TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>DEDECATION</td>
<td>iii</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENT</td>
<td>iv</td>
</tr>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td></td>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td></td>
<td>LIST OF SYMBOLS</td>
<td>xvi</td>
</tr>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.1 Background of Study</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.2 Problem Statement</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1.3 Objective of the Study</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.4 Scope of the Study</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.5 Significance of the Study</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>LITERATURE REVIEW</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.1 General</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.2 Laminated Composite Materials</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.3 Applications of Laminated Composite Materials in Civil Engineering.</td>
<td>10</td>
</tr>
</tbody>
</table>
2.4 Laminated Composite Plates 12

2.5 The Behavior of Laminated Composite Plates Subjected to Impact load 12

2.6 Factors Affecting the Behavior of Composite materials under Impact load 17
   2.6.1 The Laminate Properties Effect 18
   2.6.2 Impactor Geometry 24

2.7 Previous Studies on the Interface Layer 26

3 METHODOLOGY 30

3.1 Introduction 30
3.2 Stiffness of the Lamina 32
3.3 Stiffness of the Interface 41
3.4 Element Stiffness Matrix of the Laminate 48
3.5 Global Stiffness Matrix of the Laminate 50
3.6 Computation of the Laminate Mass Matrix 53
3.7 Boundary Conditions 54
3.8 An Overview on the MATLAB Coding for this Study 55

4 RESULTS AND DISCUSSION 61

4.1 Introduction 61
4.2 Convergence Study 61
4.3 Verification of Study 63
4.4 The Effects of Fiber Orientation 64
   4.4.1 Central Displacement 65
   4.4.2 Relationship between Area of Delamination and Maximum Central Displacement 68
   4.4.3 Force-Displacement Relation of Various Laminates Progressive Delamination 70
4.5 Simulation of the Damage Behavior due to Blasting Studied
by Naik et al. (2006)

4.5.1 Central Displacement
4.5.2 The Relationship between Fiber Orientation and Energy

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion
5.2 Recommendations

REFERENCES

Appendices A – E
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Example of the Use of Carbon Fiber in Construction in Japan.</td>
<td>11</td>
</tr>
<tr>
<td>4.1</td>
<td>Precentage of difference of convergence study</td>
<td>62</td>
</tr>
<tr>
<td>4.2</td>
<td>Plate's properties and dimensions</td>
<td>63</td>
</tr>
<tr>
<td>4.3</td>
<td>Natural frequency of the eight mode shapes</td>
<td>64</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Types of Fiber reinforced Composite materials.</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Sketch of the Interface</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>Use of CFRC panels in the Kita Kyusho Prince Hotel</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>The effects of stacking sequence in laminated composite plates.</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>Deformed shape of the laminated composite folded plate under the impact load.</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>Falling weight impact machine.</td>
<td>15</td>
</tr>
<tr>
<td>2.5</td>
<td>Pendulum impact test system</td>
<td>16</td>
</tr>
<tr>
<td>2.6</td>
<td>The gas-gun machine.</td>
<td>16</td>
</tr>
<tr>
<td>2.7</td>
<td>Delamination areas in both thick and thin laminates.</td>
<td>19</td>
</tr>
<tr>
<td>2.8</td>
<td>Compression-after-impact strength in both thick and thin laminates.</td>
<td>19</td>
</tr>
</tbody>
</table>
2.9 Saturation energy versus number of layers for the two stacking sequences. 20

2.10 Projectile shape and dimensions. 25

2.11 Displacement jumps and interlaminar tractions interfaces. 27

2.12 Mechanical properties versus thickness ratio for bonding layers. 28

2.13 Relationship between normalized stiffness of composite system and the normalized stiffness of the bonding layers. 28

3.1 The laminated composite plate subjected to impact load 31

3.2 Finite Element Method (FEM) analytical procedure for laminate composite plate with an interface layer. 31

3.3 Distance of lamina surface from the mid plane of laminate. 36

3.4 Coordinate system and degree of freedoms (DOF) of lamina sub element. 37

3.5 Coordinate system of laminate plate element 40

3.6 Coordinate system and degree of freedom (DOF) in zero-thickness interface element 42

3.7 Degree of freedom (DOF) of each layer in the laminate. 46
3.8. 2 x 2 Gaussian quadrature rules.  
3.9 Degree of freedom (DOF) of the nodes in each sub element. 
3.10 Coordinate system of one local laminate plate element and DOF at each node. 
3.11 Rearrangement of node numbering. 
3.12 Node global numbering. 
3.13 Global nodes numbering for 2x2 elements 
3.14 Input for plate information 
3.15 Stiffness matrix of lamina 
3.16 Stiffness matrix of interface 
3.17 Mass matrix of lamina 
3.18 Boundary condition. 
3.19 Impact Force 
4.1 Central deflection against number of discretized elements 
4.2 Displacement of laminate with 4×4 delamination 
4.3 Displacement of laminate with 10×10 delamination 
4.4 Displacement of laminate with 14×14 delamination
4.5 Relationship between area of delamination and maximum displacement for [0/0] laminate

4.6 Relationship between area of delamination and maximum displacement for [30/0] laminate

4.7 Relationship between area of delamination and maximum displacement for [50/0] laminate

4.8 Relationship between area of delamination and maximum displacement for [90/0] laminate

4.9 Force-displacement curve for [0/0] laminate

4.10 Force-displacement curve for [30/0] laminate

4.11 Force-displacement curve for [50/0] laminate

4.12 Force-displacement curve for [90/0] laminate

4.13 Naik et al. (2006) delamination behavior

4.14 Simulated delamination based on that of Naik et al. (2006)

4.15 Displacement of laminate with [0/0] orientation

4.16 Displacement of laminate with [30/0] orientation
4.17 Displacement of laminate with [50/0] orientation
4.18 Displacement of laminate with [90/0] orientation
4.19 Force-displacement curve for [0/0] laminate
4.20 Force-displacement curve for [30/0] laminate
4.21 Force-displacement curve for [50/0] laminate
4.22 Force-displacement curve for [90/0] laminate
LIST OF SYMBOLS

$V_f, V_m$ - Volume fraction of fiber and matrix respectively

$E_f, E_m$ - Young Modulus of fiber and matrix respectively

$G_{12f}, G_m$ - Shear modulus of fiber and matrix respectively

$v_{12f}, v_m$ - Poisson’s ratio of fiber and matrix respectively

$E_1$ - Longitudinal Young’s modulus

$E_2$ - Transverse Young’s modulus

$G_{12}$ - In-plane shear modulus

$v_{12}$ - Poisson’s ratio

$\xi$ - Measure of fiber reinforcement of the composite that depends on the fiber geometry, packing geometry, and loading conditions. The value of $\xi$ is taken as 2 for $E_2$ calculation while 1 for $G_{12}$ calculation.

$Q_{ij}$ - Lamina stiffness matrix

$\overline{Q}_{ij}$ - Transformed stiffness matrix

$N$ - In-plane force

$M$ - In-plane moment

$\varepsilon^0$ - Mid-plane strain
κ - Mid-plane curvature

$A_{ij}, B_{ij}, D_{ij}$ - Laminate extensional stiffness, laminate-coupling stiffness, and laminate-bending stiffness respectively

$u, v, w$ - Displacement in $x, y, z$ direction respectively

$\Theta_x, \Theta_y$ - Rotation about the $x, y$ direction respectively

$N_i, N_o$ - Shape function for in-plane and out-of-plane degree of freedom respectively

$[B]$ - Element strain matrix

$[K]$ - Element stiffness matrix

$F$ - Force

$q$ - Transversely distributed load

$d_{\text{lower}}$ - Interpolated displacement of node at lower surface of the zero-thickness element

$d_{\text{upper}}$ - Interpolated displacement of node at upper surface of the zero-thickness element

$N$ - Lagrange shape function for zero-thickness element

$\hat{d}_{lw}$ - Nodal displacement of node at lower surface of the zero-thickness element

$\hat{d}_{up}$ - Nodal displacement of node at upper surface of the zero-thickness element

$\sigma$ - Stress

$\varepsilon$ - Strain

$D$ - Constitutive matrix

$h$ - Thickness of interface element

$J$ - Jacobian matrix
ξ, η - Coordinate system in Gauss quadrature rule

\( w_i, w_j \) - Weight of \( i^{th} \) and \( j^{th} \) Gauss point

\( f(ξ_i, η_j) \) - Function of \( i^{th} \) and \( j^{th} \) Gauss point