ACKNOWLEDGMENTS

There are several people I would like to acknowledge for their contribution to the completion of this thesis. I would first like to thank Dr. Plaut for his guidance, patience, and encouragement which enabled me to complete this thesis. I could not have asked for a better research advisor. Dr. Holzer helped me with finite element modeling and programming in ABAQUS. I would like to thank Dr. Rojiani for being on my research committee.

Several students also helped with the completion of this research. I would like to thank Raul Andruet and Guruprasad Mysore for their help with ABAQUS, Sean Molloy for his day-to-day help with ABAQUS and Excel, Dr. J. Y. Kim for his help with Fortran, and Budi Widjaja and Surjani Suherman for their help in the Structures Lab. I would also like to thank my family, friends, and fellow graduate students for their love and support.

I am thankful for the Via family’s generous contribution to the Civil Engineering Department; without the Master’s Via Fellowship, I would not have had the financial means to attend graduate school.

Finally, I am grateful for financial support that I received for this research from the National Science Foundation under Grant No. CMS-9422248.
TABLE OF CONTENTS

Chapter 1: Introduction

1.1 Scope 1

1.2 Literature Review 2

1.2.1 Introduction 2

1.2.2 Applications 4

1.2.3 Concrete Forms 8

1.2.4 Analytical and Experimental Studies 9

1.2.5 Model Characteristics 11

Chapter 2: Computer Modeling

2.1 Assumptions 13

2.2 Using ABAQUS as a Finite Element Program 13

2.2.1 Introduction 13

2.2.2 Nonlinear Analysis 14

2.2.3 Hydrostatic Pressure 14

2.2.4 Elements 14

2.2.4.1 Shell 14

2.2.4.2 Spring 15

2.3 Models 17

2.3.1 Introduction 17

2.3.2 Initial Models Which Led to the Final Model 17

2.3.3 Final Model 22

2.4 Convergence Study 24

2.4.1 Introduction 24

2.4.2 Edges 24

2.4.3 Top and Bottom Surfaces 25

2.5 Comparison With Celep (1988b) 27

Chapter 3: Tube with Flat Length-to-Width Ratio of 2:1

3.1 Introduction 29

3.2 Distributed Spring Stiffness, $K_d$, of $4.20 \times 10^6$ N/m³ 29
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.4.2.1</td>
<td>Stiffness of a Tensionless Spring</td>
<td>16</td>
</tr>
<tr>
<td>2.3.2.1</td>
<td>Original Model</td>
<td>18</td>
</tr>
<tr>
<td>2.3.2.2</td>
<td>Cross Section of Edge, Which Was Initially Flat</td>
<td>19</td>
</tr>
<tr>
<td>2.3.2.3</td>
<td>Cross Section of “Flipped” Edge</td>
<td>20</td>
</tr>
<tr>
<td>2.3.2.4</td>
<td>Initial Shape of One-Quarter Model with “Flipped” Edges</td>
<td>20</td>
</tr>
<tr>
<td>2.3.2.5</td>
<td>Close-Up of “Flipped” Edges</td>
<td>21</td>
</tr>
<tr>
<td>2.3.2.6</td>
<td>Final Shape of One-Quarter Model with “Flipped” Edges</td>
<td>21</td>
</tr>
<tr>
<td>2.3.3.1</td>
<td>Cross Section of Edge in Final Model</td>
<td>22</td>
</tr>
<tr>
<td>2.3.3.2</td>
<td>Initial Shape of Final Model Before Convergence Study</td>
<td>23</td>
</tr>
<tr>
<td>2.3.3.3</td>
<td>Close-Up of Edge in Final Model</td>
<td>24</td>
</tr>
<tr>
<td>2.4.3.1</td>
<td>Initial Shape of Final Model After Convergence Study</td>
<td>26</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Contact Region Found From an Analytical Study</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Presented in Celep (1988b)</td>
<td></td>
</tr>
<tr>
<td>2.5.2</td>
<td>Contact Region Found Using Finite Element Analysis</td>
<td>28</td>
</tr>
<tr>
<td>3.2.1.1</td>
<td>Pressure Head of 0.5m for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_d:W_f$ of 2:1</td>
<td>31</td>
</tr>
<tr>
<td>3.2.1.2</td>
<td>Pressure Head of 0.79m for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_d:W_f$ of 2:1</td>
<td>31</td>
</tr>
<tr>
<td>3.2.1.3</td>
<td>Cross Sections of the Tube at a Pressure Head of 0.79m for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_d:W_f$ of 2:1</td>
<td>32</td>
</tr>
<tr>
<td>3.2.2.1</td>
<td>Quarter Contact Region at Pressure Heads of 0.5m and 0.79m for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_d:W_f$ of 2:1</td>
<td>33</td>
</tr>
</tbody>
</table>
Figure 3.2.2.2  Whole Contact Region at a Pressure Head of 0.79m  
for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_f:W_f$ of 2:1

Figure 3.2.3.1  Mid-Surface Stresses at a Pressure Head of 0.79m  
for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_f:W_f$ of 2:1

Figure 3.2.4.1  Pressure vs. Height for $K_d = 4.20 \times 10^6$ N/m$^3$ and  
$L_f:W_f$ of 2:1

Figure 3.3.1.1  Pressure Head of 0.69m for $K_d = 8.40 \times 10^4$ N/m$^3$  
and $L_f:W_f$ of 2:1

Figure 3.3.1.2  Cross Sections of the Tube at a Pressure Head of  
0.69m for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_f:W_f$ of 2:1

Figure 3.3.2.1  Quarter Contact Region at Pressure Heads of 0.5m  
and 0.69m for $K_d = 8.40 \times 10^4$ N/m$^3$ and  
$L_f:W_f$ of 2:1

Figure 3.3.2.2  Whole Contact Region at a Pressure Head of 0.69m  
for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_f:W_f$ of 2:1

Figure 3.3.3.1  Mid-Surface Stresses at a Pressure Head of 0.69m  
for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_f:W_f$ of 2:1

Figure 3.3.4.1  Pressure vs. Height for $K_d = 8.40 \times 10^4$ N/m$^3$ and  
$L_f:W_f$ of 2:1

Figure 3.4.1  Pressure vs. Height for $K_d = 4.20 \times 10^6$ N/m$^3$ and  
$K_d = 8.40 \times 10^4$ N/m$^3$ for $L_f:W_f$ of 2:1

Figure 4.1.1  Initial Shape of Quarter Tube with $L_f:W_f$ of 5:1

Figure 4.2.1.1  Pressure Head of 0.7m for $K_d = 4.20 \times 10^6$ N/m$^3$  
and $L_f:W_f$ of 5:1

Figure 4.2.1.2  Cross Sections of the Tube at a Pressure Head of  
0.7m for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_f:W_f$ of 5:1

Figure 4.2.2.1  Quarter Contact Region at Pressure Heads of 0.5m  
and 0.7m for $K_d = 4.20 \times 10^6$ N/m$^3$ and  
$L_f:W_f$ of 5:1
Figure 4.2.2.2 Whole Contact Region at a Pressure Head of 0.7m for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.2.3.1 Mid-Surface Stresses at a Pressure Head of 0.7m for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.2.4.1 Pressure vs. Height for $K_d = 4.20 \times 10^6$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.3.1.1 Pressure Head of 0.4m for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.3.1.2 Cross Sections of the Tube at a Pressure Head of 0.4m for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.3.2.1 Quarter Contact Region at a Pressure Head of 0.4m for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.3.2.2 Whole Contact Region at a Pressure Head of 0.4m for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.3.3.1 Mid-Surface Stresses at a Pressure Head of 0.4m for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.3.4.1 Pressure vs. Height for $K_d = 8.40 \times 10^4$ N/m$^3$ and $L_d:W_f$ of 5:1

Figure 4.4.1 Pressure vs. Height for $K_d = 4.20 \times 10^6$ N/m$^3$ and $K_d = 8.40 \times 10^4$ N/m$^3$ with $L_d:W_f$ of 5:1

Figure 5.1.1 Pressure vs. Height for Both 2:1 and 5:1 Length-to-Width Ratio Cases
LIST OF TABLES

Table 2.4.2.1 Convergence Study on Edges 25
Table 2.4.3.1 Convergence Study on the Top and Bottom Surfaces 26
NOMENCLATURE

a : one-half the flat length
b : one-half the flat width
β : length-to-width ratio
D : flexural rigidity of a plate or shell; D = Et³/[12 (1-ν²)]
E : Young’s modulus
γ : specific weight; γ = ρg; γ_{slurry} = 1.5γ_{water}
k : nondimensionalized spring stiffness; k = K_d a^4/D
H : height
K : spring stiffness in units of force/length
K_d : distributed spring stiffness in units of force/length³
L_f : flat length
ρ : density; ρ_{slurry} = 1.5ρ_{water}
R : radius
σ_{11} : stress in the direction of the local x-axis
σ_{22} : stress in the direction of the local y-axis
t : plate or shell thickness
ν : Poisson’s ratio
W_f : flat width
X : global X-axis; in the model, X is along the tube’s length with X = 0 at the center of the tube
Y : global Y-axis; in the model, Y is along the tube’s width with Y = 0 at the center of the tube
Z : global Z-axis; in the model, Z is in the vertical direction with Z = 0 at the center of the tube’s bottom surface before deformation due to weight and pressure