Parametric study of cyclic loading effects on the creep behavior of polymers and polymer based composites
by Shane Christian Schumacher

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering
Montana State University
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Abstract:
An investigation of the cyclic loading effects on the time dependent response of Nylon 6/6 and a
piezoelectric Polyvinylidene Fluoride (PVDF) based composite material is presented. A consistent
experimental program has been developed with the main objective to determine the creep behavior of
the materials under cyclic loading conditions. An extensive testing procedure employed in this study
has involved multiple experimental stages consisting of tensile stress-strain tests, constant load creep
tests, and tests under sustained tensile loads with superimposed harmonic oscillations. The creep
behavior of Nylon 6/6 and the PVDF based composite has been investigated depending on three
loading parameters, mean stress, vibration frequency and amplitude. The study has been performed
over a wide range of temperature conditions. The results of this investigation have provided a general
view on the cyclic creep response of the materials under investigation, where Nylon 6/6 is a solid
polymer and PVDF is an electroded polymer. Nonlinear creep effects induced by cyclic loading
conditions have been observed in both materials. The results of the study have demonstrated the
limitations of linear viscoelastic theory and have served as a basis for constitutive model development
and microstructural analyses of polymers subjected to asymmetric cyclic loading regimes.
PARAMETRIC STUDY OF CYCLIC LOADING EFFECTS ON THE CREEP BEHAVIOR OF POLYMERS AND POLYMER BASED COMPOSITES

by

Shane Christian Schumacher

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Montana State University
Bozeman, Montana

July 2000
APPROVAL

of a thesis submitted by

Shane Christian Schumacher

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency and is ready for submission for the College of Graduate Studies.

Dr. Aleksandra Vinogradov
(Signature) July 17, 2000
Date

Approved for the Department of Mechanical and Industrial Engineering

Dr. Vic Cundy
(Signature) 7/17/00
Date

Approved for the College of Graduate Studies

Dr. Bruce McLeod
(Signature) 7-19-00
Date
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## Table of Contents

1. **INTRODUCTION** ................................................................. 1

2. **PROPERTIES OF POLYMERS** ...................................... 4
   - Physical Properties of Polymers ........................................ 4
   - Instantaneous Elastic Behavior of Polymers ...................... 8
   - Creep Behavior of Polymers ............................................. 12
   - Fatigue Behavior of Polymers ............................................ 25

3. **OVERVIEW OF RESEARCH ON THE CYCLIC RESPONSE OF POLYMERS AND POLYMER BASED COMPOSITES** ............... 29

4. **GOALS AND OBJECTIVES** ............................................... 33

5. **GENERAL APPROACH TO A PARAMETRIC STUDY OF CYCLIC LOADING EFFECTS OF POLYMERS** ................................... 34
   - Material Selection .......................................................... 34
   - Experimental Stages ...................................................... 34
     - Tensile Testing .......................................................... 35
     - Constant Load Creep Testing ...................................... 35
     - Vibrocreep Testing .................................................... 36
     - Post Cyclic Testing ................................................... 36
   - Testing Methodology ..................................................... 37
     - Tensile and Post Cyclic Testing ................................... 37
     - Constant Load Creep Testing ...................................... 38
     - Vibrocreep Testing .................................................... 40
     - Vibrocreep Criteria .................................................... 44

6. **EXPERIMENTAL PROGRAM AND RESULTS FOR NYLON 6/6** .......... 47
   - Properties and Applications of Nylon 6/6 ....................... 47
   - Experimental Program .................................................. 47
     - Instrumentation, Equipment, and Data Acquisition ........ 47
       - Tensile Testing of Nylon 6/6 ..................................... 48
       - Constant Load Creep Testing of Nylon 6/6 ................. 49
       - Vibrocreep Testing of Nylon 6/6 ............................. 51
     - Testing Procedure .................................................... 55
       - Tensile Testing Procedure for Nylon 6/6 ................. 55
         - Constant Load Creep Testing Procedure for Nylon 6/6 56
Table of Contents - Continued

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrocreep Procedure for Nylon 6/6</td>
<td>56</td>
</tr>
<tr>
<td>Post Cyclic Testing Procedure for Nylon 6/6</td>
<td>57</td>
</tr>
<tr>
<td>Experimental Results</td>
<td>57</td>
</tr>
<tr>
<td>Tensile Testing at 23 °C</td>
<td>57</td>
</tr>
<tr>
<td>Constant Load Creep Testing at 23 °C</td>
<td>58</td>
</tr>
<tr>
<td>Vibrocreep Testing at 23 °C</td>
<td>59</td>
</tr>
<tr>
<td>Post Cyclic Testing at 23 °C</td>
<td>65</td>
</tr>
<tr>
<td>Tensile Testing at Elevated Temperatures</td>
<td>67</td>
</tr>
<tr>
<td>Constant Load Creep Testing at Elevated Temperatures</td>
<td>69</td>
</tr>
<tr>
<td>Vibrocreep Testing at Elevated Temperatures</td>
<td>70</td>
</tr>
<tr>
<td>Post Cyclic Testing at Elevated Temperatures</td>
<td>79</td>
</tr>
<tr>
<td>Conclusions</td>
<td>82</td>
</tr>
</tbody>
</table>

7. EXPERIMENTAL PROGRAM AND RESULTS FOR PVDF................................87

Properties and Applications of PVDF........................................87
Experimental Program ..........................................................88
Instrumentation, Equipment, and Data Acquisition..........................88
  Tensile Testing of Nylon PVDF............................................89
  Constant Load Creep and Vibrocreep Testing of PVDF...................89
Testing Procedure ..................................................................92
  Tensile Testing Procedure for PVDF........................................94
  Constant Load Creep Testing Procedure for PVDF.......................94
  Vibrocreep Procedure for PVDF............................................94
Experimental Results ............................................................95
  Tensile Testing at 23 °C.....................................................95
  Constant Load Creep Testing at 23 °C...................................98
  Vibrocreep Testing at 23 °C...............................................100
  Constant Load Creep Testing at Low Temperatures                    | 104  |
  Vibrocreep Testing at Low Temperatures                              | 107  |
Conclusions............................................................................116

8. STATISTICAL ANALYSIS................................................................118

9. DISCUSSION.............................................................................121

10. CONCLUSION...........................................................................127

11. FURTHER RESEARCH............................................................130
Table of Contents - Continued

REFERENCES CITED..............................................................................................131

APPENDICES...........................................................................................................138

| Appendix A | Tensile and Constant Load Creep Testing Results for Nylon 6/6 | 139 |
| Appendix B | Frequency Effects from Vibrocreep Testing of Nylon 6/6 | 158 |
| Appendix C | Amplitude Effects from Vibrocreep Testing of Nylon 6/6 | 231 |
| Appendix D | The Influence of the Parameter μ from Vibrocreep Testing of Nylon 6/6 | 301 |
| Appendix E | Mean Stress Effects from Vibrocreep Testing of Nylon 6/6 | 329 |
| Appendix F | Temperature Effects from Tensile, Constant Load Creep and Vibrocreep Testing of Nylon 6/6 | 371 |
| Appendix G | Post Cyclic Testing Results for Nylon 6/6 | 404 |
| Appendix H | Tensile and Constant Load Creep Testing Results for PVDF | 407 |
| Appendix I | Frequency Effects from Vibrocreep Testing of PVDF | 414 |
| Appendix J | Amplitude Effects from Vibrocreep Testing of PVDF | 433 |
| Appendix K | Mean Stress Effects from Vibrocreep Testing of PVDF | 460 |
| Appendix L | Temperature Effects from Tensile, Constant Load Creep and Vibrocreep Testing of PVDF | 477 |
| Appendix M | Statistical Results | 502 |
| Appendix N | Data Acquisition Programs | 539 |
| Appendix O | Macros For Data Management | 597 |
| Appendix P | Manufacture Material Data for Nylon 6/6 and PVDF | 606 |
| Appendix Q | Instron 1350 Environmental Chamber Design | 612 |
| Appendix R | Tensile and Creep Environmental Chamber Design | 633 |
| Appendix S | Creep Testing Equipment Design | 643 |
| Appendix T | Creep and Vibrocreep Test Fixture for Thin Films | 656 |
| Appendix U | Ongoing Microstructure Analysis and Model Development Based on Current Work | 670 |
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Crystal Melt Temperatures of Some Polymer Materials</td>
<td>7</td>
</tr>
<tr>
<td>Table 2</td>
<td>Glass Transition Temperatures of Some Polymers</td>
<td>8</td>
</tr>
<tr>
<td>Table 3</td>
<td>Testing Summary</td>
<td>37</td>
</tr>
<tr>
<td>Table 4</td>
<td>Preliminary Test Matrix for Creep Testing</td>
<td>39</td>
</tr>
<tr>
<td>Table 5</td>
<td>Preliminary Test Matrix for Vibrocreep</td>
<td>42</td>
</tr>
<tr>
<td>Table 6</td>
<td>Tensile Properties for Nylon 6/6 at 23 °C</td>
<td>58</td>
</tr>
<tr>
<td>Table 7</td>
<td>Batch Comparison at 23 °C</td>
<td>58</td>
</tr>
<tr>
<td>Table 8</td>
<td>Test Matrix for Nylon 6/6 Vibrocreep Testing at 23 °C</td>
<td>59</td>
</tr>
<tr>
<td>Table 9</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 23 °C</td>
<td>66</td>
</tr>
<tr>
<td>Table 10</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 23 °C</td>
<td>67</td>
</tr>
<tr>
<td>Table 11</td>
<td>Tensile Properties of Nylon 6/6 at 23 °C and Elevated Temperatures</td>
<td>68</td>
</tr>
<tr>
<td>Table 12</td>
<td>Test Matrix for Nylon 6/6 Vibrocreep Testing at Elevated Temperatures</td>
<td>71</td>
</tr>
<tr>
<td>Table 13</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C</td>
<td>80</td>
</tr>
<tr>
<td>Table 14</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C</td>
<td>81</td>
</tr>
<tr>
<td>Table 15</td>
<td>Tensile Testing Results for PVDF at 23 °C</td>
<td>96</td>
</tr>
<tr>
<td>Table 16</td>
<td>Test Matrix for Vibrocreep Testing of PVDF at 23 °C</td>
<td>100</td>
</tr>
<tr>
<td>Table 17</td>
<td>Test Matrix for Vibrocreep Testing of PVDF at -25 °C</td>
<td>108</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Lamella Formation</td>
<td>4</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Fibril Formation</td>
<td>5</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Spherulite Formation</td>
<td>6</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Brittle and Ductile Comparison</td>
<td>9</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Temperature Effects on Elastic Modulus of Some Polymer Materials</td>
<td>9</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Strain Effects of Strain Rate on Polymer Materials</td>
<td>9</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Deformation of spherulites in a Crystalline Structure</td>
<td>10</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Lamella Deformation Within a Spherulite</td>
<td>10</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Deformation of Molecular Chains in a Amorphous Material</td>
<td>11</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Fibril and Lamella Interconnection before Failure</td>
<td>12</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Maxwell Model</td>
<td>13</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Creep Curve of the Maxwell Model</td>
<td>13</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Relaxation Curve of the Maxwell Model</td>
<td>14</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Kelvin Model</td>
<td>14</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Creep Curve of the Kelvin Model</td>
<td>15</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Relaxation Curve of the Kelvin Model</td>
<td>16</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Burger Model</td>
<td>16</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Creep Curve of the Burger Model</td>
<td>17</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Relaxation Curve of the Burger Model</td>
<td>17</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Step Load History and Resulting Strain</td>
<td>18</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Continuous Loading History and Resulting Strain</td>
<td>19</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Creep Curves of the Same Polymer at Different Stress Levels</td>
<td>20</td>
</tr>
<tr>
<td>Figure 23</td>
<td>Normalized Creep Curves Showing Linear Viscoelasticity</td>
<td>21</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Periodic Strain and Stress</td>
<td>22</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Creep Strain at Multiple Temperatures</td>
<td>24</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Shifting the Temperature Curves to the Reference Temperature</td>
<td>24</td>
</tr>
<tr>
<td>Figure 27</td>
<td>Stress Amplitude vs. Cycles to Failure</td>
<td>28</td>
</tr>
<tr>
<td>Figure 28</td>
<td>Periodic Stress</td>
<td>43</td>
</tr>
<tr>
<td>Figure 29</td>
<td>Periodic Strain</td>
<td>44</td>
</tr>
<tr>
<td>Figure 30</td>
<td>Resulting Hysteresis Loop</td>
<td>44</td>
</tr>
<tr>
<td>Figure 31</td>
<td>Loading Diagram for Vibrocreep</td>
<td>45</td>
</tr>
<tr>
<td>Figure 32</td>
<td>Vibrocreep Effect Above or Below the Linear Viscoelastic Limit</td>
<td>45</td>
</tr>
<tr>
<td>Figure 33</td>
<td>Normalized Vibrocreep Effect Within the Linear Viscoelastic Limit</td>
<td>46</td>
</tr>
<tr>
<td>Figure 34</td>
<td>Creep Test Fixture for Nylon 6/6</td>
<td>51</td>
</tr>
<tr>
<td>Figure 35</td>
<td>Vibrocreep Test Fixture for Nylon 6/6</td>
<td>54</td>
</tr>
<tr>
<td>Figure 36</td>
<td>Constant Load Creep of Nylon 6/6 at 23 °C</td>
<td>61</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>37</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C</td>
<td>62</td>
</tr>
<tr>
<td>38</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C</td>
<td>63</td>
</tr>
<tr>
<td>39</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C</td>
<td>64</td>
</tr>
<tr>
<td>40</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 23 °C</td>
<td>65</td>
</tr>
<tr>
<td>41</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 23 °C</td>
<td>66</td>
</tr>
<tr>
<td>42</td>
<td>Tensile Testing of Nylon 6/6 at Different Temperatures</td>
<td>67</td>
</tr>
<tr>
<td>43</td>
<td>Yield Stress and Elastic Modulus vs. Temperature</td>
<td>68</td>
</tr>
<tr>
<td>44</td>
<td>Constant Load Creep of Nylon 6/6 at Different Temperatures</td>
<td>70</td>
</tr>
<tr>
<td>45</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C</td>
<td>72</td>
</tr>
<tr>
<td>46</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C</td>
<td>73</td>
</tr>
<tr>
<td>47</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C</td>
<td>74</td>
</tr>
<tr>
<td>48</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Temperatures</td>
<td>76</td>
</tr>
<tr>
<td>49</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Frequencies and Temperatures</td>
<td>77</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>Figure 50</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Amplitudes and Temperatures</td>
<td>78</td>
</tr>
<tr>
<td>Figure 51</td>
<td>Vibrocreep Response of Nylon 6/6 at Different Mean Stresses and Temperatures</td>
<td>79</td>
</tr>
<tr>
<td>Figure 52</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C</td>
<td>80</td>
</tr>
<tr>
<td>Figure 53</td>
<td>Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C</td>
<td>81</td>
</tr>
<tr>
<td>Figure 54</td>
<td>Thermal and Mechanical Dominated Failure Zones</td>
<td>83</td>
</tr>
<tr>
<td>Figure 55</td>
<td>Vibrocreep Response of PVDF with $\omega^*a = 100$ at 23 °C</td>
<td>84</td>
</tr>
<tr>
<td>Figure 56</td>
<td>Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 23 °C</td>
<td>86</td>
</tr>
<tr>
<td>Figure 57</td>
<td>Vibrocreep and Creep Testing Fixture for PVDF</td>
<td>90</td>
</tr>
<tr>
<td>Figure 58</td>
<td>PVDF Test Sample</td>
<td>96</td>
</tr>
<tr>
<td>Figure 59</td>
<td>Tensile Test of PVDF Direction 1 at 23 °C</td>
<td>97</td>
</tr>
<tr>
<td>Figure 60</td>
<td>Tensile Test of PVDF Direction 2 at 23 °C</td>
<td>97</td>
</tr>
<tr>
<td>Figure 61</td>
<td>Constant Load Creep of PVDF at 23 °C</td>
<td>99</td>
</tr>
<tr>
<td>Figure 62</td>
<td>Vibrocreep Response of PVDF at Different Frequencies at 23 °C</td>
<td>101</td>
</tr>
<tr>
<td>Figure 63</td>
<td>Vibrocreep Response of PVDF at Different Amplitudes at 23 °C</td>
<td>103</td>
</tr>
<tr>
<td>Figure 64</td>
<td>Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C</td>
<td>104</td>
</tr>
<tr>
<td>Figure 65</td>
<td>Constant Load Creep of PVDF at -25 °C</td>
<td>105</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Figure 66</td>
<td>Constant Load Creep of PVDF at Different Temperatures</td>
<td>107</td>
</tr>
<tr>
<td>Figure 67</td>
<td>Vibrocreep Response of PVDF at Different Frequencies at -25 °C</td>
<td>109</td>
</tr>
<tr>
<td>Figure 68</td>
<td>Vibrocreep Response of PVDF at Different Amplitudes at -25 °C</td>
<td>110</td>
</tr>
<tr>
<td>Figure 69</td>
<td>Vibrocreep Response of PVDF at Different Mean Stresses at -25 °C</td>
<td>111</td>
</tr>
<tr>
<td>Figure 70</td>
<td>Vibrocreep Response of PVDF at Different Temperatures</td>
<td>112</td>
</tr>
<tr>
<td>Figure 71</td>
<td>Vibrocreep Response of PVDF at Different Frequencies and Temperatures</td>
<td>113</td>
</tr>
<tr>
<td>Figure 72</td>
<td>Vibrocreep Response of PVDF at Different Amplitudes and Temperatures</td>
<td>114</td>
</tr>
<tr>
<td>Figure 73</td>
<td>Vibrocreep Response of PVDF at Different Mean Stresses and Temperatures</td>
<td>115</td>
</tr>
<tr>
<td>Figure 74</td>
<td>Vibrocreep Response of PVDF with $\omega a = 100$ at 23 °C</td>
<td>117</td>
</tr>
</tbody>
</table>
Abstract

An investigation of the cyclic loading effects on the time dependent response of Nylon 6/6 and a piezoelectric Polyvinylidene Fluoride (PVDF) based composite material is presented. A consistent experimental program has been developed with the main objective to determine the creep behavior of the materials under cyclic loading conditions. An extensive testing procedure employed in this study has involved multiple experimental stages consisting of tensile stress-strain tests, constant load creep tests, and tests under sustained tensile loads with superimposed harmonic oscillations. The creep behavior of Nylon 6/6 and the PVDF based composite has been investigated depending on three loading parameters, mean stress, vibration frequency and amplitude. The study has been performed over a wide range of temperature conditions. The results of this investigation have provided a general view on the cyclic creep response of the materials under investigation, where Nylon 6/6 is a solid polymer and PVDF is an electroded polymer. Nonlinear creep effects induced by cyclic loading conditions have been observed in both materials. The results of the study have demonstrated the limitations of linear viscoelastic theory and have served as a basis for constitutive model development and microstructural analyses of polymers subjected to asymmetric cyclic loading regimes.
INTRODUCTION

At present, along with the increasing demand for materials with novel or improved characteristics, there is a growing concern regarding material longevity. In this regard, two major factors are of immediate importance: time-dependent material properties and operating conditions involving cyclic loading regimes. The former represents an intrinsic material characteristic known as creep, which manifests itself through the development of time-dependent deformations under sustained loads. The second factor is associated with the loading conditions that cause material deterioration due to progressive damage processes. Apparently, certain interaction modes of these seemingly independent phenomena tend to produce qualitatively new effects altering the overall response and, ultimately, the life expectancy of materials.

The interaction effect of superimposed cyclic loads upon nonzero mean loads is a problem of immediate practical interest. This problem has been well studied in metals at high temperatures, however, fewer corresponding studies in polymers have been reported, and are practically non-existent in polymer based composites.

In the thesis, an experimental investigation of the time dependent response of Nylon 6/6 and a Polyvinylidene Fluoride (PVDF) based composite is presented. Experimental results and preliminary microstructural observations obtained in the course of the study provide new experimental evidence regarding
cyclic loading effects on the long-term behavior of the materials under consideration.

The second chapter provides background information regarding the properties of polymers, in particular, their time dependent behavior. The microstructure and physical properties of polymers are described and a theoretical background of the fundamental concepts of linear viscoelastic theory is provided.

The third chapter provides a review of previously published results on creep and vibrocreep of polymers. Emphasis has been placed upon the cyclic loading effects on the creep response of polymers.

The fourth chapter outlines the main objectives of the project. The goals are stated and progression toward these goals is set forth within the thesis.

The fifth chapter describes the general approach to a parametric study of cyclic loading effects on the behavior of polymers. The study involves the material selection, experimentation, and the criteria for vibrocreep analysis.

The sixth chapter describes the developed experimental program and provides a summary of the experimental results obtained from the experiments of Nylon 6/6 (DuPont Zytel® 42A NC010 Polyamide 66).

The seventh chapter describes the experimental program and provides a summary of the experimental results obtained from the experiments of Polyvinylidene Fluoride (PVDF) based composite laminate.
The eighth chapter contains the statistical analysis of the experimental data. The ninth chapter provides a general discussion of the results for both Nylon 6/6 and PVDF. The discussion leads to a number of conclusions formulated in the tenth chapter. The eleventh chapter describes further research directions.
The development of an understanding of polymer materials can be achieved through the analysis of the physical properties and microstructure. The microstructure and the process by which the material has been created govern the physical properties. The physical properties dictate how the material will perform in a working environment.

**Physical Properties of Polymers**

The broad class of polymers involves thermoplastics and thermosets that have different molecular structure and characteristics. The products necessary to form a thermoplastic or thermoset are raw materials such as coal, petroleum, and natural gas. The formation of polymers from monomers results in a microstructure with an amorphous form, crystalline form, or a combination of these two forms. The first stage of polymer development is characterized by the formation of lamella, small crystals, and molecular chains that align themselves in a zigzag pattern, Figure 1, Ref[16].

![Figure 1 Lamella Formation](image)
The lamellas have a random orientation in all polymer materials. To promote the lamellas growth, the temperature of the polymer is held just below the melt temperature. Once the lamella has started to grow, the second stage starts. The lamella interacts with other lamella, forming long chain branches or fibrils from the remaining molecular chain, Figure 2, Ref[16].

![Figure 2 Fibril Formation](image)

The fibrils form of inter lamella connections. As the lamellas interconnect the fibrils fill the gaps between the lamella as shown in Figure 2. The fibrils can be said to "tie a knot" between each other and initiate the third stage of the formation of spherulites, Figure 3, Ref[16].
The latter form, a large crystal that develops in radial directions. The final crystallization of the polymer is also dependent upon the temperature at this stage. As the temperature is lowered, spherulites begin to form. The amount of their growth is dependent once again on the hold time at a constant temperature. Once the polymer material is said to be past the glass transition temperature, then all movement of the molecular chains stops. The change in the specific volume of the polymer under the decreasing temperature makes the chains less mobile.

The development of crystals within these three stages determines the degree of crystallinity and orientation of the molecular structure. When microstructural analysis is performed lamella, fibrils, and spherulites can be observed. The orientation of spherulites or large crystals is dependent on hold times and additional mechanical means of molecular chain alignment. The molecular alignment and regularity directly depend on the degree of
crystallization in a polymer material. Mechanical processes such as annealing the polymer material can be performed to promote the alignment of molecular chains. Without molecular regularity and proper alignment of molecular chains the polymer becomes amorphous. Such amorphous regions are voids or gaps between lamella and spherulites due to the fact that the fibrils or remaining parts of molecular chains could not align themselves within the process described above. The amorphous region is about 85% less dense then crystalline regions.

As the polymer cools from the melt temperature, the polymer progresses through thermal transitions. Purely crystalline polymers experience only a melt transition.

Table 1 Crystal Melt Temperatures of Some Polymer Materials, Ref[52]

<table>
<thead>
<tr>
<th>Polymer</th>
<th>$T_m$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Density Polyethylene</td>
<td>95-130</td>
</tr>
<tr>
<td>High Density Polyethylene</td>
<td>120-140</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>168</td>
</tr>
<tr>
<td>Polyformaldehyde</td>
<td>181</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>216</td>
</tr>
<tr>
<td>Polyethylene Terephthalate</td>
<td>245</td>
</tr>
<tr>
<td>Nylon 6/6</td>
<td>265</td>
</tr>
<tr>
<td>Polytetrafluoroethylene</td>
<td>327</td>
</tr>
</tbody>
</table>

When a polymer develops amorphous (semi-crystalline or mostly amorphous) regions, then the polymer tends to undergo three other transitions between the melt and glass temperatures. The first state of the polymer below the melt temperature is a viscofluid state. In this state the polymer exhibits properties of a viscous fluid with molecular chains having a high degree of mobility. The second
state is the rubbery state, in which the polymer is said to have segment mobility, but does not have molecular mobility. The final state of the polymer below the glass transition temperature is a glassy state, in which the motion of molecular chains cease to exist.

Table 2 Glass Transition Temperatures of Some Polymers, Ref[52]

<table>
<thead>
<tr>
<th>Polymer</th>
<th>$T_g$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>-120</td>
</tr>
<tr>
<td>Polyisoprene</td>
<td>-73</td>
</tr>
<tr>
<td>Polyformaldehyde</td>
<td>-50, -85</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>-10, -18</td>
</tr>
<tr>
<td>Nylon 6/10</td>
<td>40</td>
</tr>
<tr>
<td>Polyvinyl Chloride</td>
<td>87</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>100</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>150</td>
</tr>
</tbody>
</table>

Instantaneous Elastic Behavior of Polymers

The instantaneous elastic properties of polymers depends upon temperature and strain rate. For example, a polymer material at a high temperature tends to exhibit properties of a ductile material, whereas a polymer exhibits brittle properties at lower temperatures, Figure 4. The effects of temperature are graphically shown in Figure 5, Ref[16]. Note that where the curve knees represents a transition temperature such as the glass transition temperature of the polymer. The effect of increasing strain rate is also shown in Figure 6, Ref[49]. It is important that experiments with polymers must be
performed according to ASTM testing specifications that dictate the prescribed
temperature and strain rates.

![Figure 4 Brittle and Ductile Comparison](image)

Figure 4  Brittle and Ductile Comparison

![Figure 5 Temperature Effects on Elastic Modulus of Some Polymer Materials](image)

Figure 5  Temperature Effects on Elastic Modulus of Some Polymer Materials

![Figure 6 Strain Effects of Strain Rate on Polymer Materials](image)

Figure 6  Strain Effects of Strain Rate on Polymer Materials
The elastic response of a crystalline polymer or crystalline region within a polymer material is stiff or brittle and does not produce large deformations. When deformation does occur the spherulites change in shape as a whole and not individually, Figure 7, Ref[16].
Thus, an amorphous polymer material or amorphous regions of a polymer deform by alignment and lengthening of the molecular chains, Figure 9, Ref[16].

![Elongation of Bonds](image1)

**Elongation of Bonds**

![Chain Alignment](image2)

**Chain Alignment**

Figure 9  Deformation of Molecular Chains in an Amorphous Material

The chain lengthening continues until molecular chains fail and the spherulites no longer exist, Figure 10, Ref[16].
Creep Behavior of Polymers

A polymer material that has properties with strain or stress rate dependence is considered to be viscoelastic, since it behaves as a viscous fluid or viscoelastic solid. Two types of tests can be performed to represent the viscous behavior of polymers, a creep test or relaxation test. A creep test is performed under a constant stress allowing strain to change over time, whereas a relaxation test is performed under a constant strain allowing stress to change in time. Models that represent the creep and relaxation behavior of a linear viscoelastic solid have been developed using linear springs and dashpots. An example of such a model is the Maxwell model shown in Figure 11, where $\sigma =$ applied stress or $\varepsilon =$ applied strain, $E_m =$ linear elastic spring coefficient, and $\eta_m =$ viscosity coefficient.
The creep and relaxation responses of the Maxwell model are shown in Figure 12, and Figure 13. Equations 1 and 2 represent the constitutive law, respectively, for creep and relaxation of the Maxwell model.

\[ \varepsilon(t) = \frac{\sigma_0}{E_m} + \frac{\sigma_0}{\eta_m} \]

Equation 1
Another viscoelastic material model is the Kelvin model shown in Figure 14, where $\sigma = \text{applied stress}$ or $\varepsilon = \text{applied strain}$, $E_k = \text{linear elastic spring coefficient}$, and $\eta_k = \text{viscous coefficient}$.

Equation 2

$$\sigma(t) = E_k \cdot \varepsilon_0 \cdot e^{-t}$$
The Kelvin model represents creep behavior but cannot represent the relaxation behavior of polymers. The creep and relaxation curves produced by the Kelvin model are shown in Figure 15, and Figure 16, respectively. The constitutive law for creep and relaxation of the Kelvin model are provided in Equations 3 and 4.

\[ \varepsilon(t) = \frac{\sigma_0}{E_k} \left( 1 - e^{-\frac{t}{\tau_k}} \right) \]

Equation 3

Figure 15  Creep Curve of the Kelvin Model
Figure 16 Relaxation Curve of the Kelvin Model

\[ \sigma(t) = \varepsilon \left( E_k H(t) + \eta_k \delta(t) \right) \]

Equation 4

The third, more realistic viscoelastic model is the Burger model that represents a linear viscoelastic solid shown in Figure 17, where \( \sigma \) = applied stress or \( \varepsilon \) = applied strain, \( E_m \) = Maxwell linear elastic spring coefficient, \( E_k \) = Kelvin linear elastic spring coefficient and \( \eta_k \) = Kelvin viscous coefficient.

Figure 17 Burger Model
The creep and relaxation curves for the Burger model are shown in Figure 18, and Figure 19, respectively. The constitutive law are provided in Equations 5 and 6, respectively.

\[
\varepsilon(t) = \frac{\sigma_0}{E_m} + \frac{\sigma_0}{E_k} \left( \frac{-t}{\tau_k} \right)
\]

Equation 5

\[
\sigma(t) = E_m \varepsilon_0
\]
A more complex model representing the response of polymers is based on the Boltzmann superposition principle which states that the response of a material to a complex loading history can be presented as the sum of individual increments at each load step. This principle applies to loading histories involving both step load increments and continuous loading function as shown in Figures 20-21, Ref[49,24].

\[
\sigma(t) = E_m \cdot \varepsilon_0 \cdot e^{-\frac{t}{\tau}}
\]

Equation 6

Figure 20  Step Load History and Resulting Strain
For a step load history, the material response in terms of strain is defined in the form of Equation 7, Ref[12]. For a continuous loading history the strain deformation in time is represented by the hereditary integral, in the form of Equation 8 and 9 for creep and relaxation, respectively, Ref [12].

\[
s(t) = \sum_{i=0}^{n} \sigma_i \cdot \frac{1}{E(t - u_i)}
\]

Equation 7

\[
s(t) = \int_{-\infty}^{t} \frac{1}{E(t - u)} \frac{d}{du} \sigma(u) \, du
\]

Equation 8
\[ \sigma(t) = \int_{-\infty}^{t} E(t-u) \cdot \frac{d}{du} \varepsilon(u) \, du \]

Equation 9

Through creep testing a variety of creep curves can be generated at different stress levels, Figure 22.

![Creep Curves of the Same Polymer at Different Stress Levels](image)

Figure 22 Creep Curves of the Same Polymer at Different Stress Levels

Once the data is generated, the normalization process is performed to determine the linear viscoelastic limit and the creep compliance. In the linear viscoelastic range, normalized creep curves at different stress levels produce one single curve defined as the creep compliance, Figure 23.
The single normalized creep curve indicates that the creep behavior of the material is stress independent. In the case of stress dependency of the creep response of polymers, nonlinear viscoelastic theories are required to adequately represent the material behavior.

Typically, dynamic testing methods are being used to characterize linear viscoelastic properties of polymers Ref[13,61]. Dynamic tests are generally performed by applying a sinusoidal strain and measuring the respective stress. The phase shift between the stress and strain sinusoidal waves represents the amount of viscous damping in the material, Figure 24.
Figure 24 Periodic Strain and Stress

On this basis, the relaxation, storage moduli and compliances are determined in the form illustrated by Equations 10 and 11, Ref[21], where $\sigma_o = \text{stress amplitude}$ and $\varepsilon_o = \text{strain amplitude}$.

\[
E_p = \frac{\sigma_o}{\varepsilon_o} \cdot \cos(\delta)
\]

\[
E_{pp} = \frac{\sigma_o}{\varepsilon_o} \cdot \sin(\delta)
\]

\[
\frac{E_p}{E_{pp}} = \frac{\sigma_o}{\varepsilon_o} \cdot \frac{\sin(\delta)}{\cos(\delta)} = \tan(\delta)
\]

Equations 10
The storage, loss moduli, and compliances calculated above are defined in the frequency domain. The material behavior in the time domain can be characterized in terms of relaxation function and creep compliance by using the following equations, Ref[21], where \( \omega = \) frequency.

\[
\begin{align*}
\text{Creep:} & \quad E(t) &= E_p(\omega) - 0.4 \cdot E_{pp}(0.4 \cdot \omega) + 0.014 \cdot E_{pp}(10 \cdot \omega) \\
\text{Relaxation:} & \quad D(t) &= D_p(\omega) + 0.4 \cdot D_{pp}(0.4 \cdot \omega) - 0.014 \cdot D_{pp}(10 \cdot \omega)
\end{align*}
\]

Equation 12

The time-temperature analogy is used to characterize the response of thermorheologically simple materials. By using a temperature dependent shift factor that relates the properties of the material at any temperature \( T \) to the properties at a reference temperature \( T_0 \), the curves at different temperatures are shifted by a factor \( (a_T(T)) \) coinciding with the reference curve at temperature \( T_0 \), as shown in Figure 25-26.
Note that in Figures 25-26, $\varepsilon_c(t)$ denotes the creep strain, defined by Equation 13, where $\varepsilon_t$ is the total strain, $\varepsilon_c$ is the creep strain, and $\varepsilon_E$ is the instantaneous elastic strain

$$\varepsilon_T(t) = \varepsilon_c(t) - \varepsilon_E$$

Equation 13
Fatigue testing of polymer materials is conducted by two test methods, stress controlled experiments or strain controlled experiments. A stress controlled test is performed by applying cyclic stress in tension, compression, or both, whereas a strain controlled system is performed by applying cyclic strain in tension, compression, or both. The variables of stress controlled experiments are:

- Cyclic Stress $\Delta \sigma$
- Corresponding $\Delta \varepsilon$
- $m$ Level
- Corresponding $\varepsilon_m$, Level
- Frequency
- Wave Form (sine, square, etc.)
- Temperature
- Specimen Size

The influence of the above fatigue test variables on a molecular level within a polymer material is broken into seven categories.

- Molecular Characteristics
- Chemical Changes
- Elastic Deformation
- Non Elastic Deformation
- Morphological Changes
- Transition Phenomena
- Thermal Effects

The molecular characteristics of polymer materials are dictated during the formation of the polymer, molecular weight, molecular composition, etc. The molecular characteristics influence the effects of fatigue testing on the remaining categories. The chemical changes in a polymer incorporate bond breaking and
stress cracking. Bond breaking (mainly C-C bonds) can be produced by crack propagation or induced during processing, flaw creation. Bond breaking energy in relation to fracture energy is more significant in crystalline \((10^2 - 10^3 \text{ J/m}^2)\) or thermoset polymers than in amorphous polymers \((.1 \text{ J/m}^2)\). Even though the total energy due to bond breakage makes up about 10% of the fracture energy in a crystalline polymer, the distribution of the stresses due to bond breakage is of consideration. A crystalline or thermoset polymer transfer the stresses to neighboring molecules or crystals while an amorphous polymer has the ability to transfer the stress through entanglements of chains thus allowing an improved stress distribution. Stress cracking within a polymer is due to environmental effects. A good example of this is a dashboard within a car, where cracks are induced due to sunlight effecting the polymer material.

Elastic deformation is the elastic behavior of the polymer under cyclic stresses. The elastic behavior being that the material can recover all deformation, elastic and visco-elastic, or strain if the testing has stopped. Non elastic deformation would include plastic and visco-plastic deformation, where the deformation is not recoverable if the fatigue testing were stopped. The nonelastic deformation is shown in a polymer by the formation of crazes or shear bands. Crazing develops at a 0° angle relative to the applied load where shear bands develop at 38°- 45° angles to the applied load. The two differ in that crazing develops cavitation with molecular chain orientation, and shear banding develops molecular chain orientation only. If the stress is applied in a manner of
which the material is unloaded for duration of time, then the material is allowed to relax. The relaxation period allows molecular chain alignment preventing deformation during the next cycle. Consequently if the stress is applied in a manner in which relaxation cannot occur, then the cycles to failure is greatly increased.

Morphological changes in a polymer material dictate the history of the processing of the polymer. The changes are noted by thermal and mechanical histories, by which drawing, chain orientation promotion techniques, or crystallization dictate the polymers history, in the case of PVDF polymer heating and stretching of the polymer creates a thermal and mechanical history. The thermal and transition properties of polymers during fatigue testing are of high importance. The effects of fatigue, mechanical deformations due to cyclic stresses, induce energy into a polymer material that is partially transformed into thermal energy, called hysteretic heating. The hysteretic heating process produces accelerated failure of a polymer material due to low thermal the thermal conductivity of polymers Figure 27, Ref[29].

The thermal energy produced is highly dependent upon the varied stress, frequency, wave pattern, and specimen size. High varied stresses and high frequencies develop the highest mechanical energy input into the polymer, thus elevating the probability of hysteretic heating. Changing the wave pattern of the applied stress by allowing the polymer to rest or dissipate heat between cycles decreases hysteretic heating. The specimen size, large surface area and small
thickness, contributes to the ability of a polymer to dissipate the heat generated. Through the heating of a polymer, a transition from glassy to rubbery phases may occur. For a crystalline or thermoset, the polymer may simply just melt away.

Where $\nabla \rightarrow \square \rightarrow o \rightarrow \Delta$ is an increase in frequency.

Failure of the material is dependent upon the rate at which the stress is applied and temperature, as described above in tensile properties. A high stress rate at low temperatures, promotes brittle type of failure, whereas a low stress rate and high temperature dictate ductile failure. If a crack is developed during fatigue, then the thermal energy within the polymer may allow mobility of molecular chains to prevent further crack propagation. The molecular chains may reduce the stress concentration at the crack tip.

Figure 27 Stress Amplitude vs. Cycles to Failure, Ref[29]
OVERVIEW OF RESEARCH ON THE CYCLIC RESPONSE OF POLYMERS AND POLYMER BASED COMPOSITES

The effects of creep and cyclic load interaction for polymers and polymer matrix composites has not been investigated to the same degree as for metals at high temperatures, Ref[59]. These effects lead to a phenomena defined as vibrocreep, Ref[46, 47]. Ref[46], the vibrocreep effect is quantified using a specific parameter defined as vibrocreep coefficient to predict vibrocreep from experimental data. With the increased use of polymers, such as PVDF, Ref[62] in vibration environments, the characterization of cyclic creep effects in polymers and polymer matrix composites is particularly important. The vibrocreep effect in glass fiber reinforced composites has been studied in Ref[66]. The effect of creep on polymers and polymer matrix composites has been investigated in Ref[21, 24]. Recent aspects of creep analysis are aimed at new polymers and polymer matrix composites, Ref[25, 31, 38, 41, 44, 47]. The same techniques are used to characterize the new materials. Recent advances in creep assessment involve the use of damage analysis to predict creep in structures, Ref[8].

Multiple authors have addressed the effect of cyclic loading on the response of polymer materials. The effect of creep in cyclic loading conditions has been investigated by Ref[22] for an Poly(Dimethylsiloxane) elastomer where the results contradicted the Boltzmann Superposition Principle. In Ref[54, 57], various factors are considered that determine the cyclic behavior of polymers.
Such as wave form, frequency, geometry, etc.. It has been observed that the effect of high stresses and frequencies lead to thermal failure, of polymers, whereas crack initiation and propagation results in mechanical failure. Research has been performed in the thermal failure regime through observations of hysteresis heating of polymers, Ref[30, 65], along with model development in Ref[51]. It has been observed that an increase of cyclic frequency lead to accelerated deformation and shorter fatigue life of polymers. The results shown in Ref[14], indicate that thermal failure has been observed at an increased frequency in glass fiber composite materials. The effect of frequency has been analyzed in Ref[72] in regard to a polyethylene copolymer. An increase in frequency was observed to increase the number of cycles to failure up to a certain frequency limit beyond which the number of cycles to failure decreased. In Ref[53], it has been observed that an increase of frequency in the sonic region produced increased deformation rate of several polymers. An increase in amplitude of the cyclic load has produced similar effects as frequency increases, Ref[36]. The problem of fatigue crack propagation rates in polymers depending on the cyclic frequencies has been studied in Ref[17]. The increase of the amplitude and frequency under cyclic loading conditions is also seen in Ref[68]. The effects of amplitude and frequency combined are quantified and related to the shear rate of deformation under relaxation conditions. The effect of the mean stress upon the deformation and failure of polymer materials is discussed in Ref[60]. It has been observed that under fully reversed cyclic conditions an
increase in the mean stress results in an increase in the number of cycles to failure. These results have been also analyzed using microscopic techniques to assess the formation and propagation of crack growth. Other researchers have analyzed the effects of temperature under cyclic loading conditions. In Ref[70], the assessment of crack growth showed that the crack propagation and initiation are highly temperature dependent. In Ref[43], the combined effect of temperature and humidity are analyzed. The increasing temperature and humidity has lead to a decrease in the strength, stiffness and fatigue life of polymers, under cyclic loading conditions.

Ref[4, 58] further verifies the alignment of the molecular structure during deformation within a polymer material. The alignment of the molecular structure during deformation within a polymer material is further verified by the result of molecular nonhomogenities and surface microcracks due to processing, Ref[17]. From the initial material defects, crazing initiation and propagation occurs first, Ref[45, 56, 42], until crack formation and propagation begins. Once the crack propagates, the crack generally arrests repeating the process Ref[11]. Methods to represent the behavior of crack growth under cyclic conditions have been performed by many researchers Ref[20, 29, 48, 71]. The damage accumulation due to the craze formation and crack growth under cyclic loading conditions has been studied by Ref[55, 63, 64].

In Ref[39], it is shown that the effect of cyclic deformation leads to softening in the thermal dominated regime, whereas hardening is shown in the
mechanical dominated regime for Nylon 6/6. Strain rate analysis has been performed using impact testing to assess response of Nylon 6/6, Ref[1]. The results are used to compare to the cyclic loading tests using linear elastic fracture mechanics. The effects of the crystallinity and molecular weight are analyzed in Ref[67]. The results show that the crystallinity showed effects upon the strength and stiffness of the material, while the molecular weight showed effects upon the ultimate strength. The effect of the residual strain is described as the effect of the Van der Waals and covalent bonding. The increase in strength and stiffness is a result of the molecular alignment where the covalent bonds are aligned about the loading direction adding reinforcement. The effect of the crystallinity was also studied in Ref[37]. The effect of time and temperature are also analyzed for a Nylon 6/6 glass fiber reinforced polymer composite under tension-tension cyclic loading, Ref[35]. The effects of crystallinity as related to the effect increasing amplitude where the increase in amplitude resulted in the crystalline deformation and amorphous regions.
It is well known that polymeric systems tend to exhibit creep behavior at room temperature that can be accurately predicted within the linear range of stress-strain relations based on linear viscoelastic theory. However, the synergistic interactions of creep and damage evolution processes in these materials are far from being well understood. The goal of the thesis is to bridge this gap and enhance the understanding of the cyclic loading effects on the time dependent behavior of polymers and polymer based composites.
GENERAL APPROACH TO A PARAMETRIC STUDY OF CYCLIC LOADING EFFECTS ON POLYMERS

Material Selection

In order to conduct a parametric study of vibrocreep effects in polymers, material selection has been performed based on three criteria. The first criteria concerning the applications of a material in industry and/or research. The second criteria takes into account the physical properties of the candidate material. The third criteria is based on the material.

The first criteria involves two questions:

- Is the material used in a wide range of applications where the cyclic loading effects might be considerable?
- Why is this material more significant than any other in a cyclic loading environment?

The second criterion involves a evaluation of the physical properties through reference materials, Ref[2, 3, 6, 10, 16, 18, 19, 23, 27, 28, 34, 69]. The third criterion involves considerations of properties of polymers such as molecular network crystallinity, transition temperatures, etc..

Experimental Stages

The following experimental stages have been implemented in the developed experimental program.
**Tensile Testing**

The objective of the tensile testing is to assess the instantaneous mechanical properties of polymer materials. The strength and stiffness characteristics obtained from the tensile testing are related to creep and vibrocreep testing. The temperature influences on the strength and stiffness of the material can also be analyzed through tensile testing. The experimental standards for tensile testing are outlined by the American Society for Testing and Materials. For solid polymers and thin plastic sheeting the ASTM standards are D638-96 and D882-95, respectively. Tensile testing requires at least 5 test specimens for analysis. The magnitude of the elastic modulus determined is somewhat approximate due to the presence of creep effects. The degree of these effects depend upon the material chosen. Note, the best methodology for determination of the elastic modulus of polymers is by dynamic methods.

**Constant Load Creep Testing**

In this program, the objectives of creep testing of polymer materials are the determination of the linear viscoelastic limit and the creep compliance. The knowledge of the linear viscoelastic limit allows reference to the applicability of linear viscoelastic theory. With the knowledge of linear viscoelastic limit, vibrocreep testing can be performed within the linear bounds. The verification of the vibrocreep phenomena requires creep testing to assess the degree of the
vibrocreep effect and also the determination if the effect is present in the behavior of a particular polymer.

**Vibrocreep Testing**

In this program, the objectives of the vibrocreep testing are to assess the effect of the four parameters, frequency, amplitude, mean stress and temperature on the response of the polymer. The degree of influence that each parameter has on the creep behavior of polymers vibrocreep is the main objective of the parametric study conducted within this program. The influence of each parameter separately may help determine the intensity of the vibrocreep effect. Ultimately the vibrocreep effect may be classified by the influence of these parameters separately or combined.

**Post Cyclic Testing**

In this program, following the stages of creep and vibrocreep testing material specimens are further tested in tension at the same feed rate as that maintained at the stage of tensile testing. The objective of the post cyclic tests are to determine the changes in material properties due to creep deformations under constant and cyclic loading conditions.

The experimental stages described above are summarized in Table V.3. This table also provides information regarding the objectives of each experimental stages, the number of samples tested in each individual experiment and the result obtained at each stage.
Table 3 Testing Summary

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Motivation</th>
<th># of Specimens to Represent One Curve</th>
<th>Information Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>Instantaneous Material Response</td>
<td>5</td>
<td>Yield Stress, Elastic Modulus, and Maximum Stress</td>
</tr>
<tr>
<td>Constant Load Creep</td>
<td>Viscoelastic Properties</td>
<td>5</td>
<td>Linear Viscoelastic Limit and Creep Compliances</td>
</tr>
<tr>
<td>Cyclic Load Testing</td>
<td>Vibrocreep Effect</td>
<td>3</td>
<td>Frequency, Amplitude, Mean Stress and Temperature Effects</td>
</tr>
<tr>
<td>Post Cyclic Testing</td>
<td>Monitor Changes in the Instantaneous Properties</td>
<td>3 or 5</td>
<td>Yield Stress, Elastic Modulus, and Maximum Stress</td>
</tr>
</tbody>
</table>

Testing Methodology

**Tensile Testing and Post Cyclic Testing**

The results of the tensile test data are averaged and condensed using the tensile and tensile average macros in Excel provided in Appendix O. The final result is strain at every .01 mm/mm. This result is plotted instead of a large number of data points at once to provide a clear and accurate representation of the test data.

Non contact strain and temperature measurements are strongly encouraged through the development of the creep and vibrocreep experimental procedures. The influence of attachments on the test specimens is not a variable
that needs to be added to the study of vibrocreep. All strain measurements are calculated from position measurements a LVDT, position transducer, etc. Temperatures are measurements of the atmospheric temperature about the test specimen except for the infrared temperature measurement system for monitoring the surface temperature of the polymer materials.

**Constant Load Creep Testing**

The experimental program for creep testing requires two stages, preliminary and final creep testing. The preliminary creep testing is designed to scan a material for the linear viscoelastic limit and more importantly be used for comparison to vibrocreep testing. The specimen geometry should be kept consistent throughout the testing procedure, for tensile, creep and vibrocreep testing. The test specimens chosen for solid polymer testing abide by the tensile testing ASTM D638-96 and for thin plastic sheeting D882-95a for thin films.

The preliminary testing matrix is shown below in Table 4. Typically one specimen is used for each test at the preliminary stage of the program. Assessment of an approximate linear viscoelastic limit can be made and also comparison of the vibrocreep effect can be assessed. The second stage of creep testing requires verification of the linear viscoelastic limit approximated at the preliminary stage. The tests are performed about the linear viscoelastic limit with the addition of 4 specimens to compose a total of 5 specimens. Once the linear limit is verified, stress levels for vibrocreep need to be analyzed for testing
below or above the linear viscoelastic limit. To verify the vibrocreep phenomena, testing within the linear viscoelastic limit is performed to show that the vibrocreep phenomena cannot be analyzed with linear viscoelastic theory. Creep testing above the linear viscoelastic limit provides reassurance of the linear viscoelastic limit and also allows approximation of the effect of the vibrocreep effect.

Table 4 Preliminary Test Matrix for Constant Load Creep Testing

<table>
<thead>
<tr>
<th>Creep Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% of Yield Stress</td>
</tr>
<tr>
<td>20% of Yield Stress</td>
</tr>
<tr>
<td>30% of Yield Stress</td>
</tr>
<tr>
<td>40% of Yield Stress</td>
</tr>
<tr>
<td>50% of Yield Stress</td>
</tr>
<tr>
<td>60% of Yield Stress</td>
</tr>
<tr>
<td>70% of Yield Stress</td>
</tr>
<tr>
<td>80% of Yield Stress</td>
</tr>
<tr>
<td>90% of Yield Stress</td>
</tr>
<tr>
<td>100% of Yield Stress</td>
</tr>
</tbody>
</table>

The results of the creep test data are therefore averaged and condensed using the 5 Sample and Average 5 macros in Excel provided in Appendix O. The final results are expressed in time at every 12 min. This result is therefore plotted instead of a large number of data points at once to provide a clear and accurate representation of the test data.

A few comments about the application of the static load to produce a creep test are needed. In theory, the load is fully applied at the time \( t = 0 \). This is physically impossible, since impacting the test specimen will occur. If the load is applied at a slower rate, then the initial elastic response may not be correct.
Efforts to perform a perfect creep test only become more complicated at lower stress levels. Non contact strain and temperature measurements are strongly encouraged through the development of the creep and vibrocreep experimental procedures. The influence of attachments on the test specimens is not a variable that needs to be added to the study of vibrocreep. All strain measurements are calculated from position measurements a LVDT, position transducer, etc. Temperatures are measurements of the atmospheric temperature about the test specimen except for the infrared temperature measurement system for monitoring the surface temperature of the polymer materials.

**Vibrocreep Testing**

The experimental program for vibrocreep testing also requires two stages, preliminary and final creep testing. The preliminary creep testing is designed to scan a material for the vibrocreep phenomena and approximate the effect of frequency, amplitude, and mean stress. The specimen geometry should be kept consistent throughout the testing procedure, for tensile, creep and vibrocreep testing. The test specimens chosen for solid polymer testing abide by the tensile testing ASTM D638-96 and for thin plastic sheeting D882-95a for thin films.

The preliminary testing matrix is shown below in Table 5. Typically one specimen is used for each test at the preliminary experimental stage. Assessment of each of the parameters can therefore be analyzed for the direction testing should be pursued in the second stage or if testing should
cease. The second stage of vibrocreep testing requires the decision of testing below or above the linear viscoelastic limit. If testing is performed within the linear viscoelastic limit, then the maximum stress should not exceed this limit. Mean stress and amplitudes must be selected to not violate this condition. Hysteresis heating effects may occur with the selection of the testing amplitude and frequency. If thermal or mechanical dominated failure regions are of particular interest, then the selections of the amplitude and frequency should be selected accordingly. Three test specimens are used to represent a mean stress, amplitude, frequency, and temperature. Three specimens reduce testing time since multiple parameters are being analyzed. The temperature effects upon the vibrocreep phenomena need to be analyzed by keeping the mean stress, amplitude, and frequency constant over a chosen temperature range. A reference temperature should be chosen for comparison. Typically the room temperature is taken since special equipment is not needed such as environmental chambers to test at this temperature, but another reference temperature may be chosen. Once these parameters are held constant, the linear limit may be violated at higher temperatures other than the reference temperature, since the linear viscoelastic limits decrease relative to reference temperature. Decreasing the temperature may be assumed to have the opposite effect with an increase in the linear viscoelastic limit relative to the reference temperature.
Table 5 Preliminary Test Matrix for Vibrocreep Testing

<table>
<thead>
<tr>
<th>Mean Stress</th>
<th>Amplitude</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>40% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>60% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>80% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>20% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>20Hz</td>
</tr>
<tr>
<td>40% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>20Hz</td>
</tr>
<tr>
<td>60% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>20Hz</td>
</tr>
<tr>
<td>80% of Yield Stress</td>
<td>+/−20% of Yield Stress</td>
<td>20Hz</td>
</tr>
<tr>
<td>20% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>40% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>60% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>80% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>10Hz</td>
</tr>
<tr>
<td>20% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>20Hz</td>
</tr>
<tr>
<td>40% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>20Hz</td>
</tr>
<tr>
<td>60% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>20Hz</td>
</tr>
<tr>
<td>80% of Yield Stress</td>
<td>+/−10% of Yield Stress</td>
<td>20Hz</td>
</tr>
</tbody>
</table>

The results of the vibrocreep test data are therefore averaged and condensed using the 3 Sample Dynamic and 3 Average Dynamic macros in Excel provided in Appendix O. The final results are expressed in time at every 12 min. This result is therefore plotted instead of a large number of data points at once to provide a clear and accurate representation of the test data.

Non contact testing for strain and temperature measurements is strongly encouraged through the development of the creep and vibrocreep experimental procedures. The influence of attachments on the test specimens is not a variable that needs to be added to the study of vibrocreep. All strain measurements are calculated from position measurements using a LVDT, position transducer, etc.
Temperatures are measurements of the atmospheric temperature about the test specimen except for the infrared temperature measurement system for monitoring the surface temperature of the polymer materials.

Knowledge of the hysteresis loop is necessary to obtain the proper mean strain values. If the hysteresis loop is "wide" then the mean strain will not be recorded properly. This is due to acquiring many data points and searching for the maximum and minimum values using the techniques described above. Other methods of acquiring the mean strain value during periodic loading have been investigated, but computer runtime becomes a factor. If the hysteresis loop is wide then averaging of the maximum and minimum strain values is only applicable if the hysteresis loop is symmetric. This technique is shown in Figures 28-30. These are simple guidelines for vibrocreep testing that have been developed from experience.

![Figure 28 Periodic Stress](image.png)
The criteria used to detect the presence of vibrocreep effects are illustrated in Figures 30-31, and in particular, if the mean strain from vibrocreep testing resides between the minimum and maximum resulting creep stain curves the vibrocreep effect does not exist. Alternatively, the vibrocreep effect is present if positioned above the creep curve obtained under maximum constant
stress. Normalization of the creep and vibrocreep results, further emphasizes the vibrocreep effect in the linear viscoelastic regime only. Specifically, the normalized vibrocreep curve that deviates from the creep compliance of the material indicates the presence of vibrocreep results shown in Figure 32. The normalization calculation for the vibrocreep result is shown by Equation 14.

\[
\sigma(t) = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{\sigma_{\text{mean}}}
\]

Figure 31 Loading Diagram for Vibrocreep

Figure 32 Vibrocreep Effect Above or Below the Linear Viscoelastic Limit
Figure 33 Normalized Vibrocreep Effect within the Linear Viscoelastic Limit

\[
\frac{\varepsilon(t)}{\sigma_{\text{mean}}} = E(t)
\]

\[
\sigma_{\text{mean}} = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2}
\]

Equation 14
EXPERIMENTAL PROGRAM AND RESULTS FOR NYLON 6/6

Properties and Applications of Nylon 6/6

In this study, Nylon 6/6 (DuPont Zytel® 42A NC010 Polyamide 66) has been selected as a test material since it is commonly used in engineering applications. Typical applications of Nylon 6/6 are gears, bearings, bushings, sprockets, and housings for power tools, Ref[12]. Recently, Nylon 6/6 has been used as a matrix in glass reinforced composites for application in automotive transmission gears, Ref[35].

Nylon 6/6 exhibits superior physical properties of stiffness, strength and fracture toughness. General and physical properties of Nylon 6/6 used in this program are described in Appendix P. In general, Nylon 6/6 can be characterized as a highly crystalline thermoplastic polymer.

Experimental Program

Instrumentation, Equipment, and Data Acquisition

In this program, computer aided data acquisition has been performed using National Instruments signal conditioning equipment and windows based data acquisition programming, LABView, version 5.0. The National Instruments signal conditioning equipment involves the following components:

- SCXI 1000 Chassis
SCXI 1200 module with SCXI 1302 attachment
- SCXI 1100 module with SCXI 1303 attachment
- SCXI 1121 module with SCXI 1321 attachment

The signal conditioning system allows data sampling at 333,000 samples per second with 12 bit resolution. This system provides excitation and the ability to monitor all types of components. The LABView program for data acquisition provided the interface between the measured voltage and the final experimental data.

**Tensile Testing of Nylon 6/6.** Tensile testing of Nylon 6/6 has been performed using an Instron 4206 screw type tensile testing machine. The displacements have been measured and converted to strain using the crosshead displacement. The load was measured using the 30,000 lbf load cell connected to signal conditioning equipment. The mechanical grips that are used for the creep testing of polymer materials are used in conjunction with the round specimen attachments of the testing apparatus to accommodate the environmental chamber. The environmental chamber was not designed for use with the Instron 4206, so revisions were made. The environmental conditions are monitored using type J thermocouples with an Instron 3111 environmental chamber. The signal conditioning equipment is connected through the control panel of the Instron 4206 test machine. The environmental conditions have been monitored using data acquisition equipment. The position and load are
connected to the SCXI 1321 attachment channels 0 to 1 respectively. The thermocouples are connected to the SCXI 1303 attachment.

The post cyclic testing of solid polymers is performed using the Instron 1350 test machine. The instrumentation and equipment is exactly the same as in vibrocreep testing of polymer materials. The only changes that are performed is output from the 8500 plus control panel which is switched to 12.7 mm/Volt (.5 in/Volt) to accommodate the longer movement required during the tensile test.

The data acquisition program for tensile and post tensile cyclic loads has been programmed to record displacement and load over the duration of the tensile test. The program reads the displacement voltage and converts the reading into strain and the strain is then recorded. The load reading has also been converted from voltage to a load value and recorded. Temperature measurement have been performed using a simple temperature data acquisition program that is executed before the tensile test to verify the steady state temperature conditions in the environmental chamber. An environmental chamber has been used for testing at elevated temperatures.

**Constant Load Creep Testing of Nylon 6/6.** Creep testing of solid polymers has been performed using an in house built test fixture that has allowed the application of high static loads for testing of Nylon 6/6. Test specimen grips for creep testing of Nylon 6/6 were specially designed and built in order to
provide a high clamping force and axial alignment. Working drawings of the grips and load trays are provided in Appendix S.

A Pentium 120 computer with 40 MB of RAM and a 500 MB hard disk has been used to perform the data acquisition. The data acquisition program has been written for load and displacement measurements. The load has been measured by an Interface 1210 2225 N (500 lbf.) load cell connected to the SCXI 1121 with the SCXI 1321 attachment. Displacement has been measured using a LVDT built by Data Instruments connected to the SCXI 1200 with the SCXI 1302 attachment. The test fixture has been modified to incorporate the environmental chamber. Four thermocouples have been used to measure the environmental conditions. Three thermocouples have been located inside the environmental chamber and the fourth has been used to measure the atmospheric temperature. National Instruments SCXI 1100 with the SCXI 1303 attachment has been used to measure the type J thermocouple voltage. One of the two environmental chambers designed and built by Shane Schumacher, has been used for creep testing and tensile testing using the Instron 4206 screw type testing machine. Working drawings are provided in Appendix Q.
Vibrocreep Testing of Nylon 6/6. The vibrocreep testing of Nylon 6/6 has been performed using an Instron 1350 servo hydraulic fatigue apparatus with an 8500 Plus control system update from Instron. The Instron 8500 Plus control system has the capability of measuring four test variables. A Pentium 120 computer with 40 MB of RAM and a 500 MB hard disk has been used to performed the data acquisition. The load and displacement have been measured by a data acquisition system at 889 N/Volt (200 lbf/Volt) and 5.08 mm/Volt (.2 in/Volt) respectively using outputs on the 8500 Plus control system control panel. The displacement has been recorded via channel 0 and load has been recorded via channel 1 of the SCXI 1100 attachment. Displacement measurements have
been taken in 3 parts, maximum, mean, and minimum. The displacement data has been converted into strain data and recorded. An initial offset for displacement, approximately 25.4 mm (1 in.), has been found to be necessary since the displacement of failure exceeds the 50.8 mm (2 in.) downward stroke from 0 of the 1350 Instron testing machine allowing a total displacement of 76.2 mm (3 in.) downward movement. The load followed a path similar to that of the displacement, respectively the maximum and minimum values are recorded. An environmental chamber has been designed and built specifically for testing using the Instron 1350 test machine by Shane Schumacher. The environmental chamber did not surround the hydraulic grips, but rested between them, heating the test specimen only. The environment remained constant by forced convection. The environmental chamber requires two holes, top and bottom, for specimen placement in the grips. There was a possibility for a temperature gradient due to the exposure to the atmosphere, therefore thermocouples are placed near the holes, and the temperature difference from the center to either hole does not fluctuate by more than .2 °C. Working drawings of the environmental chamber are provided in Appendix Q.

The monitoring of the environmental conditions and specimen conditions has been performed with infrared temperature measurement, a humidity transmitter, and type J thermocouples. The infrared temperature measurement system has been manufactured by Omega engineering (Model OS65 complete NEMA system). The IR measurement system has provided a 3:1 field of view to
focus a 6.35 mm (.25 in) spot size at 25.4 mm (1 in). The output was measured in terms of volts (0 to 5 volts) over a temperature range of -57 to 250 °C. The humidity transmitter has been also manufactured by Omega Engineering. The transmitter (Model HX92V) that provides an output from 0 to 1 Volt over a range of 0 to 100% relative humidity. The infrared temperature measurement system connects to channel 2, and the humidity transmitter connects to channel 3 of the SCXI 1100 attachment. The temperature measurement of the sample from the IR system has been converted from voltage to °C and recorded. The humidity transmitter measured the relative humidity of the testing room and has also been converted from voltage measurements to % relative humidity and recorded. The type J thermocouples have been used to measure the temperature within the environmental chamber channels 0 to 2 and the thermocouple at channel 3 measures the testing room temperature. The type J thermocouples allow temperature measurement from 0 to 750 °C.

The programming of the data acquisition system using LABView has been accomplished through the development of case structures, similar to a "Do Loop" where the loop control represents the execution of a task. A case structure was needed to separate the gathering of data from the separate modulus, since data must be acquired from each module separately. The dynamic testing of solid polymers requires two case structures, one to control data acquisition of the hysteresis loops and the second to monitor the displacement, load and environmental changes in time. The hysteresis case structure has been
executed every 100 cycles of the second case structure, thus monitoring the changes in the hysteresis loop approximately every hour. The second structure has been designed to monitor the change in strain approximately every 30 seconds. A 30 second execution of the second case structure is controlled by a Do While loop while a time wait function has been used to control the accumulation of data. The Do While loop is also the control for the initial case structure that is executed every 100 cycles. The time to execute the case structures has been recorded along with the wait time to obtain readings with an accuracy of .001 sec.

Figure 35 Vibrocreep Test Fixture for Nylon 6/6
Testing Procedure

The specimen geometry used in all experiments has been completed according to ASTM D638-96 Type II standards. All test specimens have been prepared using a CNC milling machine by Technical Services at Montana State University, Bozeman. The material has been purchased from Laird Plastics with the properties shown in Appendix P. Nylon 6/6 has not necessarily been purchased from the same batch of processed material, therefore the effects of batch sensitivity may have effected some results. Testing temperature has been varied from room temperature of 23 °C to 50 °C, with increments of 9 °C. Once the environmental chamber for vibrocreep testing was designed and built, the temperature chamber maintained a temperature of 35 °C with the blower fan in operation by conduction of heat from the motor to the environmental chamber. Nylon 6/6 was first tested in tension to determine the strength and stiffness properties, secondly creep tests were performed, and thirdly the vibrocreep and post cyclic testing were completed.

Tensile Testing Procedure for Nylon 6/6. Tensile testing has been performed at a strain rate of .875 mm/mm * min (in/in * min) or a feed rate of 44.45 mm/min (1.75 in/min) for all temperatures ranging from .5 min at 23 °C to 5 min at 68 °C abiding by the ASTM 638-96 standard. The strength and stiffness calculations are also performed according to the ASTM D638-96 standard.
Constant Load Creep Testing Procedure for Nylon 6/6. The preliminary creep testing for Nylon 6/6 has been performed for 24 hrs. Further creep tests have been performed at a minimum of 9 hours where at least five test specimens were used to represent each resultant curve. The linear viscoelastic range has been determined for each temperature at 23 °C, 35 °C, 41 °C, 50 °C, 59 °C, and 68 °C. The environmental chamber used for tensile testing of Nylon 6/6 was also used for creep testing of Nylon 6/6 with a temperature fluctuation of not more than +-.5 °C. At 23 °C creep testing was performed for 10%, 20%, 30%, 40%, and 50% of the yield stress. The cross-section was considered to remain constant as the material deformed in time (engineering stress). The feed rate during loading of the test specimen was controlled by the use of a hydraulic jack.

Vibrocreep Procedure for Nylon 6/6. The sample geometry was kept the same as in the previous test cases (ASTM D638-96 Type II). The relative humidity was monitored during vibrocreep with readings of 15% +-.5% during testing. Approximately in the middle of the vibrocreep testing, the test machine was relocated to another room. The humidity levels remained the same between the two rooms. All testing of Nylon 6/6 was performed in tension-tension mode within the linear viscoelastic regime of the polymer determined from the above creep testing except at elevated temperature, where testing was performed at stress levels relative to the yield stress at 23 °C. Nylon 6/6 specimens have been also monitored for the effects of hysteresis heating where thermal effects
can contribute to deformation over time. Hysteresis heating was not observed, so the deformation of the polymer was considered to be in the mechanically dominated regime.

Post Cyclic Testing Procedure for Nylon 6/6. After creep and vibrocreep programs had been completed, specimens were tested in tension at the same feed rate as that of the initial tensile testing described above. The vibrocreep specimens were tested in tension directly after cyclic tests using the 1350 Instron, where creep test specimens were stored and tested in tension later on the same testing machine. The effect of recovery was initially of great concern for the creep test specimens, but the effect of recovery (testing immediately after completion of a creep test or after storage for weeks or months) did not show an effect on the post tensile properties of the material at 23 °C. At higher temperatures the effect of recovery upon the test specimens has not been investigated.

Experimental Results

Tensile Testing Experimental Results at 23 °C

Tensile testing of Nylon 6/6 provided the values of the instantaneous elastic modulus, yield strength, and ultimate strength of the polymer. Nylon 6/6 that was used for the project is an isotropic material, therefore directionality of
the tensile testing relative to the microstructure was not necessary. The results of the tensile testing are provided in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Yield Stress (MPa)</th>
<th>Maximum Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Yield Strain (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 °C</td>
<td>70</td>
<td>78</td>
<td>1.42</td>
<td>.0642</td>
</tr>
</tbody>
</table>

Tensile testing of Nylon 6/6 has been performed for two separate batches of material from Laird Plastics. The feed rates have been kept consistent for all samples. A comparison of the material properties depending on the particular batch is provided in Table 7.

<table>
<thead>
<tr>
<th></th>
<th>Yield Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch 1</td>
<td>70</td>
<td>1.42</td>
</tr>
<tr>
<td>Batch 2</td>
<td>72</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Constant Load Creep Test Results of Nylon 6/6 at 23 °C

As indicated in the previous chapter, the objectives of creep testing have been to determine the vibrocreep effect, and the linear viscoelastic limit. The results have been also used for the vibrocreep model development. After the preliminary creep testing of Nylon 6/6, the linear viscoelastic limit has been determined to be 30% the yield stress at 23 °C, shown in Figure 36. The complete results of the creep testing at 23 °C are provided in Appendix A.
Vibrocreep Experimental Results at 23 °C

The vibrocreep results for Nylon 6/6 have been divided into three categories that determine the influence of frequency, amplitude, mean stress, respectively. The preliminary vibrocreep testing was performed for 24 hrs. The tests have been used for verification of the vibrocreep in the selected polymer. Nylon 6/6 has demonstrated the effect of vibrocreep, therefore testing was pursued further. A parametric study of vibrocreep effects has been conducted following the test program summarized in Table 8.

Table 8 Test Matrix for Nylon 6/6 Vibrocreep Testing at 23 °C

<table>
<thead>
<tr>
<th>Mean Stress (% of $\sigma_y$)</th>
<th>Superimposed Cyclic Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Stress Amplitude (% of $\sigma_y$)</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>16</td>
<td>Stress Amplitude (% of $\sigma_y$)</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>20</td>
<td>Stress Amplitude (% of $\sigma_y$)</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
</tr>
</tbody>
</table>

The testing matrix shown is a compact representation of the experimental loading conditions performed. For example, testing was performed at 12%±4% of the yield stress at 1, 10, and 20 Hz to describe frequency effects. Testing is also performed at 12%±7.5% and ±10% of the yield stress at 1, 10, and 20 Hz to further investigate the frequency effects. Once these tests were completed, the
mean stress was changed from 12% to 16% and the same sequence was executed, then from 16% to 20%. Once the testing has been completed, amplitude and mean stress effects can also be investigated with substantial supporting data. All test matrices within the thesis are provided in this format with similar interpretation. The influence of the frequency in the vibrocreep effect shown in Figure 37. The complete results of the frequency effects at 23 °C are provided in Appendix B.
Figure 36. Constant Load Creep of Nylon 6/6 at 23 °C

1- (0.10)σ_y; 2- (0.20)σ_y; 3- (0.30)σ_y; 4- (0.40)σ_y; 5- (0.50)σ_y;

σ_y = 70 MPa at 23 °C
It has been shown that an increase in the loading frequency resulted in an increase in the vibrocreep effect. An increase in amplitude has also resulted in an increase in the vibrocreep effect, as shown in Figure 38. Complete results of the amplitude effects at 23 °C are provided in Appendix C. The effect of the mean stress upon the creep behavior of Nylon 6/6 is not apparent. As an example, the influence of the mean stress can be observed in Figure 39. Complete results of the mean stress effects at 23 °C are provided in Appendix E.
Figure 38 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

Vibrocreep: 1- (0.20±0.05)σ_y, 2- (0.20±0.075)σ_y, 3- (0.20±0.10)σ_y, at 20 Hz; Constant Load Creep: 4- (0.20)σ_y, 5- (0.30)σ_y;

σ_y = 70 MPa at 23 °C
Figure 39 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C
Vibrocreep: 1- \((0.12\pm0.10)\sigma_y\), 2- \((0.16\pm0.10)\sigma_y\), 3- \((0.20\pm0.10)\sigma_y\), at 20 Hz;
Constant Load Creep: 4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), 6- \((0.30)\sigma_y\);
\(\sigma_y = 70 \text{ MPa at 23 °C}\)
Post Cyclic Testing at 23 °C

The post cyclic testing is described as tensile testing following creep and vibrocreep experiments. The result is a measure of the changes in the material properties in the polymer due to cyclic loading effects. Testing has been performed for all test specimens with an example shown in Figure 40 and the results summarized in Table 9.

![Figure 40 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C](image)

Vibrocreep: \((0.16\pm0.075)\sigma_y\), 1- 1 Hz; 2- 10 Hz; 3- 20 Hz;
Constant Load Creep: 4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\); 6- Virgin Specimens; 
\(\sigma_y = 70\) MPa at 23 °C
Table 9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

<table>
<thead>
<tr>
<th>Curve #</th>
<th>Yield Stress (MPa)</th>
<th>Yield Strain (mm/mm)</th>
<th>Maximum Stress (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>79.697</td>
<td>.06164</td>
<td>83.877</td>
<td>1.56</td>
</tr>
<tr>
<td>2</td>
<td>80.754</td>
<td>.06042</td>
<td>84.414</td>
<td>1.47</td>
</tr>
<tr>
<td>3</td>
<td>77.394</td>
<td>.06105</td>
<td>82.676</td>
<td>1.44</td>
</tr>
<tr>
<td>4</td>
<td>65.567</td>
<td>.06515</td>
<td>74.543</td>
<td>1.33</td>
</tr>
<tr>
<td>5</td>
<td>63.171</td>
<td>.06885</td>
<td>76.427</td>
<td>1.35</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
<td>.06420</td>
<td>78.000</td>
<td>1.42</td>
</tr>
</tbody>
</table>

As shown in Figure 40, the strength and stiffness of the material can be seen to increase after the cyclic testing. The effects of recovery after vibrocreep testing has also been determined using post cyclic testing as shown in Figure 41 and summarized in Table 10.

Figure 41 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

Vibrocreep: (0.16±0.10)σ_y, 10 Hz; 1- Recovered, 2- Immediate; Constant Load Creep: 3- (0.16)σ_y; 4- Virgin Specimens; σ_y = 70 MPa at 23 °C
Table 10  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

<table>
<thead>
<tr>
<th>Curve #</th>
<th>Yield Stress (MPa)</th>
<th>Yield Strain (mm/mm)</th>
<th>Maximum Stress (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.718</td>
<td>0.06104</td>
<td>75.233</td>
<td>1.44</td>
</tr>
<tr>
<td>2</td>
<td>82.397</td>
<td>0.06593</td>
<td>85.779</td>
<td>1.49</td>
</tr>
<tr>
<td>3</td>
<td>65.567</td>
<td>0.06515</td>
<td>74.543</td>
<td>1.33</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>0.06420</td>
<td>78.000</td>
<td>1.42</td>
</tr>
</tbody>
</table>

After approximately one month of recovery, specimens tested under cyclic loading conditions have shown marginal changes in the tensile properties over that of the constant load creep and virgin specimens.

Tensile Testing Results at Elevated Temperatures

Tensile test results at elevated temperatures are shown in Figure 42.

Figure 42  Tensile Testing of Nylon 6/6 at Different Temperatures
1- 23 °C; 2- 35 °C; 3- 41 °C; 4- 50 °C; 5- 59 °C; 6- 68 °C;
All calculations of the strength and stiffness have been performed according to the ASTM 638-96 standard. The elastic modulus, yield stress, and ultimate stress are tabulated in Table 11.

Table 11 Tensile Properties of Nylon 6/6 at 23 °C and Elevated Temperatures

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Yield Stress (MPa)</th>
<th>Ultimate Stress (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Yield Strain (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 °C</td>
<td>70</td>
<td>78</td>
<td>1.42</td>
<td>.0642</td>
</tr>
<tr>
<td>35 °C</td>
<td>55.2</td>
<td>70.2</td>
<td>1.21</td>
<td>.0544</td>
</tr>
<tr>
<td>41 °C</td>
<td>44.9</td>
<td>65</td>
<td>.96</td>
<td>.0551</td>
</tr>
<tr>
<td>50 °C</td>
<td>22</td>
<td>57.5</td>
<td>.708</td>
<td>.0332</td>
</tr>
<tr>
<td>59 °C</td>
<td>19</td>
<td>52.4</td>
<td>.548</td>
<td>.0368</td>
</tr>
<tr>
<td>68 °C</td>
<td>10</td>
<td>48.9</td>
<td>.459</td>
<td>.0238</td>
</tr>
</tbody>
</table>

The strain values at the given temperatures are provided in engineering strain. The results of the tensile testing of virgin specimens at different temperatures are shown in Figure 43. Complete results of the tensile testing of Nylon 6/6 are provided in Appendix A.

![Figure 43 Yield Stress and Elastic Modulus vs. Temperature](image-url)
Constant Load Creep Testing Results at Elevated Temperatures

The creep tests at elevated temperatures has been performed at 20%, 30%, 40% and 50% of the yield stress at the respective temperature. Complete creep testing results for Nylon 6/6 are provided in Appendix A. As stated above the cross section of the test specimen is assumed to remain constant through the duration of the test (engineering stress) even at elevated temperatures. The linear viscoelastic limit remains at an approximate 30% of the yield stress at their respective temperature.

For Nylon 6/6, stress levels of 16% and 20% with respect to the yield stress at 23 °C is performed at each temperature. The effect of temperature on creep at 20% relative to the yield stress at 23 °C can be observed in Figure 44. From the figure shown, the creep rate is shown to increase with increasing temperature. Complete results of the temperature effect for Nylon 6/6 are provided in Appendix F.
Vibrocreep Testing Results at Elevated Temperatures

Two test temperatures have been used to characterize the vibrocreep effects, 35 °C and 41 °C at elevated temperatures. The temperatures chosen allowed testing in the linear viscoelastic regime of Nylon 6/6. Testing at stress levels relative to the test temperature is not easily accommodated at the higher temperatures, since amplitude loads at and below 100 N (22.5 lbf) are not executable due to testing machine limitations. Therefore at 41 °C, 4% amplitude relative to the yield stress at 41 °C was not executable.
The remainder of the testing within the linear viscoelastic regime provided the same results for all temperatures. The influence of temperature resulted in a decrease in the vibrocreep effect where the stress level is held constant over the temperature range. The results of the temperature effect for Nylon 6/6 are provided in Appendix F. The effect of the frequency at 35 °C at the yield stress relative to 35 °C and 23 °C upon the vibrocreep effect can be shown in Figure 45. The results of the frequency effects at 35 °C and 41 °C are provided in Appendix B. The effect of increasing amplitude at 41 °C at the yield stress relative to 41 °C and 23 °C is shown in Figure 46. The results of the amplitude effects at 35 °C and 41 °C are provided in Appendix C. The effect of the mean stress at 35 °C at the yield stress relative to 35 °C and 23 °C is shown in Figure 47. The results of the mean stress effects at 35 °C and 41 °C are provided in Appendix D.

Table 12 Test Matrix for Nylon 6/6 Vibrocreep Testing at Elevated Temperatures

<table>
<thead>
<tr>
<th>Mean Stress (% of $\sigma_y$)</th>
<th>Superimposed Cyclic Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stress Amplitude (% of $\sigma_y$)</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>


Figure 45 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

Vibrocreep: (0.20±0.10)$\sigma_y$, 1- 1 Hz, 2- 10 Hz;
Constant Load Creep: 3- (0.20)$\sigma_y$, 4- (0.30)$\sigma_y$;
$\sigma_y = 55$ MPa at 35 °C
Figure 46 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

Vibrocreep: 1- $(0.20 \pm 0.05)\sigma_y$, 2- $(0.20 \pm 0.010)\sigma_y$ at 10 Hz;
Constant Load Creep: 3- $(0.20)\sigma_y$, 4- $(0.30)\sigma_y$;

$\sigma_y = 45$ MPa at 41 °C
Figure 47 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C

Vibrocreep: 1- \((0.16\pm0.10)\sigma_y\), 2- \((0.20\pm0.10)\sigma_y\) at 10 Hz;
Constant Load Creep: 3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\);
\(\sigma_y = 55\) MPa at 35 °C
From the results shown in the figures above, the effect of increasing frequency, amplitude, and mean stress show similar results as seen from testing at 23 °C. Through the temperature range this effect is emphasized at the stress levels where the yield stress is relative to the test temperature, but is not evident at the higher stress levels where the yield stress is relative to the 23 °C. The influence of temperature is evident from Figure 48. The result of the temperature effects are provided in Appendix F. An example of the influence of the frequency, amplitude, and mean stress where the yield stress is relative to 23 °C is shown in Figures 49-51. From the results, the influence of these parameters has been analyzed above and below the linear viscoelastic limit, and also the influence of temperature.
Figure 48 Vibrocreep Response of Nylon 6/6 at Different Temperatures
Vibrocreep: \((0.16\pm0.10)\sigma_y, 10\text{ Hz}, 1- 23^\circ\text{C}, 2- 35^\circ\text{C}, 3- 41^\circ\text{C}\);
Constant Load Creep: \((0.16)\sigma_y, 4- 23^\circ\text{C}, 5- 35^\circ\text{C}, 6- 41^\circ\text{C}\);
\(\sigma_y = 70\text{ MPa at } 23^\circ\text{C}\)
Figure 49 Vibrocreep Response of Nylon 6/6 at Different Frequencies and Temperatures

Vibrocreep: \((0.20\pm0.10)\sigma_y\), 1- 1 Hz at 23 °C, 2- 10 Hz at 23 °C; 3- 1 Hz at 35 °C, 4- 10 Hz at 35 °C, 5- 1 Hz at 41 °C, 6- 10 Hz at 41 °C

\(\sigma_y = 70\) MPa at 23 °C
Figure 50 Vibrocreep Response of Nylon 6/6 at Different Amplitudes and Temperatures

Vibrocreep: 1- \((0.20 \pm 0.05)\sigma_y\) at 10 Hz, 23 °C, 2- \((0.20 \pm 0.10)\sigma_y\) at 10 Hz, 23 °C;
3- \((0.20 \pm 0.05)\sigma_y\) at 10 Hz, 35 °C, 4- \((0.20 \pm 0.10)\sigma_y\) at 10 Hz, 35 °C;
5- \((0.20 \pm 0.05)\sigma_y\) at 10 Hz, 41 °C, 6- \((0.20 \pm 0.10)\sigma_y\) at 10 Hz, 41 °C;
\(\sigma_y = 70\) MPa at 23 °C
In Figures 49-50, an increase in temperature with an increase in frequency or amplitude resulted in an increase in the vibrocreep effect. In Figure 51, the effect of increasing mean stress is shown to have a decrease in the vibrocreep effect.

Post Cyclic Testing at Elevated Temperatures

The post cyclic testing is performed for all test specimens at 35 °C and 41 °C. The effect of recovery was not tested for higher temperatures, since this is not possible with the current test equipment. The specimen would be cooled and then reheated. Therefore storage of the creep test specimens is justified. An
example of the post tensile testing at 41 °C at the yield stress relative to 41 °C and 23 °C is summarized in Tables 13-14 and shown in Figures 52-53, respectively.

Table 13 Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C

<table>
<thead>
<tr>
<th>Curve #</th>
<th>Yield Stress (MPa)</th>
<th>Yield Strain (mm/mm)</th>
<th>Maximum Stress (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66.541</td>
<td>.06424</td>
<td>68.399</td>
<td>1.32</td>
</tr>
<tr>
<td>2</td>
<td>65.318</td>
<td>.05940</td>
<td>68.372</td>
<td>1.31</td>
</tr>
<tr>
<td>3</td>
<td>57.034</td>
<td>.05005</td>
<td>64.950</td>
<td>1.27</td>
</tr>
<tr>
<td>4</td>
<td>44.600</td>
<td>.05510</td>
<td>65.000</td>
<td>.96</td>
</tr>
</tbody>
</table>

Figure 52 Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C

Vibrocreep: 1- (0.20±0.05)\(\sigma_y\), 2- (0.20±0.10)\(\sigma_y\), at 10 Hz; Constant Load Creep: 3- (0.20)\(\sigma_y\); 4- Virgin Specimens; \(\sigma_y = 45\) MPa at 41 °C
Figure 53  Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C

Vibrocreep: 1- (0.16±0.04)σy, 2- (0.16±0.10)σy, at 10 Hz;
Constant Load Creep: 3- (0.16)σy, 4- (0.20)σy; 5- Virgin Specimens;
σy = 70 MPa at 23 °C

Table 14 Tensile Testing of Nylon 6/6 Specimens after Cyclic and Constant Loading at 41 °C

<table>
<thead>
<tr>
<th>Curve #</th>
<th>Yield Stress (MPa)</th>
<th>Yield Strain (mm/mm)</th>
<th>Maximum Stress (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65.360</td>
<td>.06073</td>
<td>67.891</td>
<td>1.29</td>
</tr>
<tr>
<td>2</td>
<td>66.485</td>
<td>.06185</td>
<td>68.080</td>
<td>1.29</td>
</tr>
<tr>
<td>3</td>
<td>52.006</td>
<td>.04425</td>
<td>65.787</td>
<td>1.23</td>
</tr>
<tr>
<td>4</td>
<td>57.299</td>
<td>.05005</td>
<td>64.950</td>
<td>1.27</td>
</tr>
<tr>
<td>5</td>
<td>44.6</td>
<td>.05510</td>
<td>65.000</td>
<td>.96</td>
</tr>
</tbody>
</table>

In the figures shown, at elevated temperatures the strength and stiffness of the constant load creep and cyclic experiments have similar results. The yield stress is lower, but the elastic moduli have marginal differences.
Vibrocreep effects in Nylon 6/6 are evident from the results obtained in this study. Vibrocreep effects have been obtained at the temperatures of 23, 35 and 41°C, above and below the linear viscoelastic limit. The observable difference between creep and vibrocreep of Nylon 6/6 demonstrates that the vibrocreep phenomena is not predictable by current viscoelastic theories.

Tensile test results of Nylon 6/6 show a definite dependence upon test temperature. Increases of 9 °C have a dramatic effect on the tensile properties of the polymer in terms of decreasing elastic modulus and yield stress. The viscoelastic linearity limit remained at approximately 30% of the yield stress over the experimental temperature range. A correlation between stress and temperature effects on the creep behavior of Nylon 6/6 has been observed in all experiments leading to the belief that the material response can be modeled with time-temperature and stress-time analogies. An effect of the glass transition temperature has been shown in Figure 43 over the temperature range.

The degree of vibrocreep effects depending on the mean stress, frequency, amplitude, and temperature of the cyclic loading has been determined. The vibrocreep effect has been shown to increase with increasing frequency or amplitude. Alternatively, the vibrocreep effect has been shown to decrease with increasing mean stress and temperature range below the linear viscoelastic limit.
Typically, polymers have either thermally or mechanically dominated regimes or a combination of the two when subjected to cyclic loading condition, Figure 54, Ref[29]. In the case of Nylon 6/6, hysteresis heating of the polymer has not been observed within the experimental test range studied. This indicates that the observed vibrocreep effects result from damage development and evolution due to the presence of cyclic loading.

![Figure 54 Thermal and Mechanical Dominated Failure Zones](image)

The vibrocreep effects appear to be directly dependent upon the product of the amplitude and frequency of the cyclic load. As shown in Equation 15, this product defines the amplitude rate of loading. As can be observed from Figure 55, vibrocreep effects are directly dependent on the product of the frequency and amplitude.
Figure 55 Vibrocreep Response of Nylon 6/6 with $\omega^*a = 100$ at 23 °C

Vibrocreep: 1- $(0.20\pm0.10)\sigma_y$ at 10 Hz; 2- $(0.20\pm0.05)\sigma_y$ at 20 Hz;
Constant Load Creep: 3- $(0.20)\sigma_y$, 4- $(0.30)\sigma_y$;

$\sigma_y = 70$ MPa at 23 °C
\[ \sigma(t) = \sigma_m + \sigma_a \cdot \sin(\omega \cdot t) \]

\[ \frac{d}{dt} \sigma(t) = (\sigma_a \cdot \omega) \cdot \cos(\omega \cdot t) \]

Equation 15

Another factor considered in this study represents the ratio of the mean stress to the amplitude of the cyclic load. This factor can be related to the R ratio typically considered in the studies of fatigue, Equations 16.

\[ \mu = \frac{\sigma_{\text{mean}}}{\sigma_{\text{amp}}} = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \cdot \frac{1 + \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}}{1 - \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}} = \frac{1 + R}{1 - R} \]

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

Equations 16

The result of this correlation factor combines the amplitude and mean stress effects together as shown in Figure 56. From this figure, \( \mu = 4 \), an increase in mean stress and amplitude correlates with approximately the same difference between the creep and vibrocreep creep compliance curves. The results of \( \mu=4 \) for Nylon 6/6 are provided in Appendix D.
Figure 56 Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 23 °C

Vibrocreep: 1- $(0.16\pm0.04)\sigma_y$, 10 Hz; 2- $(0.20\pm0.05)\sigma_y$, 10 Hz;
Constant Load Creep: 3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$;

$\sigma_y = 70$ MPa at 23 °C
Properties and Applications of PVDF

Polyvinylidene Fluoride (PVDF) is a piezoelectric polymer used extensively for sensors and actuators in dynamic environments, Ref[61]. PVDF material is considered a sandwich composite where the PVDF polymer lies between two surface layers of electrode for electrical connection, thus making a laminate composite.

PVDF testing is performed with the electrodes since this is the most widely used form of the material. Piezoelectric properties of PVDF are produced by deforming a polymer material resulting in a permanent dipole polarization within the polymer, through mechanical deformation of the molecular orbitals. The deformation process is performed above the glass transition temperature, where the dipoles are constrained after cooling and dissipation of the dipole is less likely to occur.

In this study, PVDF is chosen for its physical properties, applications, and microstructure. The material is anisotropic, due to drawing the material to obtain piezoelectric properties, therefore the strength and stiffness of PVDF is dependent upon the loading direction. General and physical properties are provided from the manufacturer in Appendix P. The glass transition temperature of is about -50 °C, therefore the polymer is in the rubbery region at room temperature of 23 °C. The microstructure of PVDF is semi-crystalline. PVDF is
the first commercial piezoelectric material on the market, and there is a high
demand for characterization of its properties. The investigation of cyclic loading
effects for PVDF has not been performed even though the material is used in
cyclic loading environments.

**Experimental Program**

**Instrumentation, Equipment, and Data Acquisition**

Computer aided data acquisition is performed with National Instruments
signal conditioning equipment and windows based data acquisition programming
language called LABView. The National Instruments signal conditioning
equipment consists of the following:

- SCXI 1000 Chassis
- SCXI 1200 module with SCXI 1302 attachment
- SCXI 1100 module with SCXI 1303 attachment
- SCXI 1121 module with SCXI 1321 attachment

The signal conditioning system allows data sampling at 333,000 samples per
second with 12 bit resolution. This system provides excitation and the ability to
monitor all types of components. The LABView program for data acquisition
provides the interface between voltages and usable data. The version of
LABView is 5.0, which is used for all of the data acquisition programming.
Tensile Testing of PVDF. The tensile testing of PVDF was also performed on the 4206 Instron where a 20 lbf load cell is placed in series with the existing load cell. The mechanical grips from the creep and vibrocreep test fixture are used, since position transducer attachments are required along with provisions for the alternate load cell. A Data Instruments FS1000 Fastar A/C transducer monitors the displacement. The transducer is connected to a SP200A signal processor that allows zero and span setting and temperature compensation. The load cell is provided with excitation and monitored through the data acquisition system. The SCXI 1321 module is used with channel one connected to the displacement and channel two connected to the load. The Instron testing machine provided the constant strain rate necessary to abide by the ASTM 882-95a standards.

Constant Load Creep and Vibrocreep Testing of PVDF. Frank Halloway, a former graduate student, first built the test fixture for relaxation testing of thin films. Extensive modification has been done to the test fixture for creep testing. A pulley system was incorporated to apply the static load or mean load. The second modification was the attachment of a crosshead for axial alignment. The crosshead is adjustable and rolls on rails with steel ball bearings. At the interface of the steel rails and steel ball bearings friction is further minimized with light weight oil. The test fixture was found to have a static frictional force of .45 N. With the use of a dynamic shaker, the sinusoidal waveform could be
superimposed on the static load. Adjustable legs were installed on the dynamic shaker for proper axial alignment. The test fixture is easily portable for the purpose of testing in small rooms such as offices or cold rooms. An environmental chamber manufactured by Instron 3111 is also used for room and high temperature testing. This test fixture is diverse, in that creep and vibrocreep testing can be performed with one fixture instead of two.

Data acquisition for the creep testing of PVDF has been performed with a Gateway 486 computer with 32 MB of RAM and a 2.1 GB hard disk. The components for acquiring data for PVDF are a load cell, position transducer, accelerometer, and thermocouples. The displacement voltage is measured using a Data Instruments FS1000 Fastar A/C transducer. The transducer is connected to a SP200A signal processor that allows zero and span setting and
temperature compensation. The transducer and signal processor allows static and dynamic measurements from 0 to 15,000 Hz. The output voltage is +10 Volts to -10 Volts, therefore a circuit was built to reduce the voltage to +5 Volts to -5 Volts to connect SCXI data acquisition system. The position measurement is connected to channel 0 of the 1321 SCXI attachment and converted to mm and then recorded. The load measurements are acquired from an 88.9 N (20 lbf) fatigue rated Interface load cell model 1500. A gain of 100 is necessary to receive the greatest resolution from the load cell. The load cell is connected to the SCXI 1321 attachment and also excited with 10 Volts from this attachment. The voltage measurement is converted to load and recorded. The influence of outside vibration is measured with a +10 g to -10 g Sensotec JTF flat pack accelerometer perpendicular to the base or floor. The accelerometer is connected to channel 2 of the 1321 SCXI attachment and also excited with 10 Volts from this attachment. The voltage measurement is converted to g's and then recorded. The environmental temperature was measured using type T thermocouples. Type T thermocouples allow temperature measurement from -270 to 400 °C. The thermocouples are connected to channels 0 to 1 of the SCXI 1100 attachment. One thermocouple measures the temperature within the Instron 3111 environmental chamber, and the other measures the testing room temperature.

The programming of the data acquisition system with LABView is accomplished through the development of case structures. The creep testing of
PVDF only requires one case structure. The time calculations and time wait functions are calculated along with the necessary physical measurements of load, position, acceleration and temperature. The vibrocreep testing of PVDF requires two case structures, one to control data acquisition of the hysteresis loops and the second to monitor the displacement, load and environment changes in time. The hysteresis case structure is executed every 100 cycles of the second case structure; thus monitoring the changes in the hysteresis loop approximately every hour. The second structure is designed to monitor the change in strain approximately every 30 seconds of clock time. A 30 second execution of the second case structure is controlled by a Do While loop. A time wait function is used to control the accumulation of data. The Do while loop is also the control for the initial case structure that is executed every 100 cycles. The time to execute the case structures is recorded along with the time wait to accurately record time to a 1 thousandth of a second.

Testing Procedure

PVDF material was the first material to be investigated for the vibrocreep effect. The first step was the selection of the sample size for the material. Tensile and creep testing has been performed on 7.62 mm x 76.2 mm specimens with an aspect ratio of 10:1, abiding by the ASTM D882-95a standard. This sample geometry has been therefore adopted for all testing of PVDF, tensile, creep and vibrocreep. PVDF thin film have been produced by Measurement
Specialties, Inc. with a continuous electrode pattern over an area of 8.5 in x 11 in. The PVDF film is 28-31 microns thick with approximately 10 microns of silver electrode on each face, thus making the film thickness an average of 51 microns. The copper electrode film was also 28-31 microns of PVDF, but the copper electrode on each face is only approximately 1 micron. The copper electrode film provided a much more challenging task of thickness measurement; therefore a thickness of 31 microns is used to represent the film and electrodes. The PVDF film used for all testing is produced from the same batch of Bulk polymer, thus minimizing batch sensitivity problems.

To reduce the grip effects, the PVDF material was tabbed with posterboard. The tabbed test specimen provides three benefits for testing of the material, the first being the ability to reduce the grip effects, the second allowing measurement of gage length of the test specimen with a caliper, and finally insulating the polymer from the metallic grips.

The material chosen for creep and vibrocreep testing is the silver electroded PVDF. Reasons for choosing the silver electroded material over the copper is that batch sensitivity did not exist for the silver where the copper was questionable. Also, the NASA micro-g group was also using the silver electrode PVDF, therefore the experimental results would benefit the group. Testing temperatures for PVDF are 23 °C and –25 °C. The room temperature of 23 °C was chosen, as a base for the vibrocreep study, since special testing equipment would not be required at this temperature. The temperature of –25 °C was
chosen since cooling the material allowed closer proximity to the glass transition temperature of $-50 \, ^\circ\text{C}$. The cold room allowed the testing apparatus to be moved within the room where the instrumentation and testing apparatus were cooled to the temperature of $-25 \, ^\circ\text{C}$. Recalibration of the instruments was necessary, but all instruments had the ability to work properly at $-25 \, ^\circ\text{C}$.

**Tensile Testing Procedure for PVDF.** The tensile testing was performed at a strain rate of $0.5 \, \text{mm/mm} \times \text{min of } 38.1 \, \text{mm/min (1.5 in/min)}$ according to the ASTM D882-95a for both material directions. The strength and stiffness determination for PVDF in both directions of the material has been performed abiding by the ASTM 882-95a standard stated above.

**Constant Load Creep Procedure for PVDF.** The creep testing was performed at stresses 30%, 45%, and 60% of the yield stress at $23 \, ^\circ\text{C}$ and at temperatures of $23 \, ^\circ\text{C}$ and $-25 \, ^\circ\text{C}$. The same specimen geometry has been used for creep testing as in the tensile and vibrocreep testing of PVDF. After months of experimentation, the test fixture proved to be accurate and reliable.

**Vibrocreep Testing Procedure for PVDF.** The vibrocreep testing was performed at the same means stresses as in creep testing, and at multiple amplitudes, frequencies, and at the temperatures $23 \, ^\circ\text{C}$ and $-25 \, ^\circ\text{C}$. The same specimen geometry used for tensile and creep testing has been also used for vibrocreep testing of PVDF. The vibrocreep testing of PVDF proved to be
challenging also. The limitations of the combination of frequency and amplitude within the testing fixture proved to be the greatest challenge. Unlike an Instron or MTS testing machine, the load and frequency are controlled through the manual application of electromagnetic motion and weight. The lowest amplitude and frequency that the test fixture can accommodate is 5% and 5 Hz respectively. Below these values, the electromagnetic shaker that provides the oscillatory motion does not work properly. An amplitude and frequency too high will also pose a problem, since the crosshead will "jump". When the settings are too high, PVDF emits a sound of a twanging guitar string. The colder temperature within the cold room simply magnified the limitation, but high and low amplitude and frequency limitations did not pose as large limitation as can be seen from the data.

Experimental Results

Tensile Testing Results at 23 °C

Tensile testing has been performed to calculate the strength and stiffness of PVDF. The tensile testing of PVDF was performed on both the silver and copper electrode materials. PVDF is an anisotropic material, therefore tensile testing in two directions was performed. A diagram of the directionality is shown in Figure 58.
The results of the tensile testing for both the silver and copper electrode PVDF are shown in Table 15.

<table>
<thead>
<tr>
<th></th>
<th>Yield Stress (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silver Electrode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direction 1</td>
<td>30.428</td>
<td>1.96</td>
</tr>
<tr>
<td>Direction 2</td>
<td>23.498</td>
<td>1.69</td>
</tr>
<tr>
<td><strong>Copper Electrode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direction 1</td>
<td>46.568</td>
<td>3.42</td>
</tr>
<tr>
<td>Direction 2</td>
<td>37.935</td>
<td>2.84</td>
</tr>
</tbody>
</table>

The results of the tensile testing of the silver electrode PVDF are shown in Figure 59 for direction 1 and Figure 60 for direction 2.
Figure 59  Tensile Test of PVDF Direction 1 at 23 °C

Figure 60  Tensile Test of PVDF Direction 2 at 23 °C
From the figures shown above, the anisotropic behavior of the material can be easily seen. During the tensile testing of PVDF along direction 1, shear banding is not seen through the deformation process, but in direction 2, shear bands occur once the stress level surpasses the yield stress. Complete results of the tensile testing for PVDF are provided in Appendix H. Tensile testing at –25 °C was not performed for PVDF, since the temperature could not be accurately controlled with the present equipment.

**Constant Load Creep Testing Results at 23 °C**

The test specimen geometry used for creep testing was also the test specimen used for the tensile testing of PVDF, therefore geometric effects can be neglected. The same batch of PVDF from Measurement Specialties is also used in the creep testing. The stress levels used for creep testing are 30%, 45% and 60% of the yield stress at 23 °C for all temperatures. The linear viscoelastic limit was found to be 60% by a former graduate student Frank Halloway. Verification of the linear viscoelastic limit was performed since the materials were not from the same batch of material and the specimen geometry was also different. The results of the creep testing are shown below in Figure 61. Complete results of the creep testing for PVDF at 23 °C is provided in Appendix H.
Figure 61  Constant Load Creep of PVDF at 23 °C
1- (0.30)\(\sigma_y\); 2- (0.45)\(\sigma_y\); 3- (0.60)\(\sigma_y\);
\(\sigma_y = 30.428\) MPa at 23 °C
Through creep testing, verification of the linear viscoelastic limit of at least 60% is shown. The normalization techniques are similar to that of Nylon 6/6 where the strain is divided by the stress to test for stress dependence. Complete results of the creep testing for PVDF are provided in Appendix H.

**Vibrocreep Testing Results at 23 °C**

The vibrocreep testing of PVDF is performed after the creep testing where one test fixture is used for the testing of creep and vibrocreep testing. The test matrix for vibrocreep testing is shown in Table 16.

<table>
<thead>
<tr>
<th>Mean Stress (% of $\sigma_v$)</th>
<th>Superimposed Cyclic Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Amplitude (% of $\sigma_v$)</td>
<td>10</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>5</td>
</tr>
<tr>
<td>Stress Amplitude (% of $\sigma_v$)</td>
<td>10</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>5</td>
</tr>
<tr>
<td>Stress Amplitude (% of $\sigma_v$)</td>
<td>10</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>5</td>
</tr>
</tbody>
</table>

The amplitudes and frequencies are chosen by the capabilities of the testing fixture. Testing at higher frequencies such as 100 Hz and 5% amplitude has been performed, but lower frequencies were chosen to correlate with Nylon 6/6.
The frequency effect can be seen from Figure 62. Complete results of the frequency effect for PVDF at 23 °C are provided in Appendix I.

Figure 62 Vibrocreep Response of PVDF at Different Frequencies at 23 °C
Vibrocreep: (0.45±0.10)σ_y; 1- 5Hz; 2- 10 Hz; 3- 20 Hz;
Constant Load Creep; 4- (0.45)σ_y, 5- (0.60)σ_y;
σ_y = 30.428 MPa at 23 °C
At 23 °C the amplitude of 10% is included to further verify the vibrocreep effect and allow for further testing within the linear viscoelastic limit of PVDF. Testing outside of the linear viscoelastic limit can also be seen from the test amplitudes chosen. As can be seen from Figure 63, the vibrocreep effect is increased with increasing amplitude. Complete results of the amplitude effect for PVDF at 23 °C are provided in Appendix J. The effect of mean stress on PVDF can be seen from Figure 64. The vibrocreep effect is seen to increase with an increasing mean stress. Complete results of the mean stress effect for PVDF at 23 °C are provided in Appendix K.
Figure 63 Vibrocreep Response of PVDF at Amplitudes at 23 °C
Vibrocreep: 1- (0.45±0.10)σ_y; 2- (0.45±0.20)σ_y; 3- (0.45±0.35)σ_y, at 10 Hz;
Constant Load Creep; 4- (0.45)σ_y, 5- (0.60)σ_y;
σ_y = 30.428 MPa at 23 °C
Figure 64  Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C
Vibrocreep: 1- (0.30±0.20)σ_y, 2- (0.45±0.20)σ_y, 3- (0.60±0.20)σ_y, at 5 Hz;
Constant Load Creep; 4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y;
σ_y = 30.428 MPa at 23 °C

Constant Load Creep Testing at Low Temperatures

The experiments were performed in the cold room provided by the Civil
Engineering Department at Montana State University. Creep testing at a lower
temperature proved to be challenging since the test fixture provided resistance to
axial motion. The crosshead, which contains the load cell and upper grip,
showed a frictional resistance in the cold room. The crosshead rolls on ball
bearing guides, but frost created a rough path of travel not seen at 23 °C. The
effect can be easily seen in Figure 65. The results of creep tests for PVDF at -25
°C are provided in Appendix H. The results shown form testing at -25 °C show a
“jump” in the strain due to a constant creep rate and a development of frost.

From the figures in appendices G-K, over time the material recovers the

Figure 65 Constant Load Creep of PVDF at -25 °C
1- (0.30)σy; 2- (0.45)σy; 3- (0.60)σy;
σy = 30.428 MPa at 23 °C
sudden jump in the load. The jump has been removed from the data by deleting the data points since this can be done by using the temporal elastic strain due to the friction in the test fixture. The linear viscoelastic limit should increase relative to 23 °C if the material is cooled even though creep testing at -25 °C was kept at the same stress levels relative performed at 23 °C. Testing relative to the yield stress at -25 °C was not performed since the yield stress was never determined. Through literature the value may be found, but the effects of the geometry, batch, sensitivity, etc. may play a role in the determination of the yield stress. The temperature effect on the creep of PVDF is shown in Figures 66, where a decrease in the temperature greatly decreases the creep rate in PVDF. The results of the temperature effects upon the creep testing for PVDF are provided in Appendix I.
Figure 66 Constant Load Creep of PVDF at Different Temperatures

1- $(0.30)\sigma_y$ at $-25$ °C; 2- $(0.30)\sigma_y$ at $23$ °C;
3- $(0.45)\sigma_y$ at $-25$ °C; 4- $(0.45)\sigma_y$ at $23$ °C;
5- $(0.60)\sigma_y$ at $-25$ °C; 6- $(0.60)\sigma_y$ at $23$ °C;

$\sigma_y = 30.428$ MPa at $23$ °C

Vibrocreep Testing at Low Temperatures

The vibrocreep testing of PVDF at $-25$ °C has been performed following the creep testing. The test matrix for vibrocreep testing is shown in Table 17. The effect of increasing frequency at $-25$ °C is shown in Figure 67. Complete results of the frequency effect for PVDF at $-25$ °C are provided in Appendix I. The amplitudes chosen at $-25$ °C were dependent on the test fixture. The effect of increasing amplitude at $-25$ °C is shown in Figure 68. Complete results of the amplitude effects for PVDF at $-25$ °C are provided in Appendix J. The effect of the mean stress at $-25$ °C is shown in Figure 69. Complete results of the
amplitude effects for PVDF at -25 °C are provided in Appendix K.I. The effect of temperature can be seen in Figure 70. The differences in temperature greatly effect the creep rate of the PVDF. The results of the temperature effects for PVDF are provided in Appendix L. In Figures 71-73, the effect of decreasing temperature is shown with increasing frequency, amplitude, and mean stress.

Table 17 Test Matrix for Vibrocreep Testing of PVDF at -25 °C

<table>
<thead>
<tr>
<th>Mean Stress (% of $\sigma_y$)</th>
<th>Superimposed Cyclic Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stress Amplitude (% of $\sigma_y$)</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Stress Amplitude (% of $\sigma_y$)</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>60</td>
<td>Stress Amplitude (% of $\sigma_y$)</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
</tr>
</tbody>
</table>
Figure 67 Vibrocreep Response of PVDF at Different Frequencies at -25 °C

Vibrocreep: (0.45±0.20)σ_y, 1- 5 Hz, 2- 10 Hz;
Constant Load Creep: 3- (0.45)σ_y, 4- (0.60)σ_y;
σ_y = 30.428 MPa at 23 °C
Figure 68 Vibrocreep Response of PVDF at Amplitudes at -25 °C
Vibrocreep: 1- (0.45±0.20)σ_y, 2- (0.45±0.40)σ_y, at 10 Hz;
Constant Load Creep: 3- (0.45)σ_y, 4- (0.60)σ_y;
σ_y = 30.428 MPa at 23 °C
Figure 69 Vibrocreep Response of PVDF at Different Mean Stresses at -25 °C

Vibrocreep: 1- (0.30±0.20)σ, 2- (0.45±0.20)σ, 3- (0.60±0.20)σ, at 10 Hz;
Constant Load Creep: 4- (0.30)σ, 5- (0.45)σ, 6- (0.60)σ;
σ = 30.428 MPa at 23 °C
Figure 70 Vibrocreep Response of PVDF at Different Temperatures

Vibrocreep: 1- (0.45±0.20)$\sigma_y$, 5 Hz at -25 °C; 2- (0.45±0.20)$\sigma_y$, 5 Hz at 23 °C;

Constant Load Creep: 3- (0.45)$\sigma_y$ at -25 °C, 4- (0.45)$\sigma_y$ at 23 °C;

$\sigma_y = 30.428$ MPa at 23 °C
Figure 71 Vibrocreep Response of PVDF at Different Frequencies and Temperatures

Vibrocreep: \((0.45 \pm 0.20)\sigma_y\),  
1- 5 Hz -25 °C, 2- 5 Hz 23 °C,  
3- 10 Hz -25 °C, 4- 10 Hz 23 °C;  
\(\sigma_y = 30.428\) MPa at 23 °C
Figure 72 Vibrocreep Response of PVDF at Different Amplitudes and Temperatures

Vibrocreep: 1- (0.45±0.20)σ_y at 10 Hz -25 °C, 2- (0.45±0.20)σ_y at 10 Hz 23 °C
3- (0.45±0.40)σ_y at 10 Hz -25 °C, 4- (0.45±0.40)σ_y at 10 Hz 23 °C;

σ_y = 30.428 MPa at 23 °C
Vibrocreep: 1- $(0.30 \pm 0.20)\sigma_y$ at 10 Hz -25 °C, 2- $(0.30 \pm 0.20)\sigma_y$ at 10 Hz 23 °C; 3- $(0.45 \pm 0.20)\sigma_y$ at 10 Hz -25 °C, 4- $(0.45 \pm 0.20)\sigma_y$ at 10 Hz 23 °C; 5- $(0.60 \pm 0.20)\sigma_y$ at 10 Hz -25 °C, 6- $(0.60 \pm 0.20)\sigma_y$ at 10 Hz 23 °C; 

$\sigma_y = 30.428$ MPa at 23 °C
The effect of cyclic loads on the time-dependent behavior of PVDF can be seen in the figures shown in Appendix H-L. From the figures, it is clear that linear viscoelastic theory cannot be used to characterize the vibrocreep phenomena in PVDF. The need for nonlinear material characterization of PVDF is evident from the increase in creep once an oscillatory load is combined with the constant load. The vibrocreep effect has been shown to increase with increasing frequency, amplitude, mean stress and temperature range below the linear viscoelastic limit.

Similarly to Nylon 6/6, the vibrocreep effects appear to be directly dependent upon the product of the amplitude and frequency of the cyclic load, Equation 17. As can be observed from Figure 74, vibrocreep effects are directly dependent on the product of the frequency and amplitude. The product of the two therefore can also be used to correlate other vibrocreep curves at the same mean stress as shown.
Figure 74 Vibrocreep Response of PVDF with $\omega^a = 100$ at 23 °C
Vibrocreep: 1- $(0.30\pm0.20)\sigma_y$ at 5 Hz; 2- $(0.30\pm0.10)\sigma_y$ at 10 Hz;
3- $(0.45\pm0.20)\sigma_y$ at 5 Hz; 4- $(0.45\pm0.10)\sigma_y$ at 10 Hz;
5- $(0.60\pm0.20)\sigma_y$ at 5 Hz; 6- $(0.60\pm0.10)\sigma_y$ at 10 Hz;
Constant Load Creep: 7- $(0.30)\sigma_y$, 8- $(0.45)\sigma_y$, 9- $(0.60)\sigma_y$;
$\sigma_y = 30.428$ MPa at 23 °C
The use of statistics to predict error and/or uncertainty is widely used. The difficulty is in the testing requirements to develop a population of samples that a handful can be taken from. In the aspect of material testing, developing a population of tensile specimens is not uncommon, but for creep and vibrocreep of polymer materials a high number of samples is usually unattainable since creep testing requires long periods of time Ref[5,50].

In order to assume a Gaussian statistical distribution, etc, 30 samples are needed to represent each curve. The use of small sample theory is therefore used, where the assumption of a statistical distribution is not done. The sample size used for vibrocreep is 3 and for tensile and creep tests is 5. The level of confidence that is typically used by researchers for their experimental statistical representation, is 20:1 (95%). The equation for statistical prediction of the data is provided in Equation 18, Ref[5], where \( \mu = \) mean population or mean strain at the particular time, \( t_{\nu/2,v} = \) t distribution value, \( \alpha = \) confidence interval, \( c = \) confidence, \( \nu = \) degrees of freedom, \( n = \) number of samples, and \( S_x = \) Standard Deviation.

\[
\mu - t_{\alpha} \frac{S_x}{\sqrt{n}} \leq \mu < \mu + t_{\alpha} \frac{S_x}{\sqrt{n}}
\]

\[
\alpha = 1 - c \quad \nu = n - 1
\]

Equation 18
The statistical representation of the curve fit equation is pursued in a different manner since a large number of data points are used to correlate to the curve fit equation. For all curves, the power law approximation to represent the data is used. The results of the curve fit parameters are provided in Appendix M. For the creep curves, data was reduced for from 600 data points to 45 data points per test. Since 5 tests make up a representative curve, then 225 samples generate the representative creep curve. The representative curve is therefore curve fitted to an approximate model, and the statistical analysis is performed with 225 n number of samples. For the vibrocreep curves, 135 n number of samples is used instead since the number of tests to for a representative curve is at least 3. The same odds of 20:1 (95%) are used to statistically predict the mean of the data. A Gaussian distribution is assumed for the curve fit relation since this is usually assumed for experimental data. The equation for statistical analysis of the curve fit equation is provided below in Equation 19, where \( t \) = particular time, \( a, b, \) and \( c \) = curve fit parameter, \( z_{\alpha/2} \) = z distribution value, \( \alpha \) = confidence interval, \( c \) = confidence, \( n \) = number of samples, \( \sigma_\Delta \) = deviation, and \( \Delta \varepsilon \) = mean strain at the particular time.

\[
\frac{(a \cdot t^b + c) - z_{\alpha/2} \cdot \frac{\sigma_\Delta \varepsilon}{\sqrt{2}}}{(a \cdot t^b + c) + z_{\alpha/2} \cdot \frac{\sigma_\Delta \varepsilon}{\sqrt{2}}} \\
\sum_{i=1}^{n} \left[ \Delta \varepsilon - (a \cdot t^b + c) \right]^2 \\
\sigma_{\Delta \varepsilon}^2 = \frac{1}{n-1} \sum_{i=1}^{n} (\Delta \varepsilon - (a \cdot t^b + c))^2 \\
\alpha = 1 - c
\]

Equation 19
The statistical analysis for Nylon 6/6 and PVDF is provided in Appendix M. The representation of the data is shown with 95% confidence intervals. The confidence interval allows the prediction of the mean of the data to be within the bound shown. Statistical analysis is only performed on one representative test. The small sample theory method assumes that the data at each point are independent and they are not, therefore large confidence intervals are a result of this assumption. For a small population, small sample theory is applicable. For Nylon 6/6, the statistical analysis of the tensile, creep, vibrocreep, and post cyclic test results are provided. The statistical analysis of the curve fit equation is also provided within Section I of Appendix M. For PVDF, the statistical analysis is shown for both testing temperatures, since the testing machine is cooled in the cold room or warmed at 23°C. The effects of the temperature on the testing machine provided difficulties such as friction, etc. that are not seen in the testing of Nylon 6/6, therefore more testing was required. The statistical analysis of PVDF is shown in the Section II of Appendix M. The tensile, creep and vibrocreep results are shown with 95% confidence interval at each temperature. The curve fit relations are also shown within the section with 95% confidence intervals.
The development of an experimental program and the quantification of the cyclic loading effects on time dependent polymers and polymer based composites have been accomplished. The experimental program involves different testing procedures for assessing the cyclic loading effects. As a result of the experimental program the vibrocreep effect has been investigated on the basis of a consistent parametric study.

The developed experimental program incorporates tensile, constant load creep, and vibrocreep testing. The experimental program involves evaluation of a polymer material by performing preliminary testing to initially verify that the cyclic loading effects can be observed according to the criteria outlined in the experimental program, Figures 31-33. The vibrocreep testing program has focused on the loading conditions below the linear viscoelastic limit of the material. Tensile testing of the polymer material has been used to determine the instantaneous elastic response or the tensile properties. Instantaneous material properties including yield stress and elastic modulus have been determined.

The second part of the experimental program involves creep testing under sustained constant loading conditions. The program has provided the information regarding the linear viscoelastic limit of the material and the respective creep compliances. These results have been used to investigate vibrocreep effects.
The third part of the experimental program, the cyclic loading effects or vibrocreep testing has been investigated using a parametric study. The study evaluates the change in loading parameters, thus assessing their effects upon the vibrocreep phenomenon. The parameters of interest are the frequency, amplitude, mean stress, and temperature. By varying each of the variables independently, the vibrocreep effect has been investigated. The testing required the use of non contact instrumentation and measurement. The use of computerized data acquisition has been developed and performed for all data measurements.

Cyclic loading effects have been examined for Nylon 6/6 through the development of the experimental program and the parametric study described above. Nylon 6/6 has been selected since this material has been used expensively in industry under cyclic loading conditions. Testing of Nylon 6/6 has involved tensile testing of the polymer at room temperature. The test specimen for all testing is the ASTM 638-96 Type II. The results provided a yield stress of 70e6 Pa and an elastic modulus of 1.41e9 Pa. Additional testing at 23 °C allowed the comparison of two different material batches to address nonhomogenenities in the material processing, Table 7. Tensile testing was also performed at the temperatures of 35, 41, 50, 59, and 68 °C, Figure 42. After tensile testing had been completed, the preliminary creep and vibrocreep testing is pursued using only one test specimen for each test. The vibrocreep effect was
evident in Nylon 6/6 by the vibrocreep criteria, therefore further testing was pursued.

By testing the material at multiple stress levels, a database of testing results has been developed and used subsequently for constitutive model development. The linear viscoelastic limit has been determined to be approximately 30% at room temperature of 23 °C, Figure 36. The vibrocreep testing was started at 23 °C with mean stresses and amplitudes selected below the linear viscoelastic limit, Table 8. The frequency selection is based upon previous literature where hysteresis heating has been seen, Ref[39]. At least three test specimens have been tested to obtain the vibrocreep results at a particular stress level, frequency and temperature. From the parametric study of the cyclic loading of Nylon 6/6 at 23 °C, the results demonstrate an increase in the vibrocreep effect with increasing frequency and amplitude, Figure 37-38. A decreasing vibrocreep effect is observed with increasing mean stress, Figure 39, and temperature below the linear viscoelastic limit.

At elevated temperatures similar effects have been observed. The results show that an increase of frequency and/or amplitude also increases the vibrocreep effect, Figures 45-46. The cyclic loading effects are also tested outside of the linear viscoelastic limit with the increase in temperature and stress levels relative to 23 °C. The effects of mean stress and temperature can be further seen from Figure 47 and Figures 48-51 respectively, where an increase in temperature decreased the vibrocreep effect below the linear viscoelastic limit.
The effect of mean stress and temperature can be explained as the effect of the creep properties in the material becoming more dominate than the damage development.

The evaluation of the vibrocreep effect is seen from the two different combinations. The first factor, a ratio of the mean stress to the amplitude of the cyclic load can be related to the R ratio typically considered in the studies of fatigue. The result of this correlation factor combines the amplitude and mean stress effects together as shown in Figure 56. From this result an increase in mean stress and amplitude correlates with approximately the same difference between the creep and vibrocreep creep compliance curves. A second comparison where the vibrocreep effects appear to be directly dependent upon the product of the amplitude and frequency of the cyclic load, observed from Figure 55.

The post tensile testing results for Nylon 6/6 show an increase in stiffness and strength of the material that is recoverable from the vibrocreep testing only at 23 °C, Figure 40. The constant load creep test specimens did not result in a significant amount of residual strength until the temperatures are increased, Figure 52-53. The increase in the strength and stiffness may be due to the creep effects which are reduced after creep and vibrocreep testing since the material has been creeping for approximately 12 hrs, therefore the contribution due to creep during the tensile test would be reduced showing an increase in stiffness and strength.
The testing of PVDF has been performed in the same manner as that of Nylon 6/6 with the tensile testing, constant load creep testing, and vibrocreep testing. PVDF was selected due to its wide application in vibration environments. Through testing of PVDF, a methodology of testing thin films has been developed. Test specimen is prepared according to ASTM 882-95a standard. The results of the testing of PVDF show the material to be highly anisotropic. The highest strength and stiffness are found to be along the 1 direction of the material, Table 96. Testing has been performed in the 1 direction. The constant load creep testing results provide the linear elastic limit of at least 60% of the yield stress at 23 °C, Figure 61. The creep testing has been performed at mean stresses of 30%, 45%, and 60%. The selection of the mean stresses and amplitudes has allowed testing within the linear and nonlinear viscoelastic regimes. An additional temperature closer to the glass transition temperature was also selected. Testing within the cold room proved to be challenging, since friction in the pulley and bearing application of the load was considerable.

An increasing vibrocreep effect has been observed with an increasing frequency, amplitude, or mean stress at both temperatures. For 23 °C the results are shown in Figures 62-64 and for -25 °C, Figures 67-69. From the comparison of the two temperatures an increase in the vibrocreep effect with an increasing temperatures is observed in Figures 70-73. The results show that the linear viscoelastic regime does not effect through evaluation of each parameter individually. The product of the frequency and amplitude was therefore used as
a parameter to quantify the test results. The results have shown the product to be quite interesting, Figure 74. The vibrocreep effects appear to be directly dependent upon the product of the amplitude and frequency as seen from the Nylon 6/6 experimental results.

The statistical analysis of the test data is performed on the test data and also on the curve fit of the data. The statistical analysis of the data is based on small sample theory, where the data does not follow a distribution. The results show to be very conservative and as a result the confidence intervals are enormous. The theory applied does not take into account for the interaction of the data on the time scale, but the simple one event in time. Therefore the analysis is not entirely complete since the population is small. Typically statistical analysis is not performed on creep tests since the amount of time required generally results in a small sample population. The statistical analysis of the curve fit equation is done considering the relationship of the data points in time and the differences between the specimens. The curve fit statistical analysis uses the new mean value determined from the fit equation and relates the new mean to the data specimens. The statistical analysis shows that the confidence intervals are much smaller demonstrating the goodness of fit between the data and the curve fit model.
CONCLUSION

Through the development of this study the goals of the project have been met. With the development of an experimental program for testing and characterization of vibrocreep effects, the understanding of the response of polymers under the conditions of superimposed constant and cyclic loads over a range of temperatures has been enhanced.

The results of the investigation indicate that the materials under consideration, i.e. Nylon 6/6 and a piezoelectric PVDF based composite, exhibit accelerated creep rates under the conditions of superimposed constant and cyclic loads. Creep acceleration due to cyclic loading effects has been observed in both materials even in the range of stresses well below their respective viscoelastic linearity limits. It is clear that these effects are essentially nonlinear, as the response of the materials to cyclic loading conditions does not represent a simple superposition of the responses to constant and fully reversed cyclic loads applied separately.

Experiments consistently demonstrate an increase of creep rates in both polymers as frequencies and amplitudes of vibration tended to increase. However, no consistent results have been obtained in regard to the effects of mean stresses on the cyclic creep behavior of the polymers.

It is important to note that the effects of cyclic loading conditions on the long-term response of polymers have been discussed in the literature primarily in
the context of creep-fatigue interaction Ref[29] and Ref[12]. As indicated in the latter publications, failure of polymers subjected to superimposed constant and cyclic loads depends on the relation between the mean stress and stress amplitude of the loading cycle. At higher mean stresses and low amplitudes, the cyclic response of polymers is dominated by creep processes, whereas as mean stresses tend to decrease, progressive damage evolution in polymers becomes the major factor leading to brittle failure. Hertzberg and Manson, Ref[29] have observed that, as a result of the interaction between different deformation and damage mechanisms depending on mean stresses, in some polymers, "surprisingly beneficial influence of mean stress on fatigue crack propagation behavior is not without precedent".

Based on the experimental study reported in this paper, it is clear that the behavior of polymers subjected to superimposed constant and cyclic loads involves nonlinear effects that depend on the interaction between creep and damage evolution processes. Apparently, the character of these processes in the presence of cyclic loads is different than that typically for constant load creep. Thus, the latter is characterized by continuously uniform microstructural changes in the material until the onset of tertiary creep, at which stage progressive damage localization tends to develop. In contrast, during cyclic creep, there is an extended damage initiation process followed by an advanced stage of crack propagation. The onset of these damage mechanisms in polymers depends on a
number of factors such as temperature, strain rate, hydrostatic pressure, and strain induced crystallization.

The effect of increasing mean stress within the linear viscoelastic regime shows decreasing vibrocreep effect for Nylon 6/6 with an increasing effect for PVDF, but above the linear viscoelastic limit an increasing mean stress decreases the vibrocreep effect for both materials. An increasing vibrocreep effect has been shown for both materials, Nylon 6/6 and PVDF, with an increasing frequency and amplitude. The result of increasing temperature on the cyclic loading tests has shown a decrease in the vibrocreep effect for Nylon 6/6 and an increasing effect in PVDF. This difference may be contributed to the glass transition temperature, where cyclic load testing was performed below the glass transition temperature for Nylon 6/6, and above the glass transition temperature for PVDF.

For both Nylon 6/6 and PVDF, the cyclic loading effect showed similar results in regard to the product of two parameters, frequency and amplitude of the cyclic load. Another combination that has been investigated was the combination of the mean stress to the amplitude of the cyclic load that can be further related to the R ratio typically considered in the studies of fatigue. In Nylon 6/6, an increase in mean stress and amplitude correlates with approximately the same difference between the creep and vibrocreep creep compliance curves.
FURTHER RESEARCH

Further research should be performed in four areas. The first area of needed research is the development of a damage model for the assessment of the craze formation on the surface of polymers. This can be verified through material testing and analyzed on microscopic level to develop a damage model in time. The value of such a model would be enormous. The prediction of fatigue life of viscoelastic materials may be an outcome of such a model. The second area of further research is the analysis of the piezoelectric properties of PVDF under vibrocreep conditions. Efforts to perform such tests have been tried, but the test material needs to be custom made in order to prevent arcing of the PVDF material. The data acquisition system, testing equipment described in this document can be used. The third area of further research is the product of frequency and amplitude that needs to be further investigated. The fourth and final area of further research is the development of statistically significant effects for the evaluation of the vibrocreep phenomena in polymers. With the limitations of instrumentation and the testing methods outlined, further research may or may not be feasible.
REFERENCES CITED


40. Letton, Alan, Farrow, Allan, and Strganac, Thomas, *Viscoelastic Characterization of Thin-Film Polymers exposed to Low Earth Orbit*


58. Sakurai, Shinichi, Mokuwa, Sastoshi, Morimoto, Masato, Shibayama, Mitsuhiro, and Nomura, Shunji, *Changes in Structure and Properties Due to Mechanical Fatigue for Polyurethanes Containing Poly(dimethyl siloxane)*, Polymer, 1994, Vol. 35, No. 3


71. Williams, J.D., Fracture Mechanics of Polymers, © 1984 Ellis Horwood Limited, Chichester
APPENDIX A

Tensile and Constant Load Creep Results for Nylon 6/6
Figure A.I.1 Tensile Testing of Nylon 6/6 at 23 °C
Figure A.I.2 Constant Load Creep of Nylon 6/6 at 23 °C

1- (0.10)\sigma_y; 2- (0.20)\sigma_y; 3- (0.30)\sigma_y; 4- (0.40)\sigma_y; 5- (0.50)\sigma_y;

\sigma_y = 70 \text{ MPa at 23 °C}
Figure A.1.3  Normalized Constant Load Creep of Nylon 6/6 at 23 °C

1- (0.10)σ_y; 2- (0.20)σ_y; 3- (0.30)σ_y; 4- (0.40)σ_y; 5- (0.50)σ_y;

σ_y = 70 MPa at 23 °C
Figure A.II.1 Tensile Testing of Nylon 6/6 at 35 °C
Figure A.II.2 Constant Load Creep of Nylon 6/6 at 35 °C

1- $(0.20)\sigma_y$; 2- $(0.30)\sigma_y$; 3- $(0.40)\sigma_y$; 4- $(0.50)\sigma_y$;

$\sigma_y = 55$ MPa at 35 °C
Figure A.II.3 Normalized Constant Load Creep of Nylon 6/6 at 35 °C

1- (0.20)σ_y; 2- (0.30)σ_y; 3- (0.40)σ_y; 4- (0.50)σ_y;

σ_y = 55 MPa at 35 °C
Figure A.III.1 Tensile Testing of Nylon 6/6 at 41 °C
Figure A.III.2 Constant Load Creep of Nylon 6/6 at 41 °C

1- (0.20)σ_y; 2- (0.30)σ_y; 3- (0.40)σ_y; 4- (0.50)σ_y;

σ_y = 45 MPa at 41 °C
Figure A.III.3 Normalized Constant Load Creep of Nylon 6/6 at 41 °C

1- (0.20)σ_y; 2- (0.30)σ_y; 3- (0.40)σ_y; 4- (0.50)σ_y;

σ_y = 45 MPa at 41 °C
Figure A.IV.1 Tensile Testing of Nylon 6/6 at 50 °C
Figure A.IV.2 Constant Load Creep of Nylon 6/6 at 50 °C

1- \((0.20)\sigma_y\); 2- \((0.30)\sigma_y\); 3- \((0.40)\sigma_y\); 4- \((0.50)\sigma_y\);

\(\sigma_y = 22 \text{ MPa at } 50 ^\circ \text{C}\)
Figure A.IV.3 Normalized Constant Load Creep of Nylon 6/6 at 50 °C

1- (0.20)\(\sigma_y\); 2- (0.30)\(\sigma_y\); 3- (0.40)\(\sigma_y\); 4- (0.50)\(\sigma_y\);

\(\sigma_y = 22 \text{ MPa at 50 °C} \)
Figure A.V.1 Tensile Testing of Nylon 6/6 at 59 °C
Figure A.V.2  Constant Load Creep of Nylon 6/6 at 59 °C

1- (0.20)σ_y; 2- (0.30)σ_y; 3- (0.40)σ_y; 4- (0.50)σ_y;

σ_y = 19 MPa at 59 °C
Figure A.V.3 Normalized Constant Load Creep of Nylon 6/6 at 59 °C

1- (0.20)σ_y; 2- (0.30)σ_y; 3- (0.40)σ_y; 4- (0.50)σ_y;

σ_y = 19 MPa at 59 °C
Figure A.VI.1 Tensile Testing of Nylon 6/6 at 68 °C
Figure A.VI.2  Constant Load Creep of Nylon 6/6 at 68 °C

1- (0.20)σ, 2- (0.30)σ, 3- (0.40)σ, 4- (0.50)σ;

σ = 10 MPa at 68 °C
Figure A.VI.3 Normalized Constant Load Creep of Nylon 6/6 at 68 °C

1- (0.20)σ_y; 2- (0.30)σ_y; 3- (0.40)σ_y; 4- (0.50)σ_y;

σ_y = 10 MPa at 68 °C
APPENDIX B

Frequency Effects from Vibrocreep Testing of Nylon 6/6
Figure B.I.1 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- (0.12±0.04)σ_y, 1 Hz; 2- (0.12±0.04)σ_y, 10 Hz; 3- (0.12±0.04)σ_y, 20 Hz;
4- (0.10)σ_y, 5- (0.16)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.1.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- $(0.12 \pm 0.04)\sigma_y$, 1 Hz; 2- $(0.12 \pm 0.04)\sigma_y$, 10 Hz; 3- $(0.12 \pm 0.04)\sigma_y$, 20 Hz;
4- $(0.10)\sigma_y$, 5- $(0.16)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure B.I.3: Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- (0.12±0.04)\(\sigma_y\), 1 Hz; 2- (0.12±0.04)\(\sigma_y\), 10 Hz; 3- (0.12±0.04)\(\sigma_y\), 20 Hz;
4- (0.16)\(\sigma_y\), Constant Load Creep; 5- Virgin Specimens;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure B.I.4 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- (0.12±0.075)σ_y, 1 Hz; 2- (0.12±0.075)σ_y, 10 Hz; 3- (0.12±0.075)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.1.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- (0.12±0.075)σ_y, 1 Hz; 2- (0.12±0.075)σ_y, 10 Hz; 3- (0.12±0.075)σ_y, 20 Hz;
4- (0.16)σ_y; 5- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.I.6  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- (0.12±0.075)σ_y, 1 Hz; 2- (0.12±0.075)σ_y, 10 Hz; 3- (0.12±0.075)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep; 6- Virgin Specimens;
σ_y = 70 MPa at 23 °C
Figure B.I.7 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- \((0.12\pm0.10)\sigma_y\), 1 Hz; 2- \((0.12\pm0.10)\sigma_y\), 10 Hz; 3- \((0.12\pm0.10)\sigma_y\), 20 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure B.I.8 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- $(0.12\pm0.10)\sigma_y$, 1 Hz; 2- $(0.12\pm0.10)\sigma_y$, 10 Hz; 3- $(0.12\pm0.10)\sigma_y$, 20 Hz;
4- $(0.16)\sigma_y$; 5- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure B.1.9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- (0.12±0.10)σ_y, 1 Hz; 2- (0.12±0.10)σ_y, 10 Hz; 3- (0.12±0.10)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep; 6- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure B.I.10 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- (0.16±0.04)σ_y, 1 Hz; 2- (0.16±0.04)σ_y, 10 Hz; 3- (0.16±0.04)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.I.11  Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- (0.16±0.04)$\sigma_y$, 1 Hz; 2- (0.16±0.04)$\sigma_y$, 10 Hz; 3- (0.16±0.04)$\sigma_y$, 20 Hz;
4- (0.16)$\sigma_y$, 5- (0.20)$\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure B.I.12  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.16 \pm 0.04)\sigma_y\), 1 Hz; 2- \((0.16 \pm 0.04)\sigma_y\), 10 Hz; 3- \((0.16 \pm 0.04)\sigma_y\), 20 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep; 6- Virgin Specimens;
\(\sigma_y = 70\) MPa at 23 °C
Figure B.1.13 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- $(0.16 \pm 0.075) \sigma_y$, 1 Hz; 2- $(0.16 \pm 0.075) \sigma_y$, 10 Hz; 3- $(0.16 \pm 0.075) \sigma_y$, 20 Hz;
4- $(0.16) \sigma_y$, 5- $(0.20) \sigma_y$, Constant Load Creep;
$\sigma_y = 70$ MPa at 23 °C
Figure B.I.14 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- $(0.16 \pm 0.075)\sigma_y$, 1 Hz; 2- $(0.16 \pm 0.075)\sigma_y$, 10 Hz; 3- $(0.16 \pm 0.075)\sigma_y$, 20 Hz;
4- $(0.16)\sigma_y$, 5- $(0.20)\sigma_y$, Constant Load Creep;
\[ \sigma_y = 70 \text{ MPa at 23 °C} \]
Figure B.I.15 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23°C

1- $(0.16 \pm 0.075)\sigma_y$, 1 Hz; 2- $(0.16 \pm 0.075)\sigma_y$, 10 Hz; 3- $(0.16 \pm 0.075)\sigma_y$, 20 Hz;
4- $(0.16)\sigma_y$, 5- $(0.20)\sigma_y$, Constant Load Creep; 6- Virgin Specimens;

$\sigma_y = 70$ MPa at 23°C
Figure B.I.16 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- \((0.16\pm0.10)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz; 3- \((0.16\pm0.10)\sigma_y\), 20 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), 6- \((0.30)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70 \text{ MPa at } 23 \degree \text{C}\)
Figure B.I.17 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- (0.16±0.10)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 10 Hz; 3- (0.16±0.10)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.I.18 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- (0.16±0.10)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 10 Hz; 3- (0.16±0.10)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep; 6- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure B.I.19 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- $(0.20 \pm 0.05) \sigma_y$, 1 Hz; 2- $(0.20 \pm 0.05) \sigma_y$, 10 Hz; 3- $(0.20 \pm 0.05) \sigma_y$, 20 Hz;
4- $(0.20) \sigma_y$, 5- $(0.30) \sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure B.I.20 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.05)σ_y, 10 Hz; 3- (0.20±0.05)σ_y, 20 Hz;
4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.I.21  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- $(0.20\pm0.05)\sigma_y$, 1 Hz; 2- $(0.20\pm0.05)\sigma_y$, 10 Hz; 3- $(0.20\pm0.05)\sigma_y$, 20 Hz;
4- $(0.20)\sigma_y$, Constant Load Creep; 5- Virgin Specimens;
$\sigma_y = 70$ MPa at 23 °C
Figure B.I.22 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- \((0.20\pm0.075)\sigma_y\), 1 Hz; 2- \((0.20\pm0.075)\sigma_y\), 10 Hz; 3- \((0.20\pm0.075)\sigma_y\), 20 Hz;
4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\), Constant Load Creep;

\(\sigma_y = 70\) MPa at 23 °C
Figure B.I.23 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- (0.20±0.075)σ_y, 1 Hz; 2- (0.20±0.075)σ_y, 10 Hz; 3- (0.20±0.075)σ_y, 20 Hz;
4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.I.24 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.20\pm0.075)\sigma_y\), 1 Hz; 2- \((0.20\pm0.075)\sigma_y\), 10 Hz; 3- \((0.20\pm0.075)\sigma_y\), 20 Hz;
4- \((0.20)\sigma_y\), Constant Load Creep; 5- Virgin Specimens;
\[\sigma_y = 70 \text{ MPa at } 23 \, ^\circ\text{C}\]
Figure B.1.25 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C

1- (0.20±0.10)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 10 Hz; 3- (0.20±0.10)σ_y, 20 Hz;
4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.1.26  Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 23 °C
1- (0.20±0.10)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 10 Hz; 3- (0.20±0.10)σ_y, 20 Hz;
4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.I.27  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- (0.20±0.10)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 10 Hz; 3- (0.20±0.10)σ_y, 20 Hz;
4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;
σ_y = 70 MPa at 23 °C
Figure B.II.1 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \((0.16 \pm 0.04)\sigma_y, 1 \text{ Hz}\); 2- \((0.16 \pm 0.04)\sigma_y, 10 \text{ Hz}\);
3- \((0.16)\sigma_y, 4- (0.20)\sigma_y, \text{ Constant Load Creep};\)
\[\sigma_y = 55 \text{ MPa at 35 °C}\]
Figure B.II.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- 
(0.16±0.04)σ_y, 1 Hz;
2- 
(0.16±0.04)σ_y, 10 Hz;
3- 
(0.16)σ_y, 4- 
(0.20)σ_y, Constant Load Creep;

σ_y = 55 MPa at 35 °C
Figure B.II.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- \((0.16\pm0.04)\sigma_y\), 1 Hz; 2- \((0.16\pm0.04)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep; 5- Virgin Specimens;
\[\sigma_y = 55\text{ MPa at 35 °C}\]
Figure B.II.4 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C
1- (0.16±0.10)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.30)σ_y, Constant Load Creep;
σ_y = 55 MPa at 35 °C
Figure B.II.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \((0.16\pm0.10)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz;
3- \(0.16\sigma_y\), 4- \(0.30\sigma_y\), Constant Load Creep;
\(\sigma_y = 55\, \text{MPa at 35 °C}\)
Figure B.II.6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- \((0.16 \pm 0.10)\sigma_y\), 1 Hz; 2- \((0.16 \pm 0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\[\sigma_y = 55 \text{ MPa at 35 °C}\]
Figure B.II.7 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.05)σ_y, 10 Hz;

3- (0.20)σ_y, 4- (0.30)σ_y, Constant Load Creep;

σ_y = 55 MPa at 35 °C
Figure B.II.8 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \((0.20 \pm 0.05)\sigma_y\), 1 Hz; 2- \((0.20 \pm 0.05)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), 4- \((0.30)\sigma_y\), Constant Load Creep;
\(\sigma_y = 55\) MPa at 35 °C
Figure B.II.9  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- (0.20±0.05)$\sigma_Y$, 1 Hz; 2- (0.20±0.05)$\sigma_Y$, 10 Hz;
3- (0.20)$\sigma$, Constant Load Creep; 4- Virgin Specimens;
$\sigma_Y = 55$ MPa at 35 °C
Figure B.II.10 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \( (0.20 \pm 0.10)\sigma_y \), 1 Hz; 2- \( (0.20 \pm 0.10)\sigma_y \), 10 Hz;
3- \( (0.20)\sigma_y \), 4- \( (0.30)\sigma_y \), Constant Load Creep;
\( \sigma_y = 55 \) MPa at 35 °C
Figure B.II.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35°C

1- $(0.20 \pm 0.10)\sigma_y$; 1 Hz; 2- $(0.20 \pm 0.10)\sigma_y$; 10 Hz;
3- $(0.20)\sigma_y$; 4- $(0.30)\sigma_y$, Constant Load Creep;

$\sigma_y = 55$ MPa at 35°C
Figure B.II.12 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- (0.20±0.10)\(\sigma_y\), 1 Hz; 2- (0.20±0.10)\(\sigma_y\), 10 Hz;
3- (0.20)\(\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\(\sigma_y = 55\) MPa at 35 °C
Figure B.II.13 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \((0.16 \pm 0.04)\sigma_y\), 1 Hz; 2- \((0.16 \pm 0.04)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at } 23 \degree C\]
Figure B.II.14 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \((0.16\pm0.04)\sigma_y, 1\text{ Hz}\); 2- \((0.16\pm0.04)\sigma_y, 10\text{ Hz}\);
3- \((0.16)\sigma_y\); 4- \((0.20)\sigma_y\), Constant Load Creep;
\[
\sigma_y = 70 \text{ MPa at } 23 \text{ °C}
\]
Figure B.II.15  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- (0.16±0.04)$\sigma_y$, 1 Hz; 2- (0.16±0.04)$\sigma_y$, 10 Hz;
3- (0.16)$\sigma_y$, 4- (0.20)$\sigma_y$, Constant Load Creep; 5- Virgin Specimens;

$\sigma_y = 70$ MPa at 23 °C
Figure B.II.16 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- (0.16±0.10)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.II.17 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C
1- \((0.16\pm0.10)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure B.II.18  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- (0.16±0.10)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, Constant Load Creep; 4- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure B.II.19 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \((0.20 \pm 0.05)\sigma_y\), 1 Hz; 2- \((0.20 \pm 0.05)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep;

\[\sigma_y = 70 \text{ MPa at } 23 \degree C\]
Figure B.II.20 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.05)σ_y, 10 Hz;
3- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.II.21 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- $(0.20 \pm 0.05)\sigma_y$, 1 Hz; 2- $(0.20 \pm 0.05)\sigma_y$, 10 Hz;
3- $(0.20)\sigma$, Constant Load Creep; 4- Virgin Specimens;

$\sigma_y = 70$ MPa at 23 °C
Figure B.II.22  Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C

1- \((0.20 \pm 0.10)\sigma_y\), 1 Hz; 2- \((0.20 \pm 0.10)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep;

\(\sigma_y = 70\) MPa at 23 °C
Figure B.II.23 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 35 °C
1- $\sigma$$\times$1 Hz; 2- $\sigma$$\times$10 Hz;
3- $\sigma$ Constant Load Creep;
$\sigma$ = 70 MPa at 23 °C
Figure B.II.24  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- \((0.20 \pm 0.10)\sigma_y\), 1 Hz; 2- \((0.20 \pm 0.10)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\(\sigma_y = 70\) MPa at 23 °C
Figure B.III.1 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- \((0.16 \pm 0.10)\sigma_y\), 1 Hz; 2- \((0.16 \pm 0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.30)\sigma_y\), Constant Load Creep;
\(\sigma_y = 45\) MPa at 41 °C
Figure B.III.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- \((0.16\pm0.10)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.30)\sigma_y\), Constant Load Creep;
\(\sigma_y = 45 \text{ MPa at } 41 \degree \text{C}\)
Figure B.III.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C
1- (0.16±0.10)σy, 1 Hz; 2- (0.16±0.10)σy, 10 Hz;
3- (0.16)σy, Constant Load Creep; 4- Virgin Specimens;
σy = 45 MPa at 41 °C
Figure B.III.4 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.20±0.05)σy, 1 Hz; 2- (0.20±0.05)σy, 10 Hz;
3- (0.20)σy, 4- (0.30)σy, Constant Load Creep;
σy = 45 MPa at 41 °C
Figure B.III.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- \((0.20\pm0.05)\sigma_y\), 1 Hz; 2- \((0.20\pm0.05)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), 4- \((0.30)\sigma_y\), Constant Load Creep;
\[\sigma_y = 45 \text{ MPa at } 41 ^\circ \text{C}\]
Figure B.III.6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C
1- \((0.20\pm0.05)\sigma_y\), 1 Hz; 2- \((0.20\pm0.05)\sigma_y\), 10 Hz;
3- \((0.20)\sigma\), Constant Load Creep; 4- Virgin Specimens;
\[\sigma_y = 45 \text{ MPa at } 41 \degree \text{C}\]
Figure B.III.7 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C
1- (0.20±0.10)\(\sigma_y\), 1 Hz; 2- (0.20±0.10)\(\sigma_y\), 10 Hz;
3- (0.20)\(\sigma_y\), 4- (0.30)\(\sigma_y\), Constant Load Creep;
\(\sigma_y\) = 45 MPa at 41 °C
Figure B.III.8  Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.20±0.10)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.20)σ_y, 4- (0.30)σ_y, Constant Load Creep;

σ_y = 45 MPa at 41 °C
Figure B.III.9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- \((0.20\pm0.10)\sigma_y\), 1 Hz; 2- \((0.20\pm0.10)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\[
\sigma_y = 45 \text{ MPa at } 41 \degree C
\]
Figure B.III.10 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.16±0.04)σ_y, 1 Hz; 2- (0.16±0.04)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.III.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.16±0.04)σ_y, 1 Hz; 2- (0.16±0.04)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.III.12 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- $(0.16 \pm 0.04) \sigma_y$, 1 Hz; 2- $(0.16 \pm 0.04) \sigma_y$, 10 Hz;
3- $(0.16) \sigma_y$, 4- $(0.20) \sigma_y$, Constant Load Creep; 5- Virgin Specimens;

$\sigma_y = 70$ MPa at 23 °C
Figure B.III.13 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.16±0.10)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.III.14 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C
1- (0.16±0.10)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure B.III.15  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- \((0.16\pm0.10)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep; 5- Virgin Specimens;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure B.III.16 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.20 ± 0.05)σy, 1 Hz; 2- (0.20 ± 0.05)σy, 10 Hz;
3- (0.20)σy, Constant Load Creep;
σy = 70 MPa at 23 °C
Figure B.III.17 Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C
1- $(0.20 \pm 0.05)\sigma_y$, 1 Hz; 2- $(0.20 \pm 0.05)\sigma_y$, 10 Hz;
3- $(0.20)\sigma_y$, Constant Load Creep;
$\sigma_y = 70$ MPa at 23 °C
Figure B.III.18  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.05)σ_y, 10 Hz;
3- (0.20)σ, Constant Load Creep; 4- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure B.III.19 Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.20±0.10)\(\sigma_y\), 1 Hz; 2- (0.20±0.10)\(\sigma_y\), 10 Hz;
3- (0.20)\(\sigma_y\), Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure B.III.20  Normalized Vibrocreep Response of Nylon 6/6 at Different Frequencies at 41 °C

1- (0.20±0.10)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure B.III.21  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- (0.20±0.10)\(\sigma_y\), 1 Hz; 2- (0.20±0.10)\(\sigma_y\), 10 Hz;
3- (0.20)\(\sigma_y\), Constant Load Creep; 4- Virgin Specimens;

\(\sigma_y = 70\) MPa at 23 °C
APPENDIX C

Amplitude Effects from Vibrocreep Testing of Nylon 6/6
Figure C.I.1  Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- (0.12±0.04)σ_y, 1 Hz; 2- (0.12±0.075)σ_y, 1 Hz; 3- (0.12±0.10)σ_y, 1 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure C.I.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- (0.12±0.04)σ_y, 1 Hz; 2- (0.12±0.075)σ_y, 1 Hz; 3- (0.12±0.10)σ_y, 1 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure C.I.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- (0.12±0.04)\(\sigma_y\), 1 Hz; 2- (0.12±0.075)\(\sigma_y\), 1 Hz; 3- (0.12±0.10)\(\sigma_y\), 1 Hz;
4- (0.16)\(\sigma_y\), 5- (0.20)\(\sigma_y\), Constant Load Creep; 6- Virgin Specimens;
\(\sigma_y = 70\) MPa at 23 °C
Figure C.I.4 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- (0.12±0.04)σ_y, 10 Hz; 2- (0.12±0.075)σ_y, 10 Hz; 3- (0.12±0.10)σ_y, 10 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure C.I.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- $(0.12 \pm 0.04)\sigma_y$, 10 Hz; 2- $(0.12 \pm 0.075)\sigma_y$, 10 Hz; 3- $(0.12 \pm 0.10)\sigma_y$, 10 Hz;
4- $(0.16)\sigma_y$, 5- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure C.I.6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23°C

1- $(0.12 \pm 0.04) \sigma_y$, 10 Hz; 2- $(0.12 \pm 0.075) \sigma_y$, 10 Hz; 3- $(0.12 \pm 0.10) \sigma_y$, 10 Hz;
4- $(0.16) \sigma_y$, 5- $(0.20) \sigma_y$, Constant Load Creep; 6- Virgin Specimens;

$\sigma_y = 70$ MPa at 23°C
Figure C.1.7 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- $(0.12 \pm 0.04)\sigma_y$, 20 Hz; 2- $(0.12 \pm 0.075)\sigma_y$, 20 Hz; 3- $(0.12 \pm 0.10)\sigma_y$, 20 Hz;
4- $(0.16)\sigma_y$, 5- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure C.I.8  Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- (0.12±0.04)σ_y, 20 Hz; 2- (0.12±0.075)σ_y, 20 Hz; 3- (0.12±0.10)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure C.I.9  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- (0.12±0.04)σ_y, 20 Hz; 2- (0.12±0.075)σ_y, 20 Hz; 3- (0.12±0.10)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep; 6- Virgin Specimens;
σ_y = 70 MPa at 23 °C
Figure C.I.10  Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- \((0.16\pm 0.04)\sigma_y\), 1 Hz; 2- \((0.16\pm 0.075)\sigma_y\), 1 Hz; 3- \((0.16\pm 0.10)\sigma_y\), 1 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), 6- \((0.30)\sigma_y\), Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure C.I.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- (0.16±0.04)σ_y, 1 Hz; 2- (0.16±0.075)σ_y, 1 Hz; 3- (0.16±0.10)σ_y, 1 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure C.I.12 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.16\pm0.04)\sigma_y\), 1 Hz; 2- \((0.16\pm0.075)\sigma_y\), 1 Hz; 3- \((0.16\pm0.10)\sigma_y\), 1 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep; 6- Virgin Specimens;
\[
\sigma_y = 70 \text{ MPa at } 23 ^\circ C
\]
Figure C.I.13 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- (0.16±0.04)σ_y, 10 Hz; 2- (0.16±0.075)σ_y, 10 Hz; 3- (0.16±0.10)σ_y, 10 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure C.I.14 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- \((0.16\pm0.04)\sigma_y\), 10 Hz; 2- \((0.16\pm0.075)\sigma_y\), 10 Hz; 3- \((0.16\pm0.10)\sigma_y\), 10 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), 6- \((0.30)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure C.I.15 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.16 \pm 0.04)\sigma_y\), 10 Hz; 2- \((0.16 \pm 0.075)\sigma_y\), 10 Hz; 3- \((0.16 \pm 0.10)\sigma_y\), 10 Hz;

4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep; 6- Virgin Specimens;

\sigma_y = 70 \text{ MPa at } 23 ^\circ \text{C}
Figure C.I.16 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- (0.16±0.04)σ_y, 20 Hz; 2- (0.16±0.075)σ_y, 20 Hz; 3- (0.16±0.10)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure C.I.17 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- \((0.16 \pm 0.04)\sigma_y\), 20 Hz; 2- \((0.16 \pm 0.075)\sigma_y\), 20 Hz; 3- \((0.16 \pm 0.10)\sigma_y\), 20 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), 6- \((0.30)\sigma_y\), Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure C.I.18 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- (0.16±0.04)$\sigma_y$, 20 Hz; 2- (0.16±0.075)$\sigma_y$, 20 Hz; 3- (0.16±0.10)$\sigma_y$, 20 Hz;
4- (0.16)$\sigma_y$, 5- (0.20)$\sigma_y$, Constant Load Creep; 6- Virgin Specimens;
$\sigma_y = 70$ MPa at 23 °C
Figure C.I.19 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- (0.20±0.05)$\sigma_y$, 1 Hz; 2- (0.20±0.075)$\sigma_y$, 1 Hz; 3- (0.20±0.10)$\sigma_y$, 1 Hz;
4- (0.20)$\sigma_y$, 5- (0.30)$\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure C.I.20  Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.075)σ_y, 1 Hz; 3- (0.20±0.10)σ_y, 1 Hz;
4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure C.I.21 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.075)σ_y, 1 Hz; 3- (0.20±0.10)σ_y, 1 Hz;
4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure C.I.22 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- \((0.20 \pm 0.05)\sigma_y\), 10 Hz; 2- \((0.20 \pm 0.075)\sigma_y\), 10 Hz; 3- \((0.20 \pm 0.10)\sigma_y\), 10 Hz;
4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\), Constant Load Creep;

\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure C.I.23 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- (0.20±0.05)σ_y, 10 Hz; 2- (0.20±0.075)σ_y, 10 Hz; 3- (0.20±0.10)σ_y, 10 Hz;
4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure C.I.24: Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.20 \pm 0.05)\sigma_y\), 10 Hz; 2- \((0.20 \pm 0.075)\sigma_y\), 10 Hz; 3- \((0.20 \pm 0.10)\sigma_y\), 10 Hz;
4- \((0.20)\sigma_y\), Constant Load Creep; 5- Virgin Specimens;

\[\sigma_y = 70\, \text{MPa at 23 °C}\]
Figure C.I.25 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C

1- \((0.20 \pm 0.05)\sigma_y\), 20 Hz; 2- \((0.20 \pm 0.075)\sigma_y\), 20 Hz; 3- \((0.20 \pm 0.10)\sigma_y\), 20 Hz;
4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\), Constant Load Creep;
\sigma_y = 70 \text{ MPa at } 23 \degree \text{C}
Figure C.I.26 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 23 °C
1- (0.20±0.05)σ_y, 20 Hz; 2- (0.20±0.075)σ_y, 20 Hz; 3- (0.20±0.10)σ_y, 20 Hz;
4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure C.I.27  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- (0.20±0.05)σ_y, 20 Hz; 2- (0.20±0.075)σ_y, 20 Hz; 3- (0.20±0.10)σ_y, 20 Hz;
4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure C.II.1 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C
1- \((0.16\pm0.04)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 1 Hz;
3- \((0.16)\sigma_y\), 4- \((0.30)\sigma_y\), Constant Load Creep;
\(\sigma_y = 55\) MPa at 35 °C
Figure C.II.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- $(0.16 \pm 0.04)\sigma_Y$, 1 Hz; 2- $(0.16 \pm 0.10)\sigma_Y$, 1 Hz;
3- $(0.16)\sigma_Y$, 4- $(0.30)\sigma_Y$, Constant Load Creep;

$\sigma_Y = 55$ MPa at 35 °C
Figure C.II.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- \((0.16 \pm 0.04)\sigma_y\), 1 Hz; 2- \((0.16 \pm 0.10)\sigma_y\), 1 Hz;
3- \((0.16)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;

\(\sigma_y = 55\) MPa at 35 °C
Figure C.II.4 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- (0.16±0.04)\(\sigma_y\), 10 Hz; 2- (0.16±0.10)\(\sigma_y\), 10 Hz;
3- (0.16)\(\sigma_y\), 4- (0.30)\(\sigma_y\), Constant Load Creep;
\(\sigma_y = 55\) MPa at 35 °C
Figure C.II.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- $(0.16 \pm 0.04)\sigma_y$, 10 Hz; 2- $(0.16 \pm 0.10)\sigma_y$, 10 Hz;
3- $(0.16)\sigma_y$, 4- $(0.30)\sigma_y$, Constant Load Creep;

$\sigma_y = 55$ MPa at 35 °C
Figure C.II.6  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- (0.16±0.04)$\sigma_y$, 10 Hz; 2- (0.16±0.10)$\sigma_y$, 10 Hz;
3- (0.16)$\sigma_y$, Constant Load Creep; 4- Virgin Specimens;
$\sigma_y = 55$ MPa at 35 °C
Figure C.II.7 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C
1- (0.20 ± 0.05)σ_y, 1 Hz; 2- (0.20 ± 0.10)σ_y, 1 Hz;
3- (0.20)σ_y, 4- (0.30)σ_y, Constant Load Creep;
σ_y = 55 MPa at 35 °C
Figure C.II.8 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- (0.20±0.05)$\sigma_y$, 1 Hz; 2- (0.20±0.10)$\sigma_y$, 1 Hz;
3- (0.20)$\sigma_y$, 4- (0.30)$\sigma_y$, Constant Load Creep;
$\sigma_y = 55$ MPa at 35 °C
Figure C.II.9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- \((0.20 \pm 0.05)\sigma_y\), 1 Hz; 2- \((0.20 \pm 0.10)\sigma_y\), 1 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\(\sigma_y = 55\) MPa at 35 °C
Figure C.II.10 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- $(0.20 \pm 0.05)\sigma_y$, 10 Hz; 2- $(0.20 \pm 0.10)\sigma_y$, 10 Hz;
3- $(0.20)\sigma_y$, 4- $(0.30)\sigma_y$, Constant Load Creep;

$\sigma_y = 55$ MPa at 35 °C
Figure C.II.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- (0.20±0.05)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.20)σ_y, 4- (0.30)σ_y, Constant Load Creep;

σ_y = 55 MPa at 35 °C
Figure C.II.12 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- $(0.20 \pm 0.05)\sigma_y$, 10 Hz; 2- $(0.20 \pm 0.10)\sigma_y$, 10 Hz;
3- $(0.20)\sigma_y$, Constant Load Creep; 4- Virgin Specimens;
$\sigma_y = 55$ MPa at 35 °C
Figure C.II.13 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- \((0.16\pm0.04)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 1 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at } 23 \text{ °C}\]
Figure C.II.14 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- $(0.16 \pm 0.04) \sigma_y$, 1 Hz; 2- $(0.16 \pm 0.10) \sigma_y$, 1 Hz;
3- $(0.16) \sigma_y$, 4- $(0.20) \sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure C.II.15 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- \((0.16\pm0.04)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 1 Hz; 3- \((0.16)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\[
\sigma_y = 70 \text{ MPa at } 23 \degree C
\]
Figure C.II.16  Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- (0.16±0.04)σ_y, 10 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure C.II.17 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- \((0.16\pm0.04)\sigma_y\), 10 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure C.II.18  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- \((0.16\pm0.04)\sigma_y\), 10 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;

\[\sigma_y = 70 \text{ MPa at } 23 \degree C\]
Figure C.II.19 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C
1- $(0.20 \pm 0.05)\sigma_y$, 1 Hz; 2- $(0.20 \pm 0.10)\sigma_y$, 1 Hz;
3- $(0.20)\sigma_y$, Constant Load Creep;
$\sigma_y = 70$ MPa at 23 °C
Figure C.II.20 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- $(0.20 \pm 0.05)\sigma_y$, 1 Hz;
2- $(0.20 \pm 0.10)\sigma_y$, 1 Hz;
3- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure C.II.21  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 1 Hz;
3- (0.20)σ_y, Constant Load Creep; 4- Virgin Specimens;
σ_y = 70 MPa at 23 °C
Figure C.II.22 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C

1- (0.20±0.05)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure C.II.23 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 35 °C
1- \((0.20\pm0.05)\sigma_y\), 10 Hz; 2- \((0.20\pm0.10)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure C.II.24 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- (0.20±0.05)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.20)σ_y, Constant Load Creep; 4- Virgin Specimens;
σ_y = 70 MPa at 23 °C
Figure C.III.1 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- \((0.20 \pm 0.05)\sigma_y, 1\ Hz\); 2- \((0.20 \pm 0.10)\sigma_y, 1\ Hz\);
3- \((0.20)\sigma_y, 4- (0.30)\sigma_y, \text{Constant Load Creep};
\sigma_y = 45\ MPa\ at\ 41\ °C\)
Figure C.III.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 1 Hz;
3- (0.20)σ_y, 4- (0.30)σ_y, Constant Load Creep;

σ_y = 45 MPa at 41 °C
Figure C.III.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- (0.20±0.05)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 1 Hz;
3- (0.20)σ_y, Constant Load Creep; 4- Virgin Specimens;

σ_y = 45 MPa at 41 °C
Figure C.III.4 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- (0.20±0.05)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.20)σ_y, 4- (0.30)σ_y, Constant Load Creep;

σ_y = 45 MPa at 41 °C
Figure C.III.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- (0.20±0.05)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.20)σ_y, 4- (0.30)σ_y, Constant Load Creep;

σ_y = 45 MPa at 41 °C
Figure C.III.6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- \((0.20 \pm 0.05)\sigma_y\), 10 Hz; 2- \((0.20 \pm 0.10)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;

\(\sigma_y = 45\) MPa at 41 °C
Figure C.III.7 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- \((0.16\pm0.04)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 1 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70 \text{ MPa at 23 °C}\)
Figure C.III.8 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- (0.16±0.04)σ_y, 1 Hz; 2- (0.16±0.10)σ_y, 1 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure C.III.9  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C
1- (0.16±0.04)$\sigma_y$, 1 Hz; 2- (0.16±0.10)$\sigma_y$, 1 Hz;
3- (0.16)$\sigma_y$, 4- (0.20)$\sigma_y$, Constant Load Creep; 5- Virgin Specimens;
$\sigma_y = 70$ MPa at 23 °C
Figure C.III.10 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- (0.16±0.04)σ_y, 10 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure C.III.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- \((0.16\pm0.04)\sigma_y\), 10 Hz; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70 \text{ MPa at } 23 ^\circ \text{C}\)
Figure C.III.12  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- (0.16±0.04)σ_y, 10 Hz; 2- (0.16±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure C.III.13 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C
1- \((0.20\pm0.05)\sigma_y\), 1 Hz; 2- \((0.20\pm0.10)\sigma_y\), 1 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure C.III.14 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- \((0.20\pm0.05)\sigma_y\), 1 Hz;
2- \((0.20\pm0.10)\sigma_y\), 1 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep;

\(\sigma_y = 70\text{ MPa at } 23\text{ °C}\)
Figure C.III.15 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- \((0.20\pm0.05)\sigma_y\), 1 Hz; 2- \((0.20\pm0.10)\sigma_y\), 1 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\[
\sigma_y = 70 \text{ MPa at } 23^\circ\text{C}
\]
Figure C.III.16 Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C

1- \((0.20\pm0.05)\sigma_y\), 10 Hz; 2- \((0.20\pm0.10)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep;

\(\sigma_y = 70\) MPa at 23 °C
Figure C.III.17 Normalized Vibrocreep Response of Nylon 6/6 at Different Amplitudes at 41 °C
1- \((0.20 \pm 0.05)\sigma_y\), 10 Hz; 2- \((0.20 \pm 0.10)\sigma_y\), 10 Hz;
3- \((0.20)\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure C.III.18  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- (0.20±0.05)\(\sigma_y\), 10 Hz; 2- (0.20±0.10)\(\sigma_y\), 10 Hz;
3- (0.20)\(\sigma_y\), Constant Load Creep; 4- Virgin Specimens;
\(\sigma_y = 70\) MPa at 23 °C
APPENDIX D

The Influence of the Parameter \( \mu \) from Vibrocreep Testing of Nylon 6/6
Figure D.I.1 Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 23 °C

1- $(0.16\pm0.04)\sigma_y$, 1 Hz; 2- $(0.20\pm0.05)\sigma_y$, 1 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$ Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.I.2 Normalized Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 23 °C

1- $(0.16\pm0.04)\sigma_y$, 1 Hz; 2- $(0.20\pm0.05)\sigma_y$, 1 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$ Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.I.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- $(0.16 \pm 0.04)\sigma_y$, 1 Hz; 2- $(0.20 \pm 0.05)\sigma_y$, 1 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$ Constant Load Creep; 5- Virgin Specimens;

$\sigma_y = 70$ MPa at 23 °C
Figure D.I.4 Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 23 °C

1- $0.16\pm0.04\sigma_y$, 10 Hz; 2- $(0.20\pm0.05)\sigma_y$, 10 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$ Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.I.5 Normalized Vibrocreep Response of Nylon 6/6 with μ=4 at 23 °C.

1- (0.16±0.04)σy, 10 Hz; 2- (0.20±0.05)σy, 10 Hz;
3- (0.16)σy, 4- (0.20)σy Constant Load Creep;
σy = 70 MPa at 23 °C
Figure D.I.6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- (0.16±0.04)σ_y, 10 Hz; 2- (0.20±0.05)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y Constant Load Creep; 5- Virgin Specimens;
σ_y = 70 MPa at 23 °C
Figure D.I.7 Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 23 °C
1- $(0.16\pm0.04)\sigma_y$, 20 Hz; 2- $(0.20\pm0.05)\sigma_y$, 20 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$ Constant Load Creep;
$\sigma_y = 70$ MPa at 23 °C
Figure D.1.8 Normalized Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 23 °C

1- $(0.16 \pm 0.04) \sigma_y$, 20 Hz; 2- $(0.20 \pm 0.05) \sigma_y$, 20 Hz;
3- $(0.16) \sigma_y$, 4- $(0.20) \sigma_y$ Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.I.9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- $(0.16 \pm 0.04) \sigma_y$, 20 Hz; 2- $(0.20 \pm 0.05) \sigma_y$, 20 Hz;
3- $(0.16) \sigma_y$, 4- $(0.20) \sigma_y$ Constant Load Creep; 5- Virgin Specimens;
$\sigma_y = 70$ MPa at 23 °C
Figure D.II.1 Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 35 °C
1- $(0.16\pm0.04)\sigma_y$, 1 Hz; 2- $(0.20\pm0.05)\sigma_y$, 1 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, Constant Load Creep;
$\sigma_y = 55 \text{ MPa at 35 °C}$
Figure D.II.2 Normalized Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 35 °C
1- $(0.16\pm0.04)\sigma_y$, 1 Hz; 2- $(0.20\pm0.05)\sigma_y$, 1 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, Constant Load Creep;
$\sigma_y = 55$ MPa at 35 °C
Figure D.II.3  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- \((0.16\pm0.04)\sigma_y\), 1 Hz; 2- \((0.20\pm0.05)\sigma_y\), 1 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep; 5- Virgin Specimens;
\[\sigma_y = 55\ \text{MPa at 35 °C}\]
Figure D.11.4 Vibrocreep Response of Nylon 6/6 with \( \mu = 4 \) at 35 °C

1- \((0.16 \pm 0.04)\sigma_y, 10 \text{ Hz}\); 2- \((0.20 \pm 0.05)\sigma_y, 10 \text{ Hz}\);
3- \(0.16)\sigma_y, 4- (0.20)\sigma_y, \text{Constant Load Creep};
\(\sigma_y = 55 \text{ MPa at 35 °C}\)
Figure D.II.5. Normalized Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 35 °C

1- (0.16±0.04)$\sigma_y$, 10 Hz; 2- (0.20±0.05)$\sigma_y$, 10 Hz;
3- (0.16)$\sigma_y$, 4- (0.20)$\sigma_y$, Constant Load Creep;

$\sigma_y = 55$ MPa at 35 °C
Figure D.II.6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- \((0.16\pm0.04)\sigma_y\), 10 Hz; 2- \((0.20\pm0.05)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep; 5- Virgin Specimens;

\(\sigma_y = 55\) MPa at 35 °C
Figure D.II.7 Vibrocreep Response of Nylon 6/6 with $\mu = 4$ at 35 °C

1- $(0.16 \pm 0.04) \sigma_y$, 1 Hz; 2- $(0.20 \pm 0.05) \sigma_y$, 1 Hz;
3- $(0.16) \sigma_y$; 4- $(0.20) \sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.II.8  Normalized Vibrocreep Response of Nylon 6/6 with μ=4 at 35 °C
1- (0.16±0.04)σ_y, 1 Hz; 2- (0.20±0.05)σ_y, 1 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure D.II.9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading \( \mu=4 \) at 35 °C

1- \((0.16 \pm 0.04)\sigma_y, 1 \text{ Hz}\);
2- \((0.20 \pm 0.05)\sigma_y, 1 \text{ Hz}\);
3- \((0.16)\sigma_y, 4- (0.20)\sigma_y, \) Constant Load Creep;
5- Virgin Specimens;

\( \sigma_y = 70 \text{ MPa at 23 °C} \)
Figure D.II.10 Vibrocreep Response of Nylon 6/6 with \( \mu = 4 \) at 35 \( ^\circ \)C

1- \((0.16 \pm 0.04)\sigma_y\), 10 Hz; 2- \((0.20 \pm 0.05)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\[ \sigma_y = 70 \text{ MPa at 23} \, ^\circ \text{C} \]
Figure D.II.11  Normalized Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 35 °C

1- $(0.16 \pm 0.04)\sigma_y$, 10 Hz;
2- $(0.20 \pm 0.05)\sigma_y$, 10 Hz;
3- $(0.16)\sigma_y$,
4- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.II.12  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading μ=4 at 35 °C

1- (0.16±0.04)σ_y, 10 Hz; 2- (0.20±0.05)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure D.III.1 Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 41 °C

1- $(0.16\pm0.04)\sigma_y$, 1 Hz; 2- $(0.20\pm0.05)\sigma_y$, 1 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.III.2 Normalized Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 41 °C

1- $(0.16\pm0.04)\sigma_y$, 1 Hz; 2- $(0.20\pm0.05)\sigma_y$, 1 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.III.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant at 41 °C

1- (0.16±0.04)σ_y, 1 Hz; 2- (0.20±0.05)σ_y, 1 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure D.III.4 Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 41 °C

1- $(0.16 \pm 0.04) \sigma_y$, 10 Hz; 2- $(0.20 \pm 0.05) \sigma_y$, 10 Hz;
3- $(0.16) \sigma_y$, 4- $(0.20) \sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure D.III.5 Normalized Vibrocreep Response of Nylon 6/6 with $\mu=4$ at 41 °C
1- $(0.16\pm0.04)\sigma_y$, 10 Hz; 2- $(0.20\pm0.05)\sigma_y$, 10 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, Constant Load Creep;
$\sigma_y = 70$ MPa at 23 °C
Figure D.III.6  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- $(0.16\pm0.04)\sigma_y$, 10 Hz; 2- $(0.20\pm0.05)\sigma_y$, 10 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, Constant Load Creep; 5- Virgin Specimens;

$\sigma_y = 70$ MPa at 23 °C
APPENDIX E

Mean Stress Effects from Vibrocreep Testing of Nylon 6/6
Figure E.1.1 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C

1- \((0.12 \pm 0.075)\sigma_y\), 1 Hz; 2- \((0.16 \pm 0.075)\sigma_y\), 1 Hz; 3- \((0.20 \pm 0.075)\sigma_y\), 1 Hz;

4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), 6- \((0.30)\sigma_y\) Constant Load Creep;

\[\sigma_y = 70 \text{ MPa at } 23 \degree \text{C} \]
Figure E.I.2  Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C

1- (0.12±0.075)σ_y, 1 Hz; 2- (0.16±0.075)σ_y, 1 Hz; 3- (0.20±0.075)σ_y, 1 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure E.I.3 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.12 \pm 0.075)\sigma_y\), 1 Hz; 2- \((0.16 \pm 0.075)\sigma_y\), 1 Hz; 3- \((0.20 \pm 0.075)\sigma_y\), 1 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep; 6- Virgin Specimens;

\(\sigma_y = 70\) MPa at 23 °C
Figure E.I.4  Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C
1- (0.12±0.075)σy, 10 Hz; 2- (0.16±0.075)σy, 10 Hz; 3- (0.20±0.075)σy, 10 Hz;
4- (0.16)σy, 5- (0.20)σy, 6- (0.30)σy Constant Load Creep;
σy = 70 MPa at 23 °C
Figure E.I.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C
1- (0.12±0.075)σ_y, 10 Hz; 2- (0.16±0.075)σ_y, 10 Hz; 3- (0.20±0.075)σ_y, 10 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure E.I.6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.12\pm0.075)\sigma_y\), 10 Hz
2- \((0.16\pm0.075)\sigma_y\), 10 Hz
3- \((0.20\pm0.075)\sigma_y\), 10 Hz
4- \((0.16)\sigma_y\)
5- \((0.20)\sigma_y\), Constant Load Creep
6- Virgin Specimens

\(\sigma_y = 70\) MPa at 23 °C
Figure E.I.7 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C
1- (0.12±0.075)σ_y, 20 Hz; 2- (0.16±0.075)σ_y, 20 Hz; 3- (0.20±0.075)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure E.I.8 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C
1- (0.12±0.075)σ_y, 20 Hz; 2- (0.16±0.075)σ_y, 20 Hz; 3- (0.20±0.075)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure E.I.9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- \((0.12 \pm 0.075)\sigma_y\), 20 Hz; 2- \((0.16 \pm 0.075)\sigma_y\), 20 Hz; 3- \((0.20 \pm 0.075)\sigma_y\), 20 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep; 6- Virgin Specimens;
\[\sigma_y = 70 \text{ MPa at } 23 \degree \text{C}\]
Figure E.I.10  Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C
1- \((0.12 \pm 0.10) \sigma_y\), 1 Hz; 2- \((0.16 \pm 0.10) \sigma_y\), 1 Hz; 3- \((0.20 \pm 0.10) \sigma_y\), 1 Hz;
4- \((0.16) \sigma_y\), 5- \((0.20) \sigma_y\), 6- \((0.30) \sigma_y\) Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at } 23 \degree \text{C}\]
Figure E.I.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C

1- (0.12±0.10)\(\sigma_y\), 1 Hz; 2- (0.16±0.10)\(\sigma_y\), 1 Hz; 3- (0.20±0.10)\(\sigma_y\), 1 Hz;
4- (0.16)\(\sigma_y\), 5- (0.20)\(\sigma_y\), 6- (0.30)\(\sigma_y\) Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure E.I.12 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C
1- \((0.12\pm0.10)\sigma_y\), 1 Hz; 2- \((0.16\pm0.10)\sigma_y\), 1 Hz; 3- \((0.20\pm0.10)\sigma_y\), 1 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep; 6- Virgin Specimens;
\(\sigma_y = 70\) MPa at 23 °C
Figure E.I.13  Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C

1- (0.12±0.10)σ_y, 10 Hz; 2- (0.16±0.10)σ_y, 10 Hz; 3- (0.20±0.10)σ_y, 10 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure E.I.14 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C

1- (0.12±0.10)\(\sigma_y\), 10 Hz; 2- (0.16±0.10)\(\sigma_y\), 10 Hz; 3- (0.20±0.10)\(\sigma_y\), 10 Hz;
4- (0.16)\(\sigma_y\), 5- (0.20)\(\sigma_y\), 6- (0.30)\(\sigma_y\) Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure E.I.15 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23°C

1- \((0.12 \pm 0.10)\sigma_y\), 10 Hz; 2- \((0.16 \pm 0.10)\sigma_y\), 10 Hz; 3- \((0.20 \pm 0.10)\sigma_y\), 10 Hz;
4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), Constant Load Creep; 6- Virgin Specimens;

\(\sigma_y = 70\) MPa at 23°C
Figure E.I.16 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C

1- \((0.12 \pm 0.10)\sigma_y\), 20 Hz; 2- \((0.16 \pm 0.10)\sigma_y\), 20 Hz; 3- \((0.20 \pm 0.10)\sigma_y\), 20 Hz; 4- \((0.16)\sigma_y\), 5- \((0.20)\sigma_y\), 6- \((0.30)\sigma_y\) Constant Load Creep;

\(\sigma_y = 70\) MPa at 23 °C
Figure E.I.17 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 23 °C

1- (0.12±0.10)σ_y, 20 Hz; 2- (0.16±0.10)σ_y, 20 Hz; 3- (0.20±0.10)σ_y, 20 Hz;
4- (0.16)σ_y, 5- (0.20)σ_y, 6- (0.30)σ_y Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure E.I.18 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 23 °C

1- (0.12±0.10)σ_y, 20 Hz; 2- (0.16±0.10)σ_y, 20 Hz; 3- (0.20±0.10)σ_y, 20 Hz;

4- (0.16)σ_y, 5- (0.20)σ_y, Constant Load Creep; 6- Virgin Specimens;

σ_y = 70 MPa at 23 °C
Figure E.II.1 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C

1- (0.16±0.10)σy, 1 Hz; 2- (0.20±0.10)σy, 1 Hz;
3- (0.16)σy, 4- (0.20)σy, 5- (0.30)σy, Constant Load Creep;

σy = 55 MPa at 35 °C
Figure E.II.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C

1- \((0.16\pm0.10)\sigma_y\), 1 Hz; 2- \((0.20\pm0.10)\sigma_y\), 1 Hz;

3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\), Constant Load Creep;

\(\sigma_y = 55 \text{ MPa at } 35 \text{ °C}\)
Figure E.II.3  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- (0.16±0.10)σ_y, 1 Hz; 2- (0.20±0.10)σ_y, 1 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;
σ_y = 55 MPa at 35 °C
Figure E.II.4 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C

1- \((0.16\pm0.10)\sigma_y\), 10 Hz; 2- \((0.20\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\), Constant Load Creep;
\[\sigma_y = 55\text{ MPa at }35\text{ °C}\]
Figure E.II.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C

1- \((0.16\pm0.10)\sigma_y\), 10 Hz; 2- \((0.20\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\), Constant Load Creep;
\(
\sigma_y = 55 \text{ MPa at 35 °C} 
\)
Figure E.II:6 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- (0.16±0.10)σy, 10 Hz; 2- (0.20±0.10)σy, 10 Hz;
3- (0.16)σy, 4- (0.20)σy, Constant Load Creep; 5- Virgin Specimens;

σy = 55 MPa at 35 °C
Figure E.II.7 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C
1- (0.16±0.10)σy, 1 Hz; 2- (0.20±0.10)σy, 1 Hz;
3- (0.16)σy, 4- (0.20)σy, Constant Load Creep;
σy = 70 MPa at 23 °C
Figure E.II.8 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C
1 - (0.16±0.10)σ_y, 1 Hz; 2 - (0.20±0.10)σ_y, 1 Hz;
3 - (0.16)σ_y, 4 - (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure E.II.9 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C

1- \((0.16\pm0.10)\sigma_y\), 1 Hz; 2- \((0.20\pm0.10)\sigma_y\), 1 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep; 5- Virgin Specimens;

\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure E.II.10 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C

1- $(0.16\pm0.10)\sigma_y$, 10 Hz; 2- $(0.20\pm0.10)\sigma_y$, 10 Hz;

3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure E.II.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 35 °C
1- (0.16±0.10)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure E.II.12  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 35 °C
1- (0.16±0.10)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;
σ_y = 70 MPa at 23 °C
Figure E.III.2 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 41 °C

1- \((0.16 \pm 0.10)\sigma_y\), 1 Hz; 2- \((0.20 \pm 0.10)\sigma_y\), 1 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), 5- \((0.30)\sigma_y\), Constant Load Creep;

\(\sigma_y = 45\) MPa at 41 °C
Figure E.III.3  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- (0.16±0.10)\(\sigma_y\), 1 Hz; 2- (0.20±0.10)\(\sigma_y\), 1 Hz;
3- (0.16)\(\sigma_y\), 4- (0.20)\(\sigma_y\), Constant Load Creep; 5- Virgin Specimens;
\[\sigma_y = 45 \text{ MPa at 41 °C}\]
Figure E.III.4 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 41 °C

1- (0.16±0.10)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, 5- (0.30)σ_y, Constant Load Creep;

σ_y = 45 MPa at 41 °C
Figure E.III.5 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 41 °C

1- $(0.16 \pm 0.10)\sigma_y$, 10 Hz; 2- $(0.20 \pm 0.10)\sigma_y$, 10 Hz;
3- $(0.16)\sigma_y$, 4- $(0.20)\sigma_y$, 5- $(0.30)\sigma_y$, Constant Load Creep;

$\sigma_y = 45$ MPa at 41 °C
Figure E.III.6  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- (0.16±0.10)σ_y, 10 Hz; 2- (0.20±0.10)σ_y, 10 Hz;
3- (0.16)σ_y, 4- (0.20)σ_y, Constant Load Creep; 5- Virgin Specimens;

σ_y = 45 MPa at 41 °C
Figure E.III.7 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 41 °C

1- \((0.16 \pm 0.10)\sigma_y, 1\ Hz\); 2- \((0.20 \pm 0.10)\sigma_y, 1\ Hz\);
3- \((0.16)\sigma_y, 4- (0.20)\sigma_y, \text{Constant Load Creep};
\sigma_y = 70 \text{ MPa at } 23 \degree \text{C}
Figure E.III.8 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 41 °C

1- (0.16±0.10)\(\sigma_y\), 1 Hz; 2- (0.20±0.10)\(\sigma_y\), 1 Hz;
3- (0.16)\(\sigma_y\), 4- (0.20)\(\sigma_y\), Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure E.III.9  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C

1- \((0.16\pm0.10)\sigma_y, 1 \text{ Hz}\); 2- \((0.20\pm0.10)\sigma_y, 1 \text{ Hz}\);
3- \((0.16)\sigma_y, 4- (0.20)\sigma_y, \text{ Constant Load Creep}; 5- \text{ Virgin Specimens}; \sigma_y = 70 \text{ MPa at } 23 \text{ °C}
Figure E.III.10 Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 41 °C
1- \((0.16\pm0.10)\sigma_y\), 10 Hz; 2- \((0.20\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at } 23 \degree \text{C}\]
Figure E.III.11 Normalized Vibrocreep Response of Nylon 6/6 at Different Mean Stresses at 41 °C

1- \((0.16\pm0.10)\sigma_y\), 10 Hz; 2- \((0.20\pm0.10)\sigma_y\), 10 Hz;
3- \((0.16)\sigma_y\), 4- \((0.20)\sigma_y\), Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at } 23 \text{ °C}\]
Figure E.III.12 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading at 41 °C
1- $(0.16 \pm 0.10) \sigma_y$, 10 Hz; 2- $(0.20 \pm 0.10) \sigma_y$, 10 Hz;
3- $(0.16) \sigma_y$, 4- $(0.20) \sigma_y$, Constant Load Creep; 5- Virgin Specimens;
$\sigma_y = 70$ MPa at 23 °C
APPENDIX F

Temperature Effects from Tensile, Constant Load Creep, and Vibrocreep Testing of Nylon 6/6
Figure F.1 Tensile Testing of Nylon 6/6 at Different Temperatures
1- 23 °C; 2- 35 °C; 3- 41 °C; 4- 50 °C; 5- 59 °C; 6- 68 °C;
σ_y = 70 MPa at 23 °C
Figure F.2 Yield Stress and Elastic Modulus vs. Temperature
Figure F.3 Constant Load Creep of Nylon 6/6 at Different Temperatures

1- (0.16)σ_y at 23 °C; 2- (0.16)σ_y at 35 °C; 3- (0.16)σ_y at 41 °C;
4- (0.16)σ_y at 50 °C; 5- (0.16)σ_y at 59 °C; 6- (0.16)σ_y at 68 °C;

σ_y = 70 MPa at 23 °C
Figure F.4 Normalized Constant Load Creep of Nylon 6/6 at Different Temperatures

1- $(10.16) \sigma_y$ at $23 \degree C$; 2- $(0.16) \sigma_y$ at $35 \degree C$; 3- $(0.16) \sigma_y$ at $41 \degree C$;
4- $(0.16) \sigma_y$ at $50 \degree C$; 5- $(0.16) \sigma_y$ at $59 \degree C$; 6- $(0.16) \sigma_y$ at $68 \degree C$;

$\sigma_y = 70 \text{ MPa at } 23 \degree C$
Figure F.5 Tensile Testing of Nylon 6/6 Specimens After Constant Loading

1- $(0.16)\sigma_y$ at 23 °C; 2- $(0.16)\sigma_y$ at 35 °C; 3- $(0.16)\sigma_y$ at 41 °C;
4- $(0.16)\sigma_y$ at 50 °C; 5- $(0.16)\sigma_y$ at 59 °C; 6- $(0.16)\sigma_y$ at 68 °C;

$\sigma_y = 70$ MPa at 23 °C
Figure F.6 Constant Load Creep of Nylon 6/6 at Different Temperatures

1- (0.20)\(\sigma_y\) at 23 °C; 2- (0.20)\(\sigma_y\) at 35 °C; 3- (0.20)\(\sigma_y\) at 41 °C;
4- (0.20)\(\sigma_y\) at 50 °C; 5- (0.20)\(\sigma_y\) at 59 °C; 6- (0.20)\(\sigma_y\) at 68 °C;
\(\sigma_y = 70\) MPa at 23 °C
Figure F.7 Normalized Constant Load Creep of Nylon 6/6 at Different Temperatures

1- (0.20)$\sigma_y$ at 23 °C; 2- (0.20)$\sigma_y$ at 35 °C; 3- (0.20)$\sigma_y$ at 41 °C;
4- (0.20)$\sigma_y$ at 50 °C; 5- (0.20)$\sigma_y$ at 59 °C; 6- (0.20)$\sigma_y$ at 68 °C;

$\sigma_y = 70 \text{ MPa at 23 °C}$
Figure F.8 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading

1- (0.20)$\sigma_y$ at 23 °C; 2- (0.20)$\sigma_y$ at 35 °C; 3- (0.20)$\sigma_y$ at 41 °C;
4- (0.20)$\sigma_y$ at 50 °C; 5- (0.20)$\sigma_y$ at 59 °C; 6- (0.20)$\sigma_y$ at 68 °C;

$\sigma_y = 70$ MPa at 23 °C
Figure F.9 Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- $(0.16 \pm 0.04)\sigma_y$, 1 Hz at 23 °C; 2- $(0.16 \pm 0.04)\sigma_y$, 1 Hz at 35 °C; 3- $(0.16 \pm 0.04)\sigma_y$, 1 Hz at 41 °C;
4- $(0.16)\sigma_y$ at 23 °C, 5- $(0.16)\sigma_y$ at 35 °C, 6- $(0.16)\sigma_y$ at 41 °C, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure F.10 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.16\pm0.04)\sigma_y\), 1 Hz at 23 °C; 2- \((0.16\pm0.04)\sigma_y\), 1 Hz at 35 °C; 3- \((0.16\pm0.04)\sigma_y\), 1 Hz at 41 °C;
4- \((0.16)\sigma_y\) at 23 °C, 5- \((0.16)\sigma_y\) at 35 °C, 6- \((0.16)\sigma_y\) at 41 °C, Constant Load Creep;

\[\sigma_y = 70\,\text{MPa at 23 °C}\]
Figure F.11  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading
1- \((0.16 \pm 0.04)\sigma_y\), 1 Hz at 23 °C; 2- \((0.16 \pm 0.04)\sigma_y\), 1 Hz at 35 °C; 3- \((0.16 \pm 0.04)\sigma_y\), 1 Hz at 41 °C;
4- \((0.16)\sigma_y\) at 23 °C, 5- \((0.16)\sigma_y\) at 35 °C, 6- \((0.16)\sigma_y\) at 41 °C, Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure F.12 Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- $(0.16\pm0.04)\sigma_y$, 10 Hz at 23 °C; 2- $(0.16\pm0.04)\sigma_y$, 10 Hz at 35 °C; 3- $(0.16\pm0.04)\sigma_y$, 10 Hz at 41 °C;
4- $(0.16)\sigma_y$ at 23 °C, 5- $(0.16)\sigma_y$ at 35 °C, 6- $(0.16)\sigma_y$ at 41 °C, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure F.13 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.16 \pm 0.04)\sigma_y\), 10 Hz at 23 °C; 2- \((0.16 \pm 0.04)\sigma_y\), 10 Hz at 35 °C; 3- \((0.16 \pm 0.04)\sigma_y\), 10 Hz at 41 °C;
4- \((0.16)\sigma_y\) at 23 °C, 5- \((0.16)\sigma_y\) at 35 °C, 6- \((0.16)\sigma_y\) at 41 °C, Constant Load Creep;
\[
\sigma_y = 70 \text{ MPa at 23 °C}
\]
Figure F.14 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading

1- $(0.16\pm0.04)\sigma_y$, 10 Hz at 23 °C; 2- $(0.16\pm0.04)\sigma_y$, 10 Hz at 35 °C; 3- $(0.16\pm0.04)\sigma_y$, 10 Hz at 41 °C;
4- $(0.16)\sigma_y$ at 23 °C, 5- $(0.16)\sigma_y$ at 35 °C, 6- $(0.16)\sigma_y$ at 41 °C, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure F.15 Vibrocreep Response of Nylon 6/6 at Different Temperatures
1- (0.16±0.10)$\sigma_y$, 1 Hz at 23 °C; 2- (0.16±0.10)$\sigma_y$, 1 Hz at 35 °C; 3- (0.16±0.10)$\sigma_y$, 1 Hz at 41 °C;
4- (0.16)$\sigma_y$ at 23 °C; 5- (0.16)$\sigma_y$ at 35 °C, 6- (0.16)$\sigma_y$ at 41 °C, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure F.16 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.16 \pm 0.10) \sigma_y\), 1 Hz at 23 °C; 2- \((0.16 \pm 0.10) \sigma_y\), 1 Hz at 35 °C; 3- \((0.16 \pm 0.10) \sigma_y\), 1 Hz at 41 °C;
4- \((0.16) \sigma_y\) at 23 °C; 5- \((0.16) \sigma_y\) at 35 °C, 6- \((0.16) \sigma_y\) at 41 °C, Constant Load Creep;

\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure F.17 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading
1- \( (0.16 \pm 0.10) \sigma_y \), 1 Hz at 23 °C; 2- \( (0.16 \pm 0.10) \sigma_y \), 1 Hz at 35 °C; 3- \( (0.16 \pm 0.10) \sigma_y \), 1 Hz at 41 °C;
4- \( (0.16) \sigma_y \) at 23 °C, 5- \( (0.16) \sigma_y \) at 35 °C, 6- \( (0.16) \sigma_y \) at 41 °C, Constant Load Creep;
\[ \sigma_y = 70 \text{ MPa at 23 °C} \]
Figure F.18 Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.16\pm0.10)\sigma_y\), 10 Hz at 23 °C; 2- \((0.16\pm0.10)\sigma_y\), 10 Hz at 35 °C; 3- \((0.16\pm0.10)\sigma_y\), 10 Hz at 41 °C; 4- \((0.16)\sigma_y\) at 23 °C, 5- \((0.16)\sigma_y\) at 35 °C, 6- \((0.16)\sigma_y\) at 41 °C, Constant Load Creep;

\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure F.19 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.16 \pm 0.10)\sigma_y\), 10 Hz at 23 °C; 2- \((0.16 \pm 0.10)\sigma_y\), 10 Hz at 35 °C; 3- \((0.16 \pm 0.10)\sigma_y\), 10 Hz at 41 °C;
4- \(0.16\sigma_y\) at 23 °C, 5- \(0.16\sigma_y\) at 35 °C, 6- \(0.16\sigma_y\) at 41 °C, Constant Load Creep;

\(\sigma_y = 70\) MPa at 23 °C
Figure F.20  Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading

1- (0.16±0.10)σ_y, 10 Hz at 23 °C; 2- (0.16±0.10)σ_y, 10 Hz at 35 °C; 3- (0.16±0.10)σ_y, 10 Hz at 41 °C;
4- (0.16)σ_y at 23 °C, 5- (0.16)σ_y at 35 °C, 6- (0.16)σ_y at 41 °C, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure F.21 Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.20\pm0.05)\sigma_y\), 1 Hz at 23 \(^\circ\)C; 2- \((0.20\pm0.05)\sigma_y\), 1 Hz at 35 \(^\circ\)C; 3- \((0.20\pm0.05)\sigma_y\), 1 Hz at 41 \(^\circ\)C; 4- \((0.20)\sigma_y\) at 23 \(^\circ\)C; 5- \((0.20)\sigma_y\) at 35 \(^\circ\)C; 6- \((0.20)\sigma_y\) at 41 \(^\circ\)C, Constant Load Creep;

\[\sigma_y = 70 \text{ MPa at } 23 \text{ } ^\circ\text{C}\]
Figure F.22 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures
1- \((0.20\pm0.05)\sigma_y\), 1 Hz at 23 °C; 2- \((0.20\pm0.05)\sigma_y\), 1 Hz at 35 °C; 3- \((0.20\pm0.05)\sigma_y\), 1 Hz at 41 °C;
4- \((0.20)\sigma_y\) at 23 °C, 5- \((0.20)\sigma_y\) at 35 °C, 6- \((0.20)\sigma_y\) at 41 °C, Constant Load Creep;
\(\sigma_y = 70\) MPa at 23 °C
Figure F.23 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading

1- \((0.20\pm0.05)\sigma_y\), 1 Hz at 23 °C; 2- \((0.20\pm0.05)\sigma_y\), 1 Hz at 35 °C; 3- \((0.20\pm0.05)\sigma_y\), 1 Hz at 41 °C;
4- \((0.20)\sigma_y\) at 23 °C, 5- \((0.20)\sigma_y\) at 35 °C, 6- \((0.20)\sigma_y\) at 41 °C, Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure F.24 Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- (0.20±0.05)σ_y, 10 Hz at 23 °C; 2- (0.20±0.05)σ_y, 10 Hz at 35 °C; 3- (0.20±0.05)σ_y, 10 Hz at 41 °C; 4- (0.20)σ_y at 23 °C, 5- (0.20)σ_y at 35 °C, 6- (0.20)σ_y at 41 °C, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure F.25 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.20 \pm 0.05)\sigma_y\), 10 Hz at 23 °C; 2- \((0.20 \pm 0.05)\sigma_y\), 10 Hz at 35 °C; 3- \((0.20 \pm 0.05)\sigma_y\), 10 Hz at 41 °C; 4- \((0.20)\sigma_y\) at 23 °C, 5- \((0.20)\sigma_y\) at 35 °C, 6- \((0.20)\sigma_y\) at 41 °C, Constant Load Creep;

\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure F.26 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading

1- \((0.20\pm0.05)\sigma_y\), 10 Hz at 23 °C; 2- \((0.20\pm0.05)\sigma_y\), 10 Hz at 35 °C; 3- \((0.20\pm0.05)\sigma_y\), 10 Hz at 41 °C;
4- \((0.20)\sigma_y\) at 23 °C, 5- \((0.20)\sigma_y\) at 35 °C, 6- \((0.20)\sigma_y\) at 41 °C, Constant Load Creep;
\[\sigma_y = 70 \text{ MPa at 23 °C}\]
Figure F.27  Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- (0.20±0.10)σ_y, 1 Hz at 23 °C; 2- (0.20±0.10)σ_y, 1 Hz at 35 °C; 3- (0.20±0.10)σ_y, 1 Hz at 41 °C;
4- (0.20)σ_y at 23 °C, 5- (0.20)σ_y at 35 °C, 6- (0.20)σ_y at 41 °C, Constant Load Creep;

σ_y = 70 MPa at 23 °C
Figure F.28 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- \((0.20\pm0.10)\sigma_y\), 1 Hz at 23 °C; 2- \((0.20\pm0.10)\sigma_y\), 1 Hz at 35 °C; 3- \((0.20\pm0.10)\sigma_y\), 1 Hz at 41 °C;
4- \((0.20)\sigma_y\) at 23 °C, 5- \((0.20)\sigma_y\) at 35 °C, 6- \((0.20)\sigma_y\) at 41 °C, Constant Load Creep;

\(\sigma_y = 70\) MPa at 23 °C
Figure F.29 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading

1- (0.20±0.10)σ_y, 1 Hz at 23 °C; 2- (0.20±0.10)σ_y, 1 Hz at 35 °C; 3- (0.20±0.10)σ_y, 1 Hz at 41 °C;
4- (0.20)σ_y at 23 °C, 5- (0.20)σ_y at 35 °C, 6- (0.20)σ_y at 41 °C, Constant Load Creep;
σ_y = 70 MPa at 23 °C
Figure F.30 Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- $(0.20 \pm 0.10)\sigma_y$, 10 Hz at 23 °C; 2- $(0.20 \pm 0.10)\sigma_y$, 10 Hz at 35 °C; 3- $(0.20 \pm 0.10)\sigma_y$, 10 Hz at 41 °C;
4- $(0.20)\sigma_y$ at 23 °C, 5- $(0.20)\sigma_y$ at 35 °C, 6- $(0.20)\sigma_y$ at 41 °C, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure F.31 Normalized Vibrocreep Response of Nylon 6/6 at Different Temperatures

1- (0.20±0.10)$\sigma_y$, 10 Hz at 23 °C; 2- (0.20±0.10)$\sigma_y$, 10 Hz at 35 °C; 3- (0.20±0.10)$\sigma_y$, 10 Hz at 41 °C;
4- (0.20)$\sigma_y$ at 23 °C, 5- (0.20)$\sigma_y$ at 35 °C, 6- (0.20)$\sigma_y$ at 41 °C, Constant Load Creep;

$\sigma_y = 70$ MPa at 23 °C
Figure F.32 Tensile Testing of Nylon 6/6 Specimens After Cyclic and Constant Loading

1- (0.20±0.10)$\sigma_y$, 10 Hz at 23 °C; 2- (0.20±0.10)$\sigma_y$, 10 Hz at 35 °C; 3- (0.20±0.10)$\sigma_y$, 10 Hz at 41 °C;
4- (0.20)$\sigma_y$ at 23 °C, 5- (0.20)$\sigma_y$ at 35 °C, 6- (0.20)$\sigma_y$ at 41 °C, Constant Load Creep;

$\sigma_y$ = 70 MPa at 23 °C
APPENDIX G

Post Cyclic Testing Results
<table>
<thead>
<tr>
<th>Data</th>
<th>Yield Stress (MPa)</th>
<th>Strain at Yield (mm/mm)</th>
<th>Maximum Stress (MPa)</th>
<th>Elastic Modulus (GPa)</th>
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<td></td>
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<tr>
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<td>78.000</td>
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<td>65.567</td>
<td>0.06515</td>
<td>74.543</td>
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<td>Virgin</td>
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</table>
APPENDIX H

Tensile and Constant Load Creep Testing Results for PVDF
Figure H.I.1 Constant Load Creep of PVDF at -25 °C

1- (0.30)σ_y; 2- (0.45)σ_y; 3- (0.60)σ_y;

σ_y = 30.428 MPa at 23 °C
Figure H.I.2 Normalized Constant Load Creep of PVDF at -25 °C

1- (0.30)σ_y; 2- (0.45)σ_y; 3- (0.60)σ_y;

σ_y = 30.428 MPa at 23 °C
Figure H.II.1 Tensile Test of PVDF Direction 1 at 23 °C
Figure H.II.2  Tensile Test of PVDF Direction 2 at 23 °C
Figure H.II.3 Constant Load Creep of PVDF at 23 °C

1- (0.30)\(\sigma_y\); 2- (0.45)\(\sigma_y\); 3- (0.60)\(\sigma_y\);

\(\sigma_y = 30.428\) MPa at 23 °C
Figure H.II.4 Normalized Constant Load Creep of PVDF at 23 °C

1- $(0.30)\sigma_y$; 2- $(0.45)\sigma_y$; 3- $(0.60)\sigma_y$;

$\sigma_y = 30.428$ MPa at 23 °C
APPENDIX I

Frequency Effects from Vibrocreep Testing of PVDF
Figure I.I.1 Vibrocreep Response of PVDF at Different Frequencies at -25 °C

1- (0.30±0.20)$\sigma_y$, 5 Hz; 2- (0.30±0.20)$\sigma_y$, 10 Hz; 3- (0.30±0.020)$\sigma_y$, 20 Hz;
4- (0.30)$\sigma_y$, 5- (0.45)$\sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure I.I.2 Normalized Vibrocreep Response of PVDF at Different Frequencies at -25 °C

1- \((0.30\pm0.20)\sigma_y\), 5 Hz; 2- \((0.30\pm0.20)\sigma_y\), 10 Hz; 3- \((0.30\pm0.020)\sigma_y\), 20 Hz;
4- \((0.30)\sigma_y\), 5- \((0.45)\sigma_y\), Constant Load Creep;

\(\sigma_y = 30.428\) MPa at 23 °C
Figure I.I.3 Vibrocreep Response of PVDF at Different Frequencies at -25 °C
1- (0.45±0.20)σ_y, 5 Hz; 2- (0.45±0.20)σ_y, 10 Hz;
3- (0.45)σ_y, 4- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure I.I.4 Normalized Vibrocreep Response of PVDF at Different Frequencies at -25 °C

1- (0.45±0.20)σ_y, 5 Hz; 2- (0.45±0.20)σ_y, 10 Hz;
3- (0.45)σ_y, 4- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure I.I.5 Vibrocreep Response of PVDF at Different Frequencies at -25 °C

1- \((0.60 \pm 0.20)\sigma_y\), 5 Hz; 2- \((0.60 \pm 0.20)\sigma_y\), 10 Hz;
3- \((0.60)\sigma_y\), Constant Load Creep;
\[
\sigma_y = 30.428 \text{ MPa at 23 °C}
\]
Figure I.1.6 Normalized Vibrocreep Response of PVDF at Different Frequencies at -25 °C

1- \((0.60 \pm 0.20)\sigma_y\), 5 Hz; 2- \((0.60 \pm 0.20)\sigma_y\), 10 Hz;
3- \((0.60)\sigma_y\), Constant Load Creep;
\[\sigma_y = 30.428 \text{ MPa at 23 °C}\]
Figure I.II.1 Vibrocreep Response of PVDF at Different Frequencies at 23 °C
1- (0.30±0.10)$\sigma_y$, 5 Hz; 2- (0.30±0.10)$\sigma_y$, 10 Hz; 3- (0.30±0.10)$\sigma_y$, 20 Hz;
4- (0.30)$\sigma_y$, 5- (0.45)$\sigma_y$, Constant Load Creep;
$\sigma_y = 30.428$ MPa at 23 °C
Figure I.II.2 Normalized Vibrocreep Response of PVDF at Different Frequencies at 23 °C
1- \((0.30\pm0.10)\sigma_y\), 5 Hz; 2- \((0.30\pm0.10)\sigma_y\), 10 Hz; 3- \((0.30\pm0.10)\sigma_y\), 20 Hz;
4- \((0.30)\sigma_y\), 5- \((0.45)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure I.II.3 Vibrocreep Response of PVDF at Different Frequencies at 23 °C
1- (0.30±0.20)σ_y, 5 Hz; 2- (0.30±0.20)σ_y, 10 Hz; 3- (0.30±0.20)σ_y, 20 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure I.II.4 Normalized Vibrocreep Response of PVDF at Different Frequencies at 23 °C

1- (0.30±0.20)σy, 5 Hz; 2- (0.30±0.20)σy, 10 Hz; 3- (0.30±0.20)σy, 20 Hz;
4- (0.30)σy, 5- (0.45)σy, Constant Load Creep;

σy = 30.428 MPa at 23 °C
Figure I.II.5 Vibrocreep Response of PVDF at Different Frequencies at 23 °C

1- (0.45±0.10)σ_y, 5 Hz; 2- (0.45±0.10)σ_y, 10 Hz; 3- (0.45±0.10)σ_y, 20 Hz;
4- (0.45)σ_y, 5- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure I.II.6 Normalized Vibrocreep Response of PVDF at Different Frequencies at 23 °C

1- $(0.45 \pm 0.10) \sigma_y$, 5 Hz; 2- $(0.45 \pm 0.10) \sigma_y$, 10 Hz; 3- $(0.45 \pm 0.10) \sigma_y$, 20 Hz;
4- $(0.45) \sigma_y$, 5- $(0.60) \sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure I.II.7 Vibrocreep Response of PVDF at Different Frequencies at 23 °C
1- $(0.45 \pm 0.20) \sigma_y$, 5 Hz; 2- $(0.45 \pm 0.20) \sigma_y$, 10 Hz; 3- $(0.45 \pm 0.20) \sigma_y$, 20 Hz;
4- $(0.45) \sigma_y$, 5- $(0.60) \sigma_y$, Constant Load Creep;
$\sigma_y = 30.428 \text{ MPa at } 23 \degree \text{C}$
Figure I.II.8 Normalized Vibrocreep Response of PVDF at Different Frequencies at 23 °C

1- $(0.45 \pm 0.20)\sigma_y$, 5 Hz; 2- $(0.45 \pm 0.20)\sigma_y$, 10 Hz; 3- $(0.45 \pm 0.20)\sigma_y$, 20 Hz;
4- $(0.45)\sigma_y$, 5- $(0.60)\sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure I.II.9 Vibrocreep Response of PVDF at Different Frequencies at 23 °C
1- (0.60±0.10)σ_y, 5 Hz; 2- (0.60±0.10)σ_y, 10 Hz; 3- (0.60±0.10)σ_y, 20 Hz;
4- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure I.II.10 Normalized Vibrocreep Response of PVDF at Different Frequencies at 23 °C

1- \((0.60 \pm 0.10)\sigma_y\), 5 Hz; 2- \((0.60 \pm 0.10)\sigma_y\), 10 Hz; 3- \((0.60 \pm 0.10)\sigma_y\), 20 Hz;
4- \((0.60)\sigma_y\), Constant Load Creep;

\(\sigma_y = 30.428\) MPa at 23 °C
Figure I.II.11 Vibrocreep Response of PVDF at Different Frequencies at 23 °C

1- (0.60±0.20)σ_y, 5 Hz; 2- (0.60±0.20)σ_y, 10 Hz; 3- (0.60±0.20)σ_y, 20 Hz;
4- (0.60)σ_y, Constant Load Creep;

\[ \sigma_y = 30.428 \text{ MPa at 23 °C} \]
Figure I.II.12  Normalized Vibrocreep Response of PVDF at Different Frequencies at 23 °C
1- (0.60±0.20)σ_y, 5 Hz; 2- (0.60±0.20)σ_y, 10 Hz; 3- (0.60±0.20)σ_y, 20 Hz;
4- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
APPENDIX J

Amplitude Effects from Vibrocreep Testing of PVDF
Figure J.1.1 Vibrocreep Response of PVDF at Different Amplitudes at -25 °C
1- (0.45±0.20)σ_y, 5 Hz; 2- (0.45±0.35)σ_y, 5 Hz;
3- (0.45)σ_y, 4- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure J.I.2 Normalized Vibrocreep Response of PVDF at Amplitudes at -25 °C

1- (0.45±0.20)σ_y, 5 Hz;
2- (0.45±0.35)σ_y, 5 Hz;
3- (0.45)σ_y, 4- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Strain (mm/mm)

Figure J.I.3 Vibrocreep Response of PVDF at Different Amplitudes at -25 °C

1- (0.45±0.20)σ_y, 10 Hz; 2- (0.45±0.40)σ_y, 10 Hz;
3- (0.45)σ_y, 4- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure J.I.4 Normalized Vibrocreep Response of PVDF at Amplitudes at -25 °C

1- (0.45±0.20)$\sigma_y$, 10 Hz; 2- (0.45±0.40)$\sigma_y$, 10 Hz;
3- (0.45)$\sigma_y$, 4- (0.60)$\sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure J.I.5 Vibrocreep Response of PVDF at Different Amplitudes at -25 °C

1- \( (0.60 \pm 0.20)\sigma_y \), 5 Hz; 2- \( (0.60 \pm 0.40)\sigma_y \), 5 Hz;
3- \( (0.60)\sigma_y \), Constant Load Creep;
\[ \sigma_y = 30.428 \text{ MPa at } 23 \text{ °C} \]
Figure J.1.6 Normalized Vibrocreep Response of PVDF at Different Amplitudes at -25 °C

1- \((0.60\pm0.20)\sigma_y, 5\) Hz; 2- \((0.60\pm0.40)\sigma_y, 5\) Hz;
3- \((0.60)\sigma_y, \) Constant Load Creep;

\[\sigma_y = 30.428\, \text{MPa at } 23\, ^\circ\text{C}\]
Figure J.I.7 Vibrocreep Response of PVDF at Different Amplitudes at -25 °C
1- \((0.60 \pm 0.20) \sigma_y\), 10 Hz; 2- \((0.60 \pm 0.50) \sigma_y\), 10 Hz;
3- \((0.60) \sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.1.8 Normalized Vibrocreep Response of PVDF at Different Amplitudes at -25 °C

1- \((0.60 \pm 0.20)\sigma_y\), 10 Hz; 2- \((0.60 \pm 0.50)\sigma_y\), 10 Hz;
3- \((0.60)\sigma_y\), Constant Load Creep;

\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.II.1 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C

1- \((0.30 \pm 0.10) \sigma_y\), 5 Hz; 2- \((0.30 \pm 0.20) \sigma_y\), 5 Hz;
3- \((0.30) \sigma_y\), 4- \((0.45) \sigma_y\), Constant Load Creep;

\(\sigma_y = 30.428 \text{ MPa at } 23 \, ^\circ\text{C}\)
Figure J.II.2 Normalized Vibrocreep Response of PVDF at Different Amplitudes at 23 °C

1- (0.30±0.10)σ, 5 Hz; 2- (0.30±0.20)σ, 5 Hz;
3- (0.30)σ, 4- (0.45)σ, Constant Load Creep;

σ = 30.428 MPa at 23 °C
Figure J.II.3 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- (0.30±0.10)σ_y, 10 Hz; 2- (0.30±0.20)σ_y, 10 Hz;
3- (0.30)σ_y, 4- (0.45)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure J.II.4 Normalized Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- \((0.30 \pm 0.10)\sigma_y\), 10 Hz; 2- \((0.30 \pm 0.20)\sigma_y\), 10 Hz;
4- \((0.30)\sigma_y\), 5- \((0.45)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.II.5 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- \((0.30\pm0.10)\sigma_y\), 20 Hz; 2- \((0.30\pm0.20)\sigma_y\), 20 Hz;
3- \((0.30)\sigma_y\), 4- \((0.45)\sigma_y\), Constant Load Creep;
\[
\sigma_y = 30.428 \text{ MPa at } 23 \degree \text{C}
\]
Figure J.II.6 Normalized Vibrocreep Response of PVDF at Different Amplitudes at 23 °C

1- (0.30±0.10)σy, 20 Hz; 2- (0.30±0.20)σy, 20 Hz;
4- (0.30)σy, 5- (0.45)σy, Constant Load Creep;
σy = 30.428 MPa at 23 °C
Figure J.II.7 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- \((0.45\pm0.10)\sigma_y\), 5 Hz; 2- \((0.45\pm0.20)\sigma_y\), 5 Hz; 3- \((0.45\pm0.35)\sigma_y\), 5 Hz;
4- \((0.45)\sigma_y\), 5- \((0.60)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.II.8 Normalized Vibrocreep Response of PVDF at Amplitudes at 23 °C
1- \((0.45\pm0.10)\sigma_y\), 5 Hz; 2- \((0.45\pm0.20)\sigma_y\), 5 Hz; 3- \((0.45\pm0.35)\sigma_y\), 5 Hz;
4- \((0.45)\sigma_y\), 5- \((0.60)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.II.9 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C

1- \((0.45 \pm 0.10)\sigma_y\), 10 Hz; 2- \((0.45 \pm 0.20)\sigma_y\), 10 Hz; 3- \((0.45 \pm 0.35)\sigma_y\), 10 Hz;
4- \((0.45)\sigma_y\), 5- \((0.60)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.II.10 Normalized Vibrocreep Response of PVDF at Amplitudes at 23 °C

1- \((0.45 \pm 0.10)\sigma_y, 10\ \text{Hz}\); 2- \((0.45 \pm 0.20)\sigma_y, 10\ \text{Hz}\); 3- \((0.45 \pm 0.35)\sigma_y, 10\ \text{Hz}\);
4- \((0.45)\sigma_y, 5- (0.60)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\ \text{MPa} \) at 23 °C
Figure J.II.11 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C

1- \((0.45\pm0.10)\sigma_y\), 20 Hz; 2- \((0.45\pm0.20)\sigma_y\), 20 Hz;
3- \((0.45)\sigma_y\), 4- \((0.60)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.II.12 Normalized Vibrocreep Response of PVDF at Amplitudes at 23 °C
1- \((0.45 \pm 0.10)\sigma_y\), 20 Hz; 2- \((0.45 \pm 0.20)\sigma_y\), 20 Hz;
3- \((0.45)\sigma_y\), 4- \((0.60)\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure J.II.13 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- (0.60±0.10)σ_y, 5 Hz; 2- (0.60±0.20)σ_y, 5 Hz; 3- (0.60±0.45)σ_y, 5 Hz;
4- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure J.II.14 Normalized Vibrocreep Response of PVDF at Different Amplitudes at 23 °C

1- $(0.60 \pm 0.10)\sigma_y$, 5 Hz; 2- $(0.60 \pm 0.20)\sigma_y$, 5 Hz; 3- $(0.60 \pm 0.45)\sigma_y$, 5 Hz;
3- $(0.60)\sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure J.II.15 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- (0.60±0.10)σ_y, 10 Hz; 2- (0.60±0.20)σ_y, 10 Hz; 3- (0.60±0.50)σ_y, 10 Hz;
4- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure J.II.16 Normalized Vibrocreep Response of PVDF at Different Amplitudes at 23 °C

1- $(0.60 \pm 0.10)\sigma_y$, 10 Hz; 2- $(0.60 \pm 0.20)\sigma_y$, 10 Hz; 3- $(0.60 \pm 0.50)\sigma_y$, 10 Hz;
4- $(0.60)\sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure J.II.17 Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- (0.60±0.10)σy, 20 Hz; 2- (0.60±0.20)σy, 20 Hz;
3- (0.60)σy, Constant Load Creep;
σy = 30.428 MPa at 23 °C
Figure J.II.18 Normalized Vibrocreep Response of PVDF at Different Amplitudes at 23 °C
1- (0.60±0.10)σ_y, 20 Hz; 2- (0.60±0.20)σ_y, 20 Hz;
3- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
APPENDIX K

Mean Stress Effects from Vibrocreep Testing of PVDF
Figure K.1.1 Vibrocreep Response of PVDF at Different Mean Stresses at -25 °C
1- (0.30±0.20)σy, 5 Hz; 2- (0.45±0.20)σy, 5 Hz; 3- (0.60±0.20)σy, 5 Hz;
4- (0.30)σy, 5- (0.45)σy, 6- (0.60)σy, Constant Load Creep;
σy = 30.428 MPa at 23 °C
Figure K.I.2  Normalized Vibrocreep Response of PVDF at Different Mean Stresses at -25 °C
1- (0.30±0.20)σ_y, 5 Hz; 2- (0.45±0.20)σ_y, 5 Hz; 3- (0.60±0.20)σ_y, 5 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure K.I.3 Vibrocreep Response of PVDF at Different Mean Stresses at -25 °C

1- $(0.30 \pm 0.20)\sigma_y$, 10 Hz; 2- $(0.45 \pm 0.20)\sigma_y$, 10 Hz; 3- $(0.60 \pm 0.20)\sigma_y$, 10 Hz;
4- $(0.30)\sigma_y$, 5- $(0.45)\sigma_y$, 6- $(0.60)\sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure K.I.4 Normalized Vibrocreep Response of PVDF at Different Mean Stresses at -25 °C
1- (0.30±0.20)σ_y, 10 Hz; 2- (0.45±0.20)σ_y, 10 Hz; 3- (0.60±0.20)σ_y, 10 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure K.II.1 Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C

1- (0.30±0.10)\(\sigma_y\), 5 Hz; 2- (0.45±0.10)\(\sigma_y\), 5 Hz; 3- (0.60±0.10)\(\sigma_y\), 5 Hz;
4- (0.30)\(\sigma_y\), 6- (0.45)\(\sigma_y\), 6- (0.60)\(\sigma_y\), Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure K.II.2 Normalized Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C

1- (0.30±0.10)σ_y, 5 Hz; 2- (0.45±0.10)σ_y, 5 Hz; 3- (0.60±0.10)σ_y, 5 Hz;
4- (0.30)σ_y, 5 Hz; 5- (0.45)σ_y, 6 Hz; 6- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure K.II.3 Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C

1- (0.30±0.20)σ_y, 5 Hz; 2- (0.45±0.20)σ_y, 5 Hz; 3- (0.60±0.20)σ_y, 5 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure K.II.4 Normalized Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C
1- (0.30±0.20)σ_y, 5 Hz; 2- (0.45±0.20)σ_y, 5 Hz; 3- (0.60±0.20)σ_y, 5 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure K.II.5 Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C
1- (0.30±0.10)σy, 10 Hz; 2- (0.45±0.10)σy, 10 Hz; 3- (0.60±0.10)σy, 10 Hz;
4- (0.30)σy, 5- (0.45)σy, 6- (0.60)σy, Constant Load Creep;
σy = 30.428 MPa at 23 °C
Figure K.II.6 Normalized Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C
1- (0.30±0.10)σ_y, 10 Hz; 2- (0.45±0.10)σ_y, 10 Hz; 3- (0.60±0.10)σ_y, 10 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure K.II.7 Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C

1- (0.30±0.20)$\sigma_y$, 10 Hz; 2- (0.45±0.20)$\sigma_y$, 10 Hz; 3- (0.60±0.20)$\sigma_y$, 10 Hz;
4- (0.30)$\sigma_y$, 5- (0.45)$\sigma_y$, 6- (0.60)$\sigma_y$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure K.II.8 Normalized Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C

1- \((0.30\pm0.20)\sigma_y, 10 \text{ Hz}\); 2- \((0.45\pm0.20)\sigma_y, 10 \text{ Hz}\); 3- \((0.60\pm0.20)\sigma_y, 10 \text{ Hz}\);
4- \((0.30)\sigma_y, 5- (0.45)\sigma_y, 6- (0.60)\sigma_y\), Constant Load Creep;
\[
\sigma_y = 30.428 \text{ MPa at 23 °C}
\]
Figure K.II.9 Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C

1- (0.30±0.10)σ_y, 20 Hz; 2- (0.45±0.10)σ_y, 20 Hz; 3- (0.60±0.10)σ_y, 20 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure K.II.10 Normalized Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C
1- (0.30±0.10)σ_y, 20 Hz; 2- (0.45±0.10)σ_y, 20 Hz; 3- (0.60±0.10)σ_y, 20 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure K.II.11 Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C

1- (0.30±0.20)σ_y, 20 Hz; 2- (0.45±0.20)σ_y, 20 Hz; 3- (0.60±0.20)σ_y, 20 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure K.II.12 Normalized Vibrocreep Response of PVDF at Different Mean Stresses at 23 °C
1- (0.30±0.20)σ_y, 20 Hz; 2- (0.45±0.20)σ_y, 20 Hz; 3- (0.60±0.20)σ_y, 20 Hz;
4- (0.30)σ_y, 5- (0.45)σ_y, 6- (0.60)σ_y, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
APPENDIX L

Temperature Effects from Tensile, Constant Load Creep, and Vibrocreep of PVDF
Figure L.1 Constant Load Creep of PVDF at Different Temperatures

1- (0.30)\(\sigma_y\) at -25 °C; 2- (0.30)\(\sigma_y\) at 23 °C;
3- (0.45)\(\sigma_y\) at -25 °C; 4- (0.45)\(\sigma_y\) at 23 °C;
5- (0.60)\(\sigma_y\) at -25 °C; 6- (0.60)\(\sigma_y\) at 23 °C;

\(\sigma_y = 30.428\) MPa at 23 °C.
Figure L.2 Normalized Constant Load Creep of PVDF at Different Temperatures

1- (0.30)σy at -25 °C; 2- (0.30)σy at 23 °C;
3- (0.45)σy at -25 °C; 4- (0.45)σy at 23 °C;
5- (0.60)σy at -25 °C; 6- (0.60)σy at 23 °C;

σy = 30.428 MPa at 23 °C
Figure L.3  Vibrocreep Response of PVDF at Different Temperatures

1- $(0.30\pm0.20)\sigma_y$, 5 Hz at -25 °C; 2- $(0.30\pm0.20)\sigma_y$, 5 Hz at 23 °C;
3- $(0.30)\sigma_y$ at -25 °C, 4- $(0.30)\sigma_y$ at 23 °C, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure L.4 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- \((0.30 \pm 0.20) \sigma_y\), 5 Hz at -25 °C; 2- \((0.30 \pm 0.20) \sigma_y\), 5 Hz at 23 °C;
3- \((0.30) \sigma_y\) at -25 °C, 4- \((0.30) \sigma_y\) at 23 °C, Constant Load Creep;

\[\sigma_y = 30.428 \text{ MPa at 23 °C}\]
Figure L.5 Vibrocreep Response of PVDF at Different Temperatures

1- \((0.30\pm0.20)\sigma_y\), 10 Hz at -25 °C; 2- \((0.30\pm0.20)\sigma_y\), 10 Hz at 23 °C;
3- \((0.30)\sigma_y\) at -25 °C, 4- \((0.30)\sigma_y\) at 23 °C, Constant Load Creep;

\[ \sigma_y = 30.428 \text{ MPa at 23 °C} \]
Figure L.6 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- \((0.30\pm0.20)\sigma_y\), 10 Hz at -25 °C; 2- \((0.30\pm0.20)\sigma_y\), 10 Hz at 23 °C;
3- \((0.30)\sigma_y\) at -25 °C, 4- \((0.30)\sigma_y\) at 23 °C, Constant Load Creep;

\[
\sigma_y = 30.428 \text{ MPa at 23 °C}
\]
Figure L.7 Vibrocreep Response of PVDF at Different Temperatures

1- \((0.30 \pm 0.20)\sigma_y\), 20 Hz at -25 °C; 2- \((0.30 \pm 0.20)\sigma_y\), 20 Hz at 23 °C;
3- \((0.30)\sigma_y\) at -25 °C, 4- \((0.30)\sigma_y\) at 23 °C, Constant Load Creep;

\[ \sigma_y = 30.428 \text{ MPa at 23 °C} \]
Figure L.8 Normalized Vibrocreep Response of PVDF at Different Temperatures
1- (0.30±0.20)σ_y, 20 Hz at -25 °C; 2- (0.30±0.20)σ_y, 20 Hz at 23 °C;
3- (0.30)σ_y at -25 °C, 4- (0.30)σ_y at 23 °C, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure L.9 Vibrocreep Response of PVDF at Different Temperatures

1- \((0.45 \pm 0.20)\sigma_y\), 5 Hz at -25 °C; 2- \((0.45 \pm 0.20)\sigma_y\), 5 Hz at 23 °C;
3- \((0.45)\sigma_y\) at -25 °C, 4- \((0.45)\sigma_y\) at 23 °C, Constant Load Creep;
\[
\sigma_y = 30.428 \text{ MPa at 23 °C}
\]
Figure L.10 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- $\sigma_y$ (0.45±0.20), 5 Hz at -25 °C; 2- $\sigma_y$ (0.45±0.20), 5 Hz at 23 °C;
3- $\sigma_y$ (0.45) at -25 °C; 4- $\sigma_y$ (0.45) at 23 °C, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure L.11 Vibrocreep Response of PVDF at Different Temperatures

1- \((0.45 \pm 0.35) \sigma_y\), 5 Hz at -25 °C; 2- \((0.45 \pm 0.35) \sigma_y\), 5 Hz at 23 °C;
3- \((0.45) \sigma_y\) at -25 °C, 4- \((0.45) \sigma_y\) at 23 °C, Constant Load Creep;

\[ \sigma_y = 30.428 \text{ MPa at 23 °C} \]
Figure L.12 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- \((0.45 \pm 0.35)\sigma_y\), 5 Hz at -25 °C; 2- \((0.45 \pm 0.35)\sigma_y\), 5 Hz at 23 °C;
3- \((0.45)\sigma_y\) at -25 °C, 4- \((0.45)\sigma_y\) at 23 °C, Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure L.13 Vibrocreep Response of PVDF at Different Temperatures
1- (0.45±0.20)$\sigma_y$, 10 Hz at -25 °C; 2- (0.45±0.20)$\sigma_y$, 10 Hz at 23 °C;
3- (0.45)$\sigma_y$ at -25 °C, 4- (0.45)$\sigma_y$ at 23 °C, Constant Load Creep;
$\sigma_y = 30.428$ MPa at 23 °C
Figure L.14 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- (0.45±0.20)\(\sigma_y\), 10 Hz at -25 °C; 2- (0.45±0.20)\(\sigma_y\), 10 Hz at 23 °C;
3- (0.45)\(\sigma_y\) at -25 °C, 4- (0.45)\(\sigma_y\) at 23 °C, Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure L.15 Vibrocreep Response of PVDF at Different Temperatures

1- $(0.45\pm0.40)\sigma_y$, 10 Hz at -25 °C; 2- $(0.45\pm0.40)\sigma_y$, 10 Hz at 23 °C;
3- $(0.45)\sigma_y$ at -25 °C, 4- $(0.45)\sigma_y$ at 23 °C, Constant Load Creep;

$\sigma_y = 30.428$ MPa at 23 °C
Figure L.16 Normalized Vibrocreep Response of PVDF at Different Temperatures
1- \((0.45 \pm 0.40)\sigma_y\), 10 Hz at \(-25\) °C; 2- \((0.45 \pm 0.40)\sigma_y\), 10 Hz at 23 °C;
3- \((0.45)\sigma_y\) at \(-25\) °C; 4- \((0.45)\sigma_y\) at 23 °C, Constant Load Creep;
\(\sigma_y = 30.428\) MPa at 23 °C
Figure L.17 Vibrocreep Response of PVDF at Different Temperatures
1- (0.60±0.20)σ_y, 5 Hz at -25 °C; 2- (0.60±0.20)σ_y, 5 Hz at 23 °C;
3- (0.60)σ_y at -25 °C, 4- (0.60)σ_y at 23 °C, Constant Load Creep;
σ_y = 30.428 MPa at 23 °C
Figure L.18 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- $(0.60 \pm 0.20) \sigma_y$, 5 Hz at $-25 \degree C$; 2- $(0.60 \pm 0.20) \sigma_y$, 5 Hz at $23 \degree C$; 3- $(0.60) \sigma_y$ at $-25 \degree C$; 4- $(0.60) \sigma_y$ at $23 \degree C$, Constant Load Creep;

$\sigma_y = 30.428$ MPa at $23 \degree C$
Figure L.19 Vibrocreep Response of PVDF at Different Temperatures

1- (0.60±0.45)σ_y, 5 Hz at -25 °C; 2- (0.60±0.45)σ_y, 5 Hz at 23 °C;
3- (0.60)σ_y at -25 °C, 4- (0.60)σ_y at 23 °C, Constant Load Creep;

σ_y = 30.428 MPa at 23 °C
Figure L.20 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- \((0.60 \pm 0.45)\sigma_y\), 5 Hz at -25 °C; 2- \((0.60 \pm 0.45)\sigma_y\), 5 Hz at 23 °C;
3- \((0.60)\sigma_y\) at -25 °C, 4- \((0.60)\sigma_y\) at 23 °C, Constant Load Creep;
\[\sigma_y = 30.428 \text{ MPa at 23 °C}\]
Figure L.21 Vibrocreep Response of PVDF at Different Temperatures

1- \((0.60 \pm 0.20)\sigma_y\), 10 Hz at -25°C; 2- \((0.60 \pm 0.20)\sigma_y\), 10 Hz at 23°C;

3- \((0.60)\sigma_y\) at -25°C, 4- \((0.60)\sigma_y\) at 23°C, Constant Load Creep;

\(\sigma_y = 30.428\) MPa at 23°C
Figure L.22 Normalized Vibrocreep Response of PVDF at Different Temperatures

1- \((0.60 \pm 0.20)\sigma_y\), 10 Hz at -25 °C; 2- \((0.60 \pm 0.20)\sigma_y\), 10 Hz at 23 °C;
3- \((0.60)\sigma_y\) at -25 °C; 4- \((0.60)\sigma_y\) at 23 °C, Constant Load Creep;

\[\sigma_y = 30.428 \text{ MPa at 23 °C}\]
Figure L.23 Vibrocreep Response of PVDF at Different Temperatures

1- \((0.60\pm0.50)\sigma_y\), 10 Hz at \(-25\,^\circ C\);
2- \((0.60\pm0.50)\sigma_y\), 10 Hz at \(23\,^\circ C\);
3- \((0.60)\sigma_y\) at \(-25\,^\circ C\), 4- \((0.60)\sigma_y\) at \(23\,^\circ C\), Constant Load Creep;

\[\sigma_y = 30.428\,\text{MPa at } 23\,^\circ C\]
Figure L.24 Normalized Vibrocreep Response of PVDF at Different Temperatures
1- \((0.60\pm0.50)\sigma_y\), 10 Hz at \(-25\,^\circ C\); 2- \((0.60\pm0.50)\sigma_y\), 10 Hz at \(23\,^\circ C\);
3- \((0.60)\sigma_y\) at \(-25\,^\circ C\), 4- \((0.60)\sigma_y\) at \(23\,^\circ C\), Constant Load Creep;
\[\sigma_y = 30.428\,\text{MPa at } 23\,^\circ C\]
APPENDIX M

Statistical Results
Figure M.I.1  Statistical Analysis of Nylon 6/6 Quasi Static Creep with 95% Confidence

(0.10)σ_y at 23 °C;

σ_y = 70 MPa at 23 °C
Figure M.1.2. Normalized Statistical Analysis of Nylon 6/6 Quasi Static Creep with 95% Confidence

$(0.10)\sigma_y$ at $23 \, ^\circ\text{C}$;

$\sigma_y = 70 \, \text{MPa} \text{ at } 23 \, ^\circ\text{C}$
Figure M.I.3 Statistical Analysis of Nylon 6/6 Vibrocreep Response with 95% Confidence

$(0.20 \pm 0.10) \sigma_y$, 10 Hz at 23 °C;

$\sigma_y = 70$ MPa at 23 °C
Figure M.I.4 Normalized Statistical Analysis of Nylon 6/6 Vibrocreep Response with 95% Confidence

\((0.20 \pm 0.10)\sigma_y\), 10 Hz at 23 °C;

\(\sigma_y = 70\) MPa at 23 °C
Figure M.I.5 Statistical Analysis of Nylon 6/6 Vibrocreep Response Post Tensile Testing with 95% Confidence
(0.20±0.10)σy, 10 Hz at 23 °C;
σy = 70 MPa at 23 °C
Figure M.I.6 Statistical Analysis of Nylon 6/6 Tensile Testing with 95% Confidence at 23 °C
Figure M.I.7 Statistical Curve Fit Analysis of Nylon 6/6 Quasi Static Creep with 95% Confidence

$(0.10)\sigma_y$ at $23 \, ^\circ C$;

$\sigma_y = 70 \, MPa$ at $23 \, ^\circ C$
Figure M.I.8 Normalized Statistical Curve Fit Analysis of Nylon 6/6 Quasi Static Creep with 95% Confidence

\((0.10)\sigma_y\) at 23 °C;

\(\sigma_y = 70\) MPa at 23 °C
Figure M.I.9 Statistical Curve Fit Analysis of Nylon 6/6 Vibrocreep Response with 95% Confidence
(0.20±0.10)\sigma_y, 10 Hz at 23 °C;
\sigma_y = 70 MPa at 23 °C
Figure M.I.10  Normalized Statistical Curve Fit Analysis of Nylon 6/6 Vibrocreep Response with 95% Confidence

\((0.20 \pm 0.10)\sigma_y, 10 \text{ Hz at } 23 \, ^\circ\text{C};\)

\[\sigma_y = 70 \text{ MPa at } 23 \, ^\circ\text{C}\]
Figure M.II.1  Statistical Analysis of PVDF Quasi Static Creep with 95% Confidence

(0.45)\(\sigma_y\) at -25°C;

\(\sigma_y = 30.428\) MPa at 23°C
Figure M.II.2 Normalized Statistical Analysis of PVDF Quasi Static Creep with 95% Confidence

\((0.45)\sigma_y\) at -25 °C;

\(\sigma_y = 30.428\) MPa at 23 °C
Figure M.II.3  Statistical Analysis of PVDF Vibrocreep Response with 95% Confidence
(0.45±0.20)σ_y, 10 Hz at -25 °C;
σ_y = 30.428 MPa at 23 °C
Figure M.II.4 Normalized Statistical Analysis of PVDF Vibrocreep Response with 95% Confidence

\[(0.45 \pm 0.20) \sigma_y, 10 \text{ Hz at } -25 \degree \text{C;}
\]
\[\sigma_y = 30.428 \text{ MPa at } 23 \degree \text{C} \]
Figure M.II.5 Statistical Curve Fit Analysis of PVDF Quasi Static Creep with 95% Confidence

\((0.45)\sigma_y\) at -25 °C;

\(\sigma_y = 30.428\) MPa at 23 °C
Figure M.II.6  Normalized Statistical Curve Fit Analysis of PVDF Quasi Static Creep with 95% Confidence

\((0.45)\sigma_y\) at \(-25\, ^\circ C\);

\(\sigma_y = 30.428\, \text{MPa at } 23\, ^\circ C\)
Figure M.II.7 Statistical Curve Fit Analysis of PVDF Vibrocreep Response with 95% Confidence

$(0.45 \pm 0.20) \sigma_y$, 10 Hz at -25 °C;

$\sigma_y = 30.428$ MPa at 23 °C
Figure M.II.8  Normalized Statistical Curve Fit Analysis of PVDF Vibrocreep Response with 95% Confidence

\((0.45 \pm 0.20)\sigma_y\), 10 Hz at -25 °C;

\(\sigma_y = 30.428\) MPa at 23 °C
Strain (mm/mm)

0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001

x --------------------------

O  OnO ~ O

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ono

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-O -O -

oQOnOoOo

/  X X

1 2 3 4 5 6 7 8

Time (hrs)

Figure M.II.9 Statistical Analysis of PVDF Quasi Static Creep with 95% Confidence

(0.30)σ_y at 23 °C;

σ_y = 30.428 MPa at 23 °C
Figure M.II.10 Normalized Statistical Analysis of PVDF Quasi Static Creep with 95% Confidence

\(
(0.30)\sigma_y \text{ at } 23 \, ^\circ\text{C};
\)

\(\sigma_y = 30.428 \text{ MPa at } 23 \, ^\circ\text{C}\)
Figure M.II.11 Statistical Analysis of PVDF Vibrocreep Response with 95% Confidence

\[(0.45 \pm 0.10) \sigma_y, \ 5 \text{ Hz at } 23 \degree \text{C}\;\]

\[\sigma_y = 30.428 \text{ MPa at } 23 \degree \text{C}\]
Figure M.II.12 Normalized Statistical Analysis of PVDF Vibrocreep Response with 95% Confidence

$(0.45 \pm 0.10)\sigma_y$, 5 Hz at 23 °C;

$\sigma_y = 30.428$ MPa at 23 °C
Figure M.II.13 Statistical Analysis of PVDF Direction 1 Tensile Testing with 95% Confidence at 23 °C
Figure M.II.14 Statistical Curve Fit Analysis of PVDF Quasi Static Creep with 95% Confidence

(0.30)σ_y at 23 °C;

σ_y = 30.428 MPa at 23 °C
Figure M.II.15 Normalized Statistical Curve Fit Analysis of PVDF Quasi Static Creep with 95% Confidence

\((0.30\sigma_y)\) at 23 °C;

\(\sigma_y = 30.428 \text{ MPa at 23 °C}\)
Figure M.II.16 Statistical Curve Fit Analysis of PVDF Vibrocreep Response with 95% Confidence

$(0.45\pm0.10)\sigma_y$, 5 Hz at 23 °C;

$\sigma_y = 30.428$ MPa at 23 °C
Figure M.II.17  Normalized Statistical Curve Fit Analysis of PVDF Vibrocreep Response with 95% Confidence

\((0.45 \pm 0.10)\sigma_y, 5 \text{ Hz at } 23 \, ^\circ\text{C};\)

\(\sigma_y = 30.428 \text{ MPa at } 23 \, ^\circ\text{C}\)
Curve Fit Results For Nylon 6/6
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APPENDIX N

Data Acquisition Programs
Data Acquisition Program for Tensile Testing
Data Acquisition Program for Temperature Measurement During Tensile Testing
<table>
<thead>
<tr>
<th>Temperature</th>
<th>Temp</th>
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<tr>
<td>ob0 ! sc1 ! md3 ! 0:3</td>
<td>c:\Data\Test#1item.dat</td>
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</tbody>
</table>

**thermocouple type**

| J thermocouple |

**CJC sensor type (IC)**

| thermistor | 1 |

**latest data (C)**

| 68.1 |
Data Acquisition Program for Constant Load Creep Testing of Solid Polymers
Data Acquisition Program for Constant Load Creep Testing of Solid Polymers with a Load Cell
Data Acquisition Program for Constant Load Creep Testing of Thin Films
Acceleration

![Diagram of an acceleration system with various components and labels, including a value of 0.02374.]
Data Acquisition Program for Vibrocreep of Solid Polymers
TMT

TJC sensor

Input Limits

continuous acq

output units (volts)

fiction channel buffer size

12

number of chans:

(number of samples to average for each data point (100))

>number of chans>

>temp sensor voltage>

latest temperature

thermocouple type (J)

CJC sensor type (IC Sensor)
Data Acquisition Program for Vibrocreep of Thin Films
<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Channels (0)</td>
<td></td>
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<tr>
<td>Channels Hysteresis</td>
<td></td>
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<tr>
<td>thermocouple type</td>
<td>T</td>
</tr>
<tr>
<td>number of samples/ch</td>
<td>1000</td>
</tr>
<tr>
<td>scan rate</td>
<td>500.00</td>
</tr>
<tr>
<td>latest data (C)</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
</tr>
<tr>
<td>Max (mm)</td>
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</tr>
<tr>
<td>Mean (mm)</td>
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</tr>
<tr>
<td>Min (mm)</td>
<td>-7.24298</td>
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<tr>
<td>Max (N)</td>
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<tr>
<td>Min (N)</td>
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</table>

![Graph of Max load (N)](image)

![Graph of Max Pos (mm)](image)
APPENDIX O

Macros for Data Management
Sub Sample5()
    ' Sub Sample5 Macro
    ' Macro recorded 8/10/99 by Shane Schumacher
    
    Tim = 45
    Column = 1
    Columncounter = 0
    SaveColumn = 16
    comp2 = 3
    Do Until Columncounter > 12
        Row = 1
        SaveRow = 1
        Rowcounter = 1
        Mynum = Sheets("Sheet1").Cells(Row, Column)
        Do Until Rowcounter > Tim
            comp = Rowcounter / .5
            Do Until Mynum > comp Or Mynum = comp
                Mynum = Sheets("Sheet1").Cells(Row, Column)
                Row = Row + 1
            Loop
            MinusColumn = Column
            MinusRow = Row - 1
            Do Until MinusColumn > comp2
                Sheets("Sheet1").Cells(MinusRow, MinusColumn) = Sheets("Sheet1").Cells(MinusRow, MinusColumn)
                MinusColumn = MinusColumn + 1
                SaveColumn = SaveColumn + 1
            Loop
            SaveColumn = SaveColumn - 3
            SaveRow = SaveRow + 1
            Rowcounter = Rowcounter + 1
        Loop
        Columncounter = Columncounter + 3
        Column = Column + 3
        SaveColumn = SaveColumn + 3
        comp2 = comp2 + 3
    Loop
End Sub
Sub Ave5()
    Tim = .45
    Column1 = 16
    Column2 = 19
    Column3 = 22
    Column4 = 25
    Column5 = 28
    Column = 1
    SaveColumn = 31
    Do Until Column > 3
        Row = 1
        Do Until Row > Tim
            myNum1 = Sheets("Sheet1").Cells(Row, Column1)
            myNum2 = Sheets("Sheet1").Cells(Row, Column2)
            myNum3 = Sheets("Sheet1").Cells(Row, Column3)
            myNum4 = Sheets("Sheet1").Cells(Row, Column4)
            myNum5 = Sheets("Sheet1").Cells(Row, Column5)
            total = (myNum1 + myNum2 + myNum3 + myNum4 + myNum5) / 5
            Sheets("Sheet1").Cells(Row, SaveColumn) = total
            Row = Row + 1
        Loop
    SaveColumn = SaveColumn + 1
    Column1 = Column1 + 1
    Column2 = Column2 + 1
    Column3 = Column3 + 1
    Column4 = Column4 + 1
    Column5 = Column5 + 1
    Column = Column + 1
    Loop
End Sub
Sub DynSamAve()
    Tim = 45
    Column = 1
    Columncounter = 0
    SaveColumn = 22
    comp2 = 7
    Do Until Columncounter > 14
        Row = 1
        SaveRow = 1
        Rowcounter = 1
        Mynum = Sheets("Sheet1").Cells(Row, Column)
        Do Until Rowcounter > Tim
            comp = Rowcounter / 5
            Do Until Mynum > comp Or Mynum = comp
                Mynum = Sheets("Sheet1").Cells(Row, Column)
                Row = Row + 1
            Loop
            MinusColumn = Column
            MinusRow = Row - 1
            Do Until MinusColumn > comp2
                Sheets("Sheet1").Cells(SaveRow, SaveColumn) = Sheets("Sheet1").Cells(MinusRow, MinusColumn)
                MinusColumn = MinusColumn + 1
                SaveColumn = SaveColumn + 1
            Loop
            SaveColumn = SaveColumn - 7
            SaveRow = SaveRow + 1
            Rowcounter = Rowcounter + 1
        Loop
        Columncounter = Columncounter + 7
        Column = Column + 7
        SaveColumn = SaveColumn + 7
        comp2 = comp2 + 7
    Loop
End Sub
AveDyn3 Macro
Macro recorded 8/10/99 by Shane Schumacher

Sub AveDyn3()
    Tim = 45
    Column1 = 22
    Column2 = 29
    Column3 = 36
    Column = 1
    SaveColumn = 43
    Do Until Column > 7
        Row = 1
        Do Until Row > Tim
            myNum1 = Sheets("Sheet1").Cells(Row, Column1)
            myNum2 = Sheets("Sheet1").Cells(Row, Column2)
            myNum3 = Sheets("Sheet1").Cells(Row, Column3)
            total = (myNum1 + myNum2 + myNum3) / 3
            Sheets("Sheet1").Cells(Row, SaveColumn) = total
            Row = Row + 1
        Loop
        SaveColumn = SaveColumn + 1
        Column1 = Column1 + 1
        Column2 = Column2 + 1
        Column3 = Column3 + 1
        Column = Column + 1
    Loop
End Sub
Sub Tensile3()
    Strain = 40
    Column = 1
    Columncounter = 0
    SaveColumn = 7
    comp2 = 2
    Do Until Columncounter > 4
        Row = 1
        SaveRow = 1
        Rowcounter = 1
        Mynum = Sheets("Sheet1").Cells(Row, Column)
        Do Until Rowcounter > Strain
            comp = Rowcounter / 100
            Do Until Mynum > comp Or Mynum = comp
                Mynum = Sheets("Sheet1").Cells(Row, Column)
                Row = Row + 1
            Loop
            MinusColumn = Column
            MinusRow = Row - 1
            Do Until MinusColumn > comp2
                Sheets("Sheet1").Cells(MinusRow, MinusColumn) = Sheets("Sheet1").Cells(MinusRow, MinusColumn)
                MinusColumn = MinusColumn + 1
                SaveColumn = SaveColumn + 1
            Loop
            SaveColumn = SaveColumn - 2
            SaveRow = SaveRow + 1
            Rowcounter = Rowcounter + 1
        Loop
        Columncounter = Columncounter + 2
        Column = Column + 2
        SaveColumn = SaveColumn + 2
        comp2 = comp2 + 2
    Loop
End Sub
Sub TensileAve3()
    Tim = 40
    Column1 = 7
    Column2 = 9
    Column3 = 11
    Column = 1
    SaveColumn = 13
    Do Until Column > 2
        Row = 1
        Do Until Row > Tim
            myNum1 = Sheets("Sheet1").Cells(Row, Column1)
            myNum2 = Sheets("Sheet1").Cells(Row, Column2)
            myNum3 = Sheets("Sheet1").Cells(Row, Column3)
            total = (myNum1 + myNum2 + myNum3) / 3
            Sheets("Sheet1").Cells(Row, SaveColumn) = total
            Row = Row + 1
        Loop
        SaveColumn = SaveColumn + 1
        Column1 = Column1 + 1
        Column2 = Column2 + 1
        Column3 = Column3 + 1
        Column = Column + 1
        Loop
    End Sub
Sub Tensile5()
    Strain = 40
    Column = 1
    Columncounter = 0
    SaveColumn = 11
    comp2 = 2
    Do Until Columncounter > 8
        Row = 1
        SaveRow = 1
        Rowcounter = 1
        Mynum = Sheets("Sheet1").Cells(Row, Column)
        Do Until Rowcounter > Strain
            comp = Rowcounter / 100
            Do Until Mynum > comp Or Mynum = comp
                Mynum = Sheets("Sheet1").Cells(Row, Column)
                Row = Row + 1
            Loop
            MinusColumn = Column
            MinusRow = Row - 1
            Do Until MinusColumn > comp2
                Sheets("Sheet1").Cells(SaveRow, SaveColumn) = Sheets("Sheet1").Cells(MinusRow, MinusColumn)
                MinusColumn = MinusColumn + 1
                SaveColumn = SaveColumn + 1
            Loop
            SaveColumn = SaveColumn - 2
            SaveRow = SaveRow + 1
            Rowcounter = Rowcounter + 1
        Loop
        Columncounter = Columncounter + 2
        Column = Column + 2
        SaveColumn = SaveColumn + 2
        comp2 = comp2 + 2
    Loop
End Sub
Sub TenAveS()
    Dim Tim As Integer
    Dim Column1 As Integer
    Dim Column2 As Integer
    Dim Column3 As Integer
    Dim Column4 As Integer
    Dim Column5 As Integer
    Dim Column As Integer
    Dim SaveColumn As Integer
    Dim Row As Integer
    Dim myNum1 As Double
    Dim myNum2 As Double
    Dim myNum3 As Double
    Dim myNum4 As Double
    Dim myNum5 As Double
    Dim total As Double

    Tim = 40
    Column1 = 11
    Column2 = 13
    Column3 = 15
    Column4 = 17
    Column5 = 19
    Column = 1
    SaveColumn = 21
    Do Until Column > 2
        Row = 1
        Do Until Row > Tim.
            myNum1 = Sheets("Sheet1").Cells(Row, Column1)
            myNum2 = Sheets("Sheet1").Cells(Row, Column2)
            myNum3 = Sheets("Sheet1").Cells(Row, Column3)
            myNum4 = Sheets("Sheet1").Cells(Row, Column4)
            myNum5 = Sheets("Sheet1").Cells(Row, Column5)
            total = (myNum1 + myNum2 + myNum3 + myNum4 + myNum5) / 5
            Sheets("Sheet1").Cells(Row, SaveColumn) = total
            Row = Row + 1
        Loop
        SaveColumn = SaveColumn + 1.
        Column1 = Column1 + 1
        Column2 = Column2 + 1
        Column3 = Column3 + 1
        Column4 = Column4 + 1
        Column5 = Column5 + 1
        Column = Column + 1
        Loop
    End Sub
APPENDIX P

Manufacture Material Data for Nylon 6/6 and PVDF
Zyte® 42A NC010
Nylon Resin

Zyte® 42A NC010 is a high viscosity molding and extrusion grade PA 66 resin, suitable for film and tubing applications.

<table>
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<tr>
<th>Property</th>
<th>Test Method</th>
<th>Units</th>
<th>Value (DAM)</th>
<th>Value (50% RH)</th>
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Disclaimer: The information provided is the best data available to DuPont at the time of publication. This information may be subject to revision as new knowledge and experience become available. The data provided in this sheet are typical of DuPont's products and are intended for use only as a guide. These data were developed in the DuPont laboratories and are based on tests conducted under standard conditions. The data are not intended to be used for design purposes or as an expression of the maximum or minimum performance of DuPont's products. DuPont makes no warranties and assumes no liability in connection with the use of this information. Nothing in this publication is to be considered as a license to operate under or a recommendation to infringe any patented rights.

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<td>Izod Impact</td>
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# Zytek® 42A NC010

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Contact DuPont for Material Safety Data Sheet, general guides and/or additional information about selection, handling, processing, drying, etc.

Mechanical property measured at 23°C (73°F) unless otherwise stated.

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Table 2. Comparison of piezoelectric materials

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<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>PVDF Film</th>
<th>PZT BaTiO₃</th>
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<td>ε/ε₀</td>
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<td>1,200</td>
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<td>d₃₃ Constant</td>
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<td>110</td>
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<tr>
<td>d₅₁ Constant</td>
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<td>Acoustic Impedance</td>
<td>(10⁶)kg/m²·sec.</td>
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OPERATING PROPERTIES FOR A TYPICAL PIEZO FILM ELEMENT

The DT1 element is a standard MSI piezo film configuration consisting of a 12x30 mm active area printed with silver ink electrodes on both surfaces of a 15x40 mm die-cut piezo polymer substrate.

1. Electro-Mechanical Conversion
   (1 direction) 25 x 10⁻¹²m/V, 700 x 10⁴N/V
   (3 direction) 33 x 10⁻¹¹m/V

2. Mechano-Electrical Conversion
   (1 direction) 12 x 10⁻⁹µµ/µ, 400 x 10⁻³V/µm 14.4V/N
   (3 direction) 13 x 10⁻⁹V/N

3. Pyro-Electrical Conversion
   8V/°K (@ 25°C)

4. Capacitance
   1.36 x 10⁻⁹F; Dissipation Factor 0.018 @ 10 KHz Impedance @ 10 KHz 12 KΩ

5. Maximum Operating Voltage
   DC: 280 V (yields 7 µm displacement in 1 direction)
   AC: 840 V (yields 21 µm displacement in 1 direction)

6. Maximum Applied Force (at break, 1 direction)
   6-9 kgF (yields voltage output of 830 to 1275 V)

Electrical to Mechanical Conversion

Large displacements or forces are not generally available from Piezo Film. This becomes apparent when designing loudspeaker elements for instance, as low frequency performance (below 500Hz) tends to be very limited. Even a large sheet of film is unable to create high amplitude pressure pulses as low audio frequencies. This does not apply, however, to low to high frequency ultrasonic frequencies, as seen in current designs for ultrasound air ranging transducers (40-50 kHz) and in medical ultrasonic imaging applications.

Measurement Specialties, Inc., P.O. Box 799, Valley Forge, PA 19482   610.650.1500 FAX 610.650.1509
This MSI controlled document is subject to change.
### Table 2. Comparison of piezoelectric materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
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<th>PZT</th>
<th>BaTiO₃</th>
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<td>10⁷ kg/m³</td>
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<td>7.5</td>
<td>5.7</td>
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<tr>
<td>Relative Permittivity</td>
<td>ε/ε₀</td>
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<td>1,200</td>
<td>1,700</td>
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<td>78</td>
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<tr>
<td>ｋ₅₃ Constant</td>
<td>(10⁶) Vm/N</td>
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<td>10</td>
<td>5</td>
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<tr>
<td>ｄ₃₁ Constant</td>
<td>% at 1 kHz</td>
<td>12</td>
<td>30</td>
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<tr>
<td>Acoustic Impedance</td>
<td>(10⁶) kg/m²-sec.</td>
<td>2.7</td>
<td>30</td>
<td>30</td>
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### OPERATING PROPERTIES FOR A TYPICAL PIEZO FILM ELEMENT

The DTI element is a standard MSI piezo film configuration consisting of a 12x30 mm active area painted with silver ink electrodes on both surfaces of a 15x40 mm die-cut piezo polymer substrate.

1. **Electro-Mechanical Conversion**
   - (1 direction) 25 x 10⁻⁹ m/V, 700 x 10⁻⁶ N/V
   - (3 direction) 33 x 10⁻⁹ m/V

2. **Mechano-Electrical Conversion**
   - (1 direction) 12 x 10⁶ V/μm, 400 x 10⁵ V/μm 14.4 V/N
   - (3 direction) 13 x 10⁶ V/N

3. **Pyro-Electrical Conversion**
   - 8V/°K (@ 25°C)

4. **Capacitance**
   - 1.35 x 10⁻¹² F; Dissipation Factor 0.018 @ 10 KHz
   - Impedance @ 10 KHz 12 KΩ

5. **Maximum Operating Voltage**
   - DC: 280 V (yields 7 μm displacement in 1 direction)
   - AC: 840 V (yields 21 μm displacement in 1 direction)

6. **Maximum Applied Force (at break, 1 direction)**
   - 6-9 kgF (yields voltage output of 830 to 1275 V)

### Electrical to Mechanical Conversion

Large displacements or forces are not generally available from Piezo Film. This becomes apparent when designing loudspeaker elements for instance, as low frequency performance (below 500 Hz) tends to be very limited. Even a large sheet of film is unable to create high amplitude pressure pulses as low audio frequencies. This does not apply, however, to low to high frequency ultrasonic frequencies, as seen in current designs for ultrasound air ranging transducers (40-50 kHz) and in medical ultrasonic imaging applications.
APPENDIX Q

Instron 1350 Environmental Chamber Design
Instron 1350 Environmental Chamber Design

\[ Q = \text{Heat in the insulated volume approximately} = m_{st} \cdot C_{pst} \cdot (T_{in} - T_{inf}) \]

\[ Q_{dot} = \text{Heat loss by conduction through the insulation} - k_{ins} \cdot \frac{A_{box}}{\delta_{ins}} \cdot (T_{in} - T_{inf}) \]

\[ m_{st} := 14.166 \, \text{kg} \quad \text{Mass of Steel Environmental Chamber} \]

\[ C_{pst} := 447 \, \frac{\text{J}}{\text{kg} \cdot \text{K}} \quad \text{Specific Heat Coefficient for Steel} \]

\[ k_{ins} := 0.03594 \, \frac{\text{W}}{\text{m} \cdot \text{K}} \quad \text{Thermal Conductivity of the Insulation} \]

\[ A_{box} := 0.5723 \, \text{m}^2 \quad \text{Surface Area of the Environmental Chamber} \]

\[ \delta_{ins} := 0.1016 \, \text{m} \quad \text{Thickness of the Insulation} \]

\[ T_{in} := 573 \, \text{K} \quad \text{Temperature Inside the Environmental Chamber} \]

\[ T_{inf} := 300 \, \text{K} \quad \text{Temperature of the Surroundings} \]

\[ t \quad \text{Time in seconds} \]

Derivation

\[ Q = m_{st} \cdot C_{pst} \cdot (T_{in} - T_{inf}) \]

\[ Q_{dot} = m_{st} \cdot C_{pst} \left[ \frac{d}{dt} \left( T_{in} - T_{inf} \right) \right] \]

\[ \frac{d}{dt} (T_{in} - T_{inf}) = \frac{1}{m_{st} \cdot C_{pst}} \left( -k_{ins} \cdot \frac{A_{box}}{\delta_{ins}} \right) \cdot (T_{in} - T_{inf}) \]

\[ p := k_{ins} \cdot \frac{A_{box}}{m_{st} \cdot C_{pst} \cdot \delta_{ins}} \]

\[ \frac{d}{dt} (T_{in} - T_{inf}) = -p \cdot dt \]
\[ \ln(T_{in} - T_{inf}) = C - \frac{t}{\tau} \]

\[ T_{in} - T_{inf} = e^{C - e^{\frac{-t}{\tau}}} \]

At \( t = 0 \), \( T_{in} - T_{inf} = \Delta T_0 \)

\[ \Delta T = \Delta T_0 e^{\frac{-t}{\tau}} \]

\[ \tau := \frac{1}{p} .05 \quad 5\% \text{ Fluctuation in the temperature} \]

Cycle Time \( \tau = 1.579 \cdot 10^3 \text{ sec} \)

26.3 min

Heater Sizing where Steady State Conditions Are Used

\[ \frac{dQ}{dt} = W_{dot} - k_{ins} \cdot \frac{A_{box}}{\delta_{ins}} \cdot (T_{in} - T_{inf}) \]

\( W_{dot} \) Heat Generation by the Heater

\[ k_{ins} \cdot \frac{A_{box}}{\delta_{ins}} \cdot (T_{in} - T_{inf}) = 54.73 W \]
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Enviromental Chamber</td>
</tr>
<tr>
<td>2</td>
<td>Support Stand</td>
</tr>
<tr>
<td>3</td>
<td>Enviro Chamber Door</td>
</tr>
<tr>
<td>4</td>
<td>Heater Access Door</td>
</tr>
</tbody>
</table>

**TOLERANCES** UNLESS NOTED

- \( X = \pm 0.50 \)
- \( XX = \pm 0.025 \)
- ANGULARITY = \( \pm 0.5^\circ \)
- BREAK CORNERS = \( \pm 0.010 \) MAX
- FILLET RADIUS = \( \pm 0.015 \) MAX
- DIMENSIONS ARE IN MM UNLESS NOTED

**MATERIAL** Steel

**FINISH** As Delivered

**Montana State University**

**Enviro Chamber & Stand**

**DRAWN** Carl Thrasher

**ENGINEER** Shane Schumacher

**CREATION DATE** 20-Jun-00

**SCALE:** NTS

**SHEET** 1 of 1
1. Top
2. Left Side
3. Right Side
4. Bottom
5. Center Piece
6. Back No Hole
7. Back Fan Hole
8. Slanted Top
9. Grip Cut Out Plates
10. Grip Cut Out Ring

TOLERANCES UNLESS NOTED
\[ X = \pm 0.50 \]
\[ XX = \pm 0.025 \]
ANGULARITY = ±5°
BREAK CORNERS = .010 MAX
FILLET RADIUS = .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL
Steel

FINISH
As Delivered

Montana State University

Environmental Chamber

DRAWN Carl Thrasher
ENGINEER Shane Schumacher

CREATION DATE 20-Jun-00
SCALE: NTS
SHEET 1 of 4
TOLERANCES UNLESS NOTED
.X = ±.50
.XX = ±.025
ANGULARITY = ±.5°
BREAK CORNERS - .010 MAX
FILLET RADIUS - .015 MAX
DIMENSIONS ARE IN MM
UNLESS NOTED

MATERIAL Steel
FINISH As Delivered

Montana State University
BACK VIEW - TEMP CHAMBER

DRAWN Carl Thresher
ENGINEER Shane Schumacher
CREATION DATE 20-Jun-00
SCALE: NTS
SHEET 3 of 4
TOLERANCES UNLESS NOTED

\[ x = \pm 0.50 \]
\[ xx = \pm 0.025 \]
\[ \text{ANULARITY} = \pm 0.5' \]
\[ \text{BREAK CORNERS} = 0.01 \text{ MAX} \]
\[ \text{FILLET RADIUS} = 0.015 \text{ MAX} \]

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL
Steel

FINISH
As Delivered

Montana State University

TOP VIEW - TEMP CHAMBER

DRAWN Carl Thrasher
ENGINEER Shane Schumacher
CREATION DATE 20-Jun-00

SCALE: NTS
SHEET 4 of 4
<table>
<thead>
<tr>
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<td>.X = ±.50</td>
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<td>.XX = ±.025</td>
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<td>BREAK CORNERS = .010 MAX</td>
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<tr>
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<td>UNLESS NOTED</td>
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<thead>
<tr>
<th>MONTANA STATE UNIVERSITY</th>
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<tbody>
<tr>
<td>Right Side - Enviro Chamber</td>
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<table>
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<tr>
<th>DRAWN</th>
<th>Engineer</th>
<th>SIZE</th>
<th>DVG NO.</th>
<th>SCALE</th>
<th>SHEET</th>
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<tbody>
<tr>
<td>Carl Thrasher</td>
<td>Shane Schumacher</td>
<td>A</td>
<td>RIGHT</td>
<td>NTS</td>
<td>1 of 1</td>
</tr>
</tbody>
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**Creation Date:** 20-Jun-00
TOLERANCES UNLESS NOTED
X = ±.50
XX = ±.025
ANGULARITY = ±.5°
BREAK CORNERS - .010 MAX
FILLET RADIUS - .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL Steel
FINISH As Delivered

Montana State University
Center Environ Chamber

DRAWN Carl Thrasher
ENGINEER Shane Schumacher
CREATION DATE 20-Jun-00
SCALE NTS

621
TOLERANCES UNLESS NOTED
.X = ± .50
.XX = ± .025
ANGULARITY = ± .5°
BREAK CORNERS - .010 MAX
FILLET RADIUS - .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL Steel
FINISH As Delivered

Montana State University

Left Side - Enviro Chamber

DRAWN Carl Thrasher
ENGINEER Shane Schumacher
CREATION DATE 20-Jun-00
SCALE NTS SHEET 1 of 1
TOLERANCES UNLESS NOTED
X = ± .50
XX = ± .025
ANGULARITY = ± .5°
BREAK CORNERS = .010 MAX
FILLET RADIUS = .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL Steel
FINISH As Delivered

Montana State University
Top - Enviro Chamber

DRAWN Carl Thrasher
ENGINEER Shane Schumacher
CREATION DATE 20-Jun-00

SCALE NTS SHEET 1 of 1
**TOLERANCES UNLESS NOTED**

- \( x = \pm 0.50 \)
- \( xx = \pm 0.025 \)
- ANGULARITY = \( \pm 0.5^\circ \)
- BREAK CORNERS - 0.010 MAX
- FILLET RADIUS - 0.015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

---

**MATERIAL**

Steel

**FINISH**

As Delivered

Montana State University

Grip Cut Out Plates

<table>
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<tr>
<th>DRAWN</th>
<th>Dwg No.</th>
<th>SIZE</th>
<th>SCALE</th>
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</thead>
<tbody>
<tr>
<td>Carl Thrasher</td>
<td>A</td>
<td>CUTOUTPLATES</td>
<td>NTS</td>
<td>1 of 1</td>
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**CREATION DATE**

20-Jun-00
**Tolerances Unless Noted**

- $X = \pm 0.50$
- $XX = \pm 0.025$
- **Angularity** = $\pm 0.5^\circ$  
- **Break Corners** = $0.010$ MAX  
- **Fillet Radii** = $0.015$ MAX  

**Dimensions** are in **mm** Unless Noted

**Material:** Steel  
**Finish:** As Delivered

---

**Montana State University**  
**Slanted Top**

**Drawn:** Carl Thrasher  
**Engineer:** Shane Schumacher  
**Creation Date:** 20-Jun-00  
**Scale:** NTS  
**Sheet:** 1 of 1
TOLERANCES UNLESS NOTED

X = ±.50
XX = ±.025

ANGULARITY = ±5°

BREAK CORNERS - .010 MAX
FILLET RADII - .015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL: Steel
FINISH: As Delivered

Montana State University
Back Plate With Fan Hole

DRAWN: Carl Thrasher
ENGINEER: Shane Schumacher
CREATION DATE: 20-Jun-00
SIZE: A
DWG NO: BACKFANHOLE
SCALE: NTS
SHEET 1 of 1
TO LERANCES UNLESS NOTED

X = ±.50
XX = ±.0250
ANGULARITY = ±.5°
BREAK CORNERS - .010 MAX
FILLET RADIUS - .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL
Steel

FINISH
As Delivered

Montana State University

Back Plate

DRAWN Carl Thrasher
ENGINEER Shane Schumacher
CREATION DATE 20-Jun-00
SCALE NTS
SHEET 1 of 1
3/4" Square Tube

152.4

533.4

444.5

TOLERANCES UNLESS NOTED

•X = ±.50

•XX = ±.025

ANGULARITY = ±.5°

BREAK CORNERS - .010 MAX

FILLET RADIUS - .015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL  Steel

FINISH  As Delivered

Montana State University

Enviro Chamber Support Rack

DRAWN Carl Thrasher

ENGINEER Shone Schumacher

CREATION DATE 20-Jun-00

SCALE NTS

SHEET 1 of 1

SUPPORTTRACK
TOLERANCES UNLESS NOTED
X  = ± .50
XX = ± .025
ANGULARITY = ± 5°
BREAK CORNERS - .010 MAX
FILLET RADIUS - .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL      Steel
FINISH       As Delivered

Montana State University
Support Columns

DRAWN Carl Thrasher
ENGINEER Shane Schunacher
CREATION DATE 20-Jun-00

SCALE NTS SHEET 1 of 1
TOLERANCES UNLESS NOTED

\( .X = \pm .50 \)
\( .XX = \pm .025 \)
ANGULARITY = \( \pm 5^\circ \)
BREAK CORNERS - .010 MAX
FILLET RADII - .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL Steel
FINISH As Delivered

Montana State University
Enviro Chamber Front Door

DRAWN Carl Thrasher
ENGINEER Shane Schumacher
CREATION DATE 20-Jun-00
SCALE - NTS
SHEET 1 of 1
TOLERANCES UNLESS NOTED:
\[\begin{align*}
X & = \pm 0.50 \\
XX & = \pm 0.025 \\
\text{ANGULARITY} & = \pm 0.5^\circ \\
\text{BREAK CORNERS} & = \pm 0.010 \text{ MAX} \\
\text{FILLET RADII} & = \pm 0.015 \text{ MAX} \\
\end{align*}\]

DIMENSIONS ARE IN MM UNLESS NOTED.

Montana State University

Heater Access Door

CREATION DATE: 20-Jun-00

SCALE: NTS  SHEET 1 of 1
APPENDIX R

Tensile and Creep Environmental Chamber Design
Tensile and Creep Environmental Chamber Design

\[ Q = \text{Heat in the insulated volume approximately} = m_{st} \cdot C_{pst} \cdot (T_{in} - T_{inf}) \]

\[ Q_{dot} = \text{Heat loss by conduction through the insulation} - k_{ins} \cdot \frac{A_{box}}{\delta_{ins}} \cdot (T_{in} - T_{inf}) \]

\[ m_{st} := 20.89 \text{ kg} \quad \text{Mass of Steel Environmental Chamber} \]

\[ C_{pst} := 447 \text{ J} / \text{kg} \cdot \text{K} \quad \text{Specific Heat Coefficient for Steel} \]

\[ k_{ins} := .035594 \text{ W} / \text{m} \cdot \text{K} \quad \text{Thermal Conductivity of the Insulation} \]

\[ A_{box} := 1.672 \text{ m}^2 \quad \text{Surface Area of the Environmental Chamber} \]

\[ \delta_{ins} := .1016 \text{ m} \quad \text{Thickness of the Insulation} \]

\[ T_{in} := 573 \text{ K} \quad \text{Temperature Inside the Environmental Chamber} \]

\[ T_{inf} := 300 \text{ K} \quad \text{Temperature of the Surroundings} \]

\[ t \quad \text{Time in seconds} \]

Derivation

\[ Q = m_{st} \cdot C_{pst} \cdot (T_{in} - T_{inf}) \]

\[ Q_{dot} = m_{st} \cdot C_{pst} \left[ \frac{d}{dt} (T_{in} - T_{inf}) \right] \]

\[ \frac{d}{dt} (T_{in} - T_{inf}) = \frac{1}{m_{st} \cdot C_{pst}} \left( -k_{ins} \cdot \frac{A_{box}}{\delta_{ins}} \right) \cdot (T_{in} - T_{inf}) \]

\[ p := \frac{k_{ins} \cdot A_{box}}{m_{st} \cdot C_{pst} \cdot \delta_{ins}} \]

\[ \frac{d}{dt} \left( T_{in} - T_{inf} \right) = -p \cdot dt \]
\begin{align*}
\ln(T_{in} - T_{inf}) &= C - \frac{t}{\tau} \\
T_{in} - T_{inf} &= e^{C \cdot e^{-\frac{t}{\tau}}} \\
\Delta T &= \Delta T_0 \cdot e^{-\frac{t}{\tau}} \\
\tau &= \frac{1}{p \cdot 0.05} \\
\text{5\% Fluctuation in the temperature} \\
\text{Cycle Time} &\quad \tau = 797.07 \quad \text{sec} \\
&\quad 13.28 \text{ min} \\
\text{Heater Sizing where Steady State Conditions Are Used} \\
\frac{dQ}{dt} &= W_{\text{dot}} - k_{\text{ins}} \cdot \frac{A_{\text{box}}}{\delta_{\text{ins}}} \cdot (T_{in} - T_{inf}) \\
W_{\text{dot}} &\quad \text{Heat Generation by the Heater} \\
k_{\text{ins}} \cdot \frac{A_{\text{box}}}{\delta_{\text{ins}}} \cdot (T_{in} - T_{inf}) &= 159.912 \quad \text{W} 
\end{align*}
<table>
<thead>
<tr>
<th>#</th>
<th>DESCRIPTION</th>
<th>PART #</th>
<th>QTY</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Environmental Control Chamber</td>
<td>370</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Plate Support</td>
<td>380</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>C_Channel_Heater_Bracket</td>
<td>390</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1/4&quot; X 3/4&quot; UNC Bolt</td>
<td>400</td>
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<tr>
<td>5</td>
<td>Heater</td>
<td>410</td>
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<tr>
<td>6</td>
<td>Heater Casing</td>
<td>420</td>
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<tr>
<td>7</td>
<td>Opening Door</td>
<td>430</td>
<td>2</td>
</tr>
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</table>

TOLERANCES UNLESS NOTED

- X = ±0.50
- XX = ±0.025
- ANGULARITY = ±5°
- BREAK CORNERS = 0.010 MAX
- FILLET RADIU = 0.015 MAX
- DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL

See BOM

FINISH

None

Montana State University

Assembly Environmental Chamber

DRAWN A.P

ENGINEER Shane Schumacher

CREATION DATE 15-Jun-00

SCALE NTS SHEET 1 of 7
Weld the other surface to the back of the temperature control chamber.

Weld the hinge connection to the heater casing and attach the door to it, see dimensions.

Centered the support plate and weld the bottom surface. Side fillet weld 3' - 6'.

Weld this sides together, Fillet weld 3' - 6'.

**TOLERANCES UNLESS NOTED**

- \( \pm 0.50 \)
- \( \pm 0.025 \)
- Angularity = \( \pm 0.5^\circ \)
- Break corners = 0.010 MAX
- Fillet radii = 0.015 MAX

**DIMENSIONS ARE IN MM UNLESS NOTED**

**MATERIAL**

Montana State University

Environmental Control Chamber

**FINISH**

None

**DRAWN**

A.P.

**ENGINEER**

Shane Schumacher

**CREATION DATE**

15-Jun-00

**SCALE**

N/A

**SIZE**

A

**DRAW NO.**

360

**NTS**

**SHEET**

2 of 7
TOLERANCES UNLESS NOTED

\[ x = \pm 0.50 \]
\[ xx = \pm 0.025 \]

ANGULARITY = \pm 0.5°

BREAK CORNERS = \pm 0.010 MAX

FILLET RADIUS = \pm 0.015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

Montana State University

Opening Door

D R A W N  A P SIZE DVG

ENGINEER Shane Schumacher

CREATION DATE 15-Jun-00

SCALE NTS SHEET 4 of 7
TOLERANCES UNLESS NOTED

\[ X = \pm 0.50 \]

\[ XX = \pm 0.025 \]

ANGULARITY = \pm 0.5°

BREAK CORNERS = \pm \text{0.010 MAX}

FILLET RADII = \pm \text{0.015 MAX}

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL 1/16' Sheet Metal
FINISH None

Montana State University
Plate Support

DRAWN A.P
ENGINEER Shane Schumacher
CREATION DATE 15-Jun-00
SCALE NTS
SHEET 5 of 7
Notes:
1. Bend 45°
2. Bend 90°
3. Bend radii is Mat'l thickness
4. Material: 16 gage Steel
5. Centered the whole 3 Pcs

Montana State University
Engineer Shane Schumacher

Heater Casing

Drawn A.P.

Creation Date 15-Jun-00

Material 1/16" Sheet Metal
Finish None

<table>
<thead>
<tr>
<th>TOLERANCES UNLESS NOTED</th>
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</thead>
<tbody>
<tr>
<td>X = ±.50</td>
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<td>XX = ±.025</td>
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<tr>
<td>ANGULARITY = ±.5°</td>
</tr>
<tr>
<td>BREAK CORNERS = .010 MAX</td>
</tr>
<tr>
<td>FILLET RADIUS = .015 MAX</td>
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</tbody>
</table>

Dimensions are in MM unless noted.
Threaded Bolt 1/4" x 3/4" UNC - R4, Centered 1 side only

TOLERANCES UNLESS NOTED
\( x = \pm 0.5 \)
\( xx = \pm 0.025 \)
ANGULARITY = \( \pm 0.5^\circ \)
BREAK CORNERS = 0.01 MAX
FILLET RADII = 0.015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL Steel
FINISH None

Montana State University
Assembly_C_Heater_Bracket

DRAWN A.P
ENGINEER Shane Schunacher
CREATION DATE 15-Jun-00
SCALE NTS

642
APPENDIX S

Creep Testing Equipment Design
<table>
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<td>CLAMPING BOLTS</td>
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<td>3</td>
<td>INTERCHANGEABLE GRIP PLATES</td>
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<td>SECOND L BRACKET</td>
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<td>FRONT GRIP JAW</td>
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<td>7</td>
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<td>6</td>
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TOLERANCES UNLESS NOTED
- X = ±0.50
- XX = ±0.025
- ANGULARITY = ±0.5°
- BREAK CORNERS = .010 MAX
- FILLET RADII = .015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL: n/a
FINISH: None

Montana State University

Lower Assembly Fixture

DRAWN: A.P
ENGINEER: Shane Schunacher
CREATION DATE: 15-Jun-00
SCALE: NTS
SHEET: 1 of 9

644
<table>
<thead>
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<td>2</td>
<td>CLAMPING BOLTS</td>
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<td>2</td>
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<td>3</td>
<td>INTERCHANGEABLE GRIP PLATES</td>
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</tr>
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<td>4</td>
<td>REAR GRIP JAW</td>
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<td>8</td>
<td>NUT 5/8&quot;</td>
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TOLERANCES UNLESS NOTED:
- \( X = \pm 0.50 \)
- \( XX = \pm 0.025 \)
- ANGULARITY = \( \pm 5^\circ \)
- BREAK CORNERS = 0.010 MAX
- FILLET RADIUS = 0.015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL: See BOM
FINISH: None

Montana State University
Upper Assembly Fixture

DRAWN: A.P
ENGINEER: Shane Schumacher
CREATION DATE: 15-Jun-00
SCALE: NTS
SHEET: 2 of 9
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<td>INTERCHANGEABLE GRIP PLATES</td>
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<td>5</td>
<td>SECOND L BRACKET</td>
<td>200</td>
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<td>REAR GRIP JAW B</td>
<td>210</td>
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<td>FRONT GRIP JAW</td>
<td>170</td>
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TOLERANCES UNLESS NOTED

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<td>X</td>
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DIMENSIONS ARE IN MM UNLESS NOTED

Material: n/a

Finish: None

Montana State University

Lower Assembly Fixture

Drawn: Shane Schumacher

Creation Date: 15-Jun-00

Scale: NTS

Sheet 1 of 9
Front Grip Jaw

Montana State University

TOLERANCES UNLESS NOTED
.X = ±.50
.XX = ±.025
ANGULARITY = ±.5°
BREAK CORNERS = .010 MAX
FILLET RADIUS = .015 MAX
DIMENSIONS ARE IN MM
UNLESS NOTED

MATERIAL Steel
FINISH None

DRAWN A.P
ENGINEER Shane Schumacher
CREATION DATE 15-Jun-00
SCALE NTS
SHEET 3 of 9

Material: Steel
Finish: None

Dimensions:
- Ø12.7 (2 pieces)
- 76.2
- 50.8
- 15.875
- 31.75
- 6.35

Tolerances:
- X = ±.50
- XX = ±.025
- Angularity = ±.5°
- Break corners = .010 max
- Fillet radius = .015 max

Dimensions are in mm unless noted.
Notes:
1. All features thru
2. Deburr edges

TOLERANCES UNLESS NOTED
\( X = \pm 0.50 \)
\( XX = \pm 0.025 \)
ANGULARITY = \pm 5°
BREAK CORNERS = 0.010 MAX
FILLET RADII = 0.015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL Steel
FINISH None

Montana State University
Interchangeable Grip Plate

DRAWN A.P
ENGINEER Shane Schunacher
CREATION DATE 15-Jun-00
SCALE NTS
SHEET 4 of 9

DVG NO. 130
Notes:
1. All features thru
deburr edges

TOLERANCES UNLESS NOTED
X = ±0.50
XX = ±0.025
ANGULARITY = ±0.5°
BREAK CORNERS = 0.010 MAX
FILLET RADIUS = 0.015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL: Steel
FINISH: None

Montana State University
Rear Grip Jaw B

DRAWN: A.P
ENGINEER: Shane Schumacher
CREATION DATE: 15-Jun-00
SCALE: NTS
SHEET 6 OF 9
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<thead>
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<td>BREAK CORNERS $= \pm 0.010$ MAX</td>
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<td>FILLET RADIUS $= \pm 0.015$ MAX</td>
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<td>DIMENSIONS ARE IN MM UNLESS NOTED</td>
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**Montana State University**

**Support Rod $\varnothing 5/8'' \times 24$ UNF**

**DRAWN A.P.**

**ENGINEER Shane Schumacher**

**CREATION DATE 15-Jun-00**

**SCALE NTS**

**SHEET 7 of 9**
TOLERANCES UNLESS NOTED
x = ±.50
XX = ±.025
ANGULARITY = ±.5°
BREAK CORNERS = .010 MAX
FILLET RADIUS = .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL
Aluminum

FINISH
None

MONTANA STATE UNIVERSITY

SECOND L BRACKET

NOTES:
1. All features thru.
2. Deburr edges.

DRAWN A.P
ENGINEER Shane Schumacher
CREATION DATE 15-Jun-00
SCALE NTS
SHEET 8 of 9
Notes:
1. All Features Thru.
2. Deburr edges

Tolerances Unless Noted
X = ±.50  
XX = ±.025
Angularity = ±.5°
Break Corners - .010 Max
Fillet Radii - .015 Max
Dimensions Are in mm Unless Noted

MateriAL Aluminum
Finish None

Montana State University
LVDT Mounting Block

Drawn A.P
Engineer Shane Schumacher
Creation Date 15-Jun-00

Size A
Dwg No. 150
Scale NTS
Sheet 9 of 9
TOLERANCES UNLESS NOTED
X = ±.50
XX = ±.025
ANGULARITY = ±.5°
BREAK CORNERS - .010 MAX
FILLET RADIi - .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL: Steel
FINISH: As Delivered

Montana State University

Load Tray

DRAWN: Carl Thrasher
ENGINEER: Shane Schumacher
CREATION DATE: 19-Jun-00
SCALE: NTS
SHEET 1 of 1

DRW0002
Load Tray Support

MATERIAL: Steel
FINISH: As Delivered

MONTANA STATE UNIVERSITY

LOADTRAYSUPPORT

DRAWN: Carl Throsher
ENGINEER: Shane Schumacher
CREATION DATE: 19-Jun-00

SCALE: NTS
SHEET: 1 of 1

DIMENSIONS ARE IN MM UNLESS NOTED

TOLERANCES UNLESS NOTED

X = ±.50
XX = ±.025

ANGULARITY = ±.5°

BREAK CORNERS - .010 MAX
FILLET RADIUS = .015 MAX

6.35
127
50.8
254
104.775
203.2
3.175
3.175
12.7

127
APPENDIX T

Creep and Vibrocreep Test Fixture for Thin Film Testing
527.05
190.5
381
1054.1
527.05
190.5
381
1054.1

TOLERANCES UNLESS NOTED
\( X = \pm 0.50 \)
\( XX = \pm 0.050 \)
ANGULARITY = \( \pm 5^\circ \)
BREAK CORNERS = 0.10 MAX
FILLET RADII = 0.015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL: Steel
FINISH: As Delivered

Montana State University

PVDF TEST FIXTURE

DRW0001

CREATION DATE 19-Jun-00
SCALE: NTS
SHEET 1 OF 1
TOLERANCES UNLESS NOTED

- $X = \pm 0.50$
- $XX = \pm 0.025$
- Angularity $= \pm 0.5^\circ$
- Break Corners $= 0.010$ MAX
- Fillet Radii $= 0.015$ MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL Steel
FINISH As Delivered

Montana State University

Attachment Detail

<table>
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<th>DRAWN</th>
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</thead>
<tbody>
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<td>ENGINEER</td>
<td>Shane Schumacher</td>
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# DESCRIPTION PART # QTY
1 Assembly Triangular Support 210 2
2 Assembly C Bracket 240 4
3 Assembly Roller Bearing 270 6
4 Assembly Cross Member 330 2

TOLERANCES UNLESS NOTED
- X = ±.50
- XX = ±.025
- ANGULARITY = ±.5°
- BREAK CORNERS = .010 MAX
- FILLET RADIUS = .015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MONTANA STATE UNIVERSITY

Assembly Test Fixture

DRAWN A,P
ENGINEER Shane Schumacher
CREATION DATE 15-Jun-00
SCALE NTS
SHEET 1 of 11
<table>
<thead>
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<th>QTY</th>
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<td>1</td>
</tr>
<tr>
<td>2</td>
<td>25.4 Square Tubing</td>
<td>230</td>
<td>1</td>
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Butt Weld Both Sides

TOLERANCES UNLESS NOTED
X = ±0.50
XX = ±0.025
ANGULARITY = ±0.5°
BREAK CORNERS = .010 MAX
FILLET RADIi = .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL See BOM
FINISH None

Montana State University
Assembly_Triangular_Support

DRAWN A.P
ENGINEER Shane Schumacher
CREATION DATE 15-Jun-00
SCALE NTS
SHEET 2 of 11
TOLERANCES UNLESS NOTED

- \( X = \pm 0.50 \)
- \( XX = \pm 0.025 \)
- ANGULARITY = \( \pm 0.5' \)
- BREAK CORNERS = \( 0.010 \) MAX
- FILLET RADIUS = \( 0.015 \) MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL

25.4 Square tube

FINISH

None

Montana State University

25.4 square tube

DRAWN A.P

ENGINEER Shane Schunacher

CREATION DATE 15-Jun-00

SCALE NTS

SHEET 3 of 11
TOLERANCES UNLESS NOTED

• X = ±.50

• XX = ±.025

• ANGULARITY = ±.5°

• BREAK CORNERS = .010 MAX

• FILLET RADII = .015 MAX

DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL: 25.4 Square Tube
FINISH: None

Montana State University

25.4 Square tube

DRAWN: A.P.
ENGINEER: Shane Schunacher

CREATION DATE: 15-Jun-00
SCALE: NTS
SHEET: 4 of 11
Notes:
1. 1/4"-1/2" Fillet Weld Both Sides.
2. Mat'l: 12.7 Square tubing.
3. Round Bushing, 5/8 threaded UNF
<table>
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<th>PART #</th>
<th>QTY</th>
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<tr>
<td>2</td>
<td>.75 Square Tubing</td>
<td>260</td>
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**TOLERANCES UNLESS NOTED**

- $X = \pm 0.5$
- $XX = \pm 0.025$
- ANGULARITY $= \pm 0.5^\circ$
- BREAK CORNERS $= 0.010$ MAX
- FILLET RADII $= 0.015$ MAX

**DIMENSIONS ARE IN MM UNLESS NOTED**
R5.08

135°

108

9.5

146

73

TOLERANCES UNLESS NOTED

X = ±.5
XX = ±.025
ANGULARITY = ±.5°
BREAK CORNERS = .010 MAX
FILLET RADII = .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL .75 Square Tube
FINISH None

Montana State University

.DWG NO. 250
SCALE NTS
SHEET 7 of 11
Notes:
1. All features thru
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<td>2</td>
<td>6.35MM x 3MM Roller Bearing</td>
<td>290</td>
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<td>3</td>
<td>Assembly_Bearing_Support</td>
<td>300</td>
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**TOLERANCES UNLESS NOTED**

- X = ±.5
- XX = ±.025
- ANGULARITY = ±.5°
- BREAK CORNERS = .010 MAX
- FILLET RADIUS = .015 MAX
- DIMENSIONS ARE IN MM UNLESS NOTED

**MATERIAL**

See BOM

**FINISH**

None

**Montana State University**

**Assembly_Roller_Bearing**

**DRAWN A.P**

Shane Schumacher

**ENGINEER**

Shane Schumacher

**CREATION DATE**

15-Jun-00

**SCALE**

NTS

**SHEET**

9 of 11

**DWG ND.**

A 270
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<td>0.75 Cut Off Square Tubing</td>
<td>310</td>
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<td>3/8&quot; X 2 Threaded Bolt UNF</td>
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Weld Fillet Around

### Tolerances
- **X** = ±.50
- **XX** = ±0.025
- Angularity = ±5°
- Break corners = .010 max
- Fillet radii = .015 max

Dimensions are in **mm** unless noted.

### Material
- See BOM

### Finish
- None

### Notes
- **Montana State University**
- Assembly_Bearing Support

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TOLERANCES UNLESS NOTED
X = ±.5
XX = ±.025
ANGULARITY = ±.5°
BREAK CORNERS - .010 MAX
FILLET RADIUS - .015 MAX
DIMENSIONS ARE IN MM UNLESS NOTED

MATERIAL .75 Square Tube
FINISH None

Montana State University

.75 cutt off Square tube

DRAWN A.P
ENGINEER Shane Schumacher
CREATION DATE 15-Jun-00
SCALE NTS

SHEET 11 of 11
APPENDIX U

Ongoing Microstructure Analysis and
Model Development Based on Current Work
The experimental results obtained for Nylon 6/6 has been used for microstructure analysis and model development. Dr. Rob Winter and Isamu Kitahara performed the microstructure analysis at South Dakota School of Mines and Technology. The test specimens sent to Dr. Winter were from the preliminary testing of Nylon 6/6. The test specimens were analyzed using a Scanning Electron Microscope (SEM) and an Atomic Force Microscope (AFM). From the microstructure analysis, crazes and/or cracks have been found on the surface of the same specimens. The test specimens had been recovering (unloaded) for approximately a month before they were sent to Dr. Winter. The images are shown in Figures U.1 - 8. and a summary of the analysis is provided in Table VI.6.

Figure U.1 SEM Image of Vibrocreep Testing at 23 °C
(0.80±0.20)σ_y, 20 Hz, σ_y = 70 MPa at 23 °C
Figure U.2 AFM Image of Vibrocreep Testing at 23 °C

\[(0.80 \pm 0.20) \sigma_y, 20 \text{ Hz}, \sigma_y = 70 \text{ MPa at 23 °C}\]

Figure U.3 SEM Image of Vibrocreep Testing at 23 °C

\[(0.80 \pm 0.10) \sigma_y, 20 \text{ Hz}, \sigma_y = 70 \text{ MPa at 23 °C}\]
Figure U.4 AFM Image of Vibrocreep Testing at 23 °C

\((0.80 \pm 0.10) \sigma_y, 20 \text{ Hz}, \sigma_y = 70 \text{ MPa at 23 °C}\)

Figure U.5 SEM Image of Vibrocreep Testing at 23 °C

\((0.80 \pm 0.20) \sigma_y, 10 \text{ Hz}, \sigma_y = 70 \text{ MPa at 23 °C}\)
Figure U.6 AFM Image of Vibrocreep Testing at 23 °C

\[(0.80\pm0.20)\sigma_y, 10 \text{ Hz, } \sigma_y = 70 \text{ MPa at } 23 \text{ °C}\]

Figure U.7 SEM Image of Vibrocreep Testing at 23 °C

\[(0.60\pm0.20)\sigma_y, 10 \text{ Hz, } \sigma_y = 70 \text{ MPa at } 23 \text{ °C}\]
The creep testing did not exhibit craze formations on the surface along with a few of the vibrocreep test specimens. From the microstructure analysis performed by Dr. Winter, the results were analyzed and compared on a macroscopic level by the author. Using the results from the micro to macro analysis the vibrocreep curve could be approximated from the creep curve at the end of each test. The periodicity and density results are from the SEM.
images, and the width is from the AFM images. Two methods are proposed to calculate the strain due to the crazes and/or cracks formation, one using the craze and/or crack periodicity and the second using the craze and/or crack density. The two methods are shown in Equations U.1 and U.2.

\[
\frac{L_g \cdot C_w}{P} \frac{C_w}{L_g \cdot P} = \varepsilon_{\text{Craze}}
\]

Equation U.1

\[
\frac{L_g \cdot S \cdot D \cdot C_w}{L_g} = D \cdot S \cdot C_w = \varepsilon_{\text{Craze}}
\]

Equation U.2

$L_g = \text{Gage Length (mm)}$, $S = \text{Specimen Width (mm)}$, $C_w = \text{Craze and/or Crack Width (\mu m)}$, $P = \text{Periodicity (\mu m)}$, $\varepsilon_{\text{Craze}} = \text{Strain Due To Craze and/or Crack}$, $D = \text{Density of Crazes and/or Cracks (1/mm²)}$

The results are shown in Figure U.9 for a particular case and tabulated in Table VI.7-8 with error calculations. Strain values from creep or vibrocreep testing must be taken at the time at which the test is completed creep or vibrocreep. The equation used for calculation of error is shown at Equation U.3.
The micro structural analysis was therefore continued and more testing was performed at the higher stress levels. The creep test specimens for the preliminary creep testing were also analyzed without evidence of surface crazing and/or cracking. The tests were performed for only a 12 hr. period rather than the 24 hr. period as with preliminary tests. The results of the microstructure analysis show that the craze and/or crack formations on the surface are most likely highly time dependent, since craze and/or crack formations were not seen after 12 hr. of testing at the same loading and environmental conditions as with the 24 hr. test with exhibited such defects.

![Graph of Strain vs. Time](image_url)

**Figure U.9 Results of Vibrocreep Approximation at 23 °C**

\[(0.80\pm0.10)\sigma_y, 20 \text{ Hz}, \sigma_y = 70 \text{ MPa at } 23 \text{ °C}\]
Table U.2 Results of Equation VI.1 Micro to Macroscopic Analysis

<table>
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<tr>
<th>Test #</th>
<th>Constant Load Creep (mm/mm)</th>
<th>Vibrocreep (mm/mm)</th>
<th>$\varepsilon_{\text{Craze}}$</th>
<th>Static + $\varepsilon_{\text{Craze}}$</th>
<th>Error (%)</th>
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<tr>
<td>1</td>
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<td>.2315</td>
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<td>.24809</td>
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<td>.181</td>
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<td>.18063</td>
<td>.21</td>
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<td>3</td>
<td>.139</td>
<td>.233</td>
<td>.15311</td>
<td>.29211</td>
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<td>4</td>
<td>.081</td>
<td>.128</td>
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Table U.3 Results of Equation VI.2 Micro to Macroscopic Analysis

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<th>Test #</th>
<th>Specimen Width (mm)</th>
<th>Constant Load Creep (mm/mm)</th>
<th>Vibrocreep (mm/mm)</th>
<th>$\varepsilon_{\text{Craze}}$</th>
<th>Static + $\varepsilon_{\text{Craze}}$</th>
<th>Error (%)</th>
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</tbody>
</table>

The model development to represent the vibrocreep phenomena is being performed by an exchange professor from Russia Dr. Iakov Klebanov and a fellow graduate student Carl Thrasher. A model has been developed and used to approximate Low Density Polyethylene from literature results. Currently work is being performed using the creep and vibrocreep data shown within the thesis to further support the model. The vibrocreep model is based on damage accumulation from cyclic loading. Damage accumulation is not used in creep models since damage does not exist until the tertiary creep stages, where with vibrocreep the damage is most likely initiated at the onset of the vibration loading. The verification and application to Nylon 6/6 is currently being performed. The creep test data is being used to develop a T-t and $\sigma$-t analogy.
From the creep test data, the prediction of creep test is therefore achieved. The results for 23 °C are shown in Figure VI.30. The modeling of the vibrocreep effect in Nylon 6/6 is currently being performed.

![23°C Experimental vs Analytical](image)

Figure U.10 Modeling results vs. Experimental Results