C. Yu</td>
</tr>
<tr>
<td>Licensed Content Date</td>
<td>May 13, 2010</td>
</tr>
<tr>
<td>Licensed Content Volume</td>
<td>46</td>
</tr>
<tr>
<td>Licensed Content Issue</td>
<td>3</td>
</tr>
<tr>
<td>Licensed Content Pages</td>
<td>6</td>
</tr>
<tr>
<td>Type of use</td>
<td>Dissertation/Thesis</td>
</tr>
<tr>
<td>Requestor type</td>
<td>University/Academic</td>
</tr>
<tr>
<td>Format</td>
<td>Print and electronic</td>
</tr>
<tr>
<td>Portion</td>
<td>Figure/table</td>
</tr>
<tr>
<td>Number of figures/tables</td>
<td>1</td>
</tr>
<tr>
<td>Original Wiley figure/table number(s)</td>
<td>Figure 1</td>
</tr>
<tr>
<td>Will you be translating?</td>
<td>No</td>
</tr>
<tr>
<td>Title of your thesis / dissertation</td>
<td>Behaviour of natural fibre reinforced concrete composite under impact loadings</td>
</tr>
<tr>
<td>Expected completion date</td>
<td>Jun 2018</td>
</tr>
<tr>
<td>Expected size (number of pages)</td>
<td>185</td>
</tr>
<tr>
<td>Requestor Institution</td>
<td>Civil and Environmental Engineering</td>
</tr>
<tr>
<td></td>
<td>the University of Auckland</td>
</tr>
<tr>
<td></td>
<td>20 Symonds Street, Auckland 1001</td>
</tr>
<tr>
<td></td>
<td>Auckland, Auckland 1023</td>
</tr>
<tr>
<td></td>
<td>New Zealand</td>
</tr>
<tr>
<td></td>
<td>Attn: Wenjie Wang</td>
</tr>
<tr>
<td>Publisher Tax ID</td>
<td>EU826007151</td>
</tr>
<tr>
<td>Total</td>
<td>0.00 USD</td>
</tr>
</tbody>
</table>

TERMS AND CONDITIONS

This copyrighted material is owned by or exclusively licensed to John Wiley & Sons, Inc. or one of its group companies (each a "Wiley Company") or handled on behalf of a society with which a Wiley Company has exclusive publishing rights in relation to a particular work (collectively "WILEY"). By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the billing and payment terms and conditions at:

https://s100.copyright.com/CustomerAdminPLF.jsp?ref=ae6a2433-0be3-4a9c-9626-ceed767eac80