The design and analysis of single point power-mooring cables applied to wave energy converters (WECs) is presented. WECs are mechanical devices designed and deployed to extract energy from waves in varying ways, and at varying distances from the shoreline. WEC devices operating on the water surface require mooring lines or cables to anchor the device to the ocean floor. A mooring cable design process is suggested, and effects on cable properties of cable cross-sectional layout, material selection, and conductor design are investigated. The study focuses on cable design and structural material, however manufacturing and cable termination are also investigated to ensure production feasibility. Combinations of six cable configurations and four structural materials were studied for a total of 18 different designs. The structural materials used for the study, chosen for significant strength and fatigue properties, included Vectran HS, Kevlar 49, Carbon fibers in a vinyl
ester matrix, and MP35N alloy. Copper was used as the conductor material in all cable configurations.

Structural component configuration had minimal impact on cable properties, while electrical component design, material used, and component helical angle exhibited significant effects on overall cable mechanical properties. Synthetic fiber designs exhibited more desirable cable mechanical properties and fatigue performance than carbon fibers in a vinyl ester matrix and MP35N alloy. Wave device heave motion and cable tension were not significantly affected by cable design or material. Cable termination requirements caused certain configurations to be impractical, while current cable manufacturing equipment, such as cabling, stranded, braiding, and extruding was found to be applicable to the proposed designs.
Fiber Reinforced Composite Power-Mooring Cables Design and Manufacturing applied to Wave Energy Converters

by

Andrew Miller

A THESIS

submitted to

Oregon State University

in partial fulfillment of the requirements for the degree of

Master of Science

Presented June 2, 2015
Commencement June 2015
Master of Science thesis of Andrew Miller presented on June 2, 2015.

APPROVED:

______________________________
Major Professor, representing Mechanical Engineering

______________________________
Head of the School of Mechanical, Industrial, and Manufacturing Engineering

______________________________
Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

______________________________
Andrew Miller, Author
ACKNOWLEDGEMENTS

I would like to start by thanking my adviser Dr. Roberto Albertani for help and support while pursuing this degree, as well as the opportunity to remain in school and further my education, and thank you to Oregon BEST for funding my research.

Thank you to my lab mates, the residents of Dearborn 5b, and NNMREC as a whole for answering questions and helping out from the beginning of senior design through the end of this work.

Thank you to my family for the encouragement and inspiration. While it may have sometimes seemed more like a freight train behind me in a tunnel rather than a light at the end, your advice and actions are one of my greatest motivations. Thank you especially to Brian for being so helpful when it came to anything about Corvallis, grad school, or technology.

And thank you to my friends who have gotten me out of the office when I needed a break, made me get out and try new things, and helped me grow into a better person or at least a more entertaining one.
# TABLE OF CONTENTS

1 Introduction 1

2 Background and Literature Review 4
   2.1 Wave Energy Converters ........................................... 4
   2.2 Mooring ............................................................... 5
   2.3 Fiber Reinforced Plastic Composites ............................ 7
   2.4 Composite Cables .................................................. 9
   2.5 Dual Purpose Tension-Power, Tension-Signal Cables .......... 10

3 Loads Estimation 12
   3.1 Mechanical Loads ................................................ 12
   3.2 Electrical Loads ................................................... 17

4 Cable Design 19
   4.1 Design Process .................................................... 19
   4.2 Materials ............................................................ 21
   4.3 Cable Configurations ............................................. 22
   4.4 Cable Termination ................................................ 23
   4.5 Manufacturing ....................................................... 25
   4.6 Cable Property Estimation ....................................... 29

5 Analysis of Selected Designs 37
   5.1 Cable Properties ................................................ 37
      5.1.1 Analysis of cable design ................................. 40
      5.1.2 Analysis of structural material ....................... 43
   5.2 Operational Life .................................................. 45
   5.3 Device Dynamics ................................................... 49
   5.4 Alternate Torque Balance Process .............................. 52

6 Summary and Conclusions 55
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7    Broader Impact</td>
<td>58</td>
</tr>
<tr>
<td>7.1  Deep Water Offshore Wind Energy</td>
<td>58</td>
</tr>
<tr>
<td>7.2  Airborne Wind Conversions Systems</td>
<td>60</td>
</tr>
<tr>
<td>8    Future Work</td>
<td>62</td>
</tr>
<tr>
<td>Bibliography</td>
<td>63</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Basic mooring concepts</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>Composite cables currently in use or in development. a) Electro-Optical-Mechanical for ocean observatories [25], b) Risers for TLPs [19], c) ACCC power line for high voltage power transmission [28]</td>
<td>9</td>
</tr>
<tr>
<td>2.3</td>
<td>Single point mooring system for oceanographic observatories [29]</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td>Ocean Sentinel in dry dock [33]</td>
<td>13</td>
</tr>
<tr>
<td>3.2</td>
<td>100 year wave spectrum</td>
<td>14</td>
</tr>
<tr>
<td>3.3</td>
<td>OrcaFlex model during simulation</td>
<td>15</td>
</tr>
<tr>
<td>3.4</td>
<td>Simulation of snap loading</td>
<td>16</td>
</tr>
<tr>
<td>4.1</td>
<td>Suggested design process</td>
<td>20</td>
</tr>
<tr>
<td>4.2</td>
<td>simplified CCC cable with two layers of helically wrapped armour [6]</td>
<td>23</td>
</tr>
<tr>
<td>4.3</td>
<td>Cabling machine [46]</td>
<td>26</td>
</tr>
<tr>
<td>4.4</td>
<td>Extrusion machine [47]</td>
<td>27</td>
</tr>
<tr>
<td>4.5</td>
<td>Illustration of a generic pultrusion process [49]</td>
<td>28</td>
</tr>
<tr>
<td>4.6</td>
<td>Cable designs considered in analysis. a) CSM b) CSM with protective jacket c) CSM-CCC d) CCC with braided structural member e) CCC with helically wrapped structural member f) CCC with helically wrapped structural member and modified electrical package.</td>
<td>30</td>
</tr>
<tr>
<td>4.7</td>
<td>Helical angle</td>
<td>32</td>
</tr>
<tr>
<td>5.1</td>
<td>Tension in mooring cable for configuration one using Vectran (Blue), Kevlar (Green), CFRP (Red), MP35N (Magenta), and the analytical case (Black/Dashed).</td>
<td>46</td>
</tr>
<tr>
<td>5.2</td>
<td>Tension in mooring cable for configuration one (Blue), two (Green), four (Red), five (Magenta), and six (Black) all using Vectran.</td>
<td>47</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3</td>
<td>Fatigue plots for Vectran (Blue), Kevlar (Green), CFRP (Red), and MP35N (Magenta).</td>
<td>48</td>
</tr>
<tr>
<td>5.4</td>
<td>Ocean Sentinel heave motion for configuration one using Vectran (Blue), Kevlar (Green), CFRP (Red), MP35N (Magenta), and water surface (Black/Dashed).</td>
<td>50</td>
</tr>
<tr>
<td>5.5</td>
<td>Ocean Sentinel heave motion for Vectran used in configuration one (Blue), Two (Green), Four (Red), Five (Magenta), and Six (Black) all using Vectran.</td>
<td>51</td>
</tr>
<tr>
<td>5.6</td>
<td>Ocean Sentinel heave acceleration for configuration one using Vectran (Blue), Kevlar (Green), CFRP (Red), MP35N (Magenta), and water surface (Black/Dashed).</td>
<td>51</td>
</tr>
<tr>
<td>5.7</td>
<td>Ocean Sentinel heave acceleration for Configuration One (Blue), Two (Green), Four (Red), Five (Magenta), and Six all using Vectran.</td>
<td>52</td>
</tr>
<tr>
<td>7.1</td>
<td>Floating wind turbine platform concepts [61]</td>
<td>59</td>
</tr>
<tr>
<td>7.2</td>
<td>AWEC vs. wind turbine operating areas</td>
<td>60</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Design Loads</td>
<td>17</td>
</tr>
<tr>
<td>3.2</td>
<td>Line voltages and allowable resistances for electrical conductors</td>
<td>18</td>
</tr>
<tr>
<td>4.1</td>
<td>Mechanical properties of materials used in this study</td>
<td>22</td>
</tr>
<tr>
<td>4.2</td>
<td>Structural materials used for each cable configuration</td>
<td>36</td>
</tr>
<tr>
<td>5.1</td>
<td>Vectran cable properties for configurations 1-6</td>
<td>38</td>
</tr>
<tr>
<td>5.2</td>
<td>Kevlar cable properties for configurations 1-6</td>
<td>38</td>
</tr>
<tr>
<td>5.3</td>
<td>CFRP cable properties for designs 1, 5, and 6</td>
<td>38</td>
</tr>
<tr>
<td>5.4</td>
<td>MP35N cable properties for designs 1, 5, and 6</td>
<td>39</td>
</tr>
<tr>
<td>5.5</td>
<td>Average cable properties for configurations 1-6</td>
<td>39</td>
</tr>
<tr>
<td>5.6</td>
<td>Average properties for Kevlar, CFRP, and MP35N</td>
<td>43</td>
</tr>
<tr>
<td>5.7</td>
<td>Percentage of design load carried by the structural member</td>
<td>45</td>
</tr>
<tr>
<td>5.8</td>
<td>Estimated cycles to failure under tensile load (Failure one) for each cable design</td>
<td>48</td>
</tr>
<tr>
<td>5.9</td>
<td>Average properties for Kevlar, CFRP, and MP35N</td>
<td>54</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

Marine energy generation, a relatively new method used to generate electrical energy from kinetic or potential energy stored in waves and tides, aims to generate electricity without damaging device surroundings through emissions or obstructions. Environmental impact, wave resource characterization, cost optimization, and device design are studied to ensure that wave and tidal energy devices are reducing man-made impact on the planet in a cost effective manner [1, 2, 3].

The variety of possible ways to extract energy has caused no one device to become the standard [4]. Research started with evaluating scaled designs and evolved towards full scale power generating devices in open water [5]. Currently testing facilities, such as the European Marine Energy Centre (EMEC) and the Pacific Marine Energy Center (PMEC) are being established in Europe and the United States to research devices, test grid connectivity, and environmental conditions for a variety of WEC designs. While there are currently no permanent operational marine energy generating sites, several countries are planning to grid connected devices within the next 5-10 years [4].

Wave energy converters (WECs) are held in position and constrained dynamically by a system of cables, anchors, sinkers and floats. Different WEC designs may require specific mooring systems and according to device dynamics for power generation, one or many cables may be required. A device requiring a single cable
for proper motion constraint was investigated during this study to evaluate single point power-mooring cable designs.

Transferring generated energy to shore requires a special type of cable called an Electro-Mechanical cable, which combines electrical transmission lines (Electro) with load bearing lines (mechanical) to form a cable to transfer mechanical and electrical loads [6].

Currently WECs which operate with only a single structural cable require both a mechanical and electrical cable. Infrastructure (ground and device connection points) for the mechanical and electrical cables of the system must be installed for each device resulting in high installation costs, and increased impact on the ocean environment. The results of this study can be applied to simplify and reduce the monetary and environmental cost of the WEC’s systems, and increase the viability of wave energy as a possible energy source.

This project aimed to study the feasibility of fiber-composite electro-mechanical mooring cables for wave energy converters through the design and analysis of varying cable materials and configurations. Cables will be designed to meet single point mooring requirements of a small WEC thus, the cable operates as the entire mooring assembly. Electric and hydrodynamic loads were estimated and applied to size components for each cable configuration. Vectran fibers, Kevlar fibers, carbon reinforced plastic, and MP35N were examined in this study to evaluate composite structural components and compare them to metals. Copper was employed as the conducting component for all configurations for a clear comparison of structural materials. Six cable configurations and four materials were investigated, leading
to 18 total designs, which were compared based on cable weight, cable diameter, cable strength, fatigue life, maximum cable loading, minimum bend radius and cable effects on device motion under operating conditions.
Chapter 2: Background and Literature Review

2.1 Wave Energy Converters

Ocean wave energy, currently at different stages between research and experimental deployment, represents a significantly large and untapped source of energy, with an estimated 240 TWh/yr of recoverable energy on the west coast of the United States [2].

Current technologies utilize a wide variety of energy conversion methods and device control schemes to increase energy production while decreasing costs [7, 8]. Relative motion and pressure differentials are used in different ways to extract energy from waves at different water depths. The combination of environmental and mechanical factors has caused the design of WECs to diverge to many different designs rather than converge to a single design [9].

Four general categories are used to classify different wave energy devices: 1) device operating principle, 2) device power takeoff system, 3) device directional characteristics, and 4) classification according to location [10].

Operating principle categorizes devices into oscillating water columns, overtopping devices, and Wave-Activated Bodies. Oscillating water columns use changes in pressure due to moving water columns to generate electricity, overtopping devices allow for waves to push water into reservoirs then convert potential energy
stored in the reservoir water into electricity, and wave-activated bodies use relative motion of device components to capture energy from waves [9].

Device power takeoff system describes how a device converts kinetic or potential energy into electrical energy. Power takeoff systems include linear generators and turbines, but are not limited to these two types [9].

Directional characteristics are based on the required direction of incoming waves. The three categories of directional characteristics are 1) point absorbers, 2) terminators, and 3) attenuator. Point absorbers can absorb energy from waves moving in any direction relative to the device, while terminators and attenuators can only absorb energy from waves moving in a single direction [9].

Device location is classified by its position with respect to the shore. Typical location classifications include shoreline, near shore, and offshore devices [9].

The simplified WEC device used in this study (described later) would be classified as a wave-activated body, a point absorber, and a near shore device when considering its operating principle, directional characteristics, and location respectively. The simplified WEC device modeled in this study does not contain a power take off system, so the device cannot be classified by its energy conversion method.

2.2 Mooring

A critical component of each WEC system and control scheme is mooring [11]. Mooring for a WEC must safely hold the device on station without negatively affecting the device dynamics and energy conversion [12]. Design of a mooring
system considers static, dynamic, fatigue, and abrasion loading cases, as well as WEC dynamics [13]. Fatigue and abrasion loading is of considerable concern since WEC mooring systems are required to be long-term installations [14].

Many different mooring styles are used in WEC systems. WECs use different methods to convert electricity, therefore devices may be constrained in different ways. Mooring lines, the main components of any mooring system, are typically synthetic ropes or metal chains which transfer static and dynamic loads between a device and the ocean floor. Mooring lines will impart loads and inertial damping on the device they moor, with magnitudes depending on mooring line material and length [15]. Combinations of floaters, sinkers, and mooring lines can be used to tailor these loads by adjusting line pretension and the overall mooring system stiffness. Different types of mooring systems may include any number of structural or umbilical lines, with attached floats or sinkers, in slack or taut configurations. Figure 2.1 shows six possible mooring configurations.

To maximize the number of devices which can be installed in a given area, cost and operational footprint are also considered during the design process. Single point mooring is an attractive option for WEC mooring due to relatively low costs and appeal to ocean operators due to the use of fewer components and smaller instantaneous footprints [11]. Cost of a mooring system and mooring system installation has been estimated to range from 14% to 21% of the total system cost [16].

For the current study, a Catenary Anchor Leg Mooring (CALM) system was used. While single point mooring systems are not an appropriate mooring solution
for all current WEC devices due to required motion constraints, they can be an effective low cost solution when applicable.

2.3 Fiber Reinforced Plastic Composites

Composite materials are combinations of two or more elements on a macroscopic scale, which form a composition with more desirable mechanical properties than those of the individual components [17]. For the case of carbon fibers embedded in an epoxy matrix, the fibers provide high strength and stiffness, while the epoxy provides protection and transfer of loads between fibers. For this thesis composite will refer to fiber reinforced plastics (FRP) and synthetic fibers. FRP materials
include short or long fibers depending on the desired properties, applied manufacturing technique, and allowable costs. Long fibers are oriented in a desired direction, while short fibers can have manufacturing advantages. Because cables require high tensile strength, long fibers will be used in this study.

The selected manufacturing processes also dictate part quality, properties, and cost [18]. Replacing metallic components in a system with composite components can increase manufacturing cost due to increased complexity of tooling, material placement techniques, and curing processes. Existing braiding, extruding, and pultrusion machines can be used in cable production to replace metallic components with lighter, stronger, and longer life composite or synthetic materials without extreme infrastructure changes [19].

Composite materials are growing in the transportation industry, but also civil infrastructure [20], and in offshore equipment. Use of synthetic fibers for mooring lines is being investigated, resulting in more compliant and suitable mooring systems than traditional materials [21].

Synthetic fibers are extensively used in mooring lines and marine cables [22], while FRP composites are used on a limited basis and mainly in the oil industry [23]. Synthetic fibers and composites can provide more favorable, and tailorable mechanical elastic properties when compared with traditional chain or wire rope [24]. Synthetic fibers such as Vectran, Aramid, Carbon, Dyneema, or Spectra are characterized by significantly higher specific strengths than steel, as well as other beneficial properties including better corrosion resistance and longer fatigue life [25, 26].
2.4 Composite Cables

Composite reinforced cables are employed in different applications and include Aluminum Conductor Composite Core (ACCC) power cables, risers and tethers for Tension-Leg Platforms (TLP), and Electro-Optical-Mechanical (EOM) cables for oceanographic buoys [19, 27, 25]. Each cable uses synthetic fibers or composite materials as structural members to limit loads experienced by more sensitive electrical or optical conducting wires.

Figure 2.2: Composite cables currently in use or in development. a) Electro-Optical-Mechanical for ocean observatories [25], b) Risers for TLPs [19], c) ACCC power line for high voltage power transmission [28]

In each cable, a traditional structural material has been replaced by a composite in order to increase performance by reducing the weight and increasing service life. In ACCC power cables, the reduction of weight limits power line sag during operation, which can cause power outages [27], while in composite tethers and
risers for TLPs, weight reduction allows for additional cable to be transported and deployed in deeper waters than traditional tethers and risers [19].

2.5 Dual Purpose Tension-Power, Tension-Signal Cables

Electro-mechanical cables, a combination of mechanical and electrical components to carry loads and transmit power and signals, have been investigated for single point oceanographic buoy mooring [25, 29, 30], as illustrated in Fig. 2.3. Electro-mechanical cables have not been investigated as single point mooring options for WECs, however extensive research has been performed to determine optimum umbilical layouts to limit loading [31]. While WEC umbilical cables are not intended to carry large mooring loads, they do contain large structural members to ensure no harmful loading of the electrical components occurs during normal and extreme condition operations.

Combining electrical and mechanical cables in a mooring system into a single component reduces system complexity and eliminates the risk of potentially harmful interactions between mooring and umbilical lines. Electrical and mooring components are carefully combined to ensure electrical component mechanical loading is kept to a minimum, through proper selection of cable layout and cable materials [32].
Figure 2.3: Single point mooring system for oceanographic observatories [29]
Chapter 3: Loads Estimation

3.1 Mechanical Loads

The WEC device selected in this project for the cable design was the Ocean Sentinel. The Ocean Sentinel, a 6.1 m long, 3.1 m wide, 10,000 kg modified Navy Oceanographic Meteorological Automatic Device (NOMAD) sensor buoy, is designed to test scaled wave energy devices. It is equipped with instrumentation to monitor WECs, as well as resistor banks to dissipate up to 100 kW of generated power. Although NOMAD sensing buoys were originally designed to operate on a single point mooring system, when deployed the Ocean Sentinel was equipped with a three point mooring system. The Ocean Sentinel, illustrated in Fig. 3.1, was selected for the cable design due to availability of analytical and experimental load data for validation, and its rated power which provided design loads and requirements for the electrical component of each cable [33].

The Ocean Sentinel numerical model investigated for this study, built by 3U technologies, and later updated by the Civil Engineering Department at Oregon State University, was adjusted to a single point CALM system, and to reflect 100 year storm conditions. Each model run simulated twenty minutes of random waves following 100 year wave spectrum, 100 year storm wind conditions [34], and 10 year storm current data at the North Energy Test Site (NETS). NETS, off the coast
Figure 3.1: Ocean Sentinel in dry dock [33]

of Newport, Oregon, was selected for this study, since it is the location where the ocean sentinel has been deployed in previous years [33]. Initial design loads were used to start the design cycle (discussed in chapter three), and were estimated by modeling chain as the mooring line. For iterations in the design cycle after the initial run, cables designed during the project were modeled. Maximum cable dynamic tension for chain, initial design one using Vectran, and final design one are listed in table 3.1..

To comply with Det Norske Veritas (DNV) DNV-OS-E301 [35], environmental conditions used in the design process reflected the 100 year storm, characterized by significant wave height of roughly 14 meters at the NETS location[36]. A wave spectrum with a significant wave height of 14 meters was selected from available NOAA oceanographic buoy 46050 data, and was assumed to be representative of
the wave spectrum at NETS. The wave spectrum matching the requirements was from March 3rd 1999, at 7 am, and is shown in Fig 3.2.

![Figure 3.2: 100 year wave spectrum](image)

Ten year current conditions, acceptable for extreme mooring analysis [35], were used due to non-availability of 100 year current data.

A single point CALM system was selected for the design due to moderate costs when compared with spread mooring systems, and ocean operator interest, since single point mooring systems require fewer components than comparable spread mooring systems, leading to lower installation and maintenance costs [11]. Environmental conditions, Ocean Sentinel, and associated mooring were modeled in OrcaFlex and illustrated in Figure 3.3. The cable was initially modeled as 1” chain since mechanical properties are available. For each run the length of the
mooring cable was 83 meters to model a similar watch circle to the three point
mooring system used in past deployments of the Ocean Sentinel.

Figure 3.3: OrcaFlex model during simulation

A simplified calculation of loads was performed using estimated wet weight of each cable design, and the estimated vertical acceleration of the water surface caused by waves. Water surface acceleration was assumed to be the acceleration of the Ocean Sentinel and the mooring cable. The acceleration and weight were then used to estimate maximum mooring line loads. A catenary mooring system allows for vertical motion, therefore anchor loads and cable elongation were not included.
into the simplified model. Calculated values were approximately 12 kN for each
design, significantly lower than the maximum loads estimated in OrcaFlex, but
were close to maximum loads experienced by the cable when snap loading was not
occurring. Snap loading can greatly increase mooring line loads so the OrcaFlex
data was found to be reasonable for this study [37]. Figure 3.4 shows a snap loading
case during simulation, with full results of the analytical study shown in Fig. 5.1.

Design loads were determined using a center structural member (CSM) cable
design with Vectran as the structural material and used for all cable designs.
Following the design process all Vectran cables and CSM cables using each of the four materials were modeled in OrcaFlex. Design loads for three iterations of configuration one using Vectran are shown in table 3.1

<table>
<thead>
<tr>
<th>Mooring Line</th>
<th>Chain</th>
<th>Cable 1</th>
<th>V1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Dynamic Load (kN)</td>
<td>1037.7</td>
<td>127.4</td>
<td>139.5</td>
</tr>
</tbody>
</table>

3.2 Electrical Loads

Power components of the cable design were based on requirements for the existing Ocean Sentinel umbilical cable. The cable, rated to 100 kW according to ocean sentinel specifications, contains three main power conductors sized at 2 American Wire Gauge (AWG) or larger, one ground conductor sized at 4 AWG or higher, and 2 auxiliary power conductors sized at 12 AWG or larger. Current and voltage specifications are 1) 120 Amps at 440 VAC, and 2) 50 Amps at 230 VAC for the main conductors, and 3) 3 Amps and 120 VAC for auxiliary power components. Allowable voltage drop per 200 meters is 10 percent for each main power conductor, and 5 percent for each auxiliary power conductor.

For electrical component design, allowable resistance was used in place of allowable voltage drop ($V_{Drop}$). To determine allowable resistance for each current and voltage specification, line voltage ($V_{Line}$) was calculated based on the line to neutral voltage ($V_{L−N}$) using Eq. (3.1) [38].
\[ V_{\text{Line}} = \sqrt{3} V_{L-N} \]  

(3.1)

With line voltage known, allowable voltage drop for each conductor (\(\%V_{\text{allowable}}\)) was found using Eq. (3.2).

\[ \%V_{\text{allowable}} = \frac{V_{\text{drop}}}{V_{\text{Line}}} \]  

(3.2)

With voltage drop and line current known, allowable line resistance was found using Ohms law.

Line voltage and allowable line resistance for each conductor and operating conditions are listed in Table 3.2. Because the allowable resistance in the main power conductor for Condition 1 is less than Condition 2, main power conductors were designed for Condition 1.

Table 3.2: Line voltages and allowable resistances for electrical conductors

<table>
<thead>
<tr>
<th>Condition</th>
<th>( V_{\text{Line}} ) (V)</th>
<th>( V_{\text{Drop}} ) (V)</th>
<th>( I_{\text{Max}} ) (A)</th>
<th>( R_{\text{Line}} ) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Power 1</td>
<td>254.03</td>
<td>25.4</td>
<td>120</td>
<td>0.21</td>
</tr>
<tr>
<td>Main Power 2</td>
<td>132.79</td>
<td>13.2</td>
<td>50</td>
<td>0.26</td>
</tr>
<tr>
<td>Aux Power</td>
<td>69.28</td>
<td>3.45</td>
<td>3</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Chapter 4: Cable Design

4.1 Design Process

The design process, illustrated in Fig. 4.1, was an iterative process which began by determining the WEC type and its mooring requirements. With the design factors determined, a model of the system was developed for load estimation using OrcaFlex, a fully non-linear time domain finite element program used to perform static and dynamic analyses of marine systems. Loads were used to create multiple solutions for cable designs, relevant cable properties were then determined and inserted into the OrcaFlex model to determine more accurate design loads in the next design steps, which were used to update cable designs in following iterations. The process of designing a cable, determining its properties, and updating the load data was performed until loads were reasonably close to the previous runs.
Start

Determine device, location, and environmental conditions

Generate load data (OrcaFlex)

Yes First Run? No

Compare load data with previous design simulation

Similar load results? Yes Stop

No

Structural component design (Based on OrcaFlex Data)

Electrical component design

Cable cross sectional layout

Allowable Internal Strains?

Yes

Determine relevant cable parameters

When design is complete, the OrcaFlex model is updated to reflect new design

When load data changes within acceptable amount the design process is stopped

If strain in structural or electrical components exceeds max. allowable value

Figure 4.1: Suggested design process
4.2 Materials

Materials selected for structural components were Vectran HS [39], Kevlar 49 [40], Carbon in a vinyl ester matrix [41] (referred to as CFRP for this study), and MP35N [42]. These four materials were selected to gain an understanding of how synthetic fibers and CFRP composites compare with metallic cables.

Vectran HS yarn was used as the starting material for each configuration since it is a well known material and traditionally used in current mooring cables. Further design iterations include Kevlar 49 yarn, and CFRP to examine the feasibility of application in mooring applications and electro-mechanical cables. Vinyl ester was used as the matrix material due to excellent water resistance. MP35N, a metal alloy currently used in structural members of electro-mechanical cables, was included to provide a benchmark to compare with synthetic fiber and CFRP cables.

Materials commonly used in synthetic ropes, but not for this study include Dyneema and Spectra. Both materials were determined to be unsuitable for electro-mechanical cables due to excessive creep behavior [25] caused by relatively high loads experienced in WEC applications, which will reduce the service life of the electrical component of the cable.

Properties for structural materials investigated during this study are listed in table 4.1.

Copper is used for all conductors in all cable designs. Aluminum, investigated as a possible conducting material in early design stages, was not considered later on due to lower electrical and thermal conductivity with respect to copper, and
Table 4.1: Mechanical properties of materials used in this study

<table>
<thead>
<tr>
<th>Material</th>
<th>Vectran</th>
<th>Kevlar</th>
<th>CFRP</th>
<th>MP35N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>2850</td>
<td>3000</td>
<td>1710</td>
<td>1655</td>
</tr>
<tr>
<td>Maximum Elastic Strain (%)</td>
<td>3.3</td>
<td>2.4</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>65</td>
<td>12.4</td>
<td>147</td>
<td>200</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>1.41</td>
<td>1.44</td>
<td>1.6</td>
<td>8.57</td>
</tr>
<tr>
<td>Linear Density (dtex)</td>
<td>1670</td>
<td>1270</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3 Cable Configurations

The three styles of cables designed during this project 1) center conductor core (CCC), 2) center strength member (CSM), and 3) a combination of CCC and CSM configurations are used to gain an understanding of how electrical and structural component orientation will affect cable properties. Each style is also well known, and proven technologies for manufacturing are available [32].

CSM cables locate structural members, typically consisting of several small strands, at the core of the cable with other components helically wrapped in outer layers [6], with strands twisted into a braid, a traditional fiber rope, or a wire rope.

CCC cable configurations are characterized by electrical components in a bundle at the center of the cable with structural support for the conducting core in strength members in outer layers of the cable. Structural components, typically made up of many small strands of supporting materials such as steel or polyester [6], are helically wrapped or braided around the cable core. A simplified drawing
of a CCC configuration with two layers of traditional armor is shown in Fig. 4.2.

Figure 4.2: simplified CCC cable with two layers of helically wrapped armour [6]

The CCC-CSM hybrid configuration contains a structural core consisting of a braided rope, and an outer structural layer consisting of a double braid with conductors located between the core and the outer structural layer. Structural components can be helically wrapped strands, wire rope, or traditional fiber ropes, but for this study only one structural configuration was used.

4.4 Cable Termination

Terminators secure cable ends to floating devices or anchors to safely and efficiently transfer loads to and from the cable structural component, and their design is
critical to load transfer and costs. Terminators depend on compression of the cable to create friction which transfers loads to and from the cable. Cables containing synthetic fibers or insulating materials are compressible which limits the amount of friction generated between the terminator and the cable [44]. Terminator cost will depend on the complexity required to properly load each cable component and the size of cable being terminated. Because all cables in this study contain synthetic materials (for structural or electrical insulating purposes) complex terminators are required.

Types of terminators commonly used are wire rope clips, compressed sleeves, swaged, mechanical, and helical, all using different methods to generate friction between cable structural components and terminator components. Helical and mechanical terminations were examined in this study because they both meet the design requirements caused by dynamic loading conditions that exist in mooring lines, cable design, and materials [32].

CCC cable configurations use helical terminations for load transfer from the outer structural layers to cable attachment points, with conductors passing through the terminator center to limit loading of electrical components of the cable through helically wrapped wires potted into an end fitting, making it suitable for cables with structural components in external layers. CSM cable configurations are equipped with mechanical terminations since the structural member is located at the cable center, and a sleeve, socket, and plug assembly can apply force to any layer of the cable [44]. Conductor layers need to be routed around the cable terminator, which increases terminator complexity. Helical terminators are not suitable for use on
CSM configurations since electrical components are in the outer layers of the cable which would interact with the termination. CCC-CSM combination cables will require a combination of helical and mechanical terminations to terminate the outer layers and inner layer of structural component respectively. The complexity of the cable terminator required for CSM-CCC configuration results in an impractical design.

4.5 Manufacturing

Electro-mechanical cable manufacturing consists of conductor stranding, insulation, cabling, jacketing, armoring, and prestressing [6, 45]. The manufacturing processes can be categorized by the components being operated on during the process. Conductor stranding, insulation, and cabling are applied to the cable electrical package, armoring is applied to the cable structural package, and jacketing and prestressing are applied to the cable assembly. Changes in the manufacturing process due to differences in cable designs and materials included in this study are minor.

Electrical package manufacturing begins with conductor stranding, which is the process of combining small conductors into a helically twisted, braided, or wire rope assembly. Multiple small conductors are used in place of one large conductor to reduce bending stresses in the conductor. Following stranding, insulation is extruded onto the conductor to protect the conductor from environmental conditions. Conductor stranding and insulation are not dependent on cable design.
Cabling is the process of assembling conducting components \[6, 45\]. For CCC designs insulated conductors are helically wrapped (similarly to stranding) to form the cable core, while for CSM designs, insulated conductors are helically wrapped around the structural core. Figure 4.3 shows a cabling machine typically used in cable manufacturing.

![Cabling machine](image)

**Figure 4.3: Cabling machine [46]**

Structural package manufacturing is more dependent on cable design than electrical package manufacturing. For CCC cable configurations armoring, the process of helically wrapping, or braiding the structural member around the conducting core of the cable, is used to apply the structural member to the cable assembly \[6, 45\]. In CSM configurations, the structural member is manufactured using ei-
ther a braiding or stranding machine to form a braided or stranded rope, then conductors are helically wrapped around the structural core. Braided, stranded, or helically wrapped constructions can be applied to CCC and CSM cable designs.

Jacketing, after the electrical and structural packages are combined, consists of passing the cable assembly through an extruding machine (shown in Fig 4.4) to apply a protective insulation coating (cable jacket) to the cable, and may occur multiple times during the cable assembly process based on structural and protective package design. To stabilize the cable the final assembly is prestressed by applying load to the cable to increase contact between components within the cable and decrease component surface stresses [6, 45].

![Figure 4.4: Extrusion machine [47]](image)

The addition of FRP composites or synthetic materials will require minor changes to the manufacturing process. Designs containing synthetic fibers use
the same manufacturing process, but jacketing materials must be selected so that extruder die temperature does not cause damage to the structural fibers. Designs containing composite materials require a pultrusion process during structural package manufacturing. Pultrusion, illustrated in Fig. 4.5, is the process of pulling synthetic fibers through a resin bath and shaping dies to manufacture long parts with a constant cross sectional area. The pultrusion process, a lower labor intensive process than other composite manufacturing techniques, is capable of consistently generating high quality parts at high production rates [48].

Figure 4.5: Illustration of a generic pultrusion process [49]

Excluding pultrusion of FRP composite rods, the manufacturing process for
composite and synthetic fiber cables will not deviate from standard cable production.

4.6 Cable Property Estimation

Six cable configurations were considered during this project. Three CCC cables (configurations 4, 5 and 6), two CSM cables (configurations 1 and 2), and a cable which is a combination of a CCC and CSM cable (configuration 3). The six cable configurations, illustrated in Fig. 4.6, were selected to evaluate and compare the mechanical characteristics of different cross sectional layouts and structural component orientation. Each cable configuration was originally designed with Vectran fibers as the structural material, but were then adapted to use Kevlar 49 yarn, and in some cases pultruded CFRP rods, and MP35N rods. The purpose of considering multiple materials for each design was to evaluate functionality and ease of manufacturing of different materials in a cable assembly.

After basic cable configurations were specified, the calculated mechanical and electrical loads were applied. For each configuration component sizing began with the component at center of the cable, then proceeded layer by layer moving outward, which were electrical components for CCC configurations, and CSM structural components for CSM and CSM-CCC configurations.
Figure 4.6: Cable designs considered in analysis. a) CSM b) CSM with protective jacket c) CSM-CCC d) CCC with braided structural member e) CCC with helically wrapped structural member f) CCC with helically wrapped structural member and modified electrical package.

Two different electrical packages were investigated during this study. Five configurations contained an electrical package with 22, 8 AWG wires, while the sixth configuration electrical package consisted of three, 2 AWG, and 12, 14 AWG wires. Using the same electrical component for five configurations allows for an
understanding of how the structural components in each design compare, while configuration six allows the effect of the electrical component on cable characteristics to be determined. Conductor resistance and diameter were based on values given for commercially available products from Calmont Wire and Cable [50].

Design of the cable structural component, required to carry the entire expected load per DNV-OS-E301 [35], began by establishing the total allowable cable strain, which was 0.5 percent for all designs [11]. Axial stiffness required to minimize strain to the allowable amount for each cable was determined by the following equation [51].

$$EA = \frac{PL}{\delta}$$  \hspace{1cm} (4.1)

Where $\delta$ is longitudinal displacement, $P$ is tensile load, $L$ is the original length of the cable, and $(EA)$ is the axial stiffness.

After the required axial stiffness was determined the best combination of number of strands, and strand helical angle, defined as the angle between the cable center line and the component center line and illustrated in Fig. 4.7, was estimated. Braid angle is measured the same way as helical angle, but will include components with both the positive and negative of the helical angle in each layer.

Several design iterations were required to find a suitable combination of strands and helical angles, and when determined the required strand stiffness was estimated using Eq. (4.2) below [52].
(EA)_b = \sum (EA)_s \cos^3 \beta \quad (4.2)

where \( \beta \) is the helical angle. Subscripts b and s indicate braid and strand respectively.

Equation (4.2) was used to estimate strand stiffness for helically twisted and braided structures since it is derived from Eq. (4.3), which was determined to be a reasonable estimator for both structures [52, 53].

\[ \epsilon_s = \epsilon_c \cos^2 \beta \quad (4.3) \]

Where \( \epsilon_s \) is strand strain and \( \epsilon_c \) is cable strain.
Depending on the material used, strands consisted of twisted yarn, pultruded rods, or metal wire. For designs using Vectran or Kevlar 49 the strands consist of filaments twisted into yarn. The axial stiffness of the untwisted yarn bundle, estimated using Eq. (4.2), was then used to determine the required cross sectional area of each untwisted strand, and the required number of filaments per strand. For designs using CRFRP or MP35N Eq. (4.2) is used only once to determine required cross sectional areas of each strand since strands consist of a single rod or wire component rather than twisted or braided filaments.

Once the number and required size of strands were determined the cross sectional area of the structural component in each cable could be estimated.

For CSM cable configurations using Vectran and Kevlar fibers the center strength member was a 12 strand braid with the diameter found using Eq. (4.4) [54]. A fiber aspect ratio of 1 and a compaction factor of 1.6 was assumed, based on similar strength 12 strand braided ropes. Fiber aspect ratio is the ratio of fiber width over fiber height, and compaction factor is the a mathematical representation of how braid strands affect one another within the cable.

\[
D = \frac{\sqrt{\zeta} N_c D_y}{\Xi \pi \cos \beta} \tag{4.4}
\]

Where D is braid diameter, \(N_c\) is the number of strands, \(\zeta\) is the yarn aspect ratio, \(\Xi\) is the braid compaction factor, and \(\beta\) is the braid angle.

CSM cable designs using CFRP or MP35N as structural material used a wire rope construction in place of braids since the rods and wires are not easily braided.
Radius of the wire ropes were estimated using Eq. (4.5) [55].

\[
r_2 = R_2 \left[ 1 + \frac{\tan^2 \left( \frac{\pi}{2} - \frac{\pi}{m_2} \right)}{\cos^2(\beta_2)} \right]^{\frac{1}{2}}
\]  

(4.5)

Where \( r_2 \) is the radius of the outer layer, \( R_2 \) is the radius of the helical wires, \( m_2 \) is the number of helical wires, and \( \beta_2 \) is the helical angle of wires.

For CCC cable configurations using Vectran and Kevlar fibers oriented in hollow braids, the braid size was estimated based on strand and cable core diameters. Braid thickness of each layer was approximated at twice the strand diameter due to strand cross over points along the braid.

Structural member thickness for cable designs using two layers of traditional helically wrapped cable armor was estimated using the thickness of each layer, allowing for layer thickness to be approximated as strand diameter, and total structural member thickness to be the sum of all layers.

Structural member size for the CSM-CCC configuration core braid diameter and outer braid thickness were estimated using Equation (4.4), and the CCC braid sizing method, respectively.

Electrical conductors were helically wrapped about the cable center axis in each cable design to limit strain to 0.5 percent during use [25]. As the helical angle of a given wire increases, the number of wires a layer can include decreases. A maximum helical angle exists for a given strand and core size that is allowable before no additional room is available in that layer, and no additional strands will fit. To verify that each conductor design was feasible the maximum coil angle
of each layer was determined with (Eq. (4.6) [56]), then compared to the design helical angle. If the design helical angle was smaller, the design was feasible.

\[
\cos \beta_{max} = n \left[ \pi \left(1 + \frac{1}{k} \right) \right]^{-1}
\]  

(4.6)

Where \( \beta_{max} \) is the maximum helical angle, \( n \) is the number of strands in the layer, and \( k \), Eq. (4.7), is the ratio of strand and core diameters [56].

\[
k = \frac{d_{co}}{d_{ro}}
\]  

(4.7)

Where \( d_{co} \) is the strand diameter, and \( d_{ro} \) is the core diameter.

Following the initial design of structural and electrical components, component helical angles were modified based on Eq. (4.8) to ensure torque balance while under load [57]. Torque load is introduced as axial load is transferred along helical components wrapped about the center axis inducing a moment about the cable center axis. Torque balancing ensures that no torque is introduced into the cable from tension loading due to load transfer along helically twisted strands. If torque is introduced when the cable is loaded, cable components could experience stresses beyond the design limits, reducing cable service life. Electrical components are not intended to transfer loads, but due to internal friction, the stiffness of copper, and the number of wires, some load will be carried by the conductors thus electrical layers must be torque balanced as well for maximum service life.
\[ M_\epsilon = \sum_{i=1}^{n} m_i [E_i A_i r_i \sin^2 \beta_i \cos \beta_i + [G_i J_i \cos^2 \beta_i]
- E_i I_i (1 + \sin^2 \beta_i)] \frac{\cos^3 \beta_i \sin^2 \beta_i}{r_i} \] (4.8)

Where \( M_\epsilon \) is the total torsional moment in the cable when loaded in tension, \( m_i \) is the number of wires or strands, \( E_i \) and \( G_i \) are elastic and shear moduli respectively of strands within layer \( i \), \( I_i \) and \( J_i \) are the area and polar moments of inertia respectively, \( A_i \) is cross sectional area of a given strand, \( r_i \) is the radius from the cable center to the strand center, and \( \alpha_i \) is the helical angle in layer \( i \).

The six cable configurations evaluated in this process originally designed with Vectran, were redesigned with Kevlar, Carbon fibers in vinyl ester matrix, and MP35N as structural materials, but due to practical constraints in manufacturing the structural component, such as inability to braid the material, not all materials could be used in all configurations. Structural materials used for each design are listed in table 4.2, for a total of 18 cable designs.

Table 4.2: Structural materials used for each cable configuration

<table>
<thead>
<tr>
<th>Design</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vectran</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Kevlar 49</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>CFRP</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MP35N</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 5: Analysis of Selected Designs

Cable properties, operational life, and effects on device dynamics were estimated during this study to evaluate and compare each cable design and structural material. The goal was to determine design and material configurations which best meet the requirements of the WEC-like device used in the study.

5.1 Cable Properties

Cable properties including diameter, axial stiffness, bending stiffness, minimum bend radius, and maximum load were selected for analysis since they characterize how each configuration and structural material will perform under operating conditions. Cable property parameters for all designs, estimated using the methods described in chapter four, are listed in tables 5.1-5.4.

Cable properties were compared by configuration, as well as by structural material, to gain knowledge on how cable configuration and structural material affect cable properties. Property values averaged for each cable configuration, as well as for each structural material are listed in tables 5.5 and 5.6 respectively.
Table 5.1: Vectran cable properties for configurations 1-6

<table>
<thead>
<tr>
<th>Design</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia. (mm)</td>
<td>68</td>
<td>67</td>
<td>73</td>
<td>53</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td>$EA$ (N)</td>
<td>4.64E7</td>
<td>4.70E7</td>
<td>4.69E7</td>
<td>4.76E7</td>
<td>4.81E7</td>
<td>4.88E7</td>
</tr>
<tr>
<td>$EJ$ (Nm²)</td>
<td>7.60E3</td>
<td>8.80E3</td>
<td>2.47E4</td>
<td>1.91E4</td>
<td>7.79E3</td>
<td>8.11E3</td>
</tr>
<tr>
<td>$R_{min}$ (m)</td>
<td>2.59</td>
<td>2.32</td>
<td>2.19</td>
<td>.99</td>
<td>0.98</td>
<td>1.40</td>
</tr>
<tr>
<td>Max. Load (N)</td>
<td>1.11E6</td>
<td>1.08E6</td>
<td>1.12E6</td>
<td>1.15E6</td>
<td>1.14E6</td>
<td>1.40E6</td>
</tr>
</tbody>
</table>

Table 5.2: Kevlar cable properties for configurations 1-6

<table>
<thead>
<tr>
<th>Design</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia. (mm)</td>
<td>62</td>
<td>61</td>
<td>66</td>
<td>50</td>
<td>46</td>
<td>51</td>
</tr>
<tr>
<td>$EA$ (N)</td>
<td>4.64E7</td>
<td>4.74E7</td>
<td>4.76E7</td>
<td>4.76E7</td>
<td>4.78E7</td>
<td>4.70E7</td>
</tr>
<tr>
<td>$EJ$ (Nm²)</td>
<td>5.79E3</td>
<td>6.72E3</td>
<td>2.07E4</td>
<td>2.90E4</td>
<td>6.06E3</td>
<td>7.42E3</td>
</tr>
<tr>
<td>$R_{min}$ (m)</td>
<td>2.35</td>
<td>2.15</td>
<td>2.09</td>
<td>.99</td>
<td>0.98</td>
<td>1.61</td>
</tr>
<tr>
<td>Max. Load (N)</td>
<td>7.53E5</td>
<td>7.92E5</td>
<td>8.36E5</td>
<td>8.36E5</td>
<td>8.27E5</td>
<td>1.00E6</td>
</tr>
</tbody>
</table>

Table 5.3: CFRP cable properties for designs 1, 5, and 6

<table>
<thead>
<tr>
<th>Design</th>
<th>1</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia. (mm)</td>
<td>68</td>
<td>49</td>
<td>50</td>
</tr>
<tr>
<td>$EA$ (N)</td>
<td>4.72E7</td>
<td>4.78E7</td>
<td>5.10E7</td>
</tr>
<tr>
<td>$EJ$ (Nm²)</td>
<td>7.49E3</td>
<td>5.27E3</td>
<td>6.32E3</td>
</tr>
<tr>
<td>$R_{min}$ (m)</td>
<td>2.58</td>
<td>0.98</td>
<td>1.40</td>
</tr>
<tr>
<td>Max. Load (N)</td>
<td>4.54E5</td>
<td>4.87E5</td>
<td>5.84E5</td>
</tr>
</tbody>
</table>
Table 5.4: MP35N cable properties for designs 1, 5, and 6

<table>
<thead>
<tr>
<th>Design</th>
<th>MP35N Design Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Dia. (mm)</td>
<td>65</td>
</tr>
<tr>
<td>$EA$ (N)</td>
<td>4.69E7</td>
</tr>
<tr>
<td>$EJ$ (Nm$^2$)</td>
<td>6.35E3</td>
</tr>
<tr>
<td>$R_{\text{min}}$ (m)</td>
<td>2.41</td>
</tr>
<tr>
<td>Max. Load (N)</td>
<td>2.48E5</td>
</tr>
</tbody>
</table>

Table 5.5: Average cable properties for configurations 1-6

<table>
<thead>
<tr>
<th>Design</th>
<th>Average design properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Dia. (mm)</td>
<td>66</td>
</tr>
<tr>
<td>$EA$ (N)</td>
<td>4.67E7</td>
</tr>
<tr>
<td>$EJ$ (Nm$^2$)</td>
<td>7.26E3</td>
</tr>
<tr>
<td>$R_{\text{min}}$ (m)</td>
<td>2.54</td>
</tr>
<tr>
<td>Max. Load (N)</td>
<td>7.32E5</td>
</tr>
</tbody>
</table>
5.1.1 Analysis of cable design

CSM configurations (1 and 2) had larger diameters than CCC cables (4, 5, and 6) when applying the same structural material to all configurations, but combination CSM-CCC configurations (3) had the largest average diameter. Additional space between conductors in the same layer for CSM configurations was obtained using the same electrical components for configurations one through five, causing an increase in cable diameter. Modifying the number or size of electrical components would reduce the cable diameter of CSM configurations, obtaining similar sizes to CCC configurations. Diameter of CSM-CCC cables could not be modified in the same manner because of lack of spaces between conductors.

Strain stiffness for all cable configurations was similar, with CCC configurations with traditional armor having slightly higher axial stiffnesses than both CSM and CSM-CCC configurations. Because torque balance is based on radius of the cable layer and helical angles, a balanced cable will require different helical angles for different designs, which From Eq. (4.2) can cause changes in axial stiffness. Unlike cable designs using braids, the two layers of cable armor needed to be torque balanced, causing different helical angles in different armor layers, as well as in different conductor layers.

Cable bending stiffness was estimated in order to increase accuracy of the OrcaFlex model, and was estimated for each cable according to the equation below [52].
\[ EJ = \sum_{i=1}^{n} m_i E_i \pi \frac{d_i^2}{64} \cos \beta_i + \sum_{i=1}^{n} \frac{m_i}{2} E_i A_i r_i^2 \cos^3 \beta_i \]  

(5.1)

Where \( EJ \) is bending stiffness, \( m_i \) is the number of wires or strands, \( d_i \) is the diameter of a given component, \( \beta_i \) is the helical angle, \( E_i \) is the elastic modulus, and \( r_i \) is the radius between the cable axis and the center of a component in layer \( i \).

Bending stiffness provides valuable insight into stress due to bending, and accounts for both material properties and cable cross sectional design. Cables with higher bending stiffnesses experience larger stress when subject to similar bending conditions as cables with small bending stiffnesses[52]. For each material, bending stiffness increased as the diameter increased and cable components moved further from the cable center, as expected.

Minimum bend radius is the smallest curve which the cable can withstand without damaging any component within the cable. Considering allowable conductor strain was one third of the lowest allowable strain for any structural material, minimum bend radius was dependent on the conductors. For this study, strain was calculated for each component when the cable experienced bending using Eq. (5.2).

\[ R_{min} = \frac{r_L \cos^2 \beta}{\epsilon_{max}} + \frac{D}{2\epsilon_{max}} \]  

(5.2)

Where \( R_{min} \) is the minimum bend radius, \( r_L \) is radius of a given layer, \( \beta \) is layer helical angle, \( D \) is strand or wire diameter, and \( \epsilon_{max} \) is maximum strain for
a given strand or wire.

It was assumed that no slippage occurred between the cable core and any conductor [52], causing the minimum bend radius to be highly dependent on conductor distance from the cable centroid. CCC configurations contain conductors in the core and not in outer cable layers resulting in lower minimum bend radii than CSM configurations for all materials. Adjustments in electrical package for CSM configurations would reduce the minimum bend radius, through eliminating space between conductors thus reducing cable diameter.

Maximum cable load is the theoretical load which will cause plastic deformation in the cable, estimated by finding the load which causes the maximum allowable strain in the structural component. Conductors were not included in this calculation since the structural member must be designed to hold the entire mechanical load as per DNV-OS-E301 [35]. Maximum allowable cable load was not significantly affected by cable design. As the structural member moved further from the center of the cable maximum load increased slightly, demonstrated in configurations 2, 3, and 4, and listed in table 5.5. Configurations 5 and 6 show a similar trend, but have a lower maximum load than configurations 2, 3, and 4 which only use Vectran or Kevlar fibers, indicating that structural material has a larger impact on cable properties than cable design.
5.1.2 Analysis of structural material

To analyze the effects of structural material on cable design, averaged cable properties using a given material were applied for each configuration. Properties, listed in table 5.6, were averaged over configurations 1, 5, and 6 since these configurations pair with all structural materials to create a design (illustrated in table 4.2), unlike configurations 2, 3, and 4 which only use Vectran and Kelvar.

Table 5.6: Average properties for Kevlar, CFRP, and MP35N

<table>
<thead>
<tr>
<th></th>
<th>Average Cable Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vectran</td>
</tr>
<tr>
<td>Dia. (mm)</td>
<td>59</td>
</tr>
<tr>
<td>$EA$ (N)</td>
<td>4.80E7</td>
</tr>
<tr>
<td>$EJ$ (Nm$^2$)</td>
<td>7.43E3</td>
</tr>
<tr>
<td>$R_{min}$ (m)</td>
<td>1.66</td>
</tr>
<tr>
<td>Max. Load (N)</td>
<td>1.21E6</td>
</tr>
</tbody>
</table>

As structural material stiffness increased, cable diameter decreased with the exception of cables with a Kevlar structural member, which on average had a smaller diameter than CFRP cables due to cable configuration one (diameters listed in table 5.6). Kevlar fibers were braided and CFRP rods are formed into a wire rope assembly. The braided Kevlar structure formed a cable core with a smaller diameter than the CFRP wire rope core, indicating that braided cores allow for smaller diameter cables than wire rope cores. Configurations 5 and 6 used helically wrapped strands with all materials, and showed decreasing cable diameter with increasing material modulus.
Strain stiffness ($E_A$) is dependent on the structural material’s stiffness, and the cable cross sectional area. Because of the design process, cross sectional area increased with decreasing material stiffness to keep cable axial stiffness relatively constant for all materials.

For each material, bending stiffness increased as the cable structural member moved further from the cable center, and as structural material cross sectional area increased. For Vectran and Kevlar cables the highest bending stiffness was for design three, while for FRP and MP35N cables the highest bending stiffness was exhibited by design one, which generated the largest diameter cables for the respective structural materials.

Minimum bend radius, dominated by the conductor layers, was estimated by determining the radius the cable can be wrapped around without damaging internal components, assuming that no slippage between components occurred during cable bending. Allowable strain of the conducting components was on average one third the allowable strain for the structural material, causing conductor strain to be the limiting factor in cable bend radius. As cable diameter decreased, radius of conductor layers within the cable decreased, allowing for tighter bend radius.

Structural material had a significant effect on maximum cable load, with a large variation 1.21 MN for Vectran Cables to 0.32 MN for MP35N, most likely caused by the maximum elastic strain of the materials investigated. Other material or cable properties such as tensile modulus or area will have a limited effect due to the consistency of cable axial stiffness throughout the design process.
5.2 Operational Life

To ensure maximum service life of an electro-mechanical cable, the load carried by the electrical conductor portion of the cable must be kept to a minimum. To calculate percentage of load carried by the structural member, the axial stiffness for each component was found using Eq. (4.2), then summed to find the total cable axial stiffness. Total cable elongation was then estimated using Eq. (4.1) with total cable axial stiffness and the design loads. With the assumption that longitudinal displacement will be the same for all cable components, Eq. (4.1) was used with total cable displacement and component axial stiffness to determine load carried by each component. As listed in Table 5.7, load carried by the structural member is nominally constant for different cable design and structural materials with the exception of cable configuration 6, which showed a roughly 20 percent increase in load carried by the structural components.

Table 5.7: Percentage of design load carried by the structural member

<table>
<thead>
<tr>
<th>Design</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vectran</td>
<td>63</td>
<td>60</td>
<td>63</td>
<td>64</td>
<td>64</td>
<td>74</td>
</tr>
<tr>
<td>Kevlar</td>
<td>60</td>
<td>61</td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>78</td>
</tr>
<tr>
<td>CFRP</td>
<td>62</td>
<td></td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>71</td>
</tr>
<tr>
<td>MP35N</td>
<td>61</td>
<td></td>
<td></td>
<td>63</td>
<td>63</td>
<td>71</td>
</tr>
</tbody>
</table>

To estimate the effect of structural material on mooring line dynamic tension cable configuration one was modeled in OrcaFlex with each material investigated in this study as the structural component. 100 year storm was modeled as the environmental conditions, and the Ocean Sentinel as the moored device. Cable
loading in the frequency domain for configuration one with each material are illustrated in Fig. 5.1. Vectran, CFRP, and MP35N show similar load amplitudes at low frequency, while Kevlar shows similar amplitude loads with peaks at roughly 0.1 and 0.15 Hz. As the frequency increases, Vectran, and Kevlar start to exhibit slightly higher loading amplitudes than MP35N and CRFRP which show similar loading amplitudes.

![Graph showing tension in mooring cable for configuration one using Vectran (Blue), Kevlar (Green), CFRP (Red), MP35N (Magenta), and the analytical case (Black/Dashed).]

Figure 5.1: Tension in mooring cable for configuration one using Vectran (Blue), Kevlar (Green), CFRP (Red), MP35N (Magenta), and the analytical case (Black/Dashed).

To estimate the effect of cable configuration on mooring line dynamic tension the OrcaFlex model was updated to reflect cable configuration one, two, four, five, and six, with Vectran. Configuration three was determined to be impractical and was omitted from loading and dynamic analyses. Cable loading in the frequency domain, shown in fig. 5.2, shows irrelevant difference between configurations with the exception of configuration six which shows lower amplitudes across the frequency spectrum. Changes in loading spectrum between cable designs show that
while using a single cable, minor changes can be to the dynamic response of a WEC through mooring line modification.

![Graph showing tension in mooring cable for configuration one (Blue), two (Green), four (Red), five (Magenta), and six (Black) all using Vectran.](image)

Figure 5.2: Tension in mooring cable for configuration one (Blue), two (Green), four (Red), five (Magenta), and six (Black) all using Vectran.

Fatigue properties of mooring cables are important for safety, and deployment duration. Since most of the cable designs for this project are fiber reinforced the four main fatigue failure modes evaluated were 1) tensile, 2) hysteris heating, 3) creep rupturing, and 4) internal abrasion [26].

Vectran exhibited the best resistance to tensile fatigue failure for low and medium cycles, with similar fatigue properties to Kevlar and MP35N in high cycle fatigue (illustrated in Fig. 5.3), while CFRP had consistently lower fatigue properties for both low and high cycle loading. Since each design is based on cable axial stiffness, structural member stress will vary between designs, and S-N curves will not show which cable has the best tensile fatigue properties. Fatigue life of each cable was estimated using a repeating cyclic load with amplitude of 273 kN (the
design load) and known S-N curves for each material [58, 41, 42]. Actual stresses in the structural component when the 273 kN load was applied were calculated using Eq. (4.1), Eq. (4.3), and known material properties. The fatigue curves shown in Fig. 5.3 were used to estimate fatigue life of each cable. Results of the tensile fatigue analysis are shown in table 5.8.

![Fatigue plots for Vectran (Blue), Kevlar (Green), CFRP (Red), and MP35N (Magenta).](image)

**Figure 5.3:** Fatigue plots for Vectran (Blue), Kevlar (Green), CFRP (Red), and MP35N (Magenta).

**Table 5.8:** Estimated cycles to failure under tensile load (Failure one) for each cable design

<table>
<thead>
<tr>
<th>Design</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vectran</td>
<td>1.1E9</td>
<td>9.6E8</td>
<td>1.2E9</td>
<td>1.3E9</td>
<td>1.3E9</td>
<td>3.0E9</td>
</tr>
<tr>
<td>Kevlar</td>
<td>4.3E7</td>
<td>1.1E8</td>
<td>2.6E8</td>
<td>2.6E8</td>
<td>2.2E8</td>
<td>4.2E9</td>
</tr>
<tr>
<td>CFRP</td>
<td>9.0E2</td>
<td></td>
<td></td>
<td></td>
<td>2.3E3</td>
<td>1.3E5</td>
</tr>
<tr>
<td>MP35N</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td>1.5E1</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Standard fatigue life estimation used for mooring systems (determining multiple
sea states, performing a rainflow analysis, then counting damage using minor’s rule) was not used in this case because the study focused more on cable design and materials rather than the mooring design and environmental evaluation.

Hysteresis heating and internal abrasion effects were omitted for the tensile analysis since both are dependent on friction, and through the use of barrier materials and lubrication the effects of hysteresis heating and internal abrasion for all cable designs and materials can be reduced. Cable design six showed nearly double the fatigue life of all designs. Resultant stress for a given load increased as the material stiffness increased, and as a result stresses were higher in MP35N and CRFRP cables than for Vectran and Kevlar cables leading to shorter fatigue life.

Creep behavior of each structural material is of significant importance. If the structural member is subject to large amounts of creep, increased amounts of loading will be placed on conductors, reducing the service life of the cable. Vectran, Kevlar, CFRP, and MP35N cables are loaded to roughly 11, 18, 33, and 63 percent of maximum cable load for each material respectively when the design load is applied. At these load levels, all materials exhibit irrelevant creep deformation [39, 59, 60, 42]).

5.3 Device Dynamics

To analyze how the cable affects system dynamics, floating device heave motion and vertical acceleration were estimated. Results were investigated in the frequency domain to compare response frequencies and amplitudes. Device motion,
illustrated in Fig. 5.4, was not affected by the structural material used in the mooring cable. The four simulations run with cable configuration one using different materials do not show any notable deviation from wave motion. The Vectran design exhibit the largest deviation from the wave motion with a spike at about 0.06 Hz and a dip at about 0.07 Hz. However, both the spike and the dip span small frequency regions, and may be the result of noise caused by high frequency small device movements. All configurations show small heave motions below 0.05 Hz, and above 0.2 Hz where the amplitude of surface motion is essentially zero.

![Figure 5.4: Ocean Sentinel heave motion for configuration one using Vectran (Blue), Kevlar (Green), CFRP (Red), MP35N (Magenta), and water surface (Black/Dashed).](image)

Device heave acceleration, illustrated in Fig. 5.6 and Fig. 5.7 for materials and design respectively, was not significantly effected by structural material or configuration choice. All structural materials and configurations allow for device acceleration to increase to roughly 0.1 m/s\(^2\) above 0.05 Hz, deviate around 0.2 m/s\(^2\) between 0.3 and 0.5 Hz, then drop to essentially zero above 0.6 Hz.
Figure 5.5: Ocean Sentinel heave motion for Vectran used in configuration one (Blue), Two (Green), Four (Red), Five (Magenta), and Six (Black) all using Vectran.

Figure 5.6: Ocean Sentinel heave acceleration for configuration one using Vectran (Blue), Kevlar (Green), CFRP (Red), MP35N (Magenta), and water surface (Black/Dashed).
Device heave acceleration were not significantly affected by structural material or cable configuration used. Heave motion followed wave motion closely, with the addition of small amplitude motions at high and low frequencies. Heave acceleration was higher than vertical acceleration of the water surface, but all cables showed similar heave acceleration indicating that changes in acceleration were due to the mooring scheme rather than the cable used.

5.4 Alternate Torque Balance Process

Following the analysis of cable design and structural material affects on cable properties, a brief study was performed on the torque balancing method described in chapter four. Structural and electrical components were designed to be individually torque balanced by varying helical angle layers of similar components. Differences in helical angles of components causes differences in component stress
during operation, leading to reduced operational life.

To determine the effects of varying helical angles within components, a new torque balancing method was used, applying torque caused by the structural component to compensate torque caused by the electrical component, versus torque balancing individual components of the cable (i.e. balancing only structural components with other structural components). Strand helical angles would be constant in the structural package and conductor wire helical angles would be constant in the electrical package, leading to constant stress for all component strands or wires in similar components.

It was assumed that loading of electrical components will occur uniformly throughout the length of the cable, and no torque is imparted on the cable due to lack of load transfer to the electrical component loading at the cable ends.

The alternate process was applied to cable configuration 5 due to the combination of component orientation and component helical angles. Conductor layers for all designs had a helical angle limited between 22 and 30 degrees, while structural layers had helical angles between 13 and 15 degrees to maintain low tangential force. Configuration 5, a CCC design, exhibits higher angled conductor components at the center of the cable, and lower angle structural components. Distance and force combinations allow for easy balancing of one component with the other for Vectran and Kevlar CCC configurations and property estimation, listed in table 5.9.

When using the alternate torque balancing method, cable diameter and maximum allowable load decreases approximately one percent for the Vectran cable,
Table 5.9: Average properties for Kevlar, CFRP, and MP35N

<table>
<thead>
<tr>
<th></th>
<th>Average Cable Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vectran</td>
</tr>
<tr>
<td>Dia. (mm)</td>
<td>53</td>
</tr>
<tr>
<td>$EA$ (N)</td>
<td>4.62E7</td>
</tr>
<tr>
<td>$EJ$ (Nm$^2$)</td>
<td>6.43E3</td>
</tr>
<tr>
<td>$R_{\text{min}}$ (m)</td>
<td>0.87</td>
</tr>
<tr>
<td>Max. Load (N)</td>
<td>1.13E6</td>
</tr>
</tbody>
</table>

but increase 10 percent and 30 percent respectively for the Kevlar cable. Strain stiffness decreases slightly for both cables, and bending stiffness and minimum bend radius decrease 20 and 3 percent from the original Vectran and Kevlar cables respectively. The changes in cable properties are beneficial to cable service life for both the Vectran and Kevlar cable. Applying torque balancing to the entire cable rather than individual components exhibited promising initial results, but additional work is required to analyze these designs further, and to evaluate electrical component loading assumptions that were made.
Chapter 6: Summary and Conclusions

This thesis presents a study on design and material selection for electro-mechanical cables applied to wave energy converter single-point mooring systems. Cable properties for 18 cable designs, employing six cable configurations (two CSM, three CCC, and one CSM-CCC combination) and four structural materials, were estimated, and the effects of design and structural material were investigated. Cable performance were evaluated as strain and bending stiffness, minimum bend radius, maximum load, and fatigue life.

Cable design affected cable properties and cable fatigue life minimally. Electrical component configurations, and using structural layers to balance tensile induced torque caused by the electrical components could lead to similar mechanical properties for CCC and CSM designs. CCC-CSM combination designs had similar performance characteristics to CCC and CSM cables, but cannot be modified as easily as CCC or CSM designs.

CCC and CSM were found to be applicable design options, while CCC-CSM were found to be impractical due to increased complexities in the cable and termination designs. CCC cables will provide better protection for the signal and electrical transfer components than CSM cables due to the placement of the structural components.

Cables with synthetic fibers (Vectran and Kevlar) exhibited longer fatigue life
and higher maximum cable loads when compared with CFRP and MP35N cables. Axial stiffness, minimum bend radius, and bending stiffness were not significantly affected by material choice and were adversely affected by increasing material tensile stiffness. Differences in cable properties may be amplified for larger cables, so the trend in values should be noted.

Component helical angle was the only design parameter which exhibited a significant impact on all mechanical properties of a cable. As helical angle increases or decreases, the diameter, strength, and allowable strain increase or decrease respectively.

WEC heave dynamics and mooring cable tension are not significantly affected by changes in cable structural materials or cable design, however they were mainly affected by the mooring system and device design. Service life and cost of the cable system will be affected by materials and designs selected.

Terminator design, crucial to proper load transfer to and from the cable, will influence cable properties and service life. Improper load transfer or end constraints can cause stress concentrations at either end of the mooring cable. Complex terminators will be required for all designs and materials used during this study. Mechanical and helical commercially available terminator styles were found practical for all designs with the exception of design 3, which requires a custom terminator design to transfer loads from the inner and outer strength members.

Each cable was designed to withstand snap loading scenarios. Limiting the possibility of snap loading occurring however, will increase the operational life without impacting device dynamics. The addition of floats and weights into the
mooring system could greatly reduce the risk of snap loading, while maintaining or even increasing overall mooring stiffness with limited additional cost.

Based on the analysis performed, no single design provided significantly better properties, or caused significant changes to device motion. Design three (combination CCC-CSM configuration) however, was found to be impractical due to mechanical properties and complexities in manufacturing and termination. Vec-tran was the found to be the structural material most suited for this study, but may be out performed by other structural materials when applied to larger devices.
Chapter 7: Broader Impact

The cable design process proposed in this study can potentially be applied to floating offshore wind turbines, and airborne wind energy devices.

7.1 Deep Water Offshore Wind Energy

Offshore wind energy is investigated for application in areas off the east and west coasts of the United States. To address space and visual constraints, planned offshore wind towers locations are at increasing distances from shore in deeper waters on moored floating platforms [61]. With few obstacles to block or alter wind resources, few obstructions prohibiting tower placement, and ability to move and install larger wind turbines when compared to onshore towers, floating wind turbines are becoming increasingly cost competitive [62]. Composite mechanical-power transfer mooring cables can be used as a part of mooring systems to reduce installation and maintenance costs.

Three types of floating platform stability methods (ballast, mooring line, and buoyancy, shown in 7.1), are used individually or in unison in current floating platform concepts [61]. For all current floating turbine concepts, multiple mooring lines are required for translational and rotational platform dynamic stability. Replacing mooring lines with composite mechanical-power transfer may not be cost compet-
itive for platforms using certain stabilizing methods due to potentially high costs of power-tension transmission cables. Mooring line stabilized platforms (TLPs) would benefit most from these cables through the replacement of one tension leg and the tower umbilical with a power-tension transmission cable, and possibly reducing material, installation, and maintenance costs of the mooring system.

Figure 7.1: Floating wind turbine platform concepts [61]
7.2 Airborne Wind Conversions Systems

Airborne wind energy conversion systems (AWECS) are a relatively new form of wind energy harnessing which uses airborne platforms to exploit more consistent winds at altitude. Energy is converted either through generators on the airborne device or on the ground, and driven by the wind or tension in the tethering line respectively [63]. For both methods a light weight strength cable is required, and for airborne generators a power-tension cable is required. Roughly 80% of energy converted by wind turbines is collected by the outer 20% of the blades. AWECs will operate in the area covered by the outer 20 percent of wind turbine blades, illustrated in Fig. 7.2, while removing the need for a tower, 80% of each blade, and most of the cost of the wind turbine system and installation [64].

Figure 7.2: AWEC vs. wind turbine operating areas
While cables designed during the main study cannot be applied to AWECs due to excessive weight, similar design processes can be applied to the tether system design. By applying specific materials that were not considered for this study, such as Spectra, Dyneema, and aluminum, smaller and lighter cables can be designed for AWEC use.
Chapter 8: Future Work

The main area for future work is investigating the use of composite electro-mechanical cables in mooring systems of full scale devices. The present research provides valuable insight into the performance of four materials and six cable configurations applied to a limited displacement scaled WEC. Increased mooring loads may require different cable characteristics. Study of full scale WECs would require tailoring each cable design to the optimal mooring scheme to meet WEC dynamic requirements to ensure operating force predictions are reasonable.

Additional research into manufacturing and materials should be performed to obtain detailed cost estimates of cable designs, as well as determine sustainable materials and designs. While manufacturing equipment is currently available, factors such as material cost and availability, or possible production rates may render large scale power-tension transmission cables infeasible from a cost prospective. Materials investigated in this project were selected because of high strength and fatigue life, with little weight given to the environmental cost. Materials which are easily recyclable, and require little to no harmful emissions during production should be investigated.

A final area for future research is monitoring cable health, through the application of fiber optic strain sensors within the cable, capable of providing meaningful data consistently in marine environments and helping to predict mooring line oper-
ational life and failure [65]. Additional information could be gathered using smart composites, allowing system operators to have in depth knowledge about cable loadings and operational state for more efficient required maintenance prediction.
Bibliography


[49] Creative Pultrusions, j. y. The pultrusion process.


