NUMERICAL AND EXPERIMENTAL STUDIES ON THE USE OF A SPLIT HOPKINSON PRESSURE BAR FOR HIGH STRAIN RATE TENSION TESTING

A Dissertation by

Juan Felipe Acosta

Master of Science, Wichita State University, 2002

Bachelor of Science, University of Los Andes, 1998

Submitted to the Department of Aerospace Engineering
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

July 2012
© Copyright 2012 by Juan Felipe Acosta

All Rights Reserved
NUMERICAL AND EXPERIMENTAL STUDIES ON THE USE OF A SPLIT HOPKINSON PRESSURE BAR FOR HIGH STRAIN RATE TENSION TESTING

The following faculty members have examined the final copy of this dissertation for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Doctor of Philosophy, with a major in Aerospace Engineering.

____________________________________
K. Suresh Raju, Committee Chair

____________________________________
John S. Tomblin, Committee Member

____________________________________
Gerardo Olivares, Committee Member

____________________________________
Hamid Lankarani, Committee Member

____________________________________
Bob Minaie, Committee Member

Accepted for the College of Engineering

____________________________________
Zulma Toro-Ramos, Dean

Accepted for the Graduate School

____________________________________
Abu S. Masud, Interim Dean
DEDICATION

Dedicada a las manos que con paciencia, amor, y persistencia guijaron mis manos escribiendo mis primeras letras.
El texto que hoy presente, no es más que la continuación de su trabajo.
Per Aspera ad Astra.
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor, Dr. K. Suresh Raju, for his guidance, patience, and support throughout the years. Special thanks to Dr. Gerardo Olivares and Dr. John Tomblin for their encouragement and support. I would also like to extend my gratitude to the members of the committee Dr. Bob Minaie and Dr. Hamid Lankarani for their comments and suggestions. I also want to thank the people from the National Institute for Aviation Research that contributed at some stage to this investigation.
ABSTRACT

The Split Hopkinson Pressure Bar (SHPB) technique is widely used to dynamically characterize metals and is increasingly being used to characterize non-metallic materials such as fiber reinforced polymeric composite materials. However, the tensile version of the SHPB apparatus requires specimen gripping devices and/or complex loading mechanisms that distort and attenuate the loading pulse. Strain estimations in the test specimen based on the one-dimensional wave propagation theory are found to differ from direct measurements of the same. The discrepancy between the measured and estimated strains along with a general lack of guidance for tensile load generation limit the broader application of the testing technique. The current investigation addresses tensile load generation in a tensile SHPB apparatus, establishes a reliable loading methodology, develops a correction methodology for one dimensional theory strain estimation, and identifies the factors that contribute to wave modulation. A correction methodology for one-dimensional wave propagation analysis is presented to address the discrepancy between strains estimated by one dimensional wave propagation theory and strains measured directly over the test specimen. A method for correcting the strains in the frequency domains using Fourier analysis is presented. The correction methodology is applied to virtual strain measurements from simulations to establish its applicability to experimental results. Subsequently, the methodology is validated with experimental data from carbon fabric laminated composite specimens.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.1 High Strain Rate Testing</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.2 One-Dimensional Elastic Wave Propagation Theory Review</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1.2.1 Specimen Strain, Strain Rate, and Stress</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1.2.2 Assumptions in the Hopkinson Bar Equations</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>1.2.3 Sheet-type Specimen Considerations</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1.3 Previous Work</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1.4 Summary</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>1.5 Objectives</td>
<td>20</td>
</tr>
<tr>
<td>2.</td>
<td>TENSILE SPLIT HOPKINSON PRESSURE BAR</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>2.1 Gripping Mechanisms and Specimen Geometry</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>2.2 Loading Techniques</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>2.2.1 Indirect Methodologies</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>2.2.2 Direct Methodologies</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>2.3 Summary</td>
<td>33</td>
</tr>
<tr>
<td>3.</td>
<td>EXPERIMENTAL METHODS</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>3.1 Graphical Representation of a Stress Wave</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>3.2 Compression SHPB Development</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>3.3 Data Acquisition</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>3.4 Dispersion</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>3.5 Pulse Shaping Technique</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>3.6 Tensile SHPB Development</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>3.6.1 Sleeve Flange</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>3.6.2 Momentum Trap</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>3.7 Specimen Preparation and Gripping Mechanism</td>
<td>49</td>
</tr>
<tr>
<td>4.</td>
<td>FINITE ELEMENT MODEL OF THE SPLIT HOPKINSON PRESSURE BAR</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>4.1 Numerical Model</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>4.1.1 Contact Definition</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>4.2 Finite Element Model of a Compression SHPB</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>4.3 Finite Element Model of a Tensile SHPB</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>4.3.1 Stress Analysis of the Incident Bar-Flange Intersection</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>4.4 Gripping Mechanism and Tension Specimen</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>4.5 Mesh Sensitivity</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>4.6 Experimental Validation of Numerical Model</td>
<td>69</td>
</tr>
</tbody>
</table>
## TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>TENSILE PULSE GENERATION</td>
</tr>
<tr>
<td>5.1</td>
<td>Tensile Pulse Generation Techniques in a SHPB</td>
</tr>
<tr>
<td>5.2</td>
<td>Design for Tensile Load Generation</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Transfer Flange</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Supported Bar Extension</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Coned-shape Flange</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Sleeve Transfer Flange</td>
</tr>
<tr>
<td>5.2.5</td>
<td>Momentum Trap</td>
</tr>
<tr>
<td>5.3</td>
<td>Finite Element Analysis of Tensile Pulse Generation with a Transfer Flange</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Transfer Flange</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Flange Deformation Effect</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Momentum Trap</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Sleeve Transfer Flange</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Coned-shape Flange</td>
</tr>
<tr>
<td>5.4</td>
<td>Experimental Evaluation of tensile SHPB apparatus</td>
</tr>
<tr>
<td>5.5</td>
<td>Summary</td>
</tr>
<tr>
<td>6.</td>
<td>WAVE MODULATION – ONE-DIMENSIONAL THEORY CORRECTION</td>
</tr>
<tr>
<td>6.1</td>
<td>One-Dimensional Theory Estimation of Strain</td>
</tr>
<tr>
<td>6.2</td>
<td>Fourier Analysis</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>6.3</td>
<td>Correction Methodology</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Transfer Function Generation</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Application to Simulation Results</td>
</tr>
<tr>
<td>6.4</td>
<td>Application to Experimental Results</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Material Systems and Specimen Fabrication</td>
</tr>
<tr>
<td>6.4.2</td>
<td>Preparation of Pulses for Fourier Analysis</td>
</tr>
<tr>
<td>6.4.3</td>
<td>Experimental Transfer Function</td>
</tr>
<tr>
<td>6.4.4</td>
<td>Correction of Experimental Results</td>
</tr>
<tr>
<td>6.4.5</td>
<td>Strain Correction Using an Effective Gage Length</td>
</tr>
<tr>
<td>6.5</td>
<td>Summary</td>
</tr>
<tr>
<td>7.</td>
<td>WAVE MODULATION – ONE-DIMENSIONAL THEORY CORRECTION</td>
</tr>
<tr>
<td>7.1</td>
<td>Influential Factors</td>
</tr>
<tr>
<td>7.1.1</td>
<td>Bar Thread</td>
</tr>
<tr>
<td>7.1.2</td>
<td>Pulse Shaper</td>
</tr>
<tr>
<td>7.1.3</td>
<td>Adhesive Joint</td>
</tr>
<tr>
<td>7.1.4</td>
<td>Grip</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (continued)

Chapter | Page
---|---
7.2 Experimental Evaluation | 125
  7.2.1 No Thread Baseline | 127
  7.2.2 Thread Effect | 129
  7.2.3 Pulse Shaper Effect | 133
  7.2.4 Pulse Transmission Frequency Content | 135
  7.2.5 Adhesive Joint Transfer | 137
7.3 Numerical Evaluation | 139
7.4 Summary | 143
8. CONCLUSIONS | 145
  8.1 Load Generation | 146
  8.2 Wave Modulation – One Dimensional Theory Correction | 148
  8.3 Wave Modulation – Influential Factors | 150
  8.4 Recommendations | 151
LIST OF REFERENCES | 153
APPENDIX | 160
  A. Tensile SHPB Assembly Drawings | 161
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Strain rate regime and experimental technique</td>
</tr>
<tr>
<td>2.</td>
<td>Mechanical properties used in the simulation of the compression SHPB</td>
</tr>
<tr>
<td>3.</td>
<td>Dimensions used for simulation of the compression SHPB</td>
</tr>
<tr>
<td>4.</td>
<td>Mechanical properties used in the simulation of the tensile SHPB</td>
</tr>
<tr>
<td>5.</td>
<td>Dimensions used for simulation of the tensile SHPB</td>
</tr>
<tr>
<td>6.</td>
<td>Grip mechanical properties</td>
</tr>
<tr>
<td>7.</td>
<td>Flange length comparison</td>
</tr>
<tr>
<td>8.</td>
<td>Flange height/radius comparison</td>
</tr>
<tr>
<td>9.</td>
<td>Momentum trap addition</td>
</tr>
<tr>
<td>10.</td>
<td>Coned-shaped flange effect</td>
</tr>
<tr>
<td>11.</td>
<td>Flange Impedance change with thread cross-sectional area change in a .0254 m (1 inch) bar</td>
</tr>
<tr>
<td>12.</td>
<td>Test matrix for thread effect in a compression SHPB</td>
</tr>
<tr>
<td>13.</td>
<td>Test matrix for adhesive joint effect in a compression SHPB</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Compression Split Hopkinson Pressure Bar (SHPB)</td>
</tr>
<tr>
<td>2.</td>
<td>Stress balance across a differential element</td>
</tr>
<tr>
<td>3.</td>
<td>Specimen sandwich between incident and transmitter bars</td>
</tr>
<tr>
<td>4.</td>
<td>Typical Tensile Specimen</td>
</tr>
<tr>
<td>5.</td>
<td>Threaded tensile specimen (mm)</td>
</tr>
<tr>
<td>6.</td>
<td>Hun et al. specimen and grip assembly</td>
</tr>
<tr>
<td>7.</td>
<td>Harding and Welsh specimen and test assembly (mm)</td>
</tr>
<tr>
<td>8.</td>
<td>Eskandari’s fixture assembly</td>
</tr>
<tr>
<td>9.</td>
<td>Tension test arrangement of Hauser</td>
</tr>
<tr>
<td>10.</td>
<td>Eskandari’s loading technique</td>
</tr>
<tr>
<td>11.</td>
<td>Bypass (collar) schematic diagram</td>
</tr>
<tr>
<td>12.</td>
<td>Lindholm and Yeakley specimen and test configuration (in)</td>
</tr>
<tr>
<td>13.</td>
<td>Mohr and Gary M-specimen</td>
</tr>
<tr>
<td>14.</td>
<td>Flange loading methodology</td>
</tr>
<tr>
<td>15.</td>
<td>Schematic representation of a direct tension SHPB</td>
</tr>
<tr>
<td>16.</td>
<td>Characteristic lines for a stress wave</td>
</tr>
<tr>
<td>17.</td>
<td>Stress wave propagation in a Compression SHPB</td>
</tr>
<tr>
<td>18.</td>
<td>Compression SHPB apparatus at NIAR/WSU</td>
</tr>
<tr>
<td>19.</td>
<td>Wheatstone bridge circuit</td>
</tr>
<tr>
<td>20.</td>
<td>Wheatstone bridge balancing circuit</td>
</tr>
<tr>
<td>21.</td>
<td>SHPB data acquisition</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>22.</td>
<td>Oscilloscope window - Recorded incident and transmitted pulses</td>
</tr>
<tr>
<td>23.</td>
<td>Incident pulse before and after filtering</td>
</tr>
<tr>
<td>24.</td>
<td>Schematic of the loading end of a compression SHPB with pulse shaper</td>
</tr>
<tr>
<td>25.</td>
<td>Incident pulse for three copper disk thicknesses</td>
</tr>
<tr>
<td>26.</td>
<td>Tensile SHPB apparatus at NIAR/WSU</td>
</tr>
<tr>
<td>27.</td>
<td>Dry test on a tensile SHPB</td>
</tr>
<tr>
<td>28.</td>
<td>Sleeve transfer flange design</td>
</tr>
<tr>
<td>29.</td>
<td>Additional bearing support to minimize vibrations</td>
</tr>
<tr>
<td>30.</td>
<td>Sleeve flange at the end of incident bar</td>
</tr>
<tr>
<td>31.</td>
<td>Momentum trap added after transfer flange</td>
</tr>
<tr>
<td>32.</td>
<td>Tension specimen dimensions (mm)</td>
</tr>
<tr>
<td>33.</td>
<td>Tension specimen bonded to grips</td>
</tr>
<tr>
<td>34.</td>
<td>Alignment fixture for specimen bonding to grips</td>
</tr>
<tr>
<td>35.</td>
<td>Schematic of the numerical model of a compression SHPB in “dry” conditions</td>
</tr>
<tr>
<td>36.</td>
<td>Finite element mesh for the compression SHPB set-up</td>
</tr>
<tr>
<td>37.</td>
<td>Typical compression pulse – Numerical model</td>
</tr>
<tr>
<td>38.</td>
<td>Schematic description of the numerical model in “dry” conditions</td>
</tr>
<tr>
<td>39.</td>
<td>Mesh of the incident bar, striker, and general type transfer flange</td>
</tr>
<tr>
<td>40.</td>
<td>Mesh of the sleeve transfer flange – Cross-section</td>
</tr>
<tr>
<td>41.</td>
<td>Mesh of the momentum trap and support</td>
</tr>
<tr>
<td>42.</td>
<td>Stress levels at incident bar – Flange intersection</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>43.</td>
<td>Mesh of the tension specimen and the gripping fixtures</td>
</tr>
<tr>
<td>44.</td>
<td>Mesh of partial assembly of the incident and transmitter bar, specimen, and grips</td>
</tr>
<tr>
<td>45.</td>
<td>Mesh of tension specimen</td>
</tr>
<tr>
<td>46.</td>
<td>Contact definition between the incident/transmitter bar and gripping fixtures</td>
</tr>
<tr>
<td>47.</td>
<td>Detail of contact definition between tension specimen and gripping fixture</td>
</tr>
<tr>
<td>48.</td>
<td>Tensile SHPB with supported bar extension experimental validation - Strain history</td>
</tr>
<tr>
<td>49.</td>
<td>Momentum trap addition and sleeve flange experimental validation - Strain history</td>
</tr>
<tr>
<td>50.</td>
<td>Flange loading methodology</td>
</tr>
<tr>
<td>51.</td>
<td>Desired pulse characteristics</td>
</tr>
<tr>
<td>52.</td>
<td>Flange parametric study</td>
</tr>
<tr>
<td>53.</td>
<td>Pulse super position in flange design</td>
</tr>
<tr>
<td>54.</td>
<td>Flange length reduction</td>
</tr>
<tr>
<td>55.</td>
<td>Effect of supporting bar extension on pulse propagation</td>
</tr>
<tr>
<td>56.</td>
<td>Cone-shape flange comparison</td>
</tr>
<tr>
<td>57.</td>
<td>Sleeve transfer flange attached to incident bar</td>
</tr>
<tr>
<td>58.</td>
<td>Momentum trap design</td>
</tr>
<tr>
<td>59.</td>
<td>Momentum trap wave propagation</td>
</tr>
<tr>
<td>60.</td>
<td>Incident bar axial strain history for flange length comparison</td>
</tr>
<tr>
<td>61.</td>
<td>Flange height/radius comparison</td>
</tr>
<tr>
<td>62.</td>
<td>Incident bar strain history comparison</td>
</tr>
<tr>
<td>63.</td>
<td>Compressive pulse introduction by flange deformation – Section cut</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>64.</td>
<td>Flange deformation sequence – Section cut ........................................89</td>
</tr>
<tr>
<td>65.</td>
<td>Incident bar strain history for momentum trap addition .........................90</td>
</tr>
<tr>
<td>66.</td>
<td>Incident bar axial strain history for sleeve flange comparison ................91</td>
</tr>
<tr>
<td>67.</td>
<td>Sleeve flange reflection pattern – Lagrange diagram ................................92</td>
</tr>
<tr>
<td>68.</td>
<td>Sleeve flange deformation comparison ..................................................92</td>
</tr>
<tr>
<td>69.</td>
<td>Incident bar strain history for Coned-shape flange comparison .................94</td>
</tr>
<tr>
<td>70.</td>
<td>Experimental incident bar strain history for three configurations ............95</td>
</tr>
<tr>
<td>71.</td>
<td>Specimen strain discrepancy on numerical results ..................................99</td>
</tr>
<tr>
<td>72.</td>
<td>History of pulse contribution to strain estimation ................................100</td>
</tr>
<tr>
<td>73.</td>
<td>Tensile SHPB data sources .................................................................103</td>
</tr>
<tr>
<td>74.</td>
<td>Frequency content of input and output measurements - Numerical .............104</td>
</tr>
<tr>
<td>75.</td>
<td>Transfer function - Numerical ............................................................104</td>
</tr>
<tr>
<td>76.</td>
<td>Transfer function calculation .............................................................104</td>
</tr>
<tr>
<td>77.</td>
<td>One-dimensional strain of a subsequent test in time and frequency domain ......105</td>
</tr>
<tr>
<td>78.</td>
<td>Corrected one-dimensional strain in frequency domain ............................105</td>
</tr>
<tr>
<td>79.</td>
<td>Corrected one-dimensional strain .........................................................106</td>
</tr>
<tr>
<td>80.</td>
<td>Correction process of one-dimensional strain estimation ........................106</td>
</tr>
<tr>
<td>81.</td>
<td>Aluminum and carbon fabric composite tensile specimens ........................107</td>
</tr>
<tr>
<td>82.</td>
<td>Incident and reflected pulses in a low velocity tensile test .....................108</td>
</tr>
<tr>
<td>83.</td>
<td>Pulse zeroing after pulse decaying ......................................................108</td>
</tr>
<tr>
<td>84.</td>
<td>Effect of zeroing procedure in the frequency content ................................109</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>85.</td>
<td>Specimen strain – Experimental</td>
</tr>
<tr>
<td>86.</td>
<td>Frequency content of input and output measurements - Experimental</td>
</tr>
<tr>
<td>87.</td>
<td>Transfer function - Experimental</td>
</tr>
<tr>
<td>88.</td>
<td>Transfer function repeatability</td>
</tr>
<tr>
<td>89.</td>
<td>Grip-Specimen set-up</td>
</tr>
<tr>
<td>90.</td>
<td>Strain correction of dog-bone specimen at strain-rate 250 s⁻¹</td>
</tr>
<tr>
<td>91.</td>
<td>Failed dog-bone specimen at strain-rate 250 s⁻¹</td>
</tr>
<tr>
<td>92.</td>
<td>Stress correction of dog-bone specimen at strain-rate 250 s⁻¹</td>
</tr>
<tr>
<td>93.</td>
<td>Stress vs. Strain of dog-bone specimen at strain-rate 250 s⁻¹</td>
</tr>
<tr>
<td>94.</td>
<td>Strain correction of dog-bone specimen at strain-rate 300 s⁻¹</td>
</tr>
<tr>
<td>95.</td>
<td>Failed dog-bone specimen at strain-rate 300 s⁻¹</td>
</tr>
<tr>
<td>96.</td>
<td>Stress correction of dog-bone specimen at strain-rate 300 s⁻¹</td>
</tr>
<tr>
<td>97.</td>
<td>Stress vs. Strain of dog-bone specimen at strain-rate 300 s⁻¹</td>
</tr>
<tr>
<td>98.</td>
<td>Strain correction of straight specimen at strain-rate 200 s⁻¹</td>
</tr>
<tr>
<td>99.</td>
<td>Failed straight specimen at strain-rate 250 s⁻¹</td>
</tr>
<tr>
<td>100.</td>
<td>Strain correction of straight specimen at strain-rate 250 s⁻¹</td>
</tr>
<tr>
<td>101.</td>
<td>Strain correction of dog-bone specimen at strain-rate 250 s⁻¹</td>
</tr>
<tr>
<td>102.</td>
<td>Strain correction of dog-bone specimen at strain-rate 300 s⁻¹</td>
</tr>
<tr>
<td>103.</td>
<td>Time domain dispersion effects on pulse characteristics</td>
</tr>
<tr>
<td>104.</td>
<td>Necessary grips/attachments on a tensile SHPB</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>105.</td>
<td>123</td>
</tr>
<tr>
<td>106.</td>
<td>123</td>
</tr>
<tr>
<td>107.</td>
<td>124</td>
</tr>
<tr>
<td>108.</td>
<td>125</td>
</tr>
<tr>
<td>109.</td>
<td>125</td>
</tr>
<tr>
<td>110.</td>
<td>127</td>
</tr>
<tr>
<td>111.</td>
<td>128</td>
</tr>
<tr>
<td>112.</td>
<td>128</td>
</tr>
<tr>
<td>113.</td>
<td>129</td>
</tr>
<tr>
<td>114.</td>
<td>129</td>
</tr>
<tr>
<td>115.</td>
<td>130</td>
</tr>
<tr>
<td>116.</td>
<td>130</td>
</tr>
<tr>
<td>117.</td>
<td>131</td>
</tr>
<tr>
<td>118.</td>
<td>132</td>
</tr>
<tr>
<td>119.</td>
<td>132</td>
</tr>
<tr>
<td>120.</td>
<td>132</td>
</tr>
<tr>
<td>121.</td>
<td>133</td>
</tr>
<tr>
<td>122.</td>
<td>134</td>
</tr>
<tr>
<td>123.</td>
<td>134</td>
</tr>
<tr>
<td>124.</td>
<td>135</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>125.</td>
<td>Comparison combined effect of coarse thread, pulse shaper, and thread in the time history and the frequency domain at 25 m/s</td>
</tr>
<tr>
<td>126.</td>
<td>Direct pulse transmission baseline</td>
</tr>
<tr>
<td>127.</td>
<td>Comparison incident and transmitted pulses history and frequency content at 25 m/s</td>
</tr>
<tr>
<td>128.</td>
<td>Ratio transmitted to incident pulse frequency content baseline</td>
</tr>
<tr>
<td>129.</td>
<td>Adhesive joint experimental set-up before and after test</td>
</tr>
<tr>
<td>130.</td>
<td>Comparison incident and transmitted pulses history and frequency content at 25 m/s</td>
</tr>
<tr>
<td>131.</td>
<td>Ratio transmitted to incident pulse frequency content with adhesive joint</td>
</tr>
<tr>
<td>132.</td>
<td>Comparison direct transfer vs. adhesive joint at 25 m/s</td>
</tr>
<tr>
<td>133.</td>
<td>Frequency components correlation of adhesive joint with time history at 25 m/s</td>
</tr>
<tr>
<td>134.</td>
<td>Finite element model of load transfer ideal case</td>
</tr>
<tr>
<td>135.</td>
<td>Finite element model of tensile grips designed for the current investigation</td>
</tr>
<tr>
<td>136.</td>
<td>Grip effect on reflected pulse</td>
</tr>
<tr>
<td>137.</td>
<td>Grip effect on transmitted pulse</td>
</tr>
<tr>
<td>138.</td>
<td>Strain estimation for direct case – No grips</td>
</tr>
<tr>
<td>139.</td>
<td>Strain estimation for 1 inch diameter grip</td>
</tr>
<tr>
<td>140.</td>
<td>Strain estimation for scaled-mass grip</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Design requirements for crashworthiness of aircraft and automobiles have evolved significantly during the past couple of decades [1]. Constant reassessment of the design and certification processes is required as new materials and manufacturing processes are introduced. Nevertheless, the two fundamental crashworthiness requirements during specific crash events are still applicable [2, 3]. First, the survivable volume of the structure must be preserved by controlling the structural deformation. Second, the dynamic loads transmitted to the occupants should never exceed predefined acceptable limits. Consequently, vehicle structural configurations, seats, and attachment to the frame must be conceived meeting design parameters dictated by crashworthiness requirements.

High strain rates occur not only in airplane/automobile accidents, but also in several engineering applications, such as impact or bird-strike events, plastic flow close to the tip of a fast propagating crack, high speed metal forming, etc [4]. According to Amos [1], projectile impacts produce a rather wide spectrum of phenomena depending on the energies and momentum exchanges involved. The phenomena can be classified as either global (structural) or local (material). At low velocities, structural response dominates while material response dominates the behavior at high velocities. At intermediate speeds, such as in the foreign object impact situations, it is necessary to properly account for both structural and material responses [1].

Variations in the mechanical response of most materials with increasing strain rates are reported in open literature [4, 5, 6, 7, 8, 9]. In order to include such effect in numerical modeling of structures, appropriate constitutive equations need to be developed. Constitutive equations or
equations of state, which relate stress and strain to unusual conditions of strain rate are fundamental to engineering design. The emphasis of this work is in the measurement of tensile strength since it is regarded as one of the most important intrinsic material properties needed by designers; compression strength is affected by end conditions and a combination of structural and material behavior.

Characterizing the behavior of composites under dynamic loading is not an easy task. The majority of dynamic testing techniques introduce complex stress and strain fields which complicates the fundamental formulation of strain rate effects on material properties and behavior. The Split Hopkinson Pressure Bar (SHPB) [10] facilitates material characterization under an approximate uniaxial, homogeneous state of stress. The classical compression SHPB [11] can be modified for high strain rate tensile testing. However, work published in open literature [12] report difficulties in the design of grips and specimen, as well as the estimation of error. In the classical compression SHPB apparatus, the specimen is sandwiched between the ends of the two pressure bars (incident and transmitter bars). The specimen sits flat against the ends of each bar, requiring no fixturing or additional gripping mechanism. On the other hand, several difficulties arise when tensile testing is at hand. Complex load transfer methodologies to generate tensile loading are used. Gripping mechanisms become material specific. These factors add further complexity to the wave propagation throughout the apparatus.

Mechanical interfaces between specimen, fixture, and bars will affect the stress wave transmission between different components. In addition to the wave dispersion caused by the spread of phase velocities [13], other possible sources of distortion of the pulses are fixture devices, adhesive layers, and specimen geometry. Traditionally SHPB apparatus used cylindrical testing specimens where the wave propagation is close to 1-D case [14]. However, the
application of a tensile SHPB to test sheet-type specimens is not straight forward. Sheet-type specimens are mandatory for the majority of laminated composite materials. The square cross-section of the specimen introduces a three-dimensional state of stress that could lead to erroneous strain measurements.

1.1 High Strain Rate Testing

The loading times associated with quasi-static loading are considered to be long enough in duration as compared with the material/structural response such that the internal equilibrium within the material is maintained throughout the loading process [7]. As the loading time is shortened, material inertia effects become important and the loading becomes dynamic. Most structural composite materials have been extensively characterized under quasi-static conditions. However, dynamic material characterization of composites is rather limited [8]. The variation in material strength with applied strain-rate is an important consideration when evaluating materials involved in the design of structures subjected to suddenly applied loads. The importance follows from the fact that the internal material response time might be longer than the loading duration [7], i.e., the material does not have enough time to balance transient external tractions with internal stresses of the material. It has been observed that for many materials the stress increases rapidly with strain-rate for a given suddenly applied load [8].

Various test methods used to date for material characterization of composites have advantages and limitations. As they can be used to generate a certain range of strain rate, each technique can provide information about the dynamic response of the material over a limited range of strain rates (see Table 1).

Servo-hydraulic systems are frequently used. However, the application is limited to low strain-rates (0.00167 - 10 s\(^{-1}\)). The ability to control speed is a function of the response capability
of a servo-controlled system working in a control-loop mode [15]. The distance traveled may also affect the speed capability. They are usually loaded in uniaxial test mode and they are used to test material strain rate sensitivity, mechanical properties, and failure modes.

Table 1: Strain rate regime and experimental technique [16]

<table>
<thead>
<tr>
<th>Loading Times [sec]</th>
<th>10^6 - 10^4</th>
<th>10^4 - 10^2</th>
<th>10^0 - 10^-1</th>
<th>10^-2 - 10^-4</th>
<th>&gt; 10^-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain-Rate Regime [sec^-1]</td>
<td>&lt; 10^-3</td>
<td>10^-3 - 10^-1</td>
<td>10^0 - 10^1</td>
<td>10^2 - 10^4</td>
<td>&gt; 10^4</td>
</tr>
<tr>
<td>Test Methodology</td>
<td>Constant Load Machines</td>
<td>Hydraulic or Screw Machines</td>
<td>Pneumatic or Mechanical Machines</td>
<td>Mechanical or Explosive Impact</td>
<td>Gas Gun or Explosive Driven Plate Impact</td>
</tr>
</tbody>
</table>

Another commonly used apparatus is a drop tower or drop weight impact apparatus [17, 18]. It can accommodate different specimen geometries. It introduces wave reflections on the load cell that would superimpose on specimen stress [19]. Although relatively high strain-rates can be achieved with the drop tower, difficulties arise from the existence of non-uniform stress fields and multiple types of damage. A non-uniform state of stress would make the fundamental formulation of strain-rate effects on material properties [14] extremely complicated. Data obtained relates to material energy absorption and fracture toughness [8].

The Charpy test [20] is used as a standardized material energy absorption test, notch sensitivity, and failure type. Although high rate deformation can be achieved near notches, complex stress and strain fields and combined modes of failure complicate the fundamental formulation of strain rate effects on materials properties and behavior [21]. Stress wave reflections further inhibit fundamental analysis of material response and loading rate dependence.
Expanding ring test [22, 23] is a sophisticated technique that introduces strain rates over $10^4 \text{ s}^{-1}$. Providing the expansion in the ring is symmetric, its advantage is that it subjects the material to a dynamic uniaxial state of stress without bar end effects. However, the strain rate is not usually constant and specimens experience a compressive preload in the radial direction that often exceeds the yield stress during the acceleration phase.

An approximate uniaxial homogeneous state of stress at high rates can be achieved using the classical compression Split Hopkinson Bar technique (SHPB). However, contact surfaces conditions are very critical and specimens must be short to minimize wave propagation effects [10]. Most of the compressive high strain-rate properties reported to date have been obtained by means of the pressure bar test [8]. The technique provides data related with the material strain rate sensitivity, dynamic ultimate stress, fracture mechanisms, and damage initiation.

A compression SHPB is comprised of three separate bars [10], i.e., the striker, the incident or input bar, and the transmitter bar (see Figure 1). The striker bar is accelerated using compressed air or a gas gun. An elastic stress pulse is imparted to the incident bar by impacting it with a striker bar of the same cross sectional area and modulus. The wavelength of the generated wave is equal to twice the length of the striker bar and propagates through the incident bar with the velocity of sound. The elastic wave propagates uninterrupted along the length of the incident bar until it reaches the interface with the sample. When the elastic wave reaches the specimen-incident bar interface, due to the change in material impedance [24], part of it is reflected back, and part of it is transmitted through the specimen to the transmitter bar. The velocity of the striker controls the strain level and strain-rate achieved, while the length determines the duration of the test. The impact velocity can be controlled by changing the pressure of the compressed air or gas.
In order to determine the strain within the specimen, strain gages are mounted on both, the incident and transmitter bar [10]. Strain gage data is used along with one-dimensional wave propagation theory to estimate specimen strain. Strain gages are placed in a position where no superposition between the reflected wave and incident wave will occur over the duration of the test. Since the pulse wavelength is twice the length of the striker, the incident bar must be longer than two times the length of the striker. This also implies that the strain gages must be located at least the length of the striker from the bar end to avoid superposition of the waves.

Figure 1: Compression Split Hopkinson Pressure Bar (SHPB) [10].

1.2 One-Dimensional Elastic Wave Propagation Theory Review

The theoretical foundation of the SHPB technique is provided by the one-dimensional theory of wave propagation in elastic bars. While this theory has been widely published in great detail [9, 25, 26], an abridged version has been included in this document for completeness. The longitudinal vibration of an elastic rod is described by the one-dimensional equation of motion. It is derived after enforcing force balance across a differential element \( dx \) of a long rod of cross sectional area \( A \), density \( \rho \), and modulus of elasticity \( E \), when it is been subjected to a longitudinal impact (see Figure 2). The differential force across the element for a linear elastic material can be written as

\[
\sigma = E \frac{\partial u}{\partial x} \tag{1.1}
\]

\[
dF = A \cdot E \cdot d\varepsilon \tag{1.2}
\]
Applying Newton’s second law, the equation of motion for a non-dispersive wave [25] is given by

$$\frac{\partial^2 u_x}{\partial t^2} = c_o^2 \cdot \frac{\partial^2 u_x}{\partial x^2}$$  \hspace{1cm} (1.3)

where $c_o = \sqrt{\frac{E}{\rho}}$, is the wave velocity.

![Stress balance across a differential element][9].

The displacement solution of the wave equation of motion has the form [9]:

$$u_x = f(x-c_o t) + g(x+c_o t)$$  \hspace{1cm} (1.4)

where $f$ and $g$ are arbitrary functions. The solution represents two superimposed pulses traveling in positive and negative directions. Differentiation of the displacement solution with respect to position $x$ and with respect to time $t$, leads to the axial strain $\varepsilon_x$, stress $\sigma_x$, and particle velocity $v$.

$$\varepsilon_x = \frac{\partial u_x}{\partial x} = f'(x-c_o t) + g'(x+c_o t)$$  \hspace{1cm} (1.5)

$$\sigma_x = E \left[ f'(x-c_o t) + g'(x+c_o t) \right]$$  \hspace{1cm} (1.6)

$$v = \frac{\partial u_x}{\partial t} = c_o \left[ - f''(x-c_o t) + g''(x+c_o t) \right]$$  \hspace{1cm} (1.7)

In the above equations, a wave moving in the positive direction only, may be simply expressed as

$$u_x = f(x-c_o t)$$  \hspace{1cm} (1.8)
1.2.1 Specimen Strain, Strain Rate, and Stress

One-dimensional elastic wave theory is used to determine the particle velocity in the elastic bar which is directly related to the strain in the elastic bar. Recorded strain histories on the incident and transmitter bars are used as experimental data to determine strain rate, strain, and stress on the specimen (see Figure 3).

![Diagram of Specimen sandwich between incident and transmitter bars](image)

**Figure 3:** Specimen sandwich between incident and transmitter bars [9].

Particle velocity at the end of the incident bar in contact with the specimen can be written in terms of the measured strain histories as [9]

\[ v_1 = c_o \left[ - f'(x - c_o t) + g'(x + c_o t) \right] = c_o \left[ - \varepsilon_i + \varepsilon_R \right] \]  \hspace{1cm} (1.9)

And the particle velocity at the interface of the specimen and the transmitter bar as

\[ v_2 = -c_o \cdot \varepsilon_T \]  \hspace{1cm} (1.10)

Combining these results, the change in particle velocity can be expressed in terms of the change in the strain as [9]

\[ \Delta v_{bar} = \sqrt{\frac{E}{\rho}} \cdot \Delta \varepsilon_{bar} \]  \hspace{1cm} (1.11)

which leads to the expression for the average strain rate in the specimen [9]

\[ \dot{\varepsilon} = \frac{(v_1 - v_2)}{l_o} = -\frac{c_o}{l_o} \left( \varepsilon_i - \varepsilon_R - \varepsilon_T \right) \]  \hspace{1cm} (1.12)

The average strain in the specimen simply follows as
\[
e = \frac{(u_1 - u_2)}{l_o} = -\frac{c_o}{l_o} \int_0^t (\varepsilon_i - \varepsilon_R - \varepsilon_T) dt
\]  

(1.13)

Force balance over a test specimen of area \(A_o\) sandwiched between the incident and transmitter bars reveals that the average force and average stress are simply [9]

\[
\bar{F} = \frac{F_1 + F_2}{2}
\]  

(1.14)

\[
\sigma = \frac{F_1 + F_2}{2 \cdot A_o}
\]  

(1.15)

where \(F_1\) and \(F_2\) are the applied forces on the left and right hand side of the test specimen. If the stress across the specimen is constant, i.e., it is in dynamic equilibrium, the forces at the interfaces can be expressed in terms of the strain histories recorded in the incident and transmitter bars as [9]

\[
F_1 = E \cdot A \cdot (\varepsilon_i + \varepsilon_R)
\]  

(1.16)

\[
F_2 = E \cdot A \cdot \varepsilon_T
\]  

(1.17)

Then, the average stress on the specimen can be written as

\[
\sigma = \frac{E \cdot A}{2 \cdot A_o} \cdot (\varepsilon_i + \varepsilon_R + \varepsilon_T)
\]  

(1.18)

1.2.2 Assumptions in the Hopkinson Bar Equations

The increasing need for dynamic material properties for constitutive equations used in numerical models of impact has added to the cause of SHPB to be used as a common testing methodology. However, the SHPB technique is developed based on the one-dimensional wave propagation theory, and assumptions are inherent to the applications of its principles [9].

Basic assumptions intrinsic to the method include [9, 27, 28]: the waves propagate in the bar are elastic waves, the pressure pulse is propagated without dispersion, plane sections remain
plane, the stress distribution is uniform across the rod cross-section implying that radial inertia may be neglected, and the stress and strain fields in the specimen are homogeneous.

Ideally, the pulse should propagate without dispersion. This is only true when the lateral dimensions of the bar are small in comparison to the wavelength of the pulse [27]. However, this is practically impossible due to the dispersive nature of solid bars [24] and the minimization of the mechanical dispersion is the only practical option.

If the specimen deforms uniformly such that the strains in the incident bar $\varepsilon_I$ and $\varepsilon_R$ are equal to the strain in the transmitter bar $\varepsilon_T$, the expression for stress, strain rate, and strain in the specimen, equations (1.18), (1.12), and (1.13) respectively [9], can be reduced to a 1-wave analysis given by

$$\sigma \cong \frac{E \cdot A}{A_o} \cdot \varepsilon_T$$

(1.19)

$$\dot{\varepsilon} \cong \frac{2 \cdot c_o}{l_o} \cdot \varepsilon_R$$

(1.20)

$$\varepsilon \cong \frac{2 \cdot c_o}{l_o} \int (\varepsilon_R) dt$$

(1.21)

Notice that the stress in the specimen is directly related to the amplitude of the transmitted pulse. The strain within the specimen is related to the time integral of the amplitude of the reflected pulse. The later equations provide the means to determine the dynamic stress-strain behavior of the specimen simply by strain measurements made on the surface of the pressure bars. However, the equilibrium assumption is questionable. It can be verified by establishing the time taken to achieve equilibrium and comparing the results of the classical 1-wave analysis with a 2-wave analysis; where incident and reflected waves are used for the
calculation of stress at the specimen-incident bar interface. In general, results show an initial “ringing-up” period followed by a strain range where the condition may be satisfied [29].

1.2.3 Sheet-type Specimen Considerations

The majority of test apparatus used to generate high strain rates in an experimental environment have limitations. In the SHPB case, limitations originate not only from the system itself but from the testing material and specimen geometry. Stress wave analysis of a tensile SHPB is basically the same as the classical compression SHPB [12, 41, 43, 45]. However, wave propagation is altered by additional gripping devices, i.e., there is an impedance mismatch between the components necessary for attaching the specimen to the incident and transmitter bars. In addition, tensile testing specimens require a shoulder area for gripping, a smooth transition between the shoulders and the gage section, and a reduced cross-sectional area in the gage section. These requirements, along with the fact that stress wave analysis of SHPB provides only a relative measurement of the displacement between the ends of the incident and transmitter bars, limit the definition of the specimen gage length. Researchers [6, 30, 31, 32, 33] have chosen to use an effective gage length instead of taking into account the strain in the gripping section, e.g. threads and shoulders.

The majority of research conducted up until today uses circular cross-section specimens [33, 34]. The validity of one-dimensional wave theory has been shown to approximate strain and stresses fairly well in compression testing when cylindrical specimens are used. A similar scenario is observed for tensile testing of circular cross-section specimens after introducing effective gage length corrections. However, the application of a tensile SHPB apparatus to test sheet-type specimens is not straightforward. Sheet-type specimens commonly used in the characterization of sheet metals and laminated composites represent a challenge to the
applicability of the one-dimensional wave propagation theory. Specimen dimensions have a significant effect on the friction condition and deformation behavior [9]. Therefore, questions remains about the uniaxiality of the stress field and about the uniformity of the strain distribution over the gage length of a square cross-section specimen.

1.3 Previous Work

Several authors [6, 30, 31, 32] have addressed the application of the SHPB technique and the one-dimensional wave analysis to tensile testing of materials under dynamic conditions. Early work is concerned with cylindrical specimens and the validity of the one-dimensional assumptions. Limited work [33] has been done where sheet-type specimens have been evaluated. In addition to wave perturbation introduced by the added mechanical fixtures necessary for gripping the tensile specimen, questions remain about the uniformity of the strain field and about the homogeneity of the stress field on the specimen.

As early as 1960, Harding et al. reported the implementation of SHPB technique for tensile testing. However, corrections for the active gage length that aim to take into account the contribution of the specimen shoulders were reported years later by Albertini et al. [6]. The initial length of the specimen was simply corrected for the one-dimensional wave theory formulae for strain, strain-rate, and stress. The correction was carried out by tracking the deformation of the specimen with a lattice printed by photo-etching. The deformation measurement was improved a few years later using an optical microscope [30]. The contribution of the end sections to the whole specimen deformation process was corrected under the assumption that the specific volume of the material remains constant. The corrected active length was defined as

\[ l_o^c = l_o + (\Delta l - \Delta l_o) \cdot \frac{l_o}{\Delta l_o} \]  \hspace{1cm} (1.22)
where $\Delta l$ is the change in length including the two shoulders, $l_o$ is the nominal active length.

A similar approach was followed by other researchers. Nicholas et al. [31] found an equivalent effective length $l_E$ to give the correct value for the strain in the uniform central region of the specimen. It was found to be constant at early stages of elastic deformation, but it was assumed to hold constant all over the test. From quasi-static testing, a strain-deflection expression was developed by fitting test results. The expression was used in subsequent SHPB testing to calculate strain from observed deflections.

Ellwood et al. [32] also reported an equivalent effective length $l_E$. The strain history from a small strain gage attached to the gage section of the specimen was compared with the strain obtained from one-dimensional wave analysis. It was found that the effective length was virtually independent of strain rate with 5% variation. In contrast to Nicholas et al. [31], strain was not assumed to be constant after 5% of deformation. Instead, permanent deformation was measured comparing markings scribed in the specimen and an effective length was found to remain constant up to 10% deformation. The effective gage length correction assumes a linear relationship between measured strain and estimated strain to be valid throughout the entire deformation history. Ellwood et al. provided experimental results for 321 stainless steel cylindrical specimens and the effective length was used as a characteristic of the system. It was used for correcting any subsequent measurement such that the strain gage directly attached to the specimen was no longer needed. However, a comparison with uncorrected strain data is not provided. Similarly, Nicolas et al. showed experimental results for metallic cylindrical specimens but a comparison with uncorrected results is not made. However, it is pointed out that the accuracy of the strain calculation is poor for very small strains such that a constant value is not valid at every deformations stage.
A direct strain measurement on the specimen applied to sheet-type specimens was introduced by LeBlanc and Lassila [33]. After one-dimensional wave analysis, the strain on the specimen implied that the gage length not simply as the length between the grips but as the relative displacement between two gage marks within the gage length. Photographs were taken every 3 μs using a high-speed camera. The distance between gage marks was measured on the film negative using an optical comparator. Engineering strain was calculated for each frame and corresponding time as

\[
\varepsilon = \frac{L_o \cdot M_1 \cdot M_2 - L_m}{L_o}
\]

where \(L_o\) is the undeformed specimen gage length, \(L_m\) is the distance between gage marks, \(M_1\) is the overall magnification factor, and \(M_2\) is the magnification factor for an individual framing lens. LeBlanc and Lassila’s real gage section approach is not consistent across different material systems. Apparent accuracy was observed for some materials (annealed tantalum), but not for others (annealed copper) when compared to compression results. The technique applied to measure strain in the specimen is only valid when the specimen is undergoing uniform deformation, but the deformation process is not confined to the specimen gage section in a tensile test. However, authors did not use the real gage section to correct one-dimensional wave analysis. In addition, the specimen geometry may not accommodate a direct comparison between tension and compression results.

A more comprehensive approach was introduced by Li et al. [35] where sources of individual errors were evaluated. They included strain error resulting from the threaded connection between the specimen and the bars and stress error caused by the cross-sectional area mismatch between the specimen and the bar. In their work, Li et al. idealized the connection so that wave reflection at every gap on the threads was ignored. The threaded connection was
evaluated from a material point of view. The connection portion of the specimen was treated as a composite material so that the effective modulus of this composite is estimated by the rule of mixtures. The error introduced to the specimen strain by wave reflections on the connection portion is approximated by correcting the strain from one-dimensional theory. A first-order approximation of strain is given by

$$\varepsilon^* = \varepsilon_s + \frac{L^* E}{L_s E} \cdot (\varepsilon_i + \varepsilon_R - \varepsilon_T)$$  \hspace{1cm} (1.24)$$

where $\varepsilon_s$ is the real strain in the specimen, $\tilde{E}$ is the effective modulus, $L^*$ is the connection portion, and $L$ is the specimen gage length. Notice that when the material of the specimen and the bar are different, the larger the ratio of the connection length to specimen length, the larger the error. However, the actual error introduced by the connection can be estimated experimentally by testing specimens of the same material as the bars and comparing with specimen of different materials. The strain approximation provides a design relation for the relative length of the connection with respect to the specimen length. However, only preliminary test results for aluminum cylindrical specimens are provided using the length between the middle points of the fillets as the gage length for the calculation of strain. It is not clear if the strain correction is used. Therefore, additional tests should provide the extent of the application of the strain correction to experimental results.

On the other hand, stress error estimation in Li et al. work was the result of experimental observations. Mounting strain gages directly on the specimen, the real stress was estimated in the elastic regime. The relative error between one-dimensional wave analysis stress $\sigma_s^*$ and the real stress was defined as
\[ \delta = \left| \frac{\sigma_s - \sigma_{sT}}{\sigma_s} \right| = \left| \frac{E \cdot \frac{A_b}{A_s} \cdot \varepsilon_T - \sigma_s}{\sigma_s} \right| \]  

(1.25)

where \( A_b \) is the cross sectional area of the bar and \( A_s \) is the cross sectional area of the specimen.

It was observed that the stress error decays with time. However, results were generated in the elastic range. The authors raised the question whether this trend is also valid in the plastic range since it is highly possible that the specimen enters the plastic range before reaching a uniform state of stress. Corrections for one-dimensional wave analysis were not presented. Therefore, the application of the error assessment here presented remains questionable.

Ravichandran and Subhash [36] studied in detail the assumption that stress within the specimen is equilibrated. During the initial loading, the specimen is undergoing elastic deformation under non-uniform loading conditions. Equilibrium is established after some time. Therefore, before achieving an equilibrium state no failure strength data should be obtained. Based on their analysis, equilibrium in the specimen establishes when the gradient of stress along the length of the specimen is within 5% of the mean stress. This condition is reached after a pulse has reflected back and forth within the specimen several times. Equilibrium then needs to be verified for every application. A homogenization ratio was defined as a function of the mechanical impedance mismatch between the bar and the specimen and also as a function of the shape of the incident pulse. It was implemented by Li and Lambros [37] as an experimental verification of homogeneous deformation by comparing the force on either side of the face of the specimen. The homogenization ratio is defined as

\[ R(t) = \frac{1}{2} \frac{\sigma_s - \sigma_T}{\sigma_s + \sigma_T} \]  

(1.26)
where $\sigma_i$ and $\sigma_f$ are the axial stresses at the two ends of the specimen. The lower the ratio, the closer the specimen is to a homogeneous state of stress. Originally developed for ceramic materials, the verification procedure can be extended to other materials by adjusting the impedance mismatch ratio. However, it does not constitute a correction to one-dimensional stress analysis. It defines an applicable range in which the equilibrium assumption is valid.

Eskandari and Nemes [21] questioned the accuracy of strain on the specimen calculated from one-dimensional wave analysis when applied to any testing other than compression testing. The use of specimen fixtures in a tensile SHPB creates such a complexity to wave propagation that direct use of one-dimensional wave analysis equations is not possible. A calibration of the testing apparatus was then proposed based on strain gage measurements of the strain in the specimen. It was found that a linear relationship exists between the measured and calculated strain allowing for the definition of a calibration factor. It was defined as the ratio of calculated strain to measured strain and it can be introduced into equation (1.21) to correct for specimen strain as

$$\varepsilon = -\left(\frac{1}{CF}\right) \cdot \frac{2 \cdot c_o}{l_o} \int (\varepsilon_R) dt$$

(1.27)

where $CF$ is the calibration factor. As the authors pointed out, the calibration factor is specific of the testing apparatus and should be generated for every set of grips or specimen geometries. The procedure implemented by the authors follows the lines of the one presented by Ellwood et al. where an effective gage length was suggested and used to linearly correct the strain calculation for a cylindrical specimen. Eskandari and Nemes applied the same procedure to obtain a calibration factor and linearly correct for the strain in sheet-type specimens. Experimental results showed that a linear relationship is not valid throughout the deformation history. The correction
factor suggests a linear relationship within the elastic range. However, an applicable range should be defined before extending the correction to subsequent testing.

Hun et al. [12] implemented a verification procedure on the testing apparatus to quantify the level of error caused by the grip and the specimen geometry. The level of error introduced by the grips is estimated by comparing the waves acquired from experiments with the Pochhammer-Chree solution [38]. On the other hand, the error introduced by sheet-type specimens is quantified by evaluating stress uniformity across the specimen gage length. Hun et al. defined the error in the grip as the deviation between the incident and the reflected wave. The deviation is the result of not only the wave disturbance on the grip but also, the dispersion effect as the wave propagates in the bar. However, experimental results showed slight deviations between the two waves. Therefore, the authors neglected the wave dispersion effect in calculating the grip effect. The error in the grip was evaluated solely in terms of the energy loss during propagation; 4% of the incident energy was reported as lost in the grip. Specimen strain and specimen strain rate would be erroneously estimated after one-dimensional analysis since they are functions of the measured reflected strain $\varepsilon_R$, see equations (1.20) and (1.21). The actual strain on the specimen would be higher than the measured one, but it can be corrected in terms of the energy loss.

Hun et al. also evaluated the error introduced by specimen geometry to the propagation of the one-dimensional wave through sheet-type specimens. Force equilibrium across a specimen deforming at high strain rates is only an assumption because of inertial and grip effects. Forces at the interfaces expressed in terms of the strain histories recorded in the incident and transmitter bars are not the same such that,

$$\varepsilon_i + \varepsilon_R \approx \varepsilon_T$$  

(1.28)
Hun et al. defined the amount of discrepancy, as the geometrical error of a sheet-type specimen as

\[ Error = \left( \frac{\varepsilon_i + \varepsilon_R - \varepsilon_T}{\varepsilon_i} \right) \]  

(1.29)

The geometrical error was not used to correct one-dimensional analysis; instead it provided the means to determine the optimum gage length. Specimen gage length and width were varied and the strain uniformity across the gage length was evaluated. By minimizing the loading equilibrium error, they were able to recommend optimum specimen dimensions. It was concluded that a gage length between 2 and 8 mm was acceptable. Also, optimum gage width was observed to be 6 mm.

The energy approach used by Hun et al. provides an overall estimate of the load transfer between components: incident bar, incident grip, specimen, transmitter grip, and transmitter bar. It is not discussed by the authors, but the one-dimensional strain in the specimen could be corrected to account for the lower strain measured in the incident bar. However, it would be simply a first order approximation since it neglects the dispersion error and possibly, it would overestimate the energy loss in the grip-specimen interface. In reality, the wave energy that is transmitted to the specimen may be larger than the one estimated based on the reflected wave. In addition, it can be argued that the selection of starting and ending points when estimating the wave energy can add error to the procedure. On the other hand, one-dimensional stress estimation on the specimen, calculated after the strain recorded in the transmitter bar, would also include the error due to the energy loss on the transmitter grip. The measured transmitter strain would be lower than the actual strain observed in the specimen. The geometrical error presented by the authors would only provide verification tools, but it would not correct for the lower strain measurement.
1.4 Summary

Provided that the assumptions inherent to the SHPB analysis are valid and the axial stress and strain fields estimated on the specimen represent the average response of the material, the dynamic stress-strain behavior of different metals obtained using the SHPB technique are acceptable. The technique has been widely used to characterize metals and is increasingly applied to characterize non-metallic materials such as ceramics, polymeric composites materials, foams, etc. Regardless of the limitations of the technique, it is used simply because it is more accurate than other alternative methods such as drop towers and high speed servo-hydraulic systems, and also because the axial non-uniformity due to the behavior of the sample introduces similar errors for every testing system [39].

Although the SHPB technique have been established as the most reliable technique for medium and high strain rate testing, proper understanding of its limitations provides credibility to the experimental results.

Tensile SHPB apparatus inevitably deviates from the one-dimensional wave propagation due to the introduction of grips to hold the test specimen. Additional perturbations to wave propagation also result due to choice of specimen geometry. There seems to be general agreement among researchers about the need to use an effective gage length for the strain calculation on the specimen [6, 30, 31, 32, 33]. Because strain history in the incident and transmitter bars represent an overall response of the testing apparatus, the approximation of specimen strain based on the strains history need to be corrected. However, effective gage length takes into account only the deformation present in regions adjacent to the specimen gage section. It does not correct for the overall system response affecting the single specimen response. The actual velocity of the ends of the specimen differs due to the compliance of the apparatus and
loading attachments. Although individual errors are difficult to quantify, the contribution of every component in the testing apparatus is present in overall system response. An overall correction for one-dimensional wave propagation analysis that is capable of quantifying the pulse attenuation not only due to the gripping devices but also the effect of sheet-type specimens is needed.

1.5 Objectives

A thorough understanding of the limitations and the different parameters involved when testing, under tension, at high strain rates using the SHPB apparatus is required. The testing apparatus requires calibration even before applying the technique to recovery experiments to study history effects on the material or before extending the methodology to characterize other materials such as laminated composite materials. Wave modulation resulting from the combination of individual component response(s) in the testing apparatus must be evaluated. In the present study, a tensile SHPB apparatus is developed. Tensile pulse generation techniques are investigated experimentally and numerically. Wave modulation influential factors are evaluated, and subsequent tests are corrected for wave modulation using a transfer function specific of the current testing apparatus. The primary objectives of the current investigations are:

- To identify loading pulse distortion introduced by the mechanical interfaces in a SHPB employing transfer flange method
- To design a load transfer technique that minimizes loading pulse distortion and attenuation
- To identify wave modulation introduced by individual parameters in the load generation as well as by the specimen/gripping set-up
- To develop a frequency based strain correction methodology
CHAPTER 2

TENSILE SPLIT HOPKINSON PRESSURE BAR

The Split Hopkinson Pressure Bar (SHPB) for tensile impact testing follows the same principles and data analysis methods as the classical compression SHPB. However, tensile and compression systems differ in the techniques used to grip the specimen, the methods for introducing the loading pulse, and the testing specimen geometry. Several gripping mechanisms have been used by researchers along with different loading techniques. Some gripping mechanisms are highly dependent on the material under study, i.e. specimen fabrication is only feasible with metals. A few specimen geometries are specific of the loading technique, e.g., hat shaped specimen. Different loading techniques can be applied with diverse gripping mechanisms and different specimen geometry depending on the application.

2.1 Gripping Mechanisms and Specimen Geometry

In typical tension testing, specimen grips have to meet two main conditions. First, the gripping force have to be large enough not let the specimen slip off the grip at maximum loads. Second, failure should not occur in the grip section. In high strain tension testing, the mechanical impedance of the grips must be small enough not to disturb wave propagation [12].

The majority of gripping mechanisms are used in combination with specific specimen geometry. A typical tensile specimen for metallic materials is shown in Figure 4. It shows a reduced gage section with enlarged shoulders. The cross-sectional area of the specimen should be smallest at the center of the reduced section to ensure fracture within the gage length [40]. The length of transition section between the shoulders and the gage section should be as large as the diameter to avoid end effect from the shoulders. In addition, the gage length should be larger than its diameter. Otherwise, the state of stress will be more complex than simple tension.
When tensile specimen design is under consideration, several constrains originate from the application under study and general rules cannot be applied. Instead, careful evaluation of the material being characterized need to take place before particular limitations are identified. For example, sheet-type specimens are mandatory for the majority of composite materials. Another example would be complex shapes or machining which may be limited to metals.

The next few paragraphs summarize the most common gripping mechanisms found in literature today along with its corresponding specimen geometry.

(a) Threaded-end Bar – Threaded Specimen

In this form of gripping, a threaded (male) specimen is screwed into a threaded (female) grip, i.e., the threaded-ends of the incident and transmitter bars. Extra fine or fine threads are desired to maximize the load transfer between the bars and the specimen. This will also minimize the play between the threads and would allow for a closer contact among components. Failure to remove all play from the threaded connection may result in uneven loading of the specimen and spurious wave reflections due to the open gaps in the loading path.

Threaded specimens are commonly used in metal testing, see Figure 5. However, due to their relatively low shear capability, similar specimen cannot be used with laminated composite
materials. Cracks and other kinds of damage would be introduced to a composite testing specimen if threads are machined.

![Threaded tensile specimen](image)

*Figure 5: Threaded tensile specimen (mm) [31].*

(b) Slotted Bar – Pinned Specimen

A pinned or bolted type of connection is implemented in this technique. The loading bars as well as the specimen are perforated through allowing for bolts to clamp the two parts together. The technique successfully prevents the specimen from slipping. Hun et al. [12] suggest that by using small bolts the mechanical impedance is minimized (see Figure 6).

Pinned specimens represent a common type of specimen when sheet metal testing is at hand. Several researchers have reported using similar methodologies that include pinned or bolted specimens. For example, LeBlanc and Lassila [33], implemented a combination of threaded-end bars and pinned specimens. Recently Hasebe and Imaida [42] proposed improvements to the technique. Finite element analysis was used as a design tool.
(c) Slotted Bar – Bonded Specimen

In this technique the parallel grip regions of the specimen are fixed into parallel-sided slots in the loading bars using high strength epoxy adhesive. Among the first researchers investigating high strain rates on composite materials, Harding and Welsh [19] implemented this technique. Relatively long grip sections that anticipated stress wave reflections were used, see Figure 7. However, it was reported that change in impedance across these sections was very small to be detected. From the authors’ point of view, the experimental repeatability of the specimen bonding remain to be improved.
(d) Threaded Fixture – Bonded Specimen

This technique is reported in literature in combination with the threaded-end bar. A coupling fixture is made with a cavity or slot at one end for the specimen to be cast with epoxy. At the other end, threads are made to be engaged with the input and output bars. A schematic representation of the assembly of the specimen and fixture is shown in Figure 8. This technique appeared to be appropriate for composites materials as reported by Eskandari [21] in 1998. After trying different gripping mechanisms (mechanical grips, pinned, slot-fit, etc) with unsatisfactory results, Gomez-del Río et al. [14] adopted this technique in 2004. Their fixture deviated from Eskandari’s in some minor details. The technique represents an improvement over the specimen preparation procedure compared to directly bonding the specimen to the bars.

![Epoxy Injection Hole | Aluminum Fixture | Specimen]

Figure 8: Eskandari’s fixture assembly [21].

(e) Mechanical Grip

This methodology resembles the mechanical grips used in quasi-static testing. The specimen is held in place at the end of the loading bars by clamping pressure applied to the tap region. Gomez-del Río et al. [14] reported great difficulties. Systematic slippage of the specimen was observed. Also matrix-fiber shear failure was present and eventually the methodology was abandoned.
2.2 Loading Techniques

Generating a tensile loading pulse is generally done in an indirect manner, i.e., an initial compressive loading is first introduced by an impact at one end of the bars, and the reflected wave from the free end becomes the tensile pulse. Another indirect methodology takes advantage of the specimen geometry to convert a compressive load into a tensile load. Direct loading is achieved after releasing a tensile pulse stored in the incident bar. Also, it is introduced after impacting a transfer flange directly attached to the incident bar. Techniques found in literature are summarized in the following paragraphs.

2.2.1 Indirect Methodologies

(a) Modified Compression

Indirect loading is achieved using a modified classical SHPB in which tensile loading is introduced indirectly by a compressive pulse. Hauser [43] introduced an arrangement in which a ram would impact two side bars generating a compressive stress pulse that would propagate down each bar (see Figure 9). It would reach a transfer connection introducing tensile loading in the input bar and consequently to the testing specimen. After this point, the same conditions of the compression test are reproduced but for the sign of the pulses. In Hauser’s system, the rise time of the tensile pulse is determined both by the impact of the ram with the side bars and the dimensions of the transfer connection. As a limitation, it is important to note that low strains values are not reliable since the sample does not establish equilibrium within the first few microseconds of the test.
Harding [19] and LeBlanc [41] achieved indirect loading when an initially compressive pulse is propagated down a tube and a subsequently reflected tensile pulse loads the test specimen attached to the bars inside the tube. Additional vibration can be introduced if proper alignment is not achieved between the two side bar and a flush contact is not guaranteed between the striker and the side bars. Any eccentricity of the impact will produce flexural stress waves in the tube [9]. In Eskandari’s apparatus [21], misalignment is minimized by introducing a side-bar connector as seen in Figure 10.

(b) Bypass loading

In this method, a collar is placed around the tensile specimen and is fitted in between the two pressure bars as shown in Figure 11. The compressive load initially generated in the input bar by an impact, bypasses the specimen through the collar from the input to the output bar with
no plastic deformation of the specimen. As the wave reaches the free end of the output bar, it is reflected back as a tensile load. When the tensile pulse reaches the specimen, it is partially transmitted through the specimen and partially reflected back into the bar. Since the collar around the specimen is not attached to the pressure bars, it will not support any tensile load.

This methodology was initially proposed by Nicholas [31]. A similar arrangement was developed independently by Ellwood et al. [32]. It was later modified by Ross et al. [44] so it could be used to test materials with machining difficulties, e.g., composite materials. The advantage of this methodology is simply that it can be conducted using a classical compressive SHPB. On the other hand, pre-straining of the specimen is difficult to prevent in practice. Failure to fit the collar tightly against the two pressure bars would introduce uneven loading to the specimen and would generate wave reflections. Despite its drawbacks, it continues to be used by researches, as recently reported by Sasso et al. [45]

![Figure 11: Bypass (collar) schematic diagram [32].](image)

(c) Compression Based

Tensile specimen geometries are in general application specific. However, a few geometries allow the test to be conducted using a compression SHPB. This simplifies the loading technique but introduces complex stress fields. Due to the complex specimen geometry, the application of this technique is limited to metals. The following paragraphs summarize some of the most common tensile geometries found in literature, which use compression SHPB.
**Hat-shaped:** In an effort to avoid the difficulties related to threaded connections between specimen and the pressure bars as well as the complexity of side bars configurations that load the specimen in tension, Lindholm and Yeakley [46] introduced a hat-shaped tensile specimen that fits between a solid incident bar and a tubular transmitter bar, see Figure 12. Input and transmitter bar are of equal cross-sectional area so that equations for stress, strain, and strain rate derived from 1-D theory remain applicable. Internal wave reflections in the specimen are neglected. Non-uniform distribution of stress or strain over the volume of the specimen may result from either friction at the boundaries or from inertial restraint due to particle acceleration in axial and radial directions.

![Figure 12: Specimen and test configuration reported by Lindholm and Yeakley (in) [46].](image)

**M-specimen:** In this design, the incoming compression wave in converted into tension within the characteristic gage section, see Figure 13. It was introduced by Mohr and Gary [47]. The key advantage of this technique is that it can be used without attaching the specimen to the end of the bars. Instead, the specimen is freely positioned between the flat ends of the incident
and transmitter bars. It takes advantage of a conventional SHPB to introduce a compression pulse avoiding difficulties related to dynamic tensile testing such as the gripping of the specimen. The section between points F and E is predominantly in compression. Similarly, section A-B. Sections B-C and D-E are subjected to shear and bending. On the other hand, section C-D is predominantly in tension.

![Figure 13: M-shaped specimen used by Mohr and Gary [47].](image)

### 2.2.2 Direct Methodologies

(a) Transfer Flange

In this method, a tensile loading pulse is generated after impacting a flange at the end of the incident bar with a hollow striker bar as shown in Figure 14. The hollow striker bar is accelerated along the incident bar. It can be propelled either by compressed gas or by gravity in a vertical configuration. From the impact, a tensile pulse is generated in the incident bar. It propagates down towards the specimen where it is partially transmitted through the specimen onto the transmitted bar as a tensile pulse and partially reflected back into the incident bar as a compressive pulse. Authors such as Nemat-Nasser et al. [48], and Li and Lambros [49] have used this technique as early as 1989, and it has been used lately by Hun et al. [12] in 2002 and
Gomez-del Río et al. [14] in 2004. Nevertheless, not much information/guidance is reported regarding the design of the striker and the incident bar, and the resulting pulse shapes.

(b) Pre-stressed Loading Bar

In this method, a stress wave is generated by releasing the mechanical energy stored in a pre-tensioned bar. It was initially introduced by Albertini and Montagnani [6] and later used by Staab and Gilat [50]. In Albertini’s device, the input bar is first clamped at the midspan and then prestressed by a double-screw differential device or by a hydraulic piston as shown in Figure 15. The clamping force is balanced by a tensile force in a fracture pin that connects the faces of the vise. Once the desired stress level has been reached, the fracture pin fails setting free the prestressed bar and thus propagating a tensile wave along the incident bar.

A nearly constant amplitude input wave was reported [50]. It has been attributed to the ramp loading introduced by releasing the clamp. However, loading time appears to be excessively large compared to other tensile loading techniques. Such a long loading time may hinder the ability of taking an accurate measurement since it would require fairly long incident and transmitter bars to avoid superposition of incident and reflected waves.
2.3 Summary

The key criterion for selecting the loading pulse generation method is the ability to generate a pulse that is close to the theoretical shape barring dispersion effects. Indirect loading methodologies are reported to affect the shape and length of the pulse. In Eskandari’s [21] design, the connector is reported to affect the length of the pulse in a twofold and to change the shape of the pulse. A quasi-triangular pulse is reported by Eskandari in contrast to direct impact methodologies in which a quasi-rectangular pulse is generated. Other indirect loading methodologies like the bypass loading are reported to prestrain the testing specimen with detrimental effects. Additional practical drawbacks include uneven loading of the specimen and the generation of wave reflections if collar is not tightly fitted against the two pressure bars.

Direct loading methods include prestressing the loading (incident) bar and use of transfer flange. The pre-stressed loading bar technique while producing a clean input pulse is rarely used and was found to have practical limitations in terms of the length of the bar. On the other hand, the transfer flange technique is not reported to have major drawbacks or limitations. Although it represents the methodology of choice in the current investigation, the various factors affecting its performance will be investigated.

The main criterion for selecting the gripping mechanism, on the other hand, is the feasibility of extending the technique to testing of laminated composite materials. Complex geometries or machining difficulty would exclude compression based indirect loading methods simply because they cannot be applied to composite materials, especially in sheet form. The fabrication of threaded specimens with laminated composites is not feasible. In general, damage may be introduced to the test specimen during machining adding different levels of uncertainty. The most practical methodology for testing composite materials constitutes adhesive bonding of
the specimen to the bars or bonding to some sort of a fixture. However, the adhesive shear
strength may limit the overall performance of the grip. Pinned or bolted gripping provides
excellent load carrying capabilities, although this technique may seem not to be appropriate due
to stress concentration on the tap region and spurious wave reflections that may be created by
additional mechanical elements. This technique can be improved by combining bolted gripping
and adhesive bonding.
CHAPTER 3

EXPERIMENTAL METHODS

The major objectives of the experimental program were to establish a proper momentum transfer and load generation methodology and to evaluate the effects of gripping fixtures and sheet-type specimen on pulse modulation. Wave modulation in high strain rate testing in SHPB apparatus is investigated by conducting experimental testing using two SHPB configurations; a classical compression SHPB and a direct tensile SHPB. The two testing apparatus are developed to fulfill such objectives.

Regardless of the commonalities of the stress wave analysis of a tensile SHPB and the classical compression SHPB, the compression apparatus provides some key advantages from the experimental point of view. It does not require additional fixtures or devices to hold the testing specimen in place. In addition, compressive loading is introduced in a direct manner. These characteristics can be used to study the effect of different parameters related to the tensile SHPB apparatus on wave propagation. Since gripping mechanisms and load transfer devices are necessary on several tensile SHPB systems, the perturbations to pulse propagation introduced by threads on the bars or the presence of foreign masses attached to the incident bar can be evaluated.

Individual parameters are often assessed by running the SHPB apparatus in “dry” conditions, i.e., in the absence of testing specimen. This straightforward test arrangement is used throughout the entire investigation for calibration purposes of the testing apparatus. It allows the generation of a benchmark pulse to evaluate the effect of imperfections on the surface of the pressure bars or step discontinuities along the propagation path, e.g., threads or gripping fixtures.
This test arrangement also provides the means to investigate momentum transfer in the transfer flange and the generated loading pulse.

After a thorough review of available methodologies and techniques for generating an elastic tensile loading pulse in a Split Hopkinson Pressure Bar (SHPB), the transfer flange direct methodology presented in the previous chapter is selected. This technique is by no means perfect, but it satisfies the requirements highlighted by the previous researchers, i.e., simplicity of test apparatus and generation of tensile pulse where extraneous components (due to superposition of undesirable reflections of waves) are and discontinuities (in impedances) are minimized. These characteristics make the experimental event repeatable, and thus reliable. The selected direct loading methodology is implemented through a tensile SHPB developed for the current investigation.

Measurement of the stress level of the incoming stress wave and the magnitude of the reflected wave is accomplished by the strain gages placed on the incident bar. Careful selection of the location is necessary to avoid pulse superposition and misinterpretations of the state of stress (& strain) in the specimen. Secondary pulse sources and pulse superposition are avoided by visualizing pulse propagation along the length of the pressure bar using Lagrange diagrams.

3.1 Graphical Representation of a Stress Wave

The stress, strain, and strain-rate calculations in the SHPB theory are a result of direct strain measurements on the surface of the loading bars. Such measurements should be taken at locations where there is no superposition of pressure waves (incident and reflected). Thus, it is important to track the stress waves as they propagate down the incident and transmitter bars. For that purpose, a simple but meaningful diagram provides the tools to do so, see Figure 16 (a). This diagram is referred in literature as the Lagrange Diagram [16]. On the diagram, the locations
where reflections of the waves take place can be identified. Moreover, waves’ superposition can be evaluated.

In the diagram, the stress wave front is plotted in terms of the distance traveled versus time. The straight line represents the wave front. Notice that the diagram does not represent a graph of a function $x$ that varies with time $t$. It represents a discontinuity, and it is only along the wave front that a specific relationship between $x$ and $t$ exists. The plane defined by $x$ and $t$ is called the characteristic plane, and the line is called the characteristic line for the stress wave. If the applied stress at the impact end varies with time infinite characteristic lines can be drawn. Each line then represents the stress level of the pulse at a particular time such that the stress history can be plotted for any coordinate $x$, see Figure 16 (b).

The Lagrange diagram or characteristic $x$-$t$ diagram presented in Figure 17 illustrates the pulse propagation along the pressure bars of a Compression Split Hopkinson Pressure Bar. The incident, reflected, and transmitted pulse are color coded for differentiation. One may notice at the specimen interfaces, how the incident pulse (blue) is partially reflected as the reflected pulse (orange). Also, notice how some portion of the incident pulse is transmitted through the specimen as a transmitted pulse (green). For illustration purposes, the strain gage data acquired at some arbitrary locations “SG1” and “SG2” during the test are plotted on the sides, i.e., $x$-strain vs. time.

Figure 16: Characteristic lines for a stress wave [51].
3.2 Compression SHPB Development

The compression SHPB apparatus assembled for the present investigation (see Figure 18) consisted of a gas gun, two Aluminum 6061-T4 bars of 25.4 mm diameter and of 1219.2 mm length. The bars are supported approximately every 254 mm on frelon-lined linear plane bearings.

The gas gun operated on compressed air and can fire striker bars of different lengths ranging from 38.1 mm to 304.8 mm. The air intake is controlled with a single-stage pressure regulator Norgren Model R72G-2AT-RMG, rated for a 1 MPa drop [52]. The compressed air reservoir is equipped with a digital pressure gauge for precise pressure indication before firing the striker bar. The striker was held in the firing position by a pneumatic triggering mechanism. When the desired pressure is reached in the air reservoir, the trigger air line is cut so it retracts the piston rod, thus freeing the striker to accelerate towards the incident bar. A momentum trap is placed at the very end of the SHPB apparatus. The momentum trap is simply a foam pad that
prevents the transmitted bar from flying of the apparatus. After the transmitted bar hits the foam, the bar reaches rest preventing from subsequent reloading of the specimen.

The compression SHPB apparatus provides one the ability to study in detail, the perturbations to wave propagation introduced by the gripping devices necessary in a tensile SHPB. Wave modulations resulting from the additional mass of the gripping fixture and the load transmission losses in the threaded connection are evaluated. Additional wave perturbations resulting from surface imperfections and step discontinuities are also evaluated. The effect of thread type and length are evaluated through a parametric study.

Figure 18: Compression SHPB apparatus at NIAR/WSU.

3.3 Data Acquisition

Stress waves propagating in the incident and transmitter bar are monitored by means of 350Ω resistance strain gages mounted on each bar. Strain gages used in the present investigation are Vishay EA-00-060EK-350-LE [53]. Two gages are mounted on each bar diametrically opposite from the other to complete a Wheatstone bridge configuration [54]. The Wheatstone bridge configuration is typically used to determine the change in resistance that occurs when a gage is subjected to axial strain. In the case at hand, any bending strain in the bar should be eliminated. This is achieved by having two opposite arms of the bridge active. Figure 19 shows
\( R_1 \) and \( R_3 \) as the active resistors (strain gages), where \( R_2 \) and \( R_4 \) are precision resistors of equal resistance.

![Wheatstone bridge circuit](image1.png)

Figure 19: Wheatstone bridge circuit [28].

The condition for a balanced circuit is that \( R_1 R_3 = R_2 R_4 \) which in reality is not the case due to the tolerances in the resistors [55]. As a result, the bridge output voltage is not zero. Instead, the initial imbalance may be as much as 0.1% of the excitation voltage. This may equal or surpass the true strain induced signal. Hence, it is necessary to eliminate the unbalance. This can be achieved by adding or subtracting resistors in any arm so as to satisfy the balance requirement or by employing a differential arrangement that would adjust simultaneously in both arms. There are a variety of circuits that can be used to balance the Wheatstone bridge [56]. The arrangement presented in Figure 20 was implemented in the current investigation [56].

![Wheatstone bridge balancing circuit](image2.png)

Figure 20: Wheatstone bridge balancing circuit.
Low voltage strain gage signals are amplified using a high-performance Ectron 778 wideband amplifier/conditioner [57]. The transducer excitation is set to a maximum of 15 Volts with a 5 mV resolution. Gain was set to $\times 100$ for the strain gages mounted on the incident bar, and $\times 500$ for the strain gages mounted on the transmitter bar. The gain on the signal from the transmitter bar was set to a higher number due to the fact that the strength of the signal has decayed by the time it reaches the strain gage. Strain gage signals are recorded using a Tektronix TDS 3034B digital oscilloscope [59]. The sampling rate on the oscilloscope was set to 10 MHz. The incident pulse was used as a trigger signal for the data collection. After the output voltage from the bridge is amplified, a voltage proportional to the strain is recorded by the oscilloscope. This process is illustrated in Figure 21.

Typical incident, reflected, and transmitted signals are shown on the oscilloscope window in Figure 22. Incident and reflected strain data are contained in the same raw data signal recorded from the incident bar. A short delay between the transmitted pulse relative to the reflected pulse may be seen. The timing between the reflected pulse and the transmitted pulse strongly affects interpretation of the test results in the SHPB test.

Figure 21: SHPB data acquisition.
Dispersion

Processing strain gage raw data into engineering data is not straightforward. Several sources introduce dispersion into the strain gage signal. With no dispersion, the strain history of a wave traveling in a bar is comprised of the incident and reflected waves which only differ in sign. In reality that is not the case. It can be seen in Figure 23 where an incident pulse and its reflection are observed not to be equal after propagation. The dispersive nature of the bars along with radial inertia, friction, specimen geometry, etc. introduces oscillations in the strain gage signal. It is a common practice in signal processing to reduce oscillations beyond those attributable to physical phenomena in the raw data by eliminating high-frequency components. This is done using a low-pass filter. In order to specify which frequencies are to be removed, cutoff frequencies must be defined. High-frequency components are identified by transforming the data into the frequency domain using a FFT (Fast Fourier Transform). The unwanted frequency components are eliminated by multiplying the FFT values at these frequencies by...
zero. The modified frequency domain data is then transformed back into time-domain with IFFT (Inverse FFT). Figure 23 shows an incident pulse before and after high-frequency components are filtered. A significant noise reduction is observed without compromising the shape of the pulse. The current investigation used Altair HyperGraph [58] software to process the data. Frequency components above 200 KHz where filtered using a low-pass filter.

![Graph showing incident and reflected pulses before and after filtering.](image)

Figure 23: Incident and reflected pulses before and after filtering.

### 3.5 Pulse Shaping Technique

The elastic stress pulse imparted by direct impact of a projectile on the incident bar on a conventional Split Hopkinson Bar apparatus has a high level of oscillation superimposed on their approximately trapezoidal shape. These oscillations are a consequence of the short rise time of the loading pulse [60]. Such oscillations cause difficulty in the interpretation of the stress-strain results. A slowly rising incident pulse is preferred over a pulse that rises steeply in order to minimize the effect of dispersion, and at the same time, to allow the sample to achieve dynamic stress equilibrium [61]. Longer rise times also reduce inertial effects in the specimen [62].
A modification of the conventional Split Hopkinson Pressure Bar is done by simply placing a thin disk of annealed copper on the impact surface of the incident bar (see Figure 24). This increases the impact rise time and reduces the amplitude of the oscillations by softening the impact. When pre-impacting a copper disk the resulting smooth loading pulse generates a nearly constant strain rate in the sample [61].

![Schematic of the loading end of a compression SHPB with pulse shaper.](image)

Figure 24: Schematic of the loading end of a compression SHPB with pulse shaper.

A preliminary study on the effect of introducing a copper disk at the impact surface is conducted. Several tests are conducted on compression SHPB in dry conditions, i.e., the incident bar was impacted without the specimen or transmitter bar. Disk thickness and diameter are varied to study the rise time of each impact event. Strain gage signals in Figure 25 show larger pulse rise times for thicker copper disks. Larger rise times improve data collection during the early loading stages where strain-rate sensitivity characterization is fundamental, especially for composite materials which have very little plastic capability. However, strain gage signals in Figure 25 also show that thicker copper disks (0.064 in and 0.093 in) show the largest strain level reduction among the three thicknesses. Not to lose the strength of the pulse but at the same time have the benefit of reduced oscillations, a 0.016 in thick disks is recommended since they produced larger rise times than direct impact without significant loss in signal strength. The diameter of copper disks used in the current study was 0.283 in.
3.6  Tensile SHPB Development

A Tensile Split Hopkinson Pressure Bar was assembled utilizing the transfer flange method for inducing tensile pulses. The testing apparatus consisted of a compressed air gun, two Aluminum 7075-T6 bars of 19.05 mm diameter; an incident bar 2540 mm long and a transmitter bar 1270 mm long as shown in Figure 26. The gas gun is designed so the incident bar goes through its barrel as well as the trigger box allowing mobility but capable of holding air pressure. The incident bar is concentric with the gun barrel. This allows for a hollow striker bar to ride along the incident bar and inside the gun barrel. The hollow striker bar is manufactured from the same material as the bars. The bars are supported approximately every 254 mm using frelon-lined linear plane bearings. Similarly to the compression SHPB, the air gun operated on compressed air and could fire striker bars of different lengths ranging from 38.1 mm to 304.8 mm. The air intake was controlled with a single-stage pressure regulator rated for a 1 MPa drop. A transfer flange is attached to the end of the incident bar to generate the loading pulse.
Stress waves propagating in the incident and transmitted bar are monitored by means of 350Ω resistance strain gages mounted on each bar. The location is carefully selected to prevent superposition of the incident wave with the reflected wave. Strain gage on the incident bar is located 1016 mm from the specimen and 203.2 mm from the specimen on the transmitter bar. The theoretical pulse width is equal to twice the length of the striker bar. This implies that strain gages must be located at least twice the length of the striker from the bar end. Strain gages used in the present investigation are Vishay EA-00-060EK-350-LE [53]. Two gages are mounted on each bar diametrically opposite from the other to complete a Wheatstone bridge configuration. Low voltage strain gage signals are amplified using a high-performance Ectron 778 wideband amplifier/conditioner. The transducer excitation is set to a maximum of 15 Volts with a 5 mV resolution. Gain is set to ×100 for the strain gages mounted on the incident bar, and ×500 for the strain gages mounted on the transmitter bar. A larger gain is needed for the transmitted strain signal because in the transmission process the signal is attenuated, i.e., it loses strength (since some portion of the incident pulse is reflected at the interface of the specimen with both incident and transmitter bars). Strain gage signals are recorded using a PicoScope pc oscilloscope with 12 bit resolution [63]. Sampling rate on the oscilloscope is set to 10 MHz. The incident pulse is used
as a trigger signal for the data collection. After the output voltage from the bridge is amplified, the signal is recorded by the oscilloscope.

Characterizing the incident pulse required the use of only the incident bar without the test specimen and the transmitter bar. This is referred as a “dry test,” and it provides the incident and reflected strain histories only, see Figure 27. Pulse characteristics such as width, amplitude, shape, and levels of oscillations are evaluated experimentally using the Tensile SHPB apparatus, and results are compared with analytical models for improvements. Careful examination of pulse characteristics brings an in-depth understanding of the mechanics of the momentum transfer and the tensile pulse generation in the incident bar.

![Figure 27: Dry test on a tensile SHPB.](image)

3.6.1 Sleeve Flange

As an alternative option to a threaded connection or welded connection, a sleeve flange is clamped to the end of the incident bar over a matching profile. The sleeve is comprised of two halves that are fastened together as shown in Figure 28. A potential problem with the load transfer mechanism if using a threaded or welded type connection is that it induces stress concentration at the bar-flange interface. Fatigue then becomes an issue, and the threaded connection can degrade with time, requiring expensive replacements. The transition angle on the sleeve design is 30° so the momentum transfer takes place while minimizing the stress concentration.
Introducing spurious vibrations as a result of the impact event was a concern. Depending upon the location of the flange on the incident bar an extra bearing support can be accommodated over additional bar length or directly below the flange as shown in Figures 29 and 30. The additional support not only prevents the bar from bending due to its own weight and the flange, but also minimizes vibrations resulting from the impact. In addition, the support will constrain any non-axial loading resulting from the impact event. The novel methodology is evaluated experimentally using the Tensile SHPB developed for such purpose. A sleeve flange is manufactured using Aluminum 7075-T6; the same material used for the incident bar and the striker. The length of the flange is 76.2 mm and while the diameter is 50.8 mm. The detailed drawings are shown in Appendix B. Experimental tests are conducted with the sleeve flange clamped at two different locations: (a) incident bar end and (b) seven inches from it (see Figures 29 and 30). A striker bar of 101.6 mm is used for both tests.
3.6.2 Momentum Trap

A momentum trap is added to the tensile SHPB following the transfer flange. The objective is to contain the compressive momentum generated at the collision of the striker with the flange, see Figure 31. The momentum trap is nothing but an extra bar placed in close contact with the transfer flange, but not attached to it. The effect of the trap on the pulse characteristics is evaluated numerically and experimentally. The momentum trap is manufactured using Al 7075-T6; the same material used for the incident bar and the transfer flange. The momentum trap is 304.8 mm long and has a diameter of 50.8 mm.

3.7 Specimen Preparation and Gripping Mechanism

The SHPB principle requires that the specimen reaches quasi-static equilibrium at an early stage during the test [4]. For this requirement to be satisfied, the stress distribution on the specimen and the failure process expected to dominate, need to be well understood. Several in-plane tension tests are conducted aiming to characterize the static material response. Static
failure loads were generated. Static failure strengths provide with lower end reference for suitable dynamic testing failure loads, assuming that the strength increases with strain rate. The knowledge of failure strengths aide in estimating specimen dimensions (see Figure 32). Specimen shape and size are selected taking into account several factors, i.e., specimen length required for stress equilibrium, composites machining difficulty, and specimen’s cross-sectional area relative to bar’s cross-sectional area. A “dog bone” type specimen is selected. It is typical in tension testing. Its reduced cross section ensures failure within the gage section before shear failure is observed on the adhesive tap interface. Strain gages are mounted on the specimen for calibration purposes. To check for bending, gages are mounted on each side of the specimen. Strain gage used are Vishay EA-00-060CD-350 [53].

Figure 32: Tension specimen dimensions (mm).

The majority of SHPB apparatus that introduce a tensile loading by pulling the specimen ends, necessitate gripping the test specimen. Several gripping mechanisms were reviewed in Chapter 2. However, the selection of the gripping mechanism in the current investigation is based on the feasibility of extending the technique to laminated composite materials. Fabricating testing specimens with laminated composite materials is limited to simple geometries and threaded specimens are not feasible. A more practical method for composite materials is
adhesive bonding of the specimen to the bars or to some intermediate fixture. However, careful
evaluation of the joint capability (based on bond area and adhesive shear strength) is required. If
the load carrying capability is limited, introducing a pin or bolt to the grip would improve the
joint, but the effect of bolts or pins on wave attenuation have to be evaluated.

An aluminum 2024-T3 cylindrical grip is designed to hold the specimen in place during
testing. One end of the low mass grip is threaded to the pressure bar and the other end provides
with a slot to adhesively bond the specimen to it, see Figure 33. The grip facilitates multiple
usage. Direct bonding to the bars is not practical and limits consecutive testing since only a
single specimen can be prepared and tested at a time. In addition, preparing the bar for a second
test requires complete removal of resin residuals from the bonding area which may be
cumbersome. In contrast, the grip is small enough to allow for the resin to be burned away from
the fixture by placing it in an oven.

![Figure 33: Tension specimen bonded to grips.](image)

The shear strength of the adhesive joint is measured experimentally by testing assemblies
of grip and bonded specimens under quasi-static conditions. A straight specimen is used instead
of a dog bone specimen so that a shear failure is induced rather than failing the specimen itself.
The adhesive shear strength in combination with the material strength is used to design the cross-section geometry of the test specimen.

Centering the specimens on the bar cross-section is critical for proper loading of the specimen. Any longitudinal misalignment between the specimen and the bars or the grips might induce undesirable bending loads. In order to properly center the specimen in the grip during the bonding process, an alignment fixture is developed. The alignment fixture is manufactured with Teflon to prevent any inadvertent bonding between the specimen and the fixture. The fixture is composed of two halves, with each half matching the profile of the specimen and the aluminum grip as shown in Figure 34. During the curing process, the two halves are constrained, providing the necessary pressure to keep all parts together. In addition, pins are inserted from grip to grip during the bonding process to prevent undesirable rotations or misalignments when positioning specimens which are somewhat compliant.

Figure 34: Alignment fixture for specimen bonding to grips.
CHAPTER 4

FINITE ELEMENT MODEL OF THE SPLIT HOPKINSON PRESSURE BAR

The SHPB technique is widely used for high strain rate testing regardless of the partial understanding of its limitations and capabilities. Current understanding of the technique is mostly the result of experimental observations which only provide with operational knowledge of the testing apparatus. Defining a universal methodology requires a detailed evaluation of every component in the load train. Such level of detail can only be achieved using numerical (finite element) models. Experimental testing of every possible combination of parameters may not be possible in practice and could be economically impractical. On the other hand, finite element simulations provides with great level of control over individual parameters allowing for evaluation of individual effect. Parameters can be varied over a wide range incurring only in computational cost. Ultimately, finite element simulations can be used as a design tool to tailor the test apparatus for specific needs (materials, specimen shapes, etc).

The motivation for using numerical models is driven by the possibility of conducting parametric evaluations of influential factors and the interactions among them. Designing a tensile loading technique and a specimen-gripping mechanism requires understanding the effect of individual parameters on load generation and load transfer. A numerical model to evaluate the loading technique should provide control over geometrical features that are directly related to pulse characteristics such as width, amplitude, and shape. Recall that such characteristics, and possibly the level of oscillations, are function of the impulse introduced and the striker length. Similarly, a model to evaluate the gripping mechanism should provide the means for tracking and tracing pulse propagation, pulse distortion sources, and pulse attenuation. The pulse attenuates as it propagates down the load train in a tensile SHPB due to the impedance change in
the grips, load transfer between components, and specimen geometry. Identifying key propagation issues and quantifying pulse attenuation is important for the validity and application of the one-dimensional wave propagation theory.

Several explicit numerical models are assembled to address the two main objectives of the current investigation: (a) load pulse generation and (b) load transfer to the specimen. The key concept for load generation is related to momentum transfer between components. Models of the SHPB in “dry conditions” (i.e., without test specimen and transmitter bar) are assembled to study the mechanics of momentum transfer between the striker and the bar in the case of a classical compression SHPB, or the momentum transfer between the striker and the transfer flange, and between the transfer flange and the incident bar in the case of a tensile SHPB. Tensile SHPB simulations are used to verify observations on wave propagation based on Lagrange diagrams, from the moment the pulse is generated and as it travel down the incident bar. In addition, the numerical model is used to assess two attachment techniques of the flange to the incident bar; a general type flange, representing a welded, threaded, or press fitted connection and a sleeve flange type connection. A geometrical modification of the flange is also evaluated numerically, e.g., coned-shape flange. In addition, the effect of placing a momentum trap after the flange is evaluated for the two types of flange attachments. A complete model of the tensile SHPB including grips, specimen, and transmitter bar is assembled to address load transfer and pulse attenuation in the testing system.

Specific experimental observations are also addressed. Secondary compression pulses in the form of oscillations are observed following the leading tensile pulse. The origin of the oscillations is not clear. There is particular interest in understanding the source for such compressive pulses. Simulations are used to evaluate the effect of flange deformation on the
generation of secondary pulses. Similarly, stress concentrations at the flange-incident bar interface are also evaluated.

4.1 Numerical Model

Explicit finite element models are created using the commercial code LS-Dyna [64] for the simulation of several SHPB apparatus configurations. Finite element models of a “dry” compression set-up and a “dry” tensile set-up with different transfer flanges and a momentum trap, and a complete tensile set-up with specimen gripping, specimen, and transmitter bar are assembled. The compression SHPB model is assembled to study the extent of oscillations superimposed to the incident pulse shape. The “dry” tensile SHPB is developed to evaluate the effect of geometrical parameters of the transfer flange on load generation. A momentum trap is modeled to study the benefits of adding it after the transfer flange. A complete tensile SHPB system is assembled to analyze load transfer and the validity of the one-dimensional wave analysis. At the same time, it is also used to evaluate the tensile specimen response.

Impact finite element simulations frequently experience hourglass effects when using under integrated elements. Viscous hourglass control [64] is known as proper for problems deforming with high velocities. On the other hand, stiffness control is known to be appropriate for lower velocities [67]. Even though Ls-Dyna has several hourglass control options for solid elements, the standard hourglass viscosity type is used. The eight-node solid elements used for simulation, uses by default, one integration point and viscous hourglass control. However, fully integrated solid elements could have been used which perform better when large deformations are involved, although with an added computational cost. Preliminary simulations using fully integrated elements indicated no improvement for the current application. Therefore, constant stress solid elements with appropriate measures for controlling hourglass modes, are used.
All models include supports for the incident and transmitter bar. In the case where a momentum trap is added, the trap is also supported. Gravity is included in all simulations. It is ramped up to preload the structure with a quasi-static analysis. Thus, the initial deflection resulting from the bars own weight is considered.

The incident and reflected strain history to be compared with actual strain gage data from experimental testing is obtained at the element level. Element strain history on the surface of the bars is extracted by post-processing results at the locations corresponding to where strain gages are bonded on the experimental apparatus. The total simulation time is 2000 $\mu$s. The time window allows tracking the loading pulse down the incident bar and back; from generation to reflection at the free end. The sampling time is set to 2 $\mu$s such that frequencies components as high as 250 kHz may be detected.

### 4.1.1 Contact Definition

Current simulation schemes use a penalty based two-way treatment of contact to check for potential node penetrations in the model, i.e., Ls-Dyna Automatic_Surface_to_Surface [64] contact is specified at the interfaces between all components (striker, transfer flange, incident and transmitter bar, momentum trap, and supports). In this contact definition, the treatment of contact is done symmetrically between the slave surface and the master surface [65]. The contact definition is commonly used for crash analysis since after large deformations the relative orientations of parts to one another cannot be anticipated [69]. However, the penetrations subroutines are called twice to check for penetration increasing computational cost by a factor of two.

Friction between components in the actual experiment could be present. In the simulation, special attention is given to the contact definition between the sleeve transfer flange
and the incident bar. When relative sliding occurs, tangential loads are transmitted when the contact friction is active. A Coulomb friction formulation is used with an exponential interpolation function to transition from static to dynamic friction [68]. Friction is invoked by defining in the contact card a value of 0.15 for the static friction coefficient and 0.1 for the dynamic friction coefficient between striker and transfer flange.

4.2 Finite Element Model of a Compression SHPB

A numerical model of a classical compression SHPB is assembled for simulating testing in “dry” conditions, i.e., a model consisting of a striker bar and an incident bar only. Bar lateral inertia introduces oscillations that overlap the ideal trapezoidal shape of the pulse. However, residual oscillations on the pulse after the incident pulse has decayed may introduce additional loading to the specimen in the case of a tensile testing configuration. A tensile SHPB includes several components in the load train and they may interact to introduce an unexpected behavior. A simple way to eliminate component interaction is by looking at a compression SHPB where gripping mechanisms are not required, thus minimizing components.

Aiming to identify the nature and the sources of the secondary pulses by eliminating the possibility of component interaction, a compression SHPB is simulated. A solid cylindrical striker of length \(L_s\) is fired directly against an incident bar of length \(L_i\) with initial velocity \(v_o\) as shown in Figure 35. A penalty formulation is used for the contact analysis. Ls-Dyna Automatic_surface_to_surface [64] contact definition is specified for the surfaces between striker and the incident bar. The compression SHPB was modeled using aluminum 6061-T4 to facilitate comparison with the experimental set-up which was fabricated using this material. Linear-elastic material properties for aluminum 6061-T4 are defined as in Table 2.
Figure 35: Schematic of the numerical model of a compression SHPB in “dry” conditions.

The dimensions used in the simulation corresponded to actual dimensions of the compression SHPB apparatus that is used for experimental testing. Dimensions are summarized in Table 3. Eight-node solid elements of constant stress are used to mesh the solid geometry. Average element size is 3 mm for the two parts, the incident bar and the striker. The mesh used to model the incident bar, flange, and the striker is shown in Figure 36. The incident and reflected strain histories are extracted from the element strain at locations on the incident bar corresponding to the actual location of strain gages in the experimental apparatus. Figure 37 shows a typical incident compression pulse and its reflection (tensile) from the free end of the incident bar.

Table 2: Mechanical properties used in the simulation of the compression SHPB [66]

<table>
<thead>
<tr>
<th>Material</th>
<th>Al-6061-T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [tonne/mm$^3$]</td>
<td>2.7e10$^9$</td>
</tr>
<tr>
<td>Elastic Modulus [N/mm$^2$]</td>
<td>68,900</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 3: Dimensions used for simulation of the compression SHPB

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Length [mm]</th>
<th>Diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident Bar</td>
<td>1219.8</td>
<td>25.4</td>
</tr>
<tr>
<td>Striker</td>
<td>111.6</td>
<td>25.4</td>
</tr>
</tbody>
</table>
4.3 Finite Element Model of a Tensile SHPB

A detailed numerical model of a tensile SHPB is assembled to be used as a virtual testing tool for load pulse generation and load transfer evaluation. The model includes a transfer flange for tensile load generation and gripping fixtures to load the specimen. Accordingly, the model is used in two ways, (a) in “dry” conditions, including only incident bar, striker, and flange, and (b) in full conditions, where all components of the load train are included.
Load generation evaluation provides a detail study of the mechanics of momentum transfer between the striker bar, the transfer flange, and the incident bar. The evaluation does not require modeling the specimen and the transmitter bar so that the focus is placed on the transfer flange design. The numerical model provides the tools to study and quantify stress concentrations at the flange-incident bar interface and the spurious wave reflections that result from combined loadings. Control over geometric parameters of the model provides information regarding its effect on pulse shape, width, and magnitude. The model allows the tensile loading pulse to be traced as it is propagated along the incident bar. In addition, several transfer flange configurations are modeled to evaluate its effect.

In the simulations, a hollow cylindrical striker of length $l_s$ is fired against a transfer flange of length $l_f$ with velocities ranging from 1 m/s to 20 m/s. The flange transfers the momentum of the striker to an incident bar of length $l_i$, as shown in Figure 38. The incident bar is supported laterally similar to the experimental set-up, without interfering with the path of the projectile. A penalty formulation is used for the contact analysis. Automatic surface to surface contacts are specified at the interfaces between striker and transfer flange, and between the flange and the incident bar. All components of the model are assigned the material properties of 7075-T6 aluminum which was used for the experimental set-up. Linear elastic material properties for aluminum 7075-T6 are defined in Table 4.

![Figure 38: Schematic description of the numerical model in “dry” conditions.](image)
The dimensions used for the analysis represent the actual dimensions of the SHPB apparatus developed for experimental testing and are summarized in Table 5. Constant stress eight-node solid elements are used to mesh the solid geometry. The mesh used to model the incident bar, flange, and the striker is shown in Figure 39. The average element size is 3 mm, but a finer mesh of 1 mm is used around the intersection areas. Other transfer flange configurations are modeled as the sleeve flange shown in Figure 40. In the case of the sleeve flange, a detail mesh is used to capture the deformation of the flange and the interaction between parts.

Table 4: Mechanical properties used in the simulation of the tensile SHPB [66]

<table>
<thead>
<tr>
<th>Material</th>
<th>Al-7075-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>[tonne/mm$^3$]</td>
</tr>
<tr>
<td>2.8e10$^9$</td>
<td></td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>[N/mm$^2$]</td>
</tr>
<tr>
<td>72,000</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td></td>
</tr>
<tr>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Dimensions used for simulation of the tensile SHPB

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Length [mm]</th>
<th>Inner Diameter [mm]</th>
<th>Outer Diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident Bar</td>
<td>2540</td>
<td>-</td>
<td>19.05</td>
</tr>
<tr>
<td>Striker</td>
<td>152.4</td>
<td>21.082</td>
<td>32.766</td>
</tr>
<tr>
<td>Flange</td>
<td>15.24 to 2540</td>
<td>-</td>
<td>16.38 to 25.4</td>
</tr>
<tr>
<td>Sleeve Flange</td>
<td>76.2</td>
<td>-</td>
<td>50.8</td>
</tr>
<tr>
<td>Transmitter Bar</td>
<td>1270</td>
<td>-</td>
<td>19.05</td>
</tr>
<tr>
<td>Momentum Trap</td>
<td>304.8 to 609.6</td>
<td>-</td>
<td>50.8</td>
</tr>
</tbody>
</table>

Figure 39: Mesh of the incident bar, striker, and general type transfer flange.
As a part of the evaluation, a momentum trap is included in the model immediately after the transfer flange (general type or sleeve flange). The momentum trap is simply a cylinder of length $l_t$ that is in initial contact with the free end of the flange, but it is not attached to it. The mesh used for modeling the trap is shown in Figure 41, which includes the support for the trap.

4.3.1 Stress Analysis of the Incident Bar-Flange Intersection

Stress concentration levels are evaluated at the interface between the incident bar and a general type transfer flange representing a threaded, welded, or press fitted connection. The connection in a general type transfer flange is subjected to a uni-axial tension-compression loading such that the interface undergoes a cyclic state of stress. The durability of the joint may be reduced by the fatigue nature of the loading. Absolute maximum stress levels in the bar remote from the joint do not exceed 199 MPa. On the other hand, stress levels at the interface in Figure 42 are constantly higher by a factor of 1.4. The stress concentration factor at the joint may be much higher than that indicated by the model, owing to the coarseness of the mesh relative to the joint geometry. Assuming a stress concentration factor which is closer to 3, then using typical
S-N curves for aluminum 7075-T6, the estimated a fatigue life would be around 5,000 cycles for a stress ratio of $R = -1$ [70].

![Stress levels at incident bar and flange intersection.](image)

**Figure 42:** Stress levels at incident bar and flange intersection.

### 4.4 Gripping Mechanism and Tension Specimen

Load transfer from the incident bar to the specimen and subsequently to the transmitter bar is also modeled following similar parameters to those used for load generation. The main
objective is to evaluate pulse attenuation as it propagates from the impact point down to the testing specimen. Models of the gripping fixtures and the test specimen are developed. The model allows not only load transfer evaluation but also design of the joint. Mesh and geometry are shown in Figure 43. Constant stress eight-node solid elements are used to mesh the solid model. In order to complete a “full” tensile SHPB apparatus, a transmitter bar is also modeled. The complete numerical model is assembled by putting together every component to form a tensile SHPB and by defining proper attachment and contact between parts. A partial assembly of the incident bar, transmitter bar, specimen, and grips can be seen in Figure 44.
Two different models of the specimen were assembled, one using Belytschko-Tsay [64] shell elements and one using constant stress eight-node under-integrated solid elements, see Figure 45. Tensile specimen requires a finer mesh over the gage length, especially over the shoulder area across the width so that the strain and stress distribution is properly captured. The average element size was 0.039 in (1 mm). Three elements are defined across the thickness of the specimen for the solid model. However, questions regarding the edge effect of sheet-type specimens, especially with composites, have to be further evaluated.

![Figure 45: Mesh of tension specimen.](image)

Attachment between bars and gripping fixtures is modeled using a tied contact that provides kinematic constraint equations between specified nodes [64]. The slave nodes are constraint to move with the master nodes, but rotational degrees of freedom are not constrained. It is generally recommended to use tied types of contact with solid elements since shell elements may undergo unrealistic behavior [68]. Therefore, Ls-Dyna Contact_Tied_Nodes_to_Surface [64] is specified at the interfaces between grips and the incident and transmitter bar, see Figure 46. An equivalent contact definition in Ls-Dyna is Contact_Tied_Surface_to_Surface, only differing in the input format. Threads are not modeled for simplicity. Instead, full load transfer is
assumed between the bars and the grips. The material properties used for the gripping fixtures correspond to aluminum 2024-T3 and are summarized in Table 6.

![Contact definition between the incident/transmitter bar and gripping fixtures.](image)

Table 6: Aluminum 2024-T3 mechanical properties [66]

<table>
<thead>
<tr>
<th>Material</th>
<th>Al-2024-T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [tonne/mm³]</td>
<td>2.76e10⁹</td>
</tr>
<tr>
<td>Elastic Modulus [N/mm²]</td>
<td>73,000</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Attachment between the specimen and the grips requires special attention. Minimizing geometric discontinuities (such as fastener holes, threads) in the load train is feasible in practice by attaching components with adhesive. However, modeling adhesive bonding may involve different levels of approximation depending on the desired output. Several options can be used to model the adhesive bonding but some neglect the physical behavior of an adhesive joint [69]. It can be modeled as a continuous connection, but a fine layer represents a challenge. Consider an adhesive layer of 0.33 mm connecting two parts. In order to capture stresses within the material a minimum of three elements is required, resulting in element 0.11 mm long. If only the flexibility of the joint is required, the adhesive joint can be approximated in the simulation with a single layer of solid elements. However, a material model developed using experimental testing should
provide strain-strain characteristics of the material. On the other hand, if the flexibility of the joint can be neglected, nodes could be shared to tie the parts together. An equivalent approach can be followed using a contact definition similar to the one used for the attachment of grips to the bars, but setting an offset to account for the volume of the adhesive. In this method, again the flexibility of the bonding is neglected. Before the effect of this joint is studied in detail, full load transmission is considered and the tied contact definition between these two parts is defined using Ls-Dyna Contact_Tied_Nodes_to_Surface_Offset [64] where no rupture and no flexibility in the bonding are allowed, see Figure 47.

![Figure 47: Detail of contact definition between tension specimen and gripping fixture.](image-url)

4.5 Mesh Sensitivity

The accuracy of the finite element approximation depends, among several factors, on the quality of the mesh and the element size and order [71]. In order to evaluate the dependency of the solution on the mesh size, a variable of interest has to be predefined. In the current investigation numerical models are used to evaluate issues concerning load generation and load transfer in SHPB apparatus. Mesh size is selected based on mesh sensitivity studies on SHPB analytical models reported in open-literature. The work of Govender et al. [71], evaluating mesh
sensitivity is used as a reference. Govender et al., observed no significant improvements in the approximation of phase velocity and frequency relationship below average element sizes of 5 mm.

When modeling momentum transfer in the tensile SHPB, the aim is to evaluate the effect of geometrical parameters on the generated loading pulse. Having control of the loading pulse and its characteristics is necessary for calibrating the testing apparatus. The width of the pulse is a function of the length of the striker and the dimensions of the transfer flange. Therefore, the better the approximation of the generated pulse the better the correlation of the dimensions of the pulse with the physical dimensions of the transfer flange. In laboratory testing, the SHPB technique bases the application of the one-dimensional wave propagation theory on strain measurements directly over the incident and transmitter bars. In the current work, the strain history in the bars is used as the variable of interest and several simulations are conducted with different mesh densities. No significant improvement is observed below an average element size 3 mm. However, the variable of interest on other areas of the SHPB may require finer meshes.

Another important aspect of the input expected to gain from the numerical analysis is the estimation of stress and strain fields in different sections of the load path in the testing apparatus. One goal is to minimize stress concentrations at the flange-incident bar interface. Another goal is to evaluate the strain distribution in the gage section of the test specimen. In general, sufficient refinement of the mesh is required to assure that the results are not dependent on the element size. Average and minimum element sizes over the intersection areas are 1 mm and 0.3 mm respectively, for the tensile specimen.
4.6 Experimental Validation of Numerical Model

Simulations of the loading portion of a tensile SHPB are validated with experimental data generated using the test apparatus described in Chapter 3. The configuration in which a solid sleeve flange is attached 177.8 mm from the end of the incident bar such that a portion of the bar can be supported is validated in Figure 48. The strain history obtained from the simulation is compared with the actual measurement from the experiments. Strain gages were placed at 1778 mm from the impact surface in both cases. Simulation results are in agreement with experimental data, i.e., the simulation pulse captures the secondary tensile pulses following the incident pulse, and the peak to peak distance validates the wave propagation velocity. Similarly, the simulation results for the sleeve flange including a momentum trap captured the general trend of the incident and reflected pulses. Again, the peak to peak distance correlates well with the wave propagation velocity. The strain history pulses presented in Figure 49 show similar pulse characteristics as shape and amplitude. They differ in pulse width; simulation pulse width is shorter by 18.8% than the experimental pulse. Simulation results also capture the secondary compressive pulses that prevail in the measurement area after the incident pulse has decayed.

![Figure 48: Tensile SHPB with supported bar extension experimental validation - Strain history.](image)
Figure 49: Momentum trap addition and sleeve flange experimental validation - Strain history.
CHAPTER 5
TENSILE PULSE GENERATION

Tensile pulse generation techniques are investigated experimentally and numerically in a Split Hopkinson Pressure Bar (SHPB). A comprehensive study is not presented anywhere in literature where specific guidelines are identified for the design of a momentum transfer flange. A direct loading method employing a transfer flange is often used for material characterization. However, details regarding proper attachment of the flange to the incident bar are missing. Recommended dimensions, shapes, and aspect ratios are also not specified. Careful examination of different options for attaching the flange to the bar, as well as the interactions of geometric parameters is required. Attachment options should minimize discontinuities since they may result in a stress wave propagating down the system with a series of steps. These steps would complicate the plastic analysis of the specimen [43].

The rise time of the loading pulse can be drastically modified if perfect alignment between the impact faces of the striker bar and the transfer flange is not guaranteed. Any misalignment may complicate the proper selection of pulse initiation time which is critical for the application of the one-dimensional wave theory. Pulse width is determined not only by the length of the projectile, but also by the geometric details and dimensions of the transfer flange connection. Ideally, an elastic wave of constant amplitude and known width is desired to propagate past the incident strain gage and reach the test specimen. However, even with uniform sections, the stress level will fluctuate somewhat because of the transverse stress oscillations in the bar due to dispersion (i.e., Poisson’s expansion and contraction). Notice that the magnitude of these oscillations can be minimized by using small diameter bars [43]. The magnitude of the oscillations riding the main pulse can be studied in detail. Even though, such secondary pulses
are of smaller magnitude than the leading tensile pulse, the specimen may undergo tensile loading followed by compressive loading. They could represent reflections from step discontinuities in the pulse propagation path or lateral contractions corresponding to Poisson effect.

SHPB tensile impact testing data found in literature indicate different types of loading problems. Distorted loading pulses show secondary tensile and compressive pulses superimposed over the leading loading pulse. Pulse distortions originate mainly from the way the loading method introduces the pulse and the way it is transferred between and across components. Secondary tensile pulses are observed to extend pulse width beyond the theoretical width. An example of such behavior can be found in published strain gage records generated using the transfer flange technique [12, 72] where strain gage records show local maximums preventing the unloading segment of the pulse from fading away. A tensile state of stress may exist over the measurement area by the time the reflected pulse reaches the strain gage. Since the reflected pulse is compressive in nature, the measured strain history would erroneously indicate a lesser value. The opposite scenario would occur if secondary compressive pulses prevail in the measurement area. A compressive state of stress resulting from the secondary compressive pulses may add up to the reflected pulse increasing its amplitude. Under controlled conditions the reflected pulse can be corrected for secondary pulses distortions given that the magnitude of such pulses and the exact time of incidence are known a priori. Reported strain records for the pre-stressed loading bar technique observe secondary tensile pulses followed by compressive pulses [50]. The records show irregularities over the unloading segment of the incident pulse, i.e., instead of observing a smooth decay, it shows stepped drops all the way to compressive levels. The observed pulse distortions may mask the actual reflected pulse initiation time. In
addition, the strain record next to the specimen cannot be used for direct calculations since incident and reflected pulses are superimposing at that location. Instead, particle velocity in the incident bar side is calculated taking into account such superposition and the time shift between two measurements locations.

Secondary tensile and compressive pulses may undermine the application of the one-dimensional elastic wave propagation theory, and the calibration of the testing apparatus. Recall that the strain-rate and the strain in the test specimen are functions of the reflected pulse and the area underneath the curve. When different geometrical factors interact distorting the pulse width and shape, uncertainty about the initiation of the reflected pulse would be translated to the strain and strain-rate estimation. Typically, any irregularity in the pulse beyond the loading segment is usually disregarded. Test specimen failure during the loading segment of the pulse is sufficient for material strength characterization. However, calibration of the testing apparatus requires control of the loading pulse and subsequent reflections. Nemat-Nasser et al. [48] pointed out the need to control the loading pulse not to load the specimen multiple times. However, details about the load transfer mechanism are omitted. Proper separation of the loading pulse and the reflected pulse is necessary since the measurement of the input pulse and the system output is conducted at the same location on the incident bar. Calibrating the relationship between input and output requires control over the separation between pulses and every secondary pulse that would prevent such separation. In the presence of secondary pulses distorting the leading loading pulse, simply moving the strain gages to a different location in the incident bar will not correct the problem.

A comprehensive methodology is not presented anywhere in literature where specific requirements are defined for the loading methodology. Experimental errors are not properly
addressed, adding uncertainty to the application of the one dimensional wave propagation theory to estimate the strain-rate and the strain in the testing specimen. In the present study, Lagrange diagrams and a finite element model are used to identify the sources of secondary pulses. The effect of flange geometrical parameters on pulse generation is quantified through numerical simulations. Details regarding proper attachment of the flange to the incident bar are presented. Flange dimensions, shape, and aspect ratios are recommended. An experimental testing apparatus is developed to investigate the nuances of the transfer flange technique as the load generation technique.

5.1 Tensile Pulse Generation Techniques in a SHPB

Although the SHPB technique have been established as the most consistent technique for medium and high strain rate testing, proper understanding of its limitations provides dependability to the experimental results. In a tensile SHPB, the main criterion for selecting a load transfer methodology such that it allows for a proper calibration of the testing apparatus is the reliability of the generated tensile pulse. Indirect loading methodologies are reported to affect the length and shape of the pulse. In Eskandari’s [21] design, the connector is reported to influence the length of the pulse in a twofold manner. In contrast to direct impact methodologies in which a quasi-rectangular pulse is generated, a quasi-triangular pulse is reported by Eskandari. Associated problems using similar methodologies are reported by several authors [9, 19, 31, 32, 41, 43, 44, 46]. Some of the problems include, the sample not establishing equilibrium within the first few microseconds of the test and thus making low strains values not reliable, complex stress fields, eccentricity of the impact introducing flexural stress waves in the tube, test specimen pre-straining affecting the response indirect loading methodologies as the collar methodology [31, 32, 44]. On the other hand, direct loading methodologies as the pre-stressed loading bar or the
transfer flange are not reported to have major drawbacks or limitations [12, 14, 48, 49]. However, details and specifications about the momentum transfer between the striker and the incident bar are not found in public literature.

5.2 Design for Tensile Pulse Generation

In the transfer flange technique, momentum transfer takes place after an impact of a hollow striker with a flange attached at the end of the incident bar. There are a few possibilities to attach the flange to the bar, i.e., clamp, threaded, welded, or a press fitted connection. Each attaching mechanism may affect the momentum transfer in a particular way or may represent a challenge from the mechanical point of view, e.g., a threaded connection may fatigue. The aspect ratio between the dimensions of the flange and the striker would certainly shape the resulting pulse. Wave propagation is carefully evaluated through every component on the apparatus and the interaction between striker length, flange length, and flange height is established. Moreover, pulse’s superposition is detected and corrected.

The main objective is to be able to transfer the momentum of a moving projectile to the incident bar so that the generated pulse is as smooth as possible and it represents an elastic collision. Such momentum transfer should not introduce additional loading or vary the nature of desired tensile loading. Undesirable vibrations that result from the impact event should be minimized so the tensile pulse is not distorted. The generated tensile pulse is desired to have certain characteristics before it can be used for strain rate characterization of materials, history studies, or system calibrations. Ideally, the pulse should have a trapezoidal (or triangular) shape and be free of dispersion, see Figure 51. However, this is practically impossible due to the dispersive nature of solid bars [24]. In practice, mechanical dispersion and attenuation should be minimized. Pulse width, amplitude, and shape are functions of the introduced momentum and the
striker length. Proper design of the loading pulse generation provides control over such pulse characteristics.

The transfer flange technique for tensile pulse generation in a SHPB is evaluated using Lagrange diagrams, numerical simulations, and experimental validations. The Lagrange diagrams facilitate a qualitative analysis of wave propagation, which can include the identification of reflections and superposition of waves. First, wave propagation of the generated pulse along the incident bar is studied using Lagrange diagrams. In addition, wave propagation of secondary reflections generated by different flange geometries, bar supports, and pulse trapping devices are evaluated. If the wave propagation is carefully evaluated through every component on the apparatus, the interaction between striker length, flange length, and flange height/radius can be established. Moreover, pulse’s superposition can be detected and corrected. A numerical model is assembled to verify the preliminary observations through dynamic simulations and to evaluate the effect of flange deformation on the generation of secondary pulses. The numerical model is used to assess two attachment techniques of the flange to the
incident bar; a general type flange, representing a welded, threaded, or press fitted connection and a sleeve flange type connection. A geometrical modification of the flange is also evaluated numerically, i.e., coned-shape flange. In addition, the effect of placing a momentum trap after the flange is evaluated for the two types of flange attachments. Proper design of the loading pulse generation allows control of pulse characteristics as shape, width, amplitude, and level of oscillations. Pulse width, amplitude, and shape are functions of the impulse introduced and the striker length. The conceptual development phase is followed by experimental validations of the simulation and conceptual findings. A tensile SHPB apparatus is assembled for that purpose.

5.2.1 Transfer Flange

The use of transfer flange appears to be the most reliable loading technique to introduce tensile loading into the incident bar in a SHPB. Lagrange diagrams and numerical models are used to evaluate the effect of flange dimensions on the generated pulse. Length \((l_f)\) and height/radius \((h_f)\) of the transfer flange were the parameters varied, see Figure 52. The strain history along the longitudinal axis of the incident bar is used to evaluate pulse propagation characteristics and to visualize locations of pulse superposition. Dimensions play an important role when selecting the right location for placing the strain gages on the incident bar to collect real time strain history.

![Flange parametric study](image)

Figure 52: Flange parametric study.
The Lagrange diagram in Figure 53 shows the incident pulse propagating in a system with flange length shorter than half the incident bar. Strain history is plotted on the right showing strain gage record. The relationship between the incident bar length \( l_i \), striker length \( l_s \), and the flange length \( l_f \) is given by equation (5.1)

\[
\frac{l_i}{2} > l_f > l_s
\]  

(5.1)

Incident pulse propagation in Figure 53 shows the reflection of the pulse at the free end (green pulse) reaching the strain gage location SG1 at about the same time that a tensile pulse (red) coming from the reflection of a compressive pulse at the back face of the flange. Under these conditions the reflected pulse (compressive) would overlap with a secondary tensile pulse and the strain gage would indicate a combined state of strain. This apparent reflected wave, when used in conjunction with the one-dimensional wave theory, would produce erroneous strain history in the specimen.

There are two potential options that can be used so that the two pulses do not overlap over the strain gage; one is the flange length \( l_f \) and the other is the actual location of the strain gages. However, it cannot be simply solved by relocating the strain gages. Strain gages should be placed at a distance of at least twice the striker length \( l_s \) from the free end of the incident bar. Pulse width is defined by wave theory as twice the striker length \( l_s \). If strain gages are placed at a distance less than 2 \( l_s \) from the bar end, the incident pulse would overlap with the reflected pulse. On the other hand, if strain gages SG2 are placed far away from the free end, a modified reflected pulse would be recorded, see Figure 53. The recorded reflected pulse would overlap with a secondary tensile pulse, and most likely cancel each other out.
If the flange length ($l_f$) is varied instead, better control over that secondary tensile pulse is obtained. A long enough flange would delay the secondary pulse arrival at the strain gages’ location. For this to be practical, the flange should be at least as long as half the length of the incident bar, i.e., by the time the secondary tensile pulse reaches the strain gages the test would be over. The scenario where subsequent reflections are delayed is described by equation (5.2). However, incident bars in tensile SHPB applications are already long, implying lengthy flanges. Another possible scenario would be minimizing the flange length to a practical value. It should be short enough not to alter the incident pulse, but thick enough to withstand the impact event. This is defined by equation (5.3) and represented in the Lagrange diagram of Figure 54. Shortening flange length may reduce the magnitude of the subsequent reflections, but at the same time every subsequent reflection may add to the width of the loading pulse. This observation is
verified in the simulation results in section 5.3.1, where small subsequent reflections distort and reshape the leading pulse by extending the decay time.

\[ l_f \geq \frac{l_s}{2} > l_s \]  
\[ \frac{l_s}{2} > l_s > l_f \]

\[ (5.2) \]
\[ (5.3) \]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{flange_length_reduction}
\caption{Flange length reduction.}
\end{figure}

\subsection{5.2.2 Supported Bar Extension}

The hollow striker rides on a segment of the incident bar that is not supported not to block the striker path. The weight of the bar segment and the flange deflects this bar segment. Supports can be placed to an extension of the incident bar after the flange or directly underneath the flange. The effect of the bar extension is visualized in the Lagrange diagram in Figure 55.
The tensile pulse and its symmetric compressive pulse can be traced as they travel and reach each interface. Notice that the leading pulse has not fully crossed the strain gage when a secondary pulse reaches the gage. Since the gage cannot differentiate, the final output is a summation of pulses. Superposition cannot be fixed by simply changing the location of the strain gages. A pulse under these conditions cannot be use for strain rate studies, system calibration, or history effect studies.

Figure 55: Effect of supporting bar extension on pulse propagation.

5.2.3 Coned-shape Flange

An interesting variation to the geometry of the transfer flange design is presented and evaluated. The compressive pulse generated in the flange at the time of the impact, reflects back as a tensile pulse after reaching the back face of the flange. In the proposed shape modification,
the back face is inclined by an angle $\theta$, see Figure 56. It is argued that the radial components of the pulses that reflect at the inclined surface would cancel out. Consequently, only the longitudinal component of the pulses would reflect in the axial direction. Hence, the reflected tensile pulse would have a reduced magnitude. A numerical model is used to vary the angle $\theta$ on the back face of the flange. The model is used to verify the hypothesis and to evaluate the effect on the generated pulse characteristics. Angles are varied from $0^\circ$ to $89^\circ$, i.e., $0^\circ$ representing no cone-shape at all and $89^\circ$ approximating a flange of infinite length.

![Figure 56: Cone-shape flange comparison.](image)

### 5.2.4 Sleeve Transfer Flange

A novel technique is proposed as an alternative to a threaded or welded connection. A solid sleeve flange is clamped to the end of the incident bar over a matching profile, see Figure 57. Other types of connections (threaded, welded, or press fitted) may observe stress concentration at the bar-flange interface such that fatigue can degrade the connection with time. A smooth momentum transfer is intended by allowing a shallow transition angle between the sleeve and the bar, e.g., $30^\circ$. Hence, momentum transfer takes place minimizing stress concentration.
5.2.5 Momentum Trap

A simple addition to the transfer flange methodology is evaluated, see Figure 58. A momentum trap is added after the transfer flange to contain the compressive momentum generated at the collision of the striker with the flange. The momentum trap is simply an extra bar placed in close contact with the transfer flange, but not attached to it. The trap can be supported on bearings and should have the same cross sectional area than the flange. The effect of the trap on the desired pulse characteristics is evaluated.

The Lagrange diagram is used to visualize the way the compressive pulse gets trapped after crossing the flange. One may notice in Figure 59 that the trajectory of the compressive pulse after reaching the back face of the momentum trap is reflected as a tensile pulse. Since there is no physical attachment between the flange and the trap, the tensile pulse simply moves the trap apart from the flange. Therefore, the tensile pulse is not transmitted into the incident bar and is thus captured by the trap. The Lagrange diagram shows that a trap with a minimum length equal to the projectile length is sufficient. However, from the collision point of view, the mass of the trap cannot become too large. Otherwise, it could behave as a fixed boundary condition.
5.3 Finite Element Analysis of Tensile Pulse Generation with a Transfer Flange

Results of numerical simulations for several transfer flange arrangements are presented in this section. Parameter interaction effect and attachment technique effect on pulse characteristics are evaluated by comparing strain history in the incident bar. The effect of flange length and height/radius on pulse width, amplitude, and level of oscillation is quantified on the general type
transfer flange model. The influence of the conic flange angle on pulse width is studied. The benefits of introducing a momentum trap and the effect of the proposed sleeve flange are presented.

### 5.3.1 Transfer Flange

A numerical model is used to evaluate the effect of flange length on the pulse characteristics by varying length of the flange from 15.24 mm to 2540 mm. Strain histories are plotted in Figure 60. Shorter flanges clearly show larger widths, amplitudes, and level of oscillations. The scenario defined by equation (5.3) shows larger strains in the bar, but also increments of 48.8% over the theoretical pulse width. This result verifies the width extension observed in the Lagrange diagram in Figure 54. On the other hand, the larger flange length scenario defined by equation (5.2) shows smaller strains, and more importantly, increments of only 15.73% on pulse width. Notice that flanges longer than 1524 mm do not show significant changes in pulse width or oscillations levels. Results are summarized in Table 7. Large pulse amplitudes indicate that the incident bar is withstanding large strains. Large strains in the bar-flange interface may eventually fatigue the attachment between the flange and the bar.

![Figure 60: Incident bar axial strain history for flange length comparison.](image)
Table 7: Flange length comparison

<table>
<thead>
<tr>
<th>Flange Length [mm]</th>
<th>Flange Height/Radius [mm]</th>
<th>Max Strain [mm/mm]</th>
<th>Pulse Width Δt [s]</th>
<th>Theoretical Error %</th>
<th>Oscillations Δε</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.24</td>
<td>20.90</td>
<td>0.002686</td>
<td>0.000090</td>
<td>48.80</td>
<td>0.000350</td>
</tr>
<tr>
<td>1524</td>
<td>20.90</td>
<td>0.001088</td>
<td>0.00070</td>
<td>15.73</td>
<td>0.000280</td>
</tr>
<tr>
<td>2540</td>
<td>20.90</td>
<td>0.001088</td>
<td>0.00070</td>
<td>15.73</td>
<td>0.000280</td>
</tr>
</tbody>
</table>

Based on the results, a minimum flange length can be selected, i.e., one for which the pulse width is not significantly altered and the level of oscillations introduced to the pulse is minimized. When a striker measuring 152.4 mm long is used, 1219.2 mm should be the minimum length of the flange for the pulse to be recorded without any superposition at a distance of 1524 mm from the impact point. However, if pulse shaping methodologies are to be implemented, a longer flange should be used. Pulse shaping techniques has been proven to minimize dispersion effects by several authors [60], [61]. For this reason a 1524 mm long flange is used for the simulation.

Simulation results for flange height/radius effect are shown in Figure 61 and summarized in Table 8. Flange length is held at 1524 mm to block the effect of the reflections as seen in the flange length evaluation. Impact velocity is held the same for all conditions. Striker dimensions are kept constant with outer radius 16.38 mm and 5.1 mm thickness. The height/radius of the flange is varied between 16.38 mm and 25.4 mm. All heights/radius show 15.7% deviation from the theoretical width. Flange height/radius is not observed to affect pulse width as expected for a given striker length. The oscillations riding the main pulse are not significantly different (relative to the respective amplitudes of main pulse) for the range for flange radii investigated. The amplitude of the main pulse in the incident bar decreases with increasing flange radius as a result of the mass increment. This, as the flange gets larger lower strain levels are induced due to the impact. Note that the striker size is the same for all three cases investigated.
Table 8: Flange height/radius comparison

<table>
<thead>
<tr>
<th>Flange Height/Radius [mm]</th>
<th>Flange Length [mm]</th>
<th>Max Strain $\varepsilon_{\text{max}}$ [mm/mm]</th>
<th>Pulse Width $\Delta t$ [s]</th>
<th>Theoretical Error %</th>
<th>Oscillations $\Delta \varepsilon$</th>
<th>$\Delta \varepsilon/\varepsilon_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.38</td>
<td>1524</td>
<td>0.001463</td>
<td>0.00007</td>
<td>15.73</td>
<td>0.000372</td>
<td>0.254</td>
</tr>
<tr>
<td>20.90</td>
<td></td>
<td>0.001088</td>
<td>0.00007</td>
<td>15.73</td>
<td>0.000280</td>
<td>0.257</td>
</tr>
<tr>
<td>25.40</td>
<td></td>
<td>0.000839</td>
<td>0.00007</td>
<td>15.73</td>
<td>0.000248</td>
<td>0.295</td>
</tr>
</tbody>
</table>

Figure 61: Flange height/radius comparison.

5.3.2 Flange Deformation Effect

The effect of the flange deformation on the loading pulse is evaluated through finite element simulations. Strain gage records of the incident pulse indicate secondary compressive pulses following the leading tensile pulse in numerical simulations as well as published experimental results, see Figure 62. It is argued that the secondary compressive pulses result from the radial contraction of the diameter at the bar-flange interface and also from the radial deformation of the flange. A virtual testing environment provided by the numerical model is used to evaluate the effect of the flange deformation on the introduction of compressive pulses. This is verified by limiting the radial deformation of the flange and of the incident bar in a numerical model. The conceptual problem is defined in cylindrical coordinates in Figure 63.
nodes on the flange and the bar are constrained in a nonphysical manner in the radial direction $U_r$, but are free to move in the longitudinal direction $U_z$. A simplified model of the loading portion of a tensile SHPB is used; a hollow striker is propelled against a solid flange fully fused to the incident bar. Having the bar and the flange fused together represents a welded or press-fitted connection. The effect of the flange length on the generated pulse is blocked by having a 1524 mm long flange as it was verified in the length evaluation. Simulation results are presented for both scenarios; a real case where flange and bar deform without restriction and a modified case where the radial deformation is constrained, see Figure 64 (a) and (b) respectively. Compressive longitudinal strains are observed at the bar-flange interface immediately after the impact event. Consecutive reflections of the pulse in the radial direction continue to introduce compressive strains at the interface even after the leading tensile pulse has propagated toward the free end of the bar. This observation explains the oscillations observed in the unconstrained strain history plot in Figure 62; at the top segment of the pulse oscillations following the rising segment and remaining after the pulse has unloaded. On the other hand, when the radial deformation is constrained oscillations are minimized.

Figure 62: Incident bar strain history comparison.
Figure 63: Compressive pulse introduction by flange deformation – Section cut.

Figure 64: Flange deformation sequence – Section cut.

(a) Flange and bar radially unconstrained  (b) Flange and bar radially constrained

5.3.3 Momentum Trap

A momentum trap 304.8 mm long is included in the simulation of the general type flange and in the simulation of the sleeve flange. General type flange dimensions are 15.24 mm length and 25.4 mm height/radius. Sleeve flange dimensions are 76.2 mm long and 25.4 mm radius.
Simulation results in Figure 65 show the effect of the momentum trap blocking secondary tensile pulses. Adding a momentum trap can be compared with the improvement observed by having a long flange that is larger than half the incident bar, see Table 9. A long flange, a flange and a trap, or a sleeve flange and a trap observe low level of oscillations. Pulse width is observed to reduce when a momentum trap is added; pulse width deviation from the theoretical pulse width is 28.9% compared to a 48.8% error when no momentum trap is included (see Table 7).

![Figure 65: Incident bar strain history for momentum trap addition.](image)

<table>
<thead>
<tr>
<th>Set-up</th>
<th>Trap Length [mm]</th>
<th>Flange Length [mm]</th>
<th>Max Strain [mm/mm]</th>
<th>Pulse Width ( \Delta t ) [s]</th>
<th>% difference in width</th>
<th>Oscillations ( \Delta \varepsilon )</th>
<th>Ratio Oscillation to Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Flange</td>
<td>n/a</td>
<td>1524</td>
<td>0.001088</td>
<td>0.000070</td>
<td>15.73</td>
<td>0.000280</td>
<td>0.25</td>
</tr>
<tr>
<td>Flange &amp; Trap</td>
<td>304.8</td>
<td>15.24</td>
<td>0.001338</td>
<td>0.000070</td>
<td>15.73</td>
<td>0.000290</td>
<td>0.21</td>
</tr>
<tr>
<td>Sleeve &amp; Trap</td>
<td>304.8</td>
<td>76.2</td>
<td>0.000817</td>
<td>0.000078</td>
<td>28.96</td>
<td>0.000182</td>
<td>0.22</td>
</tr>
</tbody>
</table>

### 5.3.4 Sleeve Transfer Flange

The effect of the proposed sleeve flange on the loading pulse is evaluated. A numerical model is assembled where the matching profile between the incident bar and the sleeve flange is modeled in detailed. The model includes the incident bar, the sleeve flange, the striker, and a
momentum trap to block the effect of secondary tensile pulses as it was verified before. Strain gage records of the incident pulse in the simulation results observe secondary compressive pulses following the leading tensile pulse as shown in Figure 66. It was verified when evaluating flange deformation that the radial deformation of the flange is one of the causes for such secondary compressive pulses. In addition, a complex pattern of reflections within the sleeve flange takes place adding oscillations to the loading pulse. It can be visualized in the Lagrange diagram in Figure 67. The effects of the radial deformation of the sleeve flange are verified by modeling the flange as a rigid part and comparing it with the real flange case where the sleeve flange is free to radially compress the incident bar over the attachment area, see Figure 68. Simulation results in Figure 66 show how the compressive strains are minimized in the strain history plot for the rigid flange case.

Figure 66: Incident bar axial strain history for sleeve flange comparison.
5.3.5 Coned-shape Flange

The back face angle $\theta$ of the cone-shape flange was varied from $0^\circ$ to $89^\circ$. Simulation results for relevant angles are presented. Axial strain histories are used to compare the effect of the flange geometry on the pulse characteristics (see Figure 69). Delayed secondary tensile
pulses are clearly observed in the strain history for angles between 0° and 45°. Secondary pulses results from reflections in the back face of the flange. Also from subsequent impacts of the striker since the flange cannot slow it down. Between 60° and 85°, secondary pulses overlapped with the leading tensile pulse distorting pulse shape and increasing pulse width several times over the theoretical value. Above 88° secondary pulses appeared to be controlled. However, this is not due to the inclined surface but due to the long flange effect observed before. The expected strain level reduction is rather small, i.e., it is only relevant above 85°. The strain level reduction is due to the increment of mass as the flange becomes larger. Notice maximum strains in Figure 69; there is a reduction in strain of 67.3% between 0° and 89°. It is evident how pulse width increases with larger surface angle until it reaches a break point. Even though load levels are lower, pulse shape is degraded. Table 10 summarizes the results.

Table 10: Coned-shaped flange effect

<table>
<thead>
<tr>
<th>Angle θ [Deg]</th>
<th>Flange Length [mm]</th>
<th>Flange Height/Radius [mm]</th>
<th>Max Strain [mm/mm]</th>
<th>Pulse Width Δt [s]</th>
<th>Theoretical Error %</th>
<th>Oscillations Δε</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.24</td>
<td>25.40</td>
<td>0.002723</td>
<td>0.000080</td>
<td>32.26</td>
<td>0.000380</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td>0.002759</td>
<td>0.000130</td>
<td>114.93</td>
<td>0.000650</td>
</tr>
<tr>
<td>45</td>
<td></td>
<td></td>
<td>0.002719</td>
<td>0.000150</td>
<td>148.00</td>
<td>0.000550</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
<td>0.002585</td>
<td>0.000170</td>
<td>181.06</td>
<td>0.000410</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
<td>0.002377</td>
<td>0.000190</td>
<td>214.13</td>
<td>0.000600</td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
<td>0.002244</td>
<td>0.000210</td>
<td>247.19</td>
<td>0.000899</td>
</tr>
<tr>
<td>85</td>
<td></td>
<td></td>
<td>0.001802</td>
<td>0.000240</td>
<td>296.79</td>
<td>0.001417</td>
</tr>
<tr>
<td>88</td>
<td></td>
<td></td>
<td>0.000939</td>
<td>0.000070</td>
<td>15.73</td>
<td>0.000259</td>
</tr>
<tr>
<td>89</td>
<td></td>
<td></td>
<td>0.000888</td>
<td>0.000070</td>
<td>15.73</td>
<td>0.000215</td>
</tr>
</tbody>
</table>
Figure 69: Incident bar strain history for Coned-shape flange comparison.

5.4 Experimental Evaluation of tensile SHPB apparatus

Experimental tests conducted on a Tensile SHPB including the proposed sleeve flange are presented. Strain histories measured at 1778 mm from the free end of the incident bar for three different configurations are summarized in Figure 70. In the first configuration, the sleeve flange is attached 177.8 mm from the end of the incident bar such that an extra portion of the bar can be supported. In the second configuration, the flange is attached at the end of the incident bar and support is provided directly to the flange. The third configuration includes a momentum trap in direct contact with the sleeve flange attached at the end of the incident bar. A 101.6 mm long projectile is used for all cases. Strain history for the supported bar extension configuration indicates large oscillations after the initial peak. Superimposed due to the transverse oscillations arising from Poisson effects, there are secondary pulses as predicted by Lagrange diagrams and simulation results. As a result, the pulse possesses a longer rise time, an extended pulse width, and a distorted pulse shape. The pulse width is about three times longer than the predicted length (i.e., twice the projectile length). Similarly, the pulse for the case of the flange attached at the end
of the incident bar, we may observe secondary pulses reflecting from the flange back face. Such secondary pulses are known to change the shape of the pulse. The decay time extends, increasing the pulse width by almost four times the theoretical prediction. On the other hand, the pulse for the test with a momentum trap addition indicates significant improvements. Pulse shape resembles the ideal trapezoidal shape. Secondary tensile pulses are fully eliminated, but pulse width remains 59.4% larger than the theoretical one. Part of the deviation is the result of dispersion as shown by the simulation results. Additional error is introduced by reflections within the sleeve transfer flange. On a side note, residual pulse oscillations are observed after the incident pulse has decayed. Secondary compressive pulses prevail in the measurement area when the reflected pulse initiates. Such pulses can be subtracted when estimating strain and strain-rate using 1D theory.

![Experimental configuration diagram](image)

Figure 70: Experimental incident bar strain history for three configurations.

### 5.5 Summary

Strain rate effect studies, history effect, and system calibration requires a testing apparatus that is capable of introducing an approximate uniaxial tensile loading. Tensile loading should be free of other types of extraneous loads. Subsequent loading should be controlled to
facilitate recovery experiments. Current indirect loading methodologies present several drawbacks, e.g., application is material specific, pulse shape distortion is observed, wave reflections are introduced, and they fail to generate reliable results. Direct methodologies on the other hand, provide more control over testing parameters involved. However, a proper loading methodology is not defined anywhere in literature or specific requirements are not established for the load transfer to take place.

The current investigation selected a transfer flange technique to introduce tensile loading. Selection is based on the reliability and simplicity of the momentum transfer. Careful examination of different parameters provides insight about the strength and limitations of the selected technique. Two possible flange attachment options are evaluated, i.e., a general type flange at the end of the incident bar, representing a welded, threaded, or press fitted connection and a sleeve flange type connection. At the same time, careful attention at the interaction of geometrical parameters took place, i.e., length, height, and shape.

The transfer flange technique for tensile pulse generation in a SHPB is evaluated. Secondary tensile and compressive pulses are observed to distort the loading tensile pulse. Pulse distortions may limit the application of one-dimensional wave propagation theory to estimate strain and strain-rate in the specimen. Lagrange diagrams and finite element models are used to visualize pulse propagation, to identify the sources of secondary pulses, and to establish the effect of transfer flange geometrical parameters on pulse generation and wave propagation. An experimental testing apparatus is developed. Proper attachment of the flange to the incident bar is discussed and a novel technique for flange attachment is presented.

Adding a momentum trap to the transfer flange methodology represents a practical solution. It is more feasible than having an extremely long flange attached to the incident bar and
more realistic than having a 89° coned-shape flange. The momentum trap cancel the effect of secondary pulses and the sleeve flange minimize stress concentrations that may lead to fatigue issues on the flange attachment. As a side note from the simulation, the momentum trap needs to be in contact at all times, otherwise spurious reflections are observed to alter the characteristic shape of the pulse.
CHAPTER 6
WAVE MODULATION – ONE-DIMENSIONAL THEORY CORRECTION

A methodology is developed for correcting the estimation of strain based on the one-dimensional wave propagation theory. Discrepancy between the measured strain and the one-dimensional estimated strain limits the application of the testing technique. The major source of error is introduced by dispersion in the form of wave modulation, i.e., wave attenuation and phase shift. Wave modulation results from impedance change and perturbations, among several factors, introduced to the loading pulse as it travels through every component in the load train and as it is transmitted through every mechanical interface. Additional modulation is introduced when loading sheet-type specimens. Therefore, quantifying the overall system response, although test apparatus specific, will measure to what extent the testing apparatus is modifying the input loading. Overall system response is measured experimentally directly on the testing specimen. The measured pulse on the testing specimen represents the actual output of the system to the loading pulse after it has been transmitted and thus modulated by every other component of the load train in the apparatus. The applicability of the correction methodology is evaluated numerically before it is implemented on experimental results to establish its limitations.

6.1 One-Dimensional Theory Estimation of Strain

Open literature [6, 9, 12, 14, 19, 21, 31, 32, 33] have addressed the application of the SHPB technique and the one-dimensional wave analysis to tensile testing of materials under dynamic conditions. The validity of the one-dimensional wave theory assumptions still carries some levels of uncertainty especially when dealing with sheet-type materials. Discrepancy between the measured material response and the one-dimensional estimated response is verified
in the current investigation. It has been argued that the one-dimensional wave propagation theory fails to properly estimate the strain in the specimen.

As a virtual testing tool, a numerical model of a tensile SHPB testing apparatus including gripping fixtures and testing specimen is used to verify the experimental observation under a more controlled environment. Following the concluding remarks on Chapter 5, where a tensile pulse generation technique is recommended, a finite element model including a momentum trap in combination with a sleeve flange is used. Numerical results for an impact velocity of 5 m/s showed similar discrepancy between measured and estimated strain in the testing specimen (see Figure 71).

The first step in understanding the limitations of the one-dimensional theory estimation of strain includes ensuring the proper use of experimental data. In the case of the average strain in the specimen, strain histories recorded at different locations and/or times are used to estimate particle velocity at the end of the bars. Recalling Equation 1.13, the integral expression for strain estimation includes incident, reflected, and transmitter bar strain histories. If the contribution of each history is tracked in time, as shown in Figure 72, the time at which each pulse no longer
represents a single loading state is clearly visualized, i.e., tension or compression. When looking at the contribution of each pulse to the loading segment of the strain pulse, it is clear that oscillations in the pulses post decay can be disregarded since they add only during the decaying segment of the strain pulse. This observation is relevant when conducting Fourier analysis since every set of information in the time domain has an equivalent set of information in the frequency domain.

<table>
<thead>
<tr>
<th>t = .000038 sec</th>
<th>t = .000068 sec</th>
<th>t = .00009 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 72: History of pulse contribution to strain estimation.

6.2 Fourier Analysis

In this investigation, a frequency based correction methodology is presented which uses elements from Fourier analysis. Therefore, a summary of related concepts and properties are presented herein for completeness.
Fourier analysis is a mathematical technique used to obtain the frequency content of a time signal. The technique provides a description of the time signal in terms of frequency-domain magnitude and phase [74]. Periodic and non-periodic time signals are transformed into the frequency domain by means of a Fourier transform (FT) [75]. The Fourier series or the Fourier integral allow such transformation. However, the Fourier series are limited to periodic time signals. Whereas the Fourier integral applies to non-periodic signals [74]. A continuous Fourier transform pair is given as [74]

\[
X(f) = \int_{-\infty}^{\infty} x(t) \cdot e^{-j2\pi ft} \, dt 
\]

(6.1)

\[
x(t) = \int_{-\infty}^{\infty} X(f) \cdot e^{j2\pi ft} \, df 
\]

(6.2)

where \(X(f)\) is the Continuous Fourier transform (CFT), \(f\) is the cyclic frequency, and \(i\) is the complex \(\sqrt{-1}\). Note that a non-periodic signal implies infinite period, which means that the signal does not repeat itself. The CFT has a limitation when handling non-analytical function as those generated experimentally [76]. In practical situations, continuous functions cannot be handled by computers. Signals are discretized and numerical integration is used to compute the Fourier transform over finite time duration. This process is referred as Discrete Fourier transform (DTF) and the series transform pair are given as [74]

\[
X_d(k\Delta f) = \Delta t \sum_{n=0}^{N-1} x(n\Delta t) \cdot e^{-j2\pi kdn\Delta t} 
\]

(6.3)

\[
x(n\Delta t) = \Delta f \sum_{k=0}^{N-1} X_d(k\Delta f) \cdot e^{j2\pi kdn\Delta t} 
\]

(6.4)
where \( N \) is the number of samples, \( \Delta t \) is the sampling interval, \( \Delta f \) sample interval in the frequency domain, \( n \) is the time sample index, \( k \) is the computed set of discrete frequency components, \( x(n \Delta t) \) is the set of time samples, and \( X(k \Delta f) \) is the set of Fourier coefficients.

6.2.1 Fast Fourier Transform

The Fast Fourier transform (FFT) is an efficient algorithm to compute the DFT, i.e., to perform the summations of the DFT. Operations of the DFT are reduced based on symmetries and periodicities from \( N = 2^k \) to \( N \log_2 N \) [74]. A large number of algorithms today follow the Cooly-Tukey algorithm published in 1965 in *Mathematic of Computation* [74]. In the current investigation, a conventional power of two (2) algorithm, known as radix-2, is used through commercial software Altair HyperGraph [58]. In this algorithm, the dataset should be \( N \) uniformly spaced where \( N \) is a multiple of 2. If data size is not a power of 2, zero padding is done to the next larger \( N \) [77]. The time increment in the experimental data is 1e-7 sec, while in the simulation data is 2e-6 sec.

6.3 Correction Methodology

One-dimensional specimen strain discrepancy is evaluated from a system perspective instead of an individual factor perspective. The proposed correction methodology approaches the problem as a whole and obtains a transfer function that characterizes a specific testing apparatus. The transfer function, which is generated in the frequency domain, highlights the bandwidth that is contributing to the signal from the noise embedded on it. It breaks down the magnification or reduction introduced by each frequency component. Generating a transfer function constitutes an apparatus calibration, i.e., after generating a proper transfer function subsequent specimen testing can be corrected for wave modulation without requiring the use of strain gages.
The transfer function characterizes the system modification of the input amplitude in creating the output amplitude. Using a virtual testing environment provided by a numerical model, a transfer function of a tensile SHPB apparatus is generated as an example. The input and output of this process are presented in Figure 73.

**Figure 73: Tensile SHPB data sources.**

### 6.3.1 Transfer Function Generation

The transfer function is obtained by individually mapping the system input $\varepsilon_{i-D}(t)$ and output $\varepsilon_{\text{Specimen}}(t)$ into the frequency domain where simple arithmetic operations can be conducted between the frequency content of the signals. The time domain measurements of strain presented in Figure 71 are mapped into the frequency domain by a Fast Fourier Transform (FFT) algorithm. The frequency content corresponding to the one-dimensional strain estimation based on the incident bar strain history and the system output corresponding to the real deformation of the specimen measured with strain gages are presented in Figure 74. The system transfer function $H(i\omega)$, is the ratio between the measured strain and the estimated one-dimensional strain in the frequency domain. The result is shown in Figure 75. The transfer
function estimation process is summarized. Figure 76 summarizes for the apparatus used in this investigation.

**Figure 74:** Frequency content of input and output measurements - Numerical.

**Figure 75:** Transfer function - Numerical.

**Figure 76:** Transfer function calculation.
### 6.3.2 Application to Simulation Results

In order to evaluate the applicability of the correction methodology to signals with equal or lower frequency content, the generated transfer function after a impact velocity of 5 m/s is used to correct raw strain records generated virtually at 1 m/s impact velocity. The one-dimensional strain history for a new test (1 m/s) in the time domain and its corresponding frequency content is shown in Figure 77. In the frequency domain, the new one-dimensional estimated strain is corrected by multiplying it by the transfer function, see Figure 78. Finally, the corrected strain is mapped back into the time domain by an Inverse FFT. Results are summarized in Figure 79. Subsequent testing can be corrected following the procedure presented in Figure 80 eliminating the need for strain gages.

**Figure 77:** One-dimensional strain of a subsequent test in time and frequency domain.

**Figure 78:** Corrected one-dimensional strain in frequency domain.
Figure 79: Corrected one-dimensional strain.

\[ H(i\omega) \cdot \varepsilon_{1-D}(i\omega) \]

Figure 80: Correction process of one-dimensional strain estimation.
6.4 Application to Experimental Results

An experimental transfer function is generated and used to correct for estimated strain on laminated composite materials. In order to verify the validity of the numerical observations, experimental data is generated using the tensile SHPB developed in this investigation. Experimental methods described in Chapter 3 are followed to prepare and test specimens in tension. First, Aluminum specimens are tested and a transfer function suitable for correction of composite material data is generated. Subsequently, composite material specimens are tested and specimen strain is estimated applying the one-dimensional wave propagation theory. Finally, the estimated strain is corrected using the transfer function.

6.4.1 Material Systems and Specimen Fabrication

Aluminum dog-bone specimens are fabricated from Aluminum 7075-T6 sheet metal with thickness 1.016 mm (0.04 in) along the grain direction [L]. Newport Plain Weave Carbon Fabric NB321/3K70 Prepreg is used to manufacture dog-bone and straight section composite specimens with stacking sequence [0]_4. Laminates are vacuumed-bagged and autoclave-cured. Specimen dimensions are as described in Chapter 3 for both material systems. Figure 81 shows the test specimens instrumented for the tests.

Figure 81: Aluminum and carbon fabric composite tensile specimens.
6.4.2 Preparation of Pulses for Fourier Analysis

As it was identified when tracking the contribution of each strain history to the one-dimensional estimation of strain, subsequent oscillations after the pulse has decayed, as seen in Figure 82, only add to the decaying segment of the strain history. Therefore, this segment of each individual pulse can be disregarded and manually zeroed as shown in Figure 83. By zeroing the strain (ordinate) components but keeping the time (abscissa) components, the frequency content that do not form part of pulse is removed and the energy associated to those components is shifted to neighboring frequencies. This procedure is in fact zero padding the signal and by doing so, it is increasing the apparent period of it. This procedure is observed to improve the generation of the right frequency content when implementing a FFT of the signal. The effect of the zeroing procedure along with zero padding can be visualized in the frequency content in Figure 84.

![Incident & Reflected Pulse](image1)

Figure 82: Incident and reflected pulses in a low velocity tensile test.

![Incident Pulse - Zeroing](image2)

Figure 83: Pulse zeroing after pulse decaying.
6.4.3 Experimental Transfer Function

An experimental transfer function is generated following the same procedure implemented with the numerical model. Aluminum dog-bone specimens are tested at low velocities in the tensile SHPB apparatus described in Chapter 3 to generate experimental data suitable for transfer function generation. The strain history directly measured in the specimen and the one estimated based on the one-dimensional theory is plotted in Figure 85. Both signals are mapped into the frequency domain by a FFT algorithm. Figure 86 shows the frequency content of both signals. In the frequency domain, the transfer function is calculated by taking the ratio of the directly measured strain and the one-dimensional estimated strain see Figure 87.
Additional tests are conducted to verify the repeatability of the transfer function. Since the transfer function is generated after low velocity tests that introduce only elastic deformation to the specimen, all test repetitions are conducted using the same test specimen. Figure 88 shows similar trends in the frequency content of the all pulses. However, specific frequency components seem to be modified from test to test.
6.4.4 Correction of Experimental Results

The correction methodology is applied to correct the one-dimensional estimation of strain on laminated composite materials. Carbon fabric dog-bone and straight section specimens are tested at two velocities in the tensile SHPB apparatus describe in Chapter 3. The composite specimen is instrumented with one strain gage so the corrected strain can be validated. Figure 89 shows the actual test set-up during testing. Strain gage terminal was mounted in the transmitter side of the grip.

Results for dog-bone specimen at strain-rate $250 \text{ s}^{-1}$ are summarized in Figure 90. Figure 90-a shows the strain history estimated based on the one-dimensional theory and estimated strain after incident, reflected, and transmitted pulses have been zeroed. The zeroed strain is mapped into the frequency domain by a FFT algorithm as shown in Figure 90-b. Then it is multiplied by the transfer function previously generated and its frequency content is shown in Figure 90-c. Finally, the corrected strain is mapped back into the time domain by an inverse-FFT. Figure 90-d compares the corrected strain with the uncorrected strain and the actual strain measurement on the specimen. The magnitude and trend of the corrected strain follows closely the strain history directly measured on the specimen. Figure 91 shows specimen failure close to the incident tab. The observed failure mode does not represent a desirable failure mode.
Figure 89: Grip-Specimen set-up.

Figure 90: Strain correction of dog-bone specimen at strain-rate 250 s\(^{-1}\).
The correction methodology is extended to correct the average stress history in the specimen. The stress history for dog-bone specimen at strain-rate 250 s\(^{-1}\) is shown in Figure 92. Also, Figure 93 shows the corrected stress vs. corrected strain. The quasi-static response of the material is included in the plot for reference. The strain-rate sensitivity of the material is exposed by changes in the stress-strain response; larger modulus of elasticity as well as larger failure strength. The one-dimensional estimation of stress and strain clearly overestimated the response of the material. The corrected response provides a better estimate of the response. However, a comprehensive dynamic characterization is required before material properties can be extracted for analysis.

Figure 92: Stress correction of dog-bone specimen at strain-rate 250 s\(^{-1}\).
Figure 93: Stress vs. Strain of dog-bone specimen at strain-rate 250 s\(^{-1}\).

Similarly, results for dog-bone specimen at strain-rate 300 s\(^{-1}\) are summarized in Figure 94. Figure 94-d shows the corrected strain fairly close to the actual strain measurement on the specimen. As with the previous strain-rate, the magnitude and trend of the corrected strain follows closely the strain history directly measured on the specimen. Figure 95 shows specimen failure close to the incident tab. The observed failure mode does not represent a desirable failure mode.

Figure 94: Strain correction of dog-bone specimen at strain-rate 300 s\(^{-1}\).
Figure 95: Failed dog-bone specimen at strain-rate 300 s\(^{-1}\).

The average stress history in the specimen for dog-bone specimen at strain-rate 300 s\(^{-1}\) is also corrected in Figure 96. The corrected stress vs. corrected strain is shown in Figure 93 with similar results as strain-rate 250 s\(^{-1}\).

Figure 96: Stress correction of dog-bone specimen at strain-rate 300 s\(^{-1}\).

Figure 97: Stress vs. Strain of dog-bone specimen at strain-rate 300 s\(^{-1}\).

Results for straight section specimen at strain-rate 200 s\(^{-1}\) are summarized in Figure 98. Figure 98-d shows the corrected strain overestimating the strain when compared to the actual
strain measurement on the specimen. However, the strain measured directly on the specimen is significantly smaller than the strain measured on a dog-bone specimen. This observation exposes the effect of the straight geometry of the specimen on the strain measurement; the lateral deformation is being constrained. Although, specimen failure, as shown in Figure 99, close to the center of the gage section corresponds to a desirable failure mode.

Figure 98: Strain correction of straight specimen at strain-rate 200 s\(^{-1}\).

Figure 99: Failed straight specimen at strain-rate 250 s\(^{-1}\).
Similarly, results for straight section specimen at strain-rate 250 s\(^{-1}\) are summarized in Figure 100. Figure 100-d shows the corrected strain overestimating the strain when compared to the actual strain measurement on the specimen. Clearly, the geometry limits the extent of the correction methodology. Recall the transfer function was generated using an Aluminum dog-bone specimen. Therefore, the correction methodology is case specific and a new transfer function should be generated to account for changes in the test apparatus, gripping fixture, or specimen geometry. As a side note, in contrast to the straight specimen tested at strain-rate 200 s\(^{-1}\), this specimen failed within the bonded tab region. This was the common failure mode for other tested straight specimens.

![Figure 100](image)

**Figure 100:** Strain correction of straight specimen at strain-rate 250 s\(^{-1}\).
6.4.5 Strain Correction Using an Effective Gage Length

An effective gage length is developed in this investigation to correct the one-dimensional estimation of strain on carbon reinforced fabric dog-bone specimens. Results are then compared with the frequency based correction presented herein. Strain corrections based on an effective gage length are found in open literature for metallic cylindrical specimens [6, 30, 31, 32]. A limited number of investigations have used it for sheet-type metal specimens [33]. An effective gage length is used to account for additional deformation, not in the gage length, but in the shoulder area. The effective gage length is developed experimentally after calibrating estimated deformation in the specimen with strain gage data. Ellwood et al. [32] calibrated the one-dimensional estimation of strain with direct measurements testing in a tensile SHPB over a large range of strain-rates. On the other hand, Nicholas [31] used quasi-static test data to develop a strain-deflection relation that was used to calculate strain from deflection. In both cases, researchers identified an effective gage length larger than the true gage length.

Following a similar procedure than Nicholas [31], an effective gage length is developed after quasi-static testing. The test included the gripping fixtures used in the Tensile SHPB. Specimens were instrumented with strain gages. An average effective gage length of 21.97 mm (0.865 in) was identified. Figure 101 and 102 show the results of the application of two different correction methodologies, frequency based and effective gage length, to carbon fabric dog-bone specimen at strain-rate 250 s\(^{-1}\) and 300 s\(^{-1}\) respectively. The frequency based correction, presented in this investigation, and another one using an effective gage length can be compared with the strain measured directly on the specimen and the one-dimensional estimated strain. The effective gage length correction shows a small deviation from the measured strain and does not seem to account for the failure of the specimen. The effective gage length defines a constant
correction factor all over the deformation area. A linear relation may exist between the measure strain and the estimated strain for some segments of the deformation but it is not uniform for all the strain history.

Figure 101: Strain correction of dog-bone specimen at strain-rate 250 s\(^{-1}\).

Figure 102: Strain correction of dog-bone specimen at strain-rate 300 s\(^{-1}\).

6.5 Summary

A correction methodology to one-dimensional wave propagation analysis is presented to address the discrepancy between one-dimensional theory estimated strains and directly measured strains over the test specimen. The methodology aims to correct the amplitude of the frequency components but not the shift in phase.
Pulse manipulation procedures that improved Fourier analysis, and thus, the capabilities of the methodology are presented. The correction methodology is applied to virtual strain measurements from simulations to establish its applicability to experimental results. Subsequently, the methodology is validated with experimental data from carbon fabric laminated composite specimens. The methodology seems to correct one-dimensional estimation of strain when applied to dog-bone specimens. However, it is case specific and a new transfer function should be generated to account for changes in the test apparatus, gripping fixture, or specimen geometry.

A correction based on an effective gage length is compared to the frequency based correction presented herein. The effective gage length corrected strain deviates from the measured strain because it defines a constant correction factor that may not be valid for the entire gage length. On the other hand, the methodology herein presented seems to account better for the deformation in the specimen and it is able to account for the failure of the specimen.
CHAPTER 7
WAVE MODULATION – INFLUENTIAL FACTORS

Wave modulation influential factors originating in the load transfer mechanism of a tensile SHPB are investigated experimentally and numerically. The loading pulse is modulated as it propagates down the load train by mechanical impedance changes and perturbations introduced at every mechanical interface. The effect in the pulse is depicted in Figure 103. Additional modulation is caused by sheet-type specimen cross-section. Several attempts have been made by researchers to quantify the error introduced by individual components. However, discrepancy between the measured response and the one-dimensional estimated response limits the application of the testing technique. Several factors in the gripping mechanism are single out to establish their level of significance.

![Figure 103: Time domain dispersion effects on pulse characteristics.](image)

7.2 Influential Factors

In tensile SHPB apparatus impedance changes are the result of the addition of the grips or attachment devices as shown in Figure 104. Therefore, any factor related to load transmission
may represent an influential factor depending on the attachment type, i.e., pinned specimens, bonded specimens, threaded grip cross-sectional area, the grip mass, the grip thread, the specimen geometry, etc. Some factors may be appropriate for an experimental evaluation while other for a numerical evaluation. For this reason, the evaluation is divided into two; experimental and numerical. The factors evaluated herein include: bar thread for a threaded fixture/grip, pulse shaper, adhesive joint, grip area, and grip mass.

7.2.1 Bar Thread

As it is described in the experimental method, threaded grips are designed for tensile load transfer between the bars and the specimen. Threads in the bar end, as shown in Figure 105, may distort the pulses adding reflections resulting from the change in mechanical impedance. Therefore, it is of interest to evaluate the effect of the thread length and type (fine or coarse) on wave attenuation and pulse distortion. The change in mechanical impedance is the results of the change in cross-sectional area at the root of the thread as can be seen in Figure 106. Mechanical impedance values for a .0254 m (1 inch) bar having either coarse or fine thread types are summarized in Table 11. The standard reference for .0254 m (1 inch) major diameter coarse thread is 1-8-UNC-3A and for fine thread is 1-12-UNF-3A.
Figure 105: Incident bar threaded end.

Figure 106: Thread characteristic dimensions [78].

Table 11: Impedance change with thread cross-sectional area change in a .0254 m (1 inch) bar

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>BAR</th>
<th>COARSE</th>
<th>FINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAJOR DIAMETER [m]</td>
<td>.0254</td>
<td>.0254</td>
<td>.0254</td>
</tr>
<tr>
<td>PITCH DIAMETER [m]</td>
<td>-</td>
<td>.0233</td>
<td>.0227</td>
</tr>
<tr>
<td>MIN. DIAMETER [m]</td>
<td>-</td>
<td>.0215</td>
<td>.0228</td>
</tr>
<tr>
<td>AREA [m²]</td>
<td>.000506</td>
<td>.000363</td>
<td>.000408</td>
</tr>
<tr>
<td>IMPEDANCE [Kg/s]</td>
<td>20,010</td>
<td>14,335</td>
<td>16,112</td>
</tr>
</tbody>
</table>
7.2.2 Pulse Shaper

The use of pulse shaper is widely reported in literature when using SHPB apparatus as described in Chapter 3; it is reported to minimize oscillations introduced by dispersion, to allow the specimen to achieve stress equilibrium, and to reduce the inertial effects in the specimen. Pulse shaper is placed at the interface between the striker bar and the incident bar as shown in Figure 10. Therefore, it is relevant to identify the extent of the effect of a pulse shaper in wave modulation, its benefits, and related frequency content.

![Diagram of Pulse Shaper Location](https://via.placeholder.com/150)

Figure 10: Pulse shaper location in compression SHPB.

7.2.3 Adhesive Joint

Another factor that may be isolated experimentally is the layer of adhesive present in any adhesive bonding; an adhesive joint is used to attach the test specimen to the gripping fixture in order to reduce components in the load train. Wave modulation caused by the adhesive joint may be the combined result of a visco-elastic material response if loaded in shear and the impedance change due to the change in density between materials. A complete evaluation of the effect of the adhesive in wave modulation should include the damping characteristics of visco-elastic materials. However, such evaluation is out of the scope of the current investigation. Therefore, the effect of the adhesive not on the load transfer, but on impedance change resulting from the change in density is isolated in a compression set-up as shown in Figure 108.
7.2.4 Grip

Grips/fixtures may be used in tensile apparatus to transfer the load and grip the specimen. The addition of a grip may introduce several impedance changes within one component due to changes in cross-sectional area. In addition, due to the high speed nature of the test, the effect of the mass of the grip is a relevant factor to be considered. The mass would affect the vibration characteristics of the attachment and may increase the specimen inertial effect. The reference case for the evaluation corresponds to direct load transfer similar to that observed in compression testing but in tension. In order to correlate tension to compression the test specimen should be fused to the bars representing an ideal case as shown in Figure 109.

![Figure 109: Load transfer ideal case.](image)

7.3 Experimental Evaluation

An experimental evaluation was conducted on the effect of parameters in the grip region than can be isolated experimentally and at the same time cannot be evaluated numerically due to the complexity or nature of the problem, i.e., load transfer by threaded joints. Experimentally,
isolation of parameters is done by assuring direct load transfer as it is provided by compression loading. Therefore, a compression SHPB is used for such purpose. Essentially, the effect of the grips is blocked.

The experimental evaluation includes the generation of a baseline comparison in dry conditions (incident bar only) between incident and reflected pulses in the absence of any feature, i.e., no thread or nor grip at three different impact velocities. Subsequently, the thread effect is evaluated including thread type and thread length. Both conditions are evaluated with and without pulse shaper. Table 12 summarizes the test matrix for this evaluation.

On a separate test set-up that includes the transmitter bar, the effect of an adhesive joint is evaluated. As a reference, a baseline for direct load transfer is first generated. Table 13 summarizes the test matrix for this evaluation.

Table 12: Test matrix for thread effect in a compression SHPB

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>THREAD TYPE</th>
<th>VELOCITY (THREAD LENGTH)</th>
<th>RESULT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rate 1 20 m/s</td>
<td>Rate 2 25 m/s</td>
</tr>
<tr>
<td>COMPRESSION SHPB</td>
<td>NO THREAD</td>
<td>x3</td>
<td>x3</td>
</tr>
<tr>
<td></td>
<td>COARSE</td>
<td>x3 (L1, L2, L3)</td>
<td>x3 (L1, L2, L3)</td>
</tr>
</tbody>
</table>
|                  | COARSE - SHAPER | x3 (L1, L2, L3) | x3 (L1, L2, L3) | x3 (L1, L2, L3) | $\varepsilon_i(t)$ $
\varepsilon_R(t)$ |
|                  | FINE        | x3 (L1, L2, L3) | x3 (L1, L2, L3) | x3 (L1, L2, L3) |     |
|                  | FINE - SHAPER | x3 (L1, L2, L3) | x3 (L1, L2, L3) | x3 (L1, L2, L3) |     |
Table 13: Test matrix for adhesive joint effect in a compression SHPB

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>LOAD TRANSFER</th>
<th>VELOCITY</th>
<th>RESULT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rate 1 20 m/s</td>
<td>Rate 2 25 m/s</td>
</tr>
<tr>
<td>COMPRESSION SHPB - SHAPER</td>
<td>DIRECT</td>
<td>x3</td>
<td>x3</td>
</tr>
<tr>
<td></td>
<td>JOINT</td>
<td>x3</td>
<td>x3</td>
</tr>
</tbody>
</table>

7.3.1 No Thread Baseline

Incident and reflected pulses in an unthreaded bar are compared in the time domain and in the frequency domain for three different impact velocities. In the absence of any discontinuity, the reflected pulse should be identical to the incident pulse, see figure 110. However, results in Figures 111 to 113 show various characteristics that are solely the result of dispersion, oscillations, change in slope, and pulse width extension (time-scale expansion). The small increment in rising time or slope reduction shown in the time domain can be correlated to reduction in high frequency components in the frequency domain as shown in Figure 114.

Figure 110: Incident bar unthreaded end used to generate reflected pulse baseline.
Figure 111: Comparison incident and reflected pulses history and frequency content at 20 m/s.

Figure 112: Comparison incident and reflected pulses history and frequency content at 25 m/s.
Figure 113: Comparison incident and reflected pulses history and frequency content at 30 m/s.

Figure 114: Ratio reflected to incident pulses frequency content baseline.

7.3.2 Thread Effect

Incident and reflected pulses in a threaded bar are compared in the time domain and in the frequency domain for three thread lengths and three different impact velocities. The change in mechanical impedance, resulting from the change in cross-sectional area at the root of the thread, introduces additional oscillations to the reflected pulse as it can be seen in Figure 115 to 117. The reflections in the thread slow down the rising segment of the pulse and enlarge pulse width. Small oscillations over imposed to the trapezoidal shape of the pulse resemble those
observed by the baseline pulse without thread but for the last oscillation before the pulse decays.

In the frequency domain the effect of the thread is shown by a small reduction in frequency components between 20 to 65 KHz, an amplitude increases at 70 KHz followed by a reduction at 80 KHz. The time-scale expansion introduces a small increment in frequency amplitude and a compression in frequency-scale.

Figure 115: Course thread length effect in time domain and frequency domain at 20 m/s.

Figure 116: Course thread length effect in time domain and frequency domain at 25 m/s.
Figure 117: Coarse thread length effect in time domain and frequency domain at 30 m/s.

The range of frequencies responsible for specific time domain characteristics of the pulse can be identified by carefully studying the frequency content of the signal. Once familiar with the frequency content of the pulse baseline, changes in specific components can be visualized. Correlation between time and frequency domain is investigated by removing suspected frequency components from the signal and evaluating the effect in time domain. The removal process is done with the FFT tool by enforcing a notch filter as shown in Figure 118. When removing frequencies between 20 to 65 KHz from the pulse corresponding to a coarse thread of 2 in long, the large oscillation over the pulse decay segment seems to be removed as shown in Figure 119. Therefore, frequency components in this range are correlated with that characteristic in the time history. On the other hand, when removing frequencies between 20 to 40 KHz from the baseline pulse, there is decrease in the rising slope and an extension of the width of the pulse as shown in Figure 120. Therefore, threads are partially responsible for large oscillation in the decay segment and changes in the pulse shape characteristics.
Figure 118: Notch filter used to remove specific frequency components.

Figure 119: Frequency components correlation of threaded pulse with time history at 20 m/s.

Figure 120: Frequency components correlation of unthreaded pulse with time history.
Even though the change in mechanical impedance is larger for coarse thread, there seems not be significant difference in the effect of the thread type as seen in Figure 121. In the frequency domain, coarse thread shows a small reduction in frequency components between 20 to 60 KHz when compared to fine thread. However, this seems not to change considerably the time history of the pulse. In general, the reason for the deviation of the reflected pulse from an ideal trapezoidal pulse is a combined effect of dispersion and reflection on the threads.

![Reflected Pulse - Coarse vs. Fine - Length 2 - Rate 2](chart1.png)

![Ratio - Reflected / Incident - Coarse vs. Fine - Length 2 - Rate 2](chart2.png)

Figure 121: Comparison coarse thread vs. fine thread at 25 m/s.

### 7.3.3 Pulse Shaper Effect

Similar to the baseline pulse generation but including a polyethylene pulse shaper, incident and reflected pulses in an unthreaded bar are compared in the time domain and in the frequency domain for three different impact velocities. Incident pulse is modified and oscillations over imposed to the trapezoidal shape of the pulse are removed to a great extent as shown in Figure 122. Also, pulse width almost doubles. In this case the reflected pulse falls closely the incident pulse. These effects in the frequency domain are correlated to a frequency-
scale reduction due to a time-scale expansion. Figure 123 shows frequencies above 15 KHz being shifted in phase perhaps by the visco-elastic response of the plastic shaper.

Figure 122: Effect of pulse shaper in the time history and the frequency domain at 20 m/s.

Figure 123: Comparison effect in the frequency domain of shaper vs. no shaper.
Figure 124: Combined effect of coarse thread and pulse shaper in the time history and the frequency domain at 25 m/s.

Figure 125: Comparison combined effect of coarse thread, pulse shaper, and thread in the time history and the frequency domain at 25 m/s.

7.3.4 Pulse Transmission Frequency Content

Before any grip is added into the load train, a baseline is generated for pulse transmission as shown in Figure 126. Incident bar and transmitter bar are not threaded for this case and a polyethylene pulse shaper is used representing a common practice. Incident and transmitted
pulses are compared in the time domain and in the frequency domain for three different impact velocities. Incident pulse characteristics are defined by the use of the polyethylene pulse shaper such that the pulse does not show several oscillations over imposed to the trapezoidal shape of the pulse as seen in Figure 127. Again, pulse width almost doubles. In this case the transmitted pulse falls closely the incident pulse. These effects in the frequency domain are correlated to a frequency-scale reduction due to a time-scale expansion. Figure 128 does not show significant differences in the frequency content with respect to the case where only the incident bar is considered as in Figure 123.

Figure 126: Direct pulse transmission baseline.

Figure 127: Comparison incident and transmitted pulses history and frequency content at 25 m/s.
7.3.5 Adhesive Joint Transfer

The effect of impedance change resulting from the change in density associated with the adhesive joint is isolated in a compression set-up as shown in Figure 129. In this case, incident and transmitted bar have a fine thread to allow for attachment of the gripping fixture. Incident and transmitted pulses are compared in the time domain and in the frequency domain for three different impact velocities. As in the case direct pulse transmission, a polyethylene pulse shaper is used removing oscillations from the incident pulse as shown in Figure 130. The transmitter pulse shows faster loading when compared to the incident pulse. The frequency content in Figure 131 is consistent over all rates.

Figure 129: Adhesive joint experimental set-up before and after test.
The effect of the adhesive joint is compared to direct pulse transmission in Figure 132. Incident and transmitted pulses are compared. The transmitted pulse shows a reduction in rising time. The adhesive joint seems to load the transmitter bar faster. The range of frequencies responsible for such behavior in the time domain is not clear. A correlation between frequency components between 20 to 40 KHz is attempted in Figure 133 without conclusive results. After removing such range of frequencies, the time history no longer shows the minor oscillation at the peak of the curve.
Figure 132: Comparison direct transfer vs. adhesive joint at 25 m/s.

Figure 133: Frequency components correlation of adhesive joint with time history at 25 m/s.

7.4 Numerical Evaluation

Pulse attenuation resulting from impedance change in the gripping area may be dependent on one or several factors. A systematic evaluation where one parameter is isolated at a time is simply not feasible from the experimental point of view. Exploiting the advantage of a virtual testing environment provided by numerical models, a few parameters are isolated that otherwise
would require expensive and time consuming experimental testing. In summary, the effect of the grip/fixture is evaluated in tension by generating a reference model where direct load transfer similar to that observed in compression testing. In order to correlate tension to compression the test specimen is fused to the bars representing a direct contact case as shown in Figure 134. Subsequently, grips are added to the model representing the actual grips designed for this investigation as shown in Figure 135. The grip introduces several impedance changes within one component due to changes in cross-sectional area. In addition, the effect of the mass of the grip is evaluated by scaling the density of the material by two.

![Figure 134: Finite element model of direct load transfer case.](image)

![Figure 135: Finite element model of tensile grips designed for the current investigation.](image)

The one-dimensional estimation of strain considers incident, reflected, and transmitted pulses, but in principle, the incident pulse should not be modified before it is reflected and transmitted at the grip area. Therefore, the effect of the grip in the reflected pulse and in the
transmitted pulse is evaluated independently since each pulse is modified in a particular way. The reflected pulse shows significant changes in the pulse shape as shown in Figure 13; not only the direct case without grips and the case with 1 inch grips show reflections introduced by changes in the cross-section but also the scaled-mass shows oscillations at the peak of the pulse. Since there is no difference in geometry between the case with 1 inch grip and the scale-mass grip, the mass of the grip clearly affects the nature of the reflected pulse.

The transmitted pulse history in Figure 137 reveals a totally different scenario. The case with 1 inch grip and the case with scale-mass grip show a different order of magnitude with respect to the direct case without grips. This observation can be correlated with the frequency content in Figure 137. Clearly the magnitude of the frequency components for the case with 1 inch grip and scale-mass grip drop for frequencies above 40 KHz.

Figure 136: Grip effect on reflected pulse.
The grips have a direct effect on the one-dimensional estimation of strain. The direct case without grips in Figure 138 shows the estimated strain overestimating the strain by a threefold with respect to the strain directly measured on the specimen. This is partially a consequence of a non-uniform strain field in the specimen. Figures 139 and 140 show an equivalent discrepancy between estimated strain and measured strain for both cases. In summary, additional stiffness introduced by the grips seems to transfer the load faster to the transmitter bar and the additional load path transfer the load more efficiently to the specimen. Impedance change due to change in area reduces the power of the signal and removes frequency components as low as 10 KHz. Also, increasing the mass of the grips seems to reduce even further the frequency content and ultimately reduce the natural frequency of the system.
7.5 Summary

Wave modulation influential factors originating in the load transfer mechanism of a tensile SHPB are investigated experimentally and numerically. Several factors in the gripping
mechanism are single out to establish their level of significance. The thread effect is manly reflections in the thread that slow down the rising pulse and enlarge pulse width. The thread behaves like a pulse shaper by removing oscillations and slowing down rise time which may be a desirable feature. The effect of a pulse shaper in the time domain is damping the impact by impacting a polyethylene shaper, oscillations are removed. Also pulse width almost doubles with introduction of shaper. In the frequency domain, a time-scale expansion compresses the frequency-scale, the power of signal decreases to 10 % or less at 15 KHz. A baseline for pulse transmission is generated. The transmitter bar does not seem to have any effect, although pulse transmission is smoothed by the shaper. A numerical evaluation of the grip effect is conducted. The reflected and transmitted pulses are used for comparison since they take most of the effect of the grips. Several impedance changes can occur within one gripping fixture introducing additional high frequency components into the reflected pulse. Additional stiffness of the grips seems to transfer the load faster to the transmitter bar and an additional load path transfers the load more efficiently to the specimen. Impedance changes due to change in area reduce the power of the signal and remove frequency component as low as 10 KHz. Increasing the mass reduce frequency components even further and ultimately reduce the natural frequency of the system.
CHAPTER 8

CONCLUSIONS

One-dimensional wave analysis allows the application of the SHPB technique to study the sensitivity of the material response to high strain rates. Several assumptions are made before the theoretical estimation can be regarded as the real response of the material. The difficulties related to tensile testing of sheet-type materials at high strain rates using a SHPB have been mentioned throughout this investigation. In summary, necessary gripping fixtures and the square cross section of sheet-type specimens perturb pulse propagation resulting in pulse attenuation. The overall effect is that the one-dimensional wave analysis erroneously estimates stress and strain in the testing specimen.

The first challenge faced during the course of this investigation had to do with load generation. A general lack of specifications was found in open literature. After a thorough evaluation of advantages and disadvantages of indirect and direct loading techniques, the transfer flange technique was selected. It corresponds to a direct loading technique. However, details regarding the proper momentum transfer between the striker and the incident bar were missing. Several uncertainties regarding tensile load generation had to be clarified before progressing any further. The system had to be calibrated before testing for strain rate sensitivity. In order to calibrate the testing apparatus, good control over the loading pulse was required. Once a reliable loading pulse is generated, wave modulation can be addressed. Furthermore, other specimen geometries different than cylindrical cross-section specimens can be evaluated, and the testing technique can be extended to other type of studies as history effects evaluation on recovery studies or material characterization at high strain rates.
Discrepancy between the measured response and the one-dimensional estimated response limits the application of the testing technique. Several attempts have been made by researchers quantifying the error introduced by individual components. However, pulse attenuation is the result of the perturbation introduced to the loading pulse as it travels through every component and as it is transmitted through every mechanical interface. Additional attenuation is introduced by a sheet-type specimen cross-section. Therefore, quantifying the overall system response, although specific, will measure to what extent the testing apparatus is modifying the initial loading. Overall system response is measured experimentally directly on the testing specimen. The measured pulse on the testing specimen represents the actual output to the loading pulse after it has been transmitted and thus attenuated by every other component of the load train in the apparatus.

8.1 Load Generation

The transfer flange technique for tensile pulse generation in a SHPB is evaluated. Secondary tensile and compressive pulses are observed to distort the loading tensile pulse. Pulse distortions may limit the application of one-dimensional wave propagation theory to estimate strain and strain-rate. Lagrange diagrams and finite element models are used to visualize pulse propagation, to identify the sources of secondary pulses, and to establish the effect of transfer flange geometrical parameters on pulse generation and wave propagation. An experimental testing apparatus is developed. Proper attachment of the flange to the incident bar is discussed and a novel technique for flange attachment is presented.

Transfer flange results showed that for a specific striker length, there is minimum flange length so that secondary reflections do not overlap with the leading incident pulse. Shortening flange length was expected to reduce the width of subsequent reflections such that the effect over
the leading tensile pulse was minimized. However, numerical simulations and experimental results showed that small subsequent reflections are significant enough to distort and reshape the leading pulse by extending the decay time. On the other hand, long flanges are observed to reduce the level of oscillations. However, there is no further reduction in the level of oscillations for lengths larger than the minimum. Similarly, results indicated that supporting an extra section of the incident bar does not provide any benefit; instead reflections from the back face would distort the leading pulse. The benefits of an additional support are achieved by having the flange directly supported on a bearing. Results for flange height/radius evaluation do not show any dependency of the pulse width on the flange height/radius. However, the level of oscillations is observed to decrease for larger flange height/radius.

Welded, threaded, or press fitted connections appear to be the simplest mechanical attachment to the incident bar since they minimize mechanical components. However, its durability represents a practical challenge, e.g., threads may degrade due to fatigue. In an effort to minimize stress concentration at the intersection between the transfer flange and the incident bar, a geometrical modification of the flange shape was suggested. A coned-shape flange was evaluated aiming for a reduction in the load levels at the connection, and thus an improvement in the fatigue characteristics of the coupling. The evaluation was conducted based on the premise that the vertical components of the reflected pulses would cancel out reducing the pulse to its horizontal components only. Results show better control over secondary tensile pulses above 88°. However, this is not due to the inclined surface but due to the long flange effect. In addition, load levels drop was not significant, and pulse widths increased almost in a threefold.

An improvement on the transfer flange technique was achieved by simply adding a momentum trap to the apparatus. This is another alternative that minimizes the load levels on the
flange-bar interface since the trap contains the compressive momentum and prevents any additional tensile loading over the incident bar. Simulation results showed a significant improvement over the test set-up without a momentum trap; load levels and oscillations are reduced, and pulse width deviation from the theoretical width is only 15.73%. This methodology represents a practical solution; more feasible than having an extremely long flange attached to the incident bar, and more realistic than having a 89° cone-shape flange.

As an alternative to circumvent fatigue failures, a sleeve flange was evaluated. The technique represents a direct solution not only to fatigue issues but also to stress concentration in the load transfer. The natural solution to the challenges imposed by tensile loading was a combination of a momentum trap and the proposed sleeve flange. Not only load levels on the connection were reduced, but also it provided control over the pulse width. Simulation results predicted a pulse width 29% larger than the theoretical width, while the experimental tests indicated a pulse width 59% larger than the theoretical.

8.2 Wave Modulation – One Dimensional Theory Correction

A correction methodology to one-dimensional wave propagation analysis is presented to address the discrepancy between one-dimensional theory estimated strains and directly measured strains over the test specimen. The methodology aims to correct the amplitude of the frequency components but not the shift in phase. Pulse manipulation procedures that improved Fourier analysis, and thus, the capabilities of the methodology are presented. Oscillations in the pulses can be disregarded since they add to the strain pulse only during the decaying segment. Manually zeroing values of the pulses removes from the estimated spectrum the components that do not form part of the pulses and shift the energy associated to those components to neighboring
frequencies. Zero padding increases the resolution in the frequency domain increasing the apparent period of the signal.

The correction methodology is applied to virtual strain measurements from simulations to establish its applicability to experimental results. Subsequently, the methodology is validated with experimental data from carbon fabric laminated composite specimens. The methodology seems to correct one-dimensional estimation of strain when applied to dog-bone specimens. However, it finds limitations when correcting for straight section specimens since it overestimates the strain when compared to strain measured directly over the specimen. The correction methodology provides a good estimate of the failure strain when compared to strain gage measurements. Pulse zeroing improves the capability of the correction methodology to estimate the trend of the strain history and its termination.

The methodology herein presented seems to account better for the deformation in the specimen and it is able to account for the failure of the specimen when compared to a correction based on an effective gage length. The effective gage length corrected strain deviates from the measured strain because it defines a constant correction factor that may not be valid for the entire gage length.

8.3 Wave Modulation – Influential Factors

A baseline for bar end without threads was generated. Dispersion solely seems to reduce frequency components between 80 KHz and 100 KHz. The reduction in high frequency components explains small increments in rising time or slope reductions.

The thread effect is mainly reflections in the thread that slow down the rising pulse and enlarge pulse width. In time domain, the threads introduce reflections and shear waves. Threads are partially responsible for large oscillation at the decaying segment of the pulse. The thread
behaves like a pulse shaper by removing oscillations and slowing down rise time, which may be a desirable feature. Also, no significant difference between coarse or fine thread is found from the wave modulation point of view. In the frequency domain, coarse thread shows a small reduction in frequency components between 20 KHz to 60 KHz.

The effect of a pulse shaper in the time domain is damping the impact by impacting a polyethylene shaper, oscillations are removed. Also pulse width almost doubles with introduction of shaper. In the frequency domain, a time-scale expansion compresses the frequency-scale, the power of signal decreases to 10 % or less at 15 KHz, and the effect of thread is alleviated by the shaper.

A baseline for pulse transmission is generated. The transmitter bar does not seem to have any effect, although pulse transmission is smoothed by the shaper. Also, an adhesive joint is evaluated and it seems to work as a secondary load path loading the transmitter bar faster than the incident bar. This effect is opposite to dispersion. In the frequency domain, there seems to be an apparent increment in components between 15 - 40 KHz.

A numerical evaluation of the grip effect is conducted. The reflected and transmitted pulses are used for comparison since they take most of the effect of the grips. Several impedance changes can occur within one gripping fixture introducing additional oscillations to the reflected pulse. Therefore, impedance changes in grip area responsible for changes in pulse shape. Frequency components above 40 KHz are shifted in phase by the effect of the grips. Additional stiffness of the grips seems to transfer the load faster to the transmitter bar and an additional load path transfers the load more efficiently to the specimen. Impedance changes due to change in area reduce the power of the signal and remove frequency component as low as 10 KHz.
Increasing the mass reduce frequency components even further and ultimately reduce the natural frequency of the system.

8.4 Recommendations

The methodology developed in this investigation for correcting the one-dimensional theory estimation of strain may be extended to correct for the stress estimation. A frequency based correction was shown to correct average strain in the test specimen which is estimated based on strain measurements directly on the incident and transmitter bar. Similarly, average stress in the specimen is estimated using the strain histories on the bars. Therefore, the same transfer function relating the frequency content of the output to the input may apply. Exploratory results are presented in this investigation. However, a systematic generation of material properties will further validate the results.

Conducting a dynamic material characterization of a know material will define the extent and limitations of the test apparatus and the correction methodology presented herein. The generated material properties can then be compared to material properties generated using other test techniques/apparatus over equivalent strain-rate ranges, e.g., high-stroke-rate servo-hydraulic test machines. Similarly, the material properties can be compared to material properties generated by other laboratories using equivalent tensile SHPB apparatus. The conclusion of a systematic comparison will add in the generation of standard method to generate tensile dynamic properties.

The finite element model developed herein can be used to establish the theoretical limitations of the one-dimensional theory and the fundamental assumption of uniformity of stress and strain. Additional influential factors may be evaluated using the model, i.e., the effect of the
shoulder area in the specimen geometry and the definition of an effective gage length. Also, the model can be used to calibrate the specimen geometry to generate specific strain-rates.

The repeatability of the tensile pulse generated by the transfer flange technique developed in this investigation can be evaluated to further extend the capabilities of the test apparatus. The magnitude and phase errors of the pulse can be estimated using an error metric comparison. Using these measurements of error, additional practical issues related to the way the tensile pulse is introduced can be evaluated, e.g., striker propulsion. The air flow is the gun barrel was observed to add complexity to the test. A computational fluids dynamics model (CFD) can be used to model the behavior of the air flow in front of the striker such that the variability introduced to the generated pulse is quantified.

The correction methodology developed in this investigation focus on correction the amplitude of the frequency content only. Phase corrections have not been considered. Correcting phase shifting caused by dispersion can be considered as a way to complement the work herein presented.
REFERENCES


[52] Norgren, Denver, CO.

[53] Vishay Precision Group Micro-Measurements, Raleigh, NC.


[57] Ectron corporation, San Diego, CA.

[58] HyperGraph, HyperWorks, Altair Engineering, Inc., Troy, MI.

[59] Tektronix, Inc. Beaverton, OR.


[63] Pico Technology, Cambridgeshire, United Kingdom.


APPENDIX
APPENDIX A
TENSILE SHPB ASSEMBLY DRAWINGS

1. Tension Split Hopkinson Pressure Bar
2. Bar 1- Fine Thread
3. Bottom Plate
4. Slide
5. Trigger Box Back
6. Trigger Box Front
7. Trigger Box
8. Pressure Vessel Back
9. Pressure Vessel Front
10. Pressure Vessel
11. Barrel Support
12. Bar End Support
13. Stopper Top Half
14. Stopper Bottom Half
15. Projectile – 6 in
16. Bearing Support
17. Bar End Stopper
18. Sealing Guide
19. Sealing Stopper
20. Cup-Specimen-Cup
**UNLESS OTHERWISE SPECIFIED:**

- **DIMENSIONS ARE IN INCHES**
- **TOLERANCES:**
  - FRACTIONAL: ±
  - ANGULAR: MACH ±, BEND ±, TWO PLACE DECIMAL ±
  - THREE PLACE DECIMAL PLACE ±
- **MATERIAL:**
- **COMMENTS:**
- **NEXT ASSY USED ON FINISH:**
- **APPLICATION DO NOT SCALE DRAWING**

<table>
<thead>
<tr>
<th>NAME</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAWN</td>
<td>CHECKED</td>
</tr>
<tr>
<td>ENG APPR.</td>
<td>MFG APPR.</td>
</tr>
<tr>
<td>Q.A</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TITLE:</th>
<th>CRASHWORTHINESS OF COMPOSITES</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>SIZE</th>
<th>DWG. NO.</th>
<th>REV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCALE</th>
<th>WEIGHT</th>
<th>SHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:50</td>
<td></td>
<td>1 OF 20</td>
</tr>
</tbody>
</table>
**UNLESS OTHERWISE SPECIFIED:**

- DIMENSIONS ARE IN INCHES
- TOLERANCES:
  - FRACTIONAL
  - ±
  - ANGULAR: MACH/BEND
  - TWO PLACE DECIMAL ± .003
  - THREE PLACE DECIMAL PLACE ± Q.A
- MATERIAL: ALUMINUM 7075

**TABLE:**

<table>
<thead>
<tr>
<th>TITLE:</th>
<th>CRASHWORTHINESS OF COMPOSITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIZE</td>
<td>A</td>
</tr>
<tr>
<td>DWG. NO.</td>
<td>4</td>
</tr>
<tr>
<td>REV</td>
<td>00</td>
</tr>
</tbody>
</table>

**APPLICATION:** DO NOT SCALE DRAWING

**NEXT ASSY USED ON FINISH:**

| A 4 00 |
|--------|-------|
| SCALE: | WEIGHT: |
| SHT 4 OF 20 |
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES

DRAWN

TITLE:

TRIGGER BOX FRONT

CHECKED

ENG APPR.

MFG APPR.

Q.A

COMMENTS:

SIZE:

ALUMINUM 2024

COMMENTS:

NEXT ASSY

USED ON

FINISH:

APPLICATION

DO NOT SCALE DRAWING

SCALE:

WEIGHT:

SHT 6 OF 20

COMMENT:

MATERIAL:

THREE PLACE DECIMAL PLACE ±0.003

TOLERANCES:

FRACTIONAL ±

ANGULAR: MACH ± BEND ±

TWO PLACE DECIMAL ± .003

Q.A

UNLESS OTHERWISE SPECIFIED:

NAME

DATE

PROPRITARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPRIETARY OF NIAR/WSU. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF NIAR/WSU IS PROHIBITED.
UNLESS OTHERWISE SPECIFIED:

| DIMENSIONS ARE IN INCHES | DRAWN |
| TOLERANCES: | CHECKED |
| FRACTIONAL: | ENG APPR. |
| ANGULAR: | MFG APPR. |
| BEND: | |
| TWO PLACE DECIMAL ± .003 | |
| THREE PLACE DECIMAL PLACE ± | Q.A |

MATERIAL:

| 6061 |

COMMENTS:

| SIZE | DWG. NO. | REV |
| A | 7 | 00 |

APPLICATION

| DO NOT SCALE DRAWING |

NEXT ASSY

| USED ON |

FINISH:

| 1/4-20-3B |

CRASHWORTHINESS OF COMPOSITES

TITLE:

TRIGGER BOX

PROPERTY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPRIETY OF NIAR/WSU.ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF NIAR/WSU IS PROHIBITED.
SELECTION A-A
SCALE 1:4

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±
ANGULAR: MACH BEND ±
TWO PLACE DECIMAL: ±0.003
THREE PLACE DECIMAL: ±0.003

MATERIAL:
2024

COMMENTS:

NOTE:

DO NOT SCALE DRAWING

TITLE:
PRESSURE VESSEL BACK

SIZE
DWG. NO.
REV

A
8
00

SHT 8 OF 20
SECTION A-A
SCALE 1 : 2

10.00
8.00
5.00
2.00
0.70
0.38
0.46

8.00
5.00
2.00

\( \phi 1.25 \)
\( \phi 0.77 \)

\( \phi 0.5469 \)
\( \phi 1.005 \)
\( \phi 0.136 \)

\#8-32-3B

\( R0.9375 \)

\( R1.625 \)

\( \phi 6.65 \)

\( \phi 6.11 \)

\( \phi .005 \)

CRASHWORTHINESS OF COMPOSITES

PRESSURE VESSEL FRONT

UNLESS OTHERWISE SPECIFIED:

NAME

DATE

DIMENSIONS ARE IN INCHES

DRAWN

TOLERANCES:

CHECKED

FRACTIONAL ±

ENG APPR.

ANGULAR: MACH ± BEND ±

MFG APPR.

TWO PLACE DECIMAL ± .003

Q.A

THREE PLACE DECIMAL PLACE ±

MATERIAL:

AL 2024

COMMENTS:

SIZE

DWG. NO.

REV

A

9

00

NEXT ASSY

USED ON

FINISH:

APPLICATION

DO NOT SCALE DRAWING

SCALE:

WEIGHT:

SHT 9 OF 20
### CRASHWORTHINESS OF COMPOSITES

**Title:** BAR END SUPPORT

<table>
<thead>
<tr>
<th>UNLESS OTHERWISE SPECIFIED:</th>
<th>NAME</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIMENSIONS ARE IN INCHES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOLERANCES:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRACTIONAL ±</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANGULAR: MACH ± BEND ±</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TWO PLACE DECIMAL ± .003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREE PLACE DECIMAL PLACE ±</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MATERIAL: AL 2024</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMENTS:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SIZE</th>
<th>DWG. NO.</th>
<th>REV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12</td>
<td>00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCALE</th>
<th>WEIGHT</th>
<th>SHT 12 OF 20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PROPRITARY AND CONFIDENTIAL**

The information contained in this drawing is the sole proprietary of NIAR/WSU. Any reproduction in part or as a whole without the written permission of NIAR/WSU is prohibited.
STOPPER BOTTOM HALF

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± .003
THREE PLACE DECIMAL PLACE ±0.003
MATERIAL: AL 7075
COMMENTS:
SIZE
DWG. NO.
REV
A
14
00
SCALE: WEIGHT:
SHT 14 OF 20

PROPRITARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPRIETARY OF NIAR/WSU. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF NIAR/WSU IS PROHIBITED.
**Title:** Projectile – 6 in

<table>
<thead>
<tr>
<th>UNLESS OTHERWISE SPECIFIED:</th>
<th>NAME</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIMENSIONS ARE IN INCHES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOLERANCES:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRACTIONAL ±</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANGULAR: MACH ± BEND ±</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TWO PLACE DECIMAL ± .003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THREE PLACE DECIMAL PLACE ±</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q.A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MATERIAL: AL 7075</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMENTS:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Application:** DO NOT SCALE DRAWING

**Scale:**

**Weight:**

**Sh.:** 1 of 2

**Size:** A

**Dwg. No.:** 15

**Rev.:** 00

**Next Assy.:**

**Used On:**

**Finish:** POLISHED

**Proprietary and Confidential**

The information contained in this drawing is the sole proprietary of NIAR/WSU. Any reproduction in part or as a whole without the written permission of NIAR/WSU is prohibited.
CRASHWORTHINESS OF COMPOSITES

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPRIETARY OF NIAR/WSU. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF NIAR/WSU IS PROHIBITED.

UNLESS OTHERWISE SPECIFIED:

- DIMENSIONS ARE IN INCHES
- TOLERANCES:
  - FRACTIONAL: ±
  - ANGULAR: MACH ±, BEND ±
  - TWO PLACE DECIMAL: ±.003
  - THREE PLACE DECIMAL PLACE: ±0.003
- MATERIAL: 2024
- COMMENTS:

DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A

TITLE: BAR END STOPPER

SIZE DWG. NO. REV
A 17 00

SCALE: WEIGHT:
SHT 17 OF 20

NEXT ASSY USED ON FINISH:
APPLICATION DO NOT SCALE DRAWING