STUDY OF WAVE SHAPING TECHNIQUES OF SPLIT HOPKINSON PRESSURE BAR USING FINITE ELEMENT ANALYSIS

A Thesis by

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STUDY OF WAVE SHAPING TECHNIQUES OF SPLIT HOPKINSON PRESSURE BAR USING FINITE ELEMENT ANALYSIS

We have examined the final copy of this Thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science in Mechanical Engineering.

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Dr. K. Suresh Raju, Committee Member

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DEDICATION

To my parents, Mr. Abdul Rasheed & Mrs. Gulnar Begum, who have given me the strength to accomplish anything I desire

To my husband, Dr. Eleyas Shaik, whose love and encouragement make each day a pleasure to live
I express sincere gratitude to my advisor, Dr. Hamid M. Lankarani, for providing a wonderful opportunity to work on this project and for his constant support throughout my degree.

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ABSTRACT

Graham, R.A., mentioned in his book “Solids under High-Pressure Shock Compression”, that for testing materials at high rates of strain, the split Hopkinson pressure bar (SHPB) is used. During very high impacts and extreme applications higher rates of strain are obtained. These high strains are used to induce the strain hardening and phase a transition phenomenon which affects the strength of materials [1]. For the strain rates of $10^4$ in/in-s ($s^{-1}$) SHPB is widely used to study the mechanical properties of most materials as it is very simple and robust to operate. At the National Institute for Aviation Research (NIAR), research has been conducted to study the wave shaping techniques of SHPB using finite element analysis.

In split Hopkinson pressure bar (SHPB) experiment, specimen is pressed in between two long cylindrical input and output bars. There is also a third cylindrical bar known as striker bar which is used to hit the input bar using a high pressure gas gun. With the high impact of striker bar on the input bar, a compressive stress wave is generated which travels from the input bar to the test specimen. At the interface of the specimen and input bar, partial stress wave propagates from specimen as a compressive wave and partial reflects into the input bar as a tensile stress wave. The stress wave that is transmitted from the specimen to the output bar causes elastic and plastic deformation in the test specimen. Stress generated in the specimen is calculated by the transmitted strain pulse and using this strain pulse, strain and strain rate in the specimen are calculated.

The research presented in this thesis, is not to test materials at high strain rates, rather it is to study the wave shaping testing techniques in split Hopkinson bar by using finite element code LS-DYNA and also to study the tensile testing methods of SHPB.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>INTERRODUCTION ....................................................</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Materials Testing ..................................................</td>
</tr>
<tr>
<td>1.2</td>
<td>Fundamentals of the Split Hopkinson Pressure Bar .................</td>
</tr>
<tr>
<td>1.3</td>
<td>Objective ......................................................................</td>
</tr>
<tr>
<td>1.4</td>
<td>Topics Covered in Thesis ...........................................</td>
</tr>
<tr>
<td>2</td>
<td>BACKGROUND AND LITERATURE REVIEW .................................</td>
</tr>
<tr>
<td>2.1</td>
<td>Introduction ....................................................................</td>
</tr>
<tr>
<td>2.2</td>
<td>The Hopkinson Bar – A Chronological Development ...................</td>
</tr>
<tr>
<td>2.3</td>
<td>The Split Hopkinson Pressure Bar – Additional Information .......</td>
</tr>
<tr>
<td>3</td>
<td>FUNDAMENTALS OF SHPB ..................................................</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction ....................................................................</td>
</tr>
<tr>
<td>3.2</td>
<td>The Split Hopkinson Bar ................................................</td>
</tr>
<tr>
<td>3.3</td>
<td>Relation between Stress, Strain and Strain rate ....................</td>
</tr>
<tr>
<td>4</td>
<td>SIMULATION OF CONVENTIONAL SHPB USING LS-DYNA... ............</td>
</tr>
<tr>
<td>4.1</td>
<td>General Proceeding ........................................................</td>
</tr>
<tr>
<td>4.2</td>
<td>Finite Element Method ....................................................</td>
</tr>
<tr>
<td>4.3</td>
<td>Structural Components ....................................................</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Response to mechanical loads ...........................................</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Elastic model ...................................................................</td>
</tr>
<tr>
<td>4.4</td>
<td>Geometry Production of the Conventional SHPB ......................</td>
</tr>
<tr>
<td>4.5</td>
<td>Discretisation of SHPB ....................................................</td>
</tr>
<tr>
<td>4.6</td>
<td>Pre-Processing ..............................................................</td>
</tr>
<tr>
<td>4.7</td>
<td>Contacts ..........................................................................</td>
</tr>
<tr>
<td>4.8</td>
<td>Solving ............................................................................</td>
</tr>
<tr>
<td>4.9</td>
<td>Post-Processing ..............................................................</td>
</tr>
<tr>
<td>4.10</td>
<td>Explicit Simulation ..........................................................</td>
</tr>
<tr>
<td>4.11</td>
<td>Simulation Results of Conventional SHPB .............................</td>
</tr>
<tr>
<td>4.12</td>
<td>Parametric Study of Conventional SHPB using LS-DYNA ..............</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>42</td>
</tr>
<tr>
<td></td>
<td>NUMERICAL SIMULATION OF MODIFIED SHPB</td>
</tr>
<tr>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>DYNAMIC TENSILE TEST: SPLIT HOPKINSON TENSION BAR (SHTB)</td>
</tr>
<tr>
<td>6.1</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Introduction</td>
</tr>
<tr>
<td>6.2</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>Set-up to Perform Tension Test</td>
</tr>
<tr>
<td>7</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>RESULTS AND DISCUSSION</td>
</tr>
<tr>
<td>7.1</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Computational Analysis of Conventional SHPB</td>
</tr>
<tr>
<td>7.2</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>Computational Analysis of Modified SHPB</td>
</tr>
<tr>
<td>7.3</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Split Hopkinson Tension Bar (SHTB)</td>
</tr>
<tr>
<td>8</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>CONCLUSIONS AND FUTURE WORK</td>
</tr>
<tr>
<td>8.1</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Conclusions</td>
</tr>
<tr>
<td>8.2</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>Future Recommendations</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>74</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Geometry and material properties of conventional SHPB</td>
<td>26</td>
</tr>
<tr>
<td>2: Geometry and material parameters of the modified SHPB</td>
<td>46</td>
</tr>
<tr>
<td>3: Geometry and material parameters of the SHTB</td>
<td>54</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1: Simplified schematic of a typical compressive SHPB</td>
<td>3</td>
</tr>
<tr>
<td>4.1: Two Dimensional Structural Elements [24]</td>
<td>24</td>
</tr>
<tr>
<td>4.2: Conventional SHPB</td>
<td>25</td>
</tr>
<tr>
<td>4.3: Discretised model-specimen sandwiched between pressure bars</td>
<td>28</td>
</tr>
<tr>
<td>4.4: Exploded view of a joint between elements describing the interface formulation</td>
<td>30</td>
</tr>
<tr>
<td>4.5: Stress waves generated in the pressure bars (incident &amp; transmitter bars) for numerical model of conventional SHPB</td>
<td>37</td>
</tr>
<tr>
<td>4.6: Stress wave in the specimen</td>
<td>37</td>
</tr>
<tr>
<td>4.7: Strain rate in the specimen</td>
<td>37</td>
</tr>
<tr>
<td>4.8: Arbitrarily shaped axis-symmetrical striker bars</td>
<td>39</td>
</tr>
<tr>
<td>4.9: Strain rate in the specimen using striker bar of shape 1</td>
<td>40</td>
</tr>
<tr>
<td>4.10: Strain rate in the specimen using striker bars of shapes 2, 3 and 4</td>
<td>40</td>
</tr>
<tr>
<td>5.1: Modified split Hopkinson Pressure Bar</td>
<td>42</td>
</tr>
<tr>
<td>5.2: Apparatus at NIAR as viewed from the Transmitted bar end</td>
<td>43</td>
</tr>
<tr>
<td>5.3: Apparatus as viewed from the striker bar end</td>
<td>43</td>
</tr>
<tr>
<td>5.4: Striker bar impacting the preloaded bar</td>
<td>44</td>
</tr>
<tr>
<td>5.5: Apparatus as viewed from the end of the preloaded bar</td>
<td>44</td>
</tr>
<tr>
<td>5.6: Specimen is sandwiched between the incident bar and the transmitter bar with the help of the specimen holder</td>
<td>45</td>
</tr>
<tr>
<td>5.7: Trapezoidal strain pulse generated in the preloaded bar when the striker hits the incident bar with a velocity of 100 in/s in the modified SHPB</td>
<td>48</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES (Continued)

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8: Strain pulse generated in the incident bar when the striker hits the preloaded bar with velocity of 100 in/s</td>
<td>49</td>
</tr>
<tr>
<td>5.9: Strain rate in the specimen using modified SHPB at a speed of 100 in/s</td>
<td>49</td>
</tr>
<tr>
<td>5.10: Transmitted pulse for a speed of 100 in/s using different materials for both wave shaper and specimen</td>
<td>50</td>
</tr>
<tr>
<td>5.11: Comparison of strain rate in the specimen using conventional SHPB and modified SHPB</td>
<td>51</td>
</tr>
<tr>
<td>6.1: Set up for split Hopkinson tension bar (SHTB)</td>
<td>53</td>
</tr>
<tr>
<td>7.1: Stress waves in the incident bar using conventional SHPB</td>
<td>56</td>
</tr>
<tr>
<td>7.2: Strain rate in the specimen using conventional SHPB</td>
<td>57</td>
</tr>
<tr>
<td>7.3: Strain rates in the specimen for various modulus ratios using conventional SHPB</td>
<td>57</td>
</tr>
<tr>
<td>7.4: Computational model of modified SHPB</td>
<td>58</td>
</tr>
<tr>
<td>7.5: Comparison of strain rate in the specimen using conventional SHPB and modified SHPB</td>
<td>59</td>
</tr>
<tr>
<td>7.6: Comparison of strain rate in specimen between the conventional SHPB and modified SHPB for different modulus ratios</td>
<td>59</td>
</tr>
<tr>
<td>7.7: Comparison of strain rate in specimen between the conventional SHPB and modified SHPB for different modulus ratios</td>
<td>60</td>
</tr>
<tr>
<td>7.8: Comparison of strain rate in specimen between conventional SHPB and modified SHPB for an initial velocity of 3m/s</td>
<td>61</td>
</tr>
<tr>
<td>7.9: Comparison of strain rate in specimen between conventional SHPB and modified SHPB for an initial velocity of 30m/s</td>
<td>61</td>
</tr>
<tr>
<td>7.10: Comparison of strain rate in specimen between conventional SHPB and modified SHPB for an initial velocity of 50m/s</td>
<td>62</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (Continued)

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.11: Comparison of strain rate in specimen for different modulus ratios using the same material properties for both wave shaper and specimen</td>
<td>63</td>
</tr>
<tr>
<td>7.12: Comparison of strain rate in specimen for different modulus ratios and different initial velocities using the same material properties for both wave shaper and specimen</td>
<td>63</td>
</tr>
<tr>
<td>7.13: Strain pulse generated in the incident bar when the striker hits the preloaded bar with a velocity of 250 in/s</td>
<td>64</td>
</tr>
<tr>
<td>7.14: Transmitted pulse for a speed of 250 in/s using different materials for both wave shaper and specimen</td>
<td>64</td>
</tr>
<tr>
<td>7.15: Strain rate in the specimen using modified SHPB at a speed of 250 in/s</td>
<td>65</td>
</tr>
<tr>
<td>7.16: Strain pulse generated in the incident bar when the striker hits the preloaded bar with a velocity of 500 in/s</td>
<td>65</td>
</tr>
<tr>
<td>7.17: Strain rate in the specimen using modified SHPB at a speed of 500 in/s</td>
<td>66</td>
</tr>
<tr>
<td>7.18: Strain pulse generated in the incident bar when the striker hits the preloaded bar with a velocity of 1000 in/s</td>
<td>66</td>
</tr>
<tr>
<td>7.19: Strain rate in the specimen using modified SHPB at a speed of 1000 in/s</td>
<td>67</td>
</tr>
<tr>
<td>7.20: Transmitted strain pulse shape using different materials for wave shaper and specimen in the modified SHPB</td>
<td>67</td>
</tr>
<tr>
<td>7.21: Comparison of strain rates in the specimen between conventional SHPB and modified SHPB (using same &amp; different materials) for a speed of 1000 in/s</td>
<td>68</td>
</tr>
<tr>
<td>7.22: FEA model of SHTB</td>
<td>68</td>
</tr>
<tr>
<td>7.23: Tensile incident wave in the incident bar of SHTB and the compressive reflected wave</td>
<td>69</td>
</tr>
<tr>
<td>7.24: Tensile stress wave in the specimen of SHTB</td>
<td>70</td>
</tr>
<tr>
<td>7.25: Tensile stress wave and reflected wave in the transmitter bar of SHTB</td>
<td>70</td>
</tr>
<tr>
<td>7.26: Strain rate in the specimen using SHTB</td>
<td>71</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

From past many years there has been always a huge search for materials that are stronger, corrosion resistant and much lighter in weight. With the growing popularity of these materials in the aerospace and automobile industries, it has become very necessary to study the behavior of all materials and their properties.

An important technique used for the characterization of dynamic properties of materials subjected to high rates of strain is the split Hopkinson pressure bar, which uses one-dimensional wave propagation in elastic high-impedance steel cylindrical bars to generate uni-axial stress in the material under investigation. For the evaluation of the mechanical properties of materials at a very high strain rate upto $10^4 \text{ s}^{-1}$, the split Hopkinson pressure bar (SHPB) is most widely used.

The thesis purpose is not to test materials at high strain rates but to study the compression and tensile testing techniques of split Hopkinson pressure bar.

1.1 Materials Testing

There are several mechanical properties in the family which includes Poisson’s Ratio, yield strength, brittleness, ductility, modulus of elasticity, hardness, toughness, etc; To calculate these properties in the materials, the solid piece of material is subjected to a very slow strain rates in a uni-axial direction and the end elongation is measured. This
phenomenon is described by an equation as force applied per unit area shown in Equation 1.1 [13] [32]:

\[ \sigma = \frac{P}{A} \]  

(1.1)

In the above equation, \( \sigma \) is termed for the stress factor, \( P \) is denoted for the force applied and \( A \) stands for the unit area of the solid material. The same expression is also known as Hooke’s Law which is shown in the form of an equation in 1.2 [13] [32]:

\[ E = \frac{\Delta \sigma}{\Delta \varepsilon} \]  

(1.2)

Since the above Equations 1.1 and 1.2 are used for measuring the mechanical properties of materials at a slow strain rates, we need to look for an alternative testing methods to measure the same properties at a very high strain rates. The necessity for measuring under high strain rates comes from the conditions which includes a high impact from dynamic applications. Here comes the need of split Hopkinson pressure bar to study the mechanical properties of materials at a very high strain rates.

With the invention of the split Hopkinson pressure bar which is derived from the Hopkinson bar has become the popular method of testing the materials at a medium and high strain rates. The National Institute for Aviation Research (NIAR) in Wichita, Kansas uses split Hopkinson pressure bar as an important tool to test the strain rates up to \( 10^4 \) s\(^{-1} \).

1.2 Fundamentals of the Split Hopkinson Pressure Bar

As mentioned before, the purpose of SHPB is to determine the mechanical properties of different materials at high strain rates. There is a need of evaluating at a
very high strain rates as many scientists have mentioned in their research work that materials under intense pressure behaves differently when compare to the materials under less intense pressure. The mechanical properties of different materials under a high impact load changes rapidly within a duration of a microsecond.

![Figure 1.1 Simplified schematic of a typical compressive SHPB.](image)

Above Figure 1.1 shows the compressive split Hopkinson pressure bar (SHPB). The apparatus is typically equipped with a Striker bar, Incident bar and a Transmitted bar. The test specimen usually goes in between the Incident bar and the Transmitted bar. This entire apparatus is aligned in such a way that the stress can travel in a uni-axial direction. The cylindrical test specimen is pressed between two cylindrical Incident and Transmitted bars. The striker bar which is used as a projectile to hit on one end of the Incident bar. The high impact of the striker bar on the incident or input bar creates a compressive stress wave which travels through the incident bar till it reaches the incident bar and test specimen interface. When the stress wave hits the interface, a partial stress wave is reflected back into the incident bar and the rest travels through the transmitted bar. The reflected stress wave travels as a tensile wave in the incident bar and the stress wave which is transmitted into the transmitted bar travels in the form of a compressive wave. This entire process is discussed further in detail in this thesis.
In split Hopkinson pressure bar, both the compressive and tensile stress waves are used to calculate the stress and strain in the test specimen. The tensile wave is used to calculate the strain and the compressive wave is used to calculate the stress. The specifications of the components of SHPB will be discussed in detail later in this thesis.

Very simple physics is involved in the actual impact of the striker bar with the incident bar creating the compressive stress wave which mainly depends on the laws of vibrations and dynamics. Also, the boundary conditions plays a major role in the simulation of the SHPB. The displacement of the base nodes in the incident bar, test specimen and the transmitted bar are all allowed to travel only in the uni-axial direction. This is explained in the Fig 1.1 with the arrow above the striker bar indicates the uni-axial direction of the impact.

In the computational model of SHPB, the stress and strain can be calculated using the stress-strain relationship for the material by using the incident, transmitted and tensile stress waves. The relation between the stress and strain was first published by Kolsky [4] in 1949.

\[
\sigma_s(t) = E \left( \frac{A_o}{A} \right) \epsilon_T(t)
\]  

In the above Equation 1.3, \(\sigma_s(t)\) is the history of the specimen stress, \(E\) is the transmitted bar or output bar’s modulus of elasticity, \(A_o\) is the cross sectional area of the transmitted bar, \(A\) is cross sectional area of the specimen and \(\epsilon_T(t)\) is the transmitted strain history recorded at the transmitted bar strain gage. The actual strain rate generated by the impact can be calculated via Equation 1.4 [13] [32]:

\[
\frac{d\epsilon_s(t)}{dt} = - \frac{2C_o}{L} \epsilon_R(t)
\]  

(1.4)
In the above Equation 1.4, $\varepsilon_s(t)$ is the temporal history of the specimen strain, $C_o$ is the infinite wavelength wave velocity in the incident or input bar, $L$ is the initial length of the specimen and $\varepsilon_R(t)$ is the strain history generated by the reflected pulse or the tensile wave in the incident bar. The $C_o$ term used above is, by definition, the “infinite wavelength wave velocity” in the input bar and can be estimated as

$$C_o = \sqrt{\frac{E}{\rho}}$$  \hspace{1cm} (1.5)

In the above Equation 1.5 [13] [32], $E$ is the modulus of elasticity of the incident bar and $\rho$ is the density of the incident bar. Finally, the time history of the specimen strain can be computed by integrating Equation 1.4. This results in Equation 1.6 [13] [32]:

$$\varepsilon_s(t) = -\frac{2C_o}{L} \int_0^t \varepsilon_R(t) \, dt$$  \hspace{1cm} (1.6)

By using the above calculations, the mechanical properties of the materials can be obtained and stress-strain graphs can be generated. These equations are used to calculate the higher strain rates.

1.3 Objective

The main aim of the thesis is to study the wave shaping techniques of SHPB using finite element methodology for both compression and tensile testing techniques.

Firstly, it is necessary to understand the actual behavior of the wave propagation in the split Hopkinson pressure bar before going into the details of wave shaping techniques. This objective will be achieved by modeling the conventional SHPB using a
finite element methodology. Secondly, the original work highlighted the need to carry out other techniques to modify the wave propagation in SHPB.

As work progresses, results from the numerical modeling will be used to provide advice on the construction of modified split Hopkinson pressure bar at National Institute for Aviation research (NIAR) to verify the accuracy of the model. Results from the Kaiser [13], Swantek [32], Ellwood [23], Janne [26], Ferreira, et al [27] will be combined with the tests performed at National Institute for Aviation Research and implemented in the numerical models.

1.4 Topics Covered in Thesis

The purpose of this thesis is to study the wave shaping techniques of conventional split Hopkinson pressure bar and its latest developments with the help of finite element analysis and also to study the tensile testing techniques of split Hopkinson pressure bar by using the finite element analysis code LS-DYNA. Firstly, the conventional model and the compression results will be explained, and then the results of tensile SHPB tests will be presented.

Before going into details about FEA on split Hopkinson pressure bar, description, background and work done on SHPB by previous researchers are presented. Moreover, fundamentals and the equations that explain the theory behind the Hopkinson bar are discussed. Furthermore, description of finite element software LS-DYNA and the modeling techniques involved during the construction of conventional split Hopkinson pressure bar are explained. Followed by the conventional split Hopkinson pressure bar, FEA on the modified SHPB and split Hopkinson Tensile bar (SHTB) and their results are presented.
CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

While reviewing the literature on split Hopkinson pressure bar, many other subjects were also reviewed including materials behavior, mechanical properties of various materials, composite materials. The literature study gave so much information about the relation between the material science and the engineering involved behind the materials behavior. In this chapter you will see the outlines mentioned by various authors in their work and how they are associated with the present work in the thesis. In this chapter there is also information about the chronological development of the split Hopkinson pressure bar and how it is related to the Hopkinson bar.

2.2 The Hopkinson Bar – A Chronological Development

The chronological development of split Hopkinson pressure bar is discussed in this section. The purpose of using Hopkinson bar is to measure the high strain rates in the materials and for this reason Hopkinson bar is widely used. Along with the above mentioned usage of Hopkinson bar there are also several other developments made in the testing which includes tensile testing techniques, strain gage technology and numerical modeling techniques.

During a dynamic impact, to determine the peak pressure produced was first developed in 1913 by Betram Hopkinson. It was his idea to create a compressive stress wave in a cylindrical steel bar when a very small steel cylindrical bar is compressed
between two very long cylindrical bars. The small cylindrical bar is also known as test specimen. To provide a uni-axial state, homogeneous deformation test sample is lubricated with grease on both ends and held at both ends of the steel cylindrical bar. The theory behind the Bertram Hopkinson was that the compressive pulse would travel through the test specimen by causing the specimen to impact with a ballistic pendulum which is already calibrated for momentum measurements.

The momentum measurement through elapsed time was equivalent to the measured speed of the longitudinal waves in the test specimen. He also determined that the longitudinal wave speed which was developed in the specimen is equivalent to the elapsed time of the momentum event. Moreover, Hopkinson indirectly measured the pressure developed by the impact event by measuring the displacement of the ballistic pendulum. Using the above pressure data, Hopkinson identified peak pressure estimated the longitudinal wave speeds in various specimens. However, Hopkinson was not successful to generate reliable pressure versus time relationships for the above experiments due to unavailability of reliable methods of data collection, storage and reduction. Moreover, Hopkinson discovered method of testing materials at higher strain rates that would give insight to many future scientists to investigate dynamic response of materials.

After Hopkinson’s method of testing there was no significant developments in the test setups until Davies [5] in 1940’s came up with the new technique to measure strains by using electrical condensers. Davies’ theory was that the stress developed in the pressure bar was proportional to the displacement in the pressure bar. However, he also stated that the relationship between the displacement and the stress holds good only in the
elastic region of the pressure bar. Using above principles, Davies’ generated the displacement data of the pressure bar using condenser mechanism which gives an electrical output. Davies’ in his work mentioned that the lubricant which was applied to the test specimen was improved the dynamics of the experiment by error reductions which was done by substituting the ballistic pendulum with the electrical condensers for measuring the strain in the experiments.

Apart from the Davies’ work, many physicists and material scientists used Hopkinson pressure bar theory of wave propagation in the bars for their work related to solid structures. At times of Hopkinson’s research, he was also working on the phenomenon of wave propagation which did not make significant advancements until the year 1940. During those days Pochhammer and Love [6] in their research on solid structures derived equations by relating frequency in solids to wave speed. Some of the scientists were studying that the short duration impacts would create acoustic waves with different frequencies. Out of those works, researchers were characterizing the spectral content of stress waves to wave speed, pulse shape and frequency. Dennison Bancroft [7] gathered lot of work related to this and published a set of solved equations in the cylindrical bars based on the longitudinal wave velocities. Those equations were greatly reduced by him by introducing relations to Poisson’s ratio, pressure bar density, diameter, wave length and ratio to the diameter. During his work related to original equipment by Hopkinson, he introduced different methods to determine wave velocities in the pressure bars.

Kolsky [4], in his work related to Hopkinson pressure bar, significantly modified the original setup by adding a second pressure bar to the back of the test specimen. His
idea was to add a second pressure bar at the end of the test specimen which would allow him to read the strain data not only at the front interface but also at the back side of the specimen. This addition to the Hopkinson experiment gave a new look to the researchers to measure not only the strain in the test specimen but also the stress and strain rate. In his work Kolsky also stated that by having specimen in between the two pressure bars would allow the specimen to deform homogeneously. Kolsky also used an electrical condenser from Davies’ work to measure the strains in both pressure bars. He also derived equations for calculating specimen strain, stress and strain rate for using the strain data from both the pressure bars. Kolsky’s Hopkinson bar setup using two pressure bars became successful and preferred method for testing materials at high strain rates because of its robustness and accuracy. Since Kolsky was using two pressure bars unlike one pressure bar by Hopkinson, the experimental setup was commonly recognised as split Hopkinson pressure bar (SHPB) or Kolsky’s bar.

One of the major successes to the Hopkinson pressure bar came in 1954 when Krafft, et al [11], studied the effects of static and dynamic loading by implementing strain gage technology on the yield stress of mild steel with compression. After the introduction of strain gage technology, major improvements to the strain measurements came in the year 1960. Scientists used to measure the voltage of a strain gage instrument and were able to relate the displacement by change in the resistance of a conductor to the changes in its cross sectional area and length. After the developments to the split Hopkinson pressure bar in 1960’s, Hauser, et al [12], in 1961 studied static and dynamic compressive loading of mild steel using strain gages at higher temperatures. Afterwards many scientists used strain gages in their experiments and proved using strain gage in the
experiments significantly improved the repeatability of the data and also increased the accuracy.

After availability of high speed computer data acquisition systems, digital storage, high band width signal analyzers, many scientists improved the Hopkinson bar experiment while obtaining much more accurate data with greater resolutions. After developing the Hopkinson’s experimental setup more researchers worked on studying the characteristics of pressure bars, geometry effects in the specimen and mathematical modeling. A number of researchers such as Follansbee and Franz, 1983 [25] have proposed dispersion correction techniques to eliminate the stress oscillations but their technique cannot be applied universally to all materials and, if applicable, is effective on small diameter pressure bars only.

2.3 The Split Hopkinson Pressure Bar – Additional Information

As mentioned previously, the development in the data acquisition systems and signal analyzers SHPB has been the common method for testing materials at medium and high strain rates. Moreover, researchers Al-Mousawi, et al [15], Bateman, et al [16] and Chen, et al [17] were successfully used SHPB to test non-metallic materials such as rubbers, foams, urethane and some other viscoelastic materials. After these improvements, many works on SHPB resulted in more literature and publications in the area of static and dynamic testing materials in both as a compressive and tensile testing tool. Details about the SHPB techniques can be found in the works of Gray [18]. During the 1960s the development of SHBP continued through work by Harding et al. (1960) and Lindholm & Yeakley [8] that modified the bar in order to subject specimens to uniaxial tension.
Further modifications by Baker and Yew (1966) allowed torsion to be applied to the specimen. Through these important developments the Hopkinson bar technique could now be used to subject specimens to compression, tension and shear (also see Follansbee [25], Nicholas & Bless [30]).
CHAPTER 3
FUNDAMENTALS OF SHPB

3.1 Introduction

SHPB is commonly used for testing different materials to obtain material properties at higher strain rates. Moreover, the governing principles of SHPB include one dimensional wave propagation equation, uni-axial stress relations, deformations and the momentum of conservation. The principles mentioned previously are used not only to perform the experiments but also used for simplifying the results. To develop the equations a single differential element is generally analyzed to derive the required governing equations. Using conservation of momentum which is also called the equation of motion is computed first for the differential element and then followed by stress equations, strain and strain rates. Detailed development of equations mentioned in this thesis would be found in Kaiser [13], Swantek [32] who followed the similar techniques by generating necessary equations through a single differential element.

3.2 The Split Hopkinson Bar

After development of Hopkinson’s bar in early 1900’s by Bertram Hopkinson, who developed the device to test the steel cylindrical bars [4] with very high velocity impacts, many derivatives were followed. Among those derivatives, SHPB development was more popular.
In the succeeding sections detailed description of SHPB apparatus is explained by using Figure 3.1 which shows schematics of the split Hopkinson pressure bar experiment.

![Figure 3.1: Schematics of Split Hopkinson Pressure Bar](image)

In the experiment, the striker bar is fired using a pressure gun to strike the incident bar. Striking generates compressive stress waves in the incident bar which travels in a uni-axial direction to hit the test specimen. At this instance, generated compressive stress wave by the incident bar is partially transmitted into the transmitted bar through the test specimen. However, some of the compressive stress waves in the incident bar would reflect back into it as a tensile stress wave. Strains are recorded from both incident and transmitted bars with the help of the strain gages mounted on the bars. The output of this experiment would generally be in the form of a graph plotted strain versus time. Those graphs are modified further to obtain results in the form of stress versus strain or stress versus strain rate.

SHPB is commonly used to evaluate the mechanical properties of materials at higher strain rates upto $10^4 \text{ s}^{-1}$. This is because of the following reasons:
1. Bars used in the experiments are longer to make sure the incident signal separates and transmits.

2. To maintain one dimensional wave propagation the ratio between the length and diameter of the bars are generally high.


In one of the literatures Burstow, et al [21], stated the use of SHPB towards the medium strain rates only due to its adverse effects caused by acoustic dispersions on waves. The wave propagation velocity dependence on frequency is defined as dispersion. The impact caused by striker on the incident bar excites different frequencies on the incident bar which leads to different velocities within the incident bar. Those velocity variations with respect to time are recorded by the strain gage. Those oscillations on the strain gage recordings make the data difficult to obtain peaks of strain rates.

As mentioned above pressure bars geometry is more important in the SHPB set up. Among all the pressure bars, incident bar is more sensitive to the geometry variations as this is the bar which transmits stress wave to the test sample. The dimensions of the incident bar are important in terms of length and diameter so as to maintain uni-axial stress state, homogeneous deformation in the sample or specimen while maintaining the elastic behavior inside the pressure bar. To make sure a uni-axial, homogeneous deformation within the elastic limit of the pressure bar takes place Equation 3.1 [13] [32] has to be satisfied.

\[
\frac{L}{d} \geq 11 \quad (3.1)
\]
Equation 3.1 states that length should be greater than equal to 10 times the
diameter. Moreover, the diameter of the incident bar has to be greater than twice the
wavelength of the generated compressive wave, to ensure that the pulses generated from
incident bar be separated as incident and reflected waves. So, maintaining this ratio
between length and diameter, NIAR uses the pressure bars which have dimensions of 1”
and 48” as diameter and length respectively. It will also be shown later in this chapter
that strain rates of the specimen is inversely proportional to the length of the incident bar.

Thus,

$$\dot{\varepsilon} \propto C^* \frac{1}{L}$$

(3.2)

where C is a constant of proportionality. As mentioned previously, SHPB strain
rates are approximately in the range of $10^4$ s$^{-1}$. To achieve this, pressure bars has to be
very small with respect to lengths and diameters. However, pressure bars with such small
geometric dimensions makes experiments practically impossible. Moreover, it will be
shown in the later chapter that experiments with pressure bar diameters lesser than 0.25”
would result in failure.

Along with the geometric specifications discussed above, it is important to
position and align the specimen precisely to capture the deformations in the experiments.
For the homogeneous deformation to occur both ends of the specimen are lubricated to
decrease the friction between the incident bar-specimen and transmitted bar-specimen
interfaces [22]. Moreover, accurate positioning of the specimen in the center has to be
maintained in order to achieve separation and compressive of the stress waves [13], [32].
All the above conditions are necessary in order to generate a uni-axial stress state and
homogeneous deformation.
3.3 Relation Between Stress, Strain and Strain Rates

Before generating these equations, theory behind the experiment has to be understood. When the striker bar strikes incident bar, a compressive wave which is elastic in nature is generated. The generated wave propagates towards and into the specimen. The wave then from the specimen is partially reflected and transmitted through the specimen to incident bar and transmitted bar respectively. Strain gages which are placed on the surfaces of the pressure bars records the strains of the reflected and transmitted waves which are used in the Equation 3.3 [13] [32].

\[
\frac{d\varepsilon_{\text{Specimen}}}{dt} = -\frac{2C_o}{l_s} \varepsilon_R
\]

\[
\varepsilon_{\text{Specimen}}(t) = -\frac{2C_o}{l_s} \int \varepsilon_R(t) dt
\]

(3.3)

\[
\sigma_s(t) = E \left( \frac{A_o}{A} \right) \varepsilon_T(t)
\]

Those recordings of the strain histories of both reflected and transmitted waves have to be corrected for dispersion. After correcting, starting and end points of the waves has to be identified. For example, the impact between incident bar and the specimen gives the length of the deformation occurred in the specimen. Lubrication at both ends of the specimen helps a specimen to deform uniformly. Moreover, appropriate geometric dimensions [13], [32] of the specimen would also help to deform uniformly. In order to achieve dynamic stress strain relations for a broad range of materials using Equations 3.3 above conditions has to be met.
In this work, an attempt was made to study the wave shaping techniques of SHPB with the help of finite element analysis. Considering all the above mentioned experimental factors, finite element modeling of SHPB is carried out using LS-DYNA. This is because the computational approach is considered as far easier and faster than the experimental approach in studying the behavior of waves in the pressure bars. The computational analysis has given a better chance to study the propagation of waves in SHPB and to modify the conventional SHPB in a more precise manner. Based on this finite element study, the modified SHPB is constructed at National Institute for Aviation Research (NIAR) lab.
CHAPTER 4

SIMULATION OF CONVENTIONAL SHPB USING LS-DYNA

In the next chapters, we deal with finite element concepts and the theory behind the method, over suitable material models for the description of the mechanical behavior of elastics. LS-DYNA, the explicit finite element program for dynamic analysis is used to build models of SHPB and numerically simulate the testing. In this chapter, we now see the application of the existing software and its description, with which the experimentally examined elastic behavior is to be simulated.

4.1 General Proceeding

LS-DYNA is divided into three parts. These are LS-Pre (pre-processor), Solver (equations solver) and LS-Post (post processor). All three parts are built in, as sub-programs within the software for the specific tasks respectively. For their start, the appropriate input instructions are used. To get the particular description of the input instructions, LS-DYNA manual [24] is to be referred. In the following one of the most important characteristics of individual program modules as well as the proceedings with the simulation are described with the LS-DYNA.

For the construction and meshing of the geometry, PATRAN (pre-processor) is used. The FEA model of SHPB is then transformed into the LS-DYNA readable file and is then used for the simulation.
4.2 Finite Element Method

In this a short overview of the Finite element method (FEM) which is widely spread in the simulations world is given. However, a detailed entrance into the very comprehensive theory is missing here anyway. In addition to some of the concepts of FEM, details of the very complex elastic behavior are described. Different material models are described, which illustrates the dependence on the applied load.

FEM is a numerical approximation method, which is based on the solution of a system of differential equations [24]. These differential equations, contains the parameters such as stress-strain that are used to calculate the forces and displacements for a prescribed geometry. The finite element method can be viewed as an application of the Rayleigh-Ritz method and is mostly based on a displacement approximation. It consists in subdividing the deformable body or the structure in several finite elements, interconnected at nodal points (called nodes) on the element edges. These elements have simple geometry: line segment (1-dimensional), triangle and quadrangle (2-dimensional), tetrahedron and hexahedron (3-dimensional). These finite elements have also special structural function: truss (tensile and compressive deformations), beam (tensile, compressive and flexion deformations), shell, solid etc. Consequently, each node is associated with a DOF number: number of degree of freedom. A translation or a rotation is a special kind of DOF and for example, the classical beam based on Euler-Bernoulli theory has 6 DOF per node (3 translations and 3 rotations). Finally, the continuous body becomes a discrete body, resulting from a discretization by the FEM.

The employment of the FEM takes place not only for the standard problems of strength calculation (Structural), but also in the area of Fracture Mechanics, Fluid
Mechanics, Thermal conduction and Electrostatics. Using this method it is possible to make close-to-reality statements by computer simulation in the development stage and contributes thereby substantially for the reduction of the product development time. Thus, for example crash investigations of vehicle bodies are realized with the help of this method to replace time-consuming and cost-intensive crash attempts.

The formal FEM what we are using today, in principle consists of the following steps:

1. Analysis of the initial situation (concrete problem definition)
2. Pre-processing
3. Computation
4. Post-processing

1. With the Finite element program, in order to understand the behavior of a structural component we need to simulate the model under a concrete technical setting. With the mechanical model at hand, one examines if a simplification of the geometry (idealization of the structure) is feasible or not, in order to omit the structural details which are not important for setting the tasks so that the computation time can be saved. For developing the geometry most frequently CAD methods are used. If no direct coupling between CAD and FEM system exists, structural geometry must be imported over a standard interface (for example by using PATRAN).

2. The phase, Pre-processing (preparatory program) begins with the discretisation of the existing structure. A meaningful mesh is to be developed by the elements linked over discrete places (nodes). Finite Element method determines a numerical solution by approximation of the elements by the algebraic set of equations for
the unknown nodal displacements (the problem of differential equations). The geometrical discretisation serves the numerical discretisation of these equations. The advantage of the method is in the fact that the differential equations are structure-fairly approximated only within each element. The linkage of the elements over the nodes serves thereby the correct transition conditions. Depending upon the concrete problem definition and used material for the structure, the selection of the material model is to be done, which is crucial for the success of the computation. In the material model, a qualitative description of the material behavior under any stress can be found out. The mathematical connections are specified between the parameters involved for the computation, and from the computation, the conserving sizes of the parameters are determined. Likewise the definition of the loads and the appropriate boundary conditions are given in the Pre-processor.

3. Afterwards in the Solver (so-called equation solver) the numerical procedure takes place to solve the defined set of equations and all interesting parameters (stress, strain) are determined.

4. Postprocessor allows us to view the results (graphical analysis). In the post processor, those obtained diagrams give an overview of prevailing circumstances immediately. There by critical assessment is indicated. The plausibility of the results is checked, and a comparison with experimental investigations can be done. Initially formulated technical setting of the problem can be resolvable, by the interpretation of the results. Based on the results and result evaluation it is necessary to repeat the simulation whereby sometimes the structure idealization and load definition that are selected should be changed.
4.3 Structural Components

The structural components represent one and two-dimensional finite elements [24]. With this group of elements, the displacements inside the elements on different assumptions and simplifications are computed. These calculations with certain load cases can be used to reduce complexity, both during meshing and with concrete computation with respect to a smaller computational time. Insufficient description of the problem because of the unfulfilled boundary conditions and the unsuitable element selection, which can lead to wrong results, should be avoided. The use of unsuitable elements can lead to the termination of the simulation or to wrong results. The mostly used structural elements are beams, bars, solids, shells and membrane elements. In this chapter, we deal with shell elements somewhat in detail, since the thin-walled elements are most suitable in particular for the elastic components. A shell element represents a two-dimensional continuum, which can take up both forces within its mid surface and perpendicular to it. At the same time a shell element can be loaded both in axial and in bending. One of the most important characteristic features of the shell element is the small thickness in the normal direction when compared with the longitudinal direction dimensions. It is accepted that with this type of elements, the stress in the mid surface and in the thickness direction is zero. A shell element consists of several layers. For this reason, it is important during the input of the total thickness to consider the number and the thickness of individual layers. In the case of multilayered or laminated shell elements, it is possible to assign different layers with different material properties. With respect to the shape of the shell elements, most frequently the quadrilateral and triangular elements are used. The Figure 4.1 shows these elements with its usual notation.
In this work, Quad finite elements were used, since they make a faster meshing for the available components.

4.3.1 Response to various loads

Various loads which are discussed above, are applied to the material provide various responses. The first response to the load would be purely elastic followed by plastic. Elastic response is generally defined as a response in which the deformation stays as long as the load is applied. After the removal of the load the deformation is instantly recovered. These responses will not leave any permanent deformations on the material. One such example of elastic material is steel. Plastic response is defined as a response in which the deformation stays after the load has been removed. These responses will leave permanent deformations on the materials which are not recovered after the load has been removed.
4.3.2 Elastic model

For the description of the purely elastic material behavior, rheological model such as spring is used. The reversible deformation of the spring corresponds to the elastic deformation of the body. No energy is lost when a body is subjected to an outside load. Nevertheless, the energy is stored in the body and contributes after the end of the load to get back the deformation of the body to its original condition, in nature, the existence of ideal-elastic bodies is not well known. However, within the range of very small strains and brief loads, the material behavior can be described using springs.

\[ \sigma = E \varepsilon_{\text{elastic}} \]  

\( (4.1) \)

With “E” as Young’s modulus, “\( \sigma \)” as Stress and “\( \varepsilon_{\text{elastic}} \)” as elastic Strain.

The proportionality factor “E” between the stress and the strain is called as Young’s modulus. In the stress-strain curve, the elastic modulus within the range of small strains is represented as the slope of the curve.

4.4 Geometry Production of the Conventional SHPB

The SHPB has a very simple geometry. The Figure 4.2 shows the schematic representation of the conventional SHPB based on the parameters shown in Table 1. Using this data, the geometry of the SHPB is prepared using the software PATRAN on a Windows operating system.

![Figure 4.2: Conventional SHPB](image)
SHPB apparatus has the following components. They include an impact bar (striker), an incident bar and transmitter bar. These incident and transmitter bars usually known as pressure bars. The pressure bars are generally made of Steel. The specimen is sandwiched between the pressure bars. As explained in Chapter 3, appropriate selections of components in SHPB are influenced by several factors.

The equations developed in chapter 3 are valid only for an elastic bar. The pressure bars used in NIAR’s apparatus as well as in the computational analysis are high strength Steel-AISI 4340 and the specimen used for the computational analysis is made of Aluminium-AA 7075. The properties used for the components of SHPB are tabulated in Table 1.

Table 1: Geometry and material properties of conventional SHPB

<table>
<thead>
<tr>
<th>Properties</th>
<th>Striker Steel: AISI 4340</th>
<th>Incident bar Steel: AISI 4340</th>
<th>Specimen Aluminium: AA 7075</th>
<th>Transmitter bar Steel: AISI 4340</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus (E) [Pa]</td>
<td>2e11</td>
<td>2e11</td>
<td>7e10</td>
<td>2e11</td>
</tr>
<tr>
<td>Density (ρ) [kg/ m³]</td>
<td>7700</td>
<td>7700</td>
<td>2800</td>
<td>7700</td>
</tr>
<tr>
<td>Poisson’s Ratio (ν)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Diameter [in]</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Length [in]</td>
<td>4.0</td>
<td>60</td>
<td>0.5</td>
<td>60</td>
</tr>
</tbody>
</table>
4.5 Discretization of SHPB

How fine the mesh for SHPB should be, depends on the requirements of the accuracy and computation time. With increasing mesh refinement (large number of elements) the accuracy increases, likewise the computing time also increases. So, compromise is made between the computation time and the accuracy of the results to limit the number of elements. Besides the number of elements, the selection of the element type is of great importance. Already in this chapter the characteristics and the differences of various types of element are described. In this work for the simulation, shell elements with fine discretized models were used. Also since the split Hopkinson pressure bar is a symmetrical model, an axis-symmetrical element model is used for the computational analysis. Hence axis-symmetrical element 14 [24] is used to proceed for further analysis.

4.6 Pre-Processing

The pre-processor PATRAN is used for the pre-processing, In addition to meshing the necessary boundary conditions, specifications, control parameters, contacts can also be defined. The simulation should show the entire test as close-to-reality as possible, for this the similar boundary conditions are to be given. Figure 4.3 is the discretized SHPB and the boundary conditions for the compression test. After creating all, PATRAN generates a file of the produced mesh with all the specifications included. Now this file is imported through PATRAN interface to a readable LS-DYNA input file, which is used as input for the solver.
Figure 4.3: Discretised model-specimen sandwiched between pressure bars

For the uniaxial compression test, nodes on one side of the FE model will have all DOF’s fixed (Neumann boundary condition) in reality they do not move. The nodes on other side will move with a speed (Dirchlet boundary condition) in longitudinal direction and the movements in lateral directions are fixed. In this test all components of SHPB are allowed to move only in one direction of compression. Since in the test nothing was fixed but an initial velocity boundary condition is given to the striker to hit the incident bar at a required speed. The mesh is made very fine only in the longitudinal direction and not in the lateral direction, since we are interested in the one dimensional longitudinal wave propagation in the bars. After defining the boundary conditions to each element, we then proceed to define the proper materials selection for the individual component of the split Hopkinson pressure bar. Once the selection of materials is done, then the respective materials properties described in Table 1 were assigned to each element of the incident bar, transmitter bar, striker and specimen. Now using these specifications file is imported through PATRAN interface to a readable LS-DYNA input file for the solver LS-DYNA.
4.7 Contacts

The uni-axial compression simulation has contact situation involved in it. However, the SHPB involves the contacts of two components with one another. In the software, there are many contact options available. These options primarily treat contact of deformable to deformable bodies, single surface contact in deformable bodies, and deformable body to rigid body contact.

In this work, contact 2D automatic surface to surface option in LS-DYNA is used for treating contact between a surface (usually defined as an analytical surface) and another surface. Where the striker and incident bar surface geometry’s can be input as non-rigid surfaces respectively, which is similar to occupant modeling, where the rigid-body occupant dummy (made up of geometric surfaces) contacts deformable structures such as airbags and instrument panels.

Contact (or impact in case of high velocity phenomenon) appears when at least two bodies come together. This body interaction must be computed. From a finite element point of view, the contact entities, i.e. nodes and elements in contact, must be accurately detected. LS-DYNA has a very efficient contact search algorithm [24]. For simplicity, the bodies in contact are decomposed in two parts: the slave and the master and it is assumed that slaves entities must not go through master surfaces, i.e. slaves nodes must not penetrate master segments, where a segment is a shell surface or a side-surface of a volume element. The slave body usually corresponds to the finest mesh body or the softest material body.
Figure 4.4: Exploded view of a joint between elements describing the interface formulation

The surfaces between adjacent elements were defined with either ‘slave’ or ‘master’ properties (Figure 4.4). The selection of surfaces as either slave or master is arbitrary. Nodes that lie on a slave surface are termed slave nodes and nodes that lie on a master surface are termed master nodes. This is standard contact terminology where the master elements are considered rigid and the slave elements deformable [24]. The first stage in contact modeling is to detect the movement of slave nodes on the master surface and determine the state of contact. Three different states are able to exist:

- Sticking
- Sliding
- Separation

The sticking phase occurs when the relative sliding of the element is totally prevented. Once the sticking phase is completed, sliding starts to occur. The sliding phase can be described by a Coulomb friction relationship that models shear strength in the
presence of normal compression. When the interface has reached the initial failure surface, the bodies start to separate by following a softening branch.

In order to compute the contact forces, i.e. the forces resulting from impenetrability assumption, a mathematical method is used: the penalty function method. It consists in introducing fictitious springs between contact entities. The main point of this method is the choice of the spring stiffness that drives the strength of the contact phenomenon. LS-DYNA uses special formulas to establish contact stiffness that is a function of the geometric and material features of contact entities.

Contact detection and computation require rather complex procedures and make up for a lot of CPU time. In addition, when increasing contact stiffness in order to improve the satisfaction of contact conditions (and to decrease penetration events between bodies), the computational time step, depending on the biggest stiffness value of all finite elements and contact springs, has to be decreased. Other CPU time problems are linked to the detection of all the slave and master entities potentially in contact, at each computation step, when bodies are moving fast and deform considerably.

4.8 Solving

Here, in the work explicit simulations are carried out. Since the computational test is done at a very short time explicit simulations will give good results for this type of dynamics. Within the software LS-Solver, different problem definitions (implicit etc) are present for the computation. The LS-Solver is started over the Unix surface with all the necessary input files such as material card file, pre-processor file etc; for the instructions refer LS-DYNA manual. SHPB contains numerous nodes and shell elements with one material model described as the MAT_ELASTIC. The Solver solves underlying
differential equations using numerical approach, which have been set for the respective tasks. In the concrete case deformations of the specimen, models are computed from beginning to the break. Many numerical operations are accomplished in the Solver and large data sets are processed. Hardware-: specifically fast computer processors and sufficiently large storage location are needed. The simulation that is to be fired should be free from errors, if not the simulation is aborted in the middle. Then the error messages are to be analyzed and the steps for the successful execution of the simulation are to be made. In addition, it is possible during the computation to look at in the output file how far the simulation is executed and/or how many time cycles it has already finished. After successful accomplishment of the computation, the Solver ends the simulation and the results can be analyzed in the post-processor.

4.9 Post-Processing

The post processor is started just like the Solver on the UNIX surface. In LS-POST, the results of the accomplished Simulations are plotted. These results can be analyzed and evaluated both in the form of diagrams and in the form of distorted FE models. The individual operations are dealt in detailed in the manuals. A comparison with the experimentally determined force-displacement behavior can be done by data transfer with whom the curve originating from the simulation is exported as data points which can be accomplished in the form of an ASCII file, and compared outside of LS-POST (e.g. Excel) with the measuring curve.
4.10 Explicit Simulation

Implicit formulation allows pseudo-static and a dynamic approach. In the pseudo-static case where acceleration and velocity forces are neglected, the principle of virtual work leads to [24]

\[ [K] [u] = [F] \] (4.2)

With

\([K]\) = Stiffness matrix

\([u]\) = Displacement vector

\([F]\) = External force vector

The displacement is found directly by inversion of the stiffness matrix, which is a classical inversion problem. It uses Gauss elimination, with its usual matrix conditioning problems. In this case, computer time is proportional to the square of the mean wave front size.

For the implicit dynamic case where acceleration and velocity forces are carried using [24]

\[ [M]\ddot{u} + [C]\dot{u} + [K]u = [F] \] (4.3)

With

\([M]\) = Mass matrix

\([c]\) = Damping matrix

To solve the above equation LS-DYNA uses Newmark time integration method and then the matrix inversions are done to calculate the displacements respectively.
Explicit formulation is based on the fundamental differential equation of dynamics.

\[
[M]\dddot{\bar{u}} = [F_{\text{ex}}] + [F_{\text{int}}]
\]

(4.4)

Central difference integration with

\[
\dot{u}_{n+1/2} = \frac{u_{n+1} - u_n}{\Delta t}
\]

(4.5)

\[
\ddot{u} = \frac{\dot{u}_{n+1} - \dot{u}_{n+1}}{\Delta t}
\]

(4.6)

This yield

\[
u_{n+1} = (2u_n - u_{n-1}) + [M]^{-1}(\Delta t)^2(F_{\text{ext}_n} - F_{\text{int}_n})
\]

(4.7)

Where new matrices and vectors are

- Mass matrix \( M \),

\[
[M] = \sum_{\text{elements}} \left( \int \rho N^T N d\Omega \right)
\]

(4.8)

- Matrix \( N \) contains the derivatives of the interpolation,
- \( \Omega \) elementary volume/body volume,
- \( \rho \) represents the mass density (constant value),

- Internal force vector,

\[
F^\text{int} = \sum_{\text{elements}} \left( \int B^T \sigma d\Omega \right)
\]

(4.9)

- \( B \), the strain-displacement matrix,
- \( \sigma \), the stress vector
That can be written with linear elastodynamics and small displacement assumptions as

\[ F^{\text{int}} = [K] \dot{U}, \]

\[ [K] = \sum_{\text{elements}} \left( \int_{\Omega_e} B^T D B d\Omega \right) \]

- \(K\), the stiffness matrix,
- \(D\), the constitutive matrix, characterising the material

- External force vector

\[ F^{\text{ext}} = \sum_{\text{elements}} \left( \int_{\Omega_e} N^T b d\Omega + \int_{\Gamma_e} N^T f d\Gamma \right) \]

- \(b\), the body force vector,
- \(f\), the surface force vector,
- \(\Gamma\), the body/elementary surface

Because \([M]\) is a diagonal mass matrix, the inversion is direct. The only difficulty is to ensure stable time integration by introducing the condition that the time increments be very small, that is

\[ \Delta t < \frac{L}{C} \]

Where

- \(L\) = some characteristic element dimension,
- \(C\) = Longitudinal velocity of sound,
- \(t\) = smallest transit time of dilatational waves to cross any element in the mesh
The smallness of the time increment is an obvious disadvantage. If it is sufficiently small to be negligible for fast dynamic events, it is also highly penalizing for low speed processes. However, the analysis can be accelerated by increasing artificially the mass density ($\rho$) of the material, the impact velocity if inertia effects remain negligible.

4.11 Simulation Results of Conventional SHPB

Based on the above numerical methods, LS-DYNA Post-Processor shows the behavior of the wave propagating in the incident bar, transmitter bar and specimen. When the striker moves with the initial velocity and impacts the incident bar, a one dimensional compressive stress wave which is in a trapezoidal shape is generated in the incident bar as shown in the below Figure 4.5. After the impact, the stress wave generated travels along the bar towards the specimen where some of the wave is reflected back into the incident bar and the remaining wave is transmitted through the specimen into the transmitted bar. The reflected wave reflects back into the incident bar as a tensile wave, whereas the transmitted wave in the transmitted bar would still be in the form of compressive wave as shown in the Figure 4.5. This is similar to the previous experiments done on SHPB by many researchers [4], [6], [13], [32], [25], [26], [27].
Using the Equation 3.3, the stress, strain and strain rate in the specimen are calculated. Similar one dimensional compressive stress wave is generated in the specimen as shown in the Figure 4.6, of which the strain and strain rate (Figure 4.7) are calculated using the above mentioned equations.
An average strain rate is ascribed by dividing the total strain during loading by its time of application. From the Figure 4.7 we can see that the strain rate is not constant. The dynamic mechanical properties of many materials vary significantly with strain rate, and so to characterize their behavior correctly testing should be carried out under constant strain rate conditions [26]. In the normal SHPB method the strain and strain rate are dependent on the relative impedances of the main bars and specimen, and on the speed of the projectile.

The high initial and lower subsequent strain rate in a normal SHPB test are a consequence of the trapezoidal, short rise time incident pulse. During this rise time the specimen generally reaches its yield stress, and the resulting abrupt reduction in modulus causes a rapid increase in strain since the rate of loading is still at its greatest. However, during the trapezoidal region of the incident pulse the rate of loading is considerably less and so the strain rate decreases [23].

4.12 Parametric Study of Conventional SHPB using LS-DYNA

A typical trapezoidal waveform using a solid cylindrical striker bar is shown in the Figure 4.5. It can be observed that violent stress oscillations exist as the rectangular waveform propagates along the bar. A number of researchers have proposed dispersion correction techniques to eliminate these stress oscillations, Follansbee and Frantz [25] but their technique cannot be applied universally to all materials and, if applicable, is effective on small diameter pressure bars only. To overcome these problems, Liu and Li [28] showed how the shape of a striker bar could influence the rise time of incident waveform, resulting in considerable reduction of stress oscillation. Although it is possible to conduct tests with the existing linear shaped striker bar by reducing the impact velocity
of the striker bar, studies have confirmed that the low impact velocity is inadequate to fracture the specimens. Hence different shapes of striker bars were designed by using finite element code LS-DYNA.

Figure 4.8: Arbitrarily shaped axis-symmetrical striker bars
The face of the striker bar which impedes the incident bar is modified using various shapes and also by introducing spring in the striker bar, for further refining the incident pulse which leads to a constant strain rate in the specimen. The length, \( L \) of the different striker shapes were maintained same as that of the cylindrical striker used in the conventional SHPB. By using the shapes of the striker bar as shown in the Figure 4.8, strain rates in the specimen is calculated and the result is shown in Figures 4.9 and 4.10.

![Strain rate in the specimen](image1)

Figure 4.9: Strain rate in the specimen using striker bar of shape 1

![Strain rate in the specimen](image2)

Figure 4.10: Strain rate in the specimen using striker bars of shapes 2, 3 and 4
By using the stress waves in the specimen, strain and strain rate is calculated and the behavior of the strain rate is observed. In the conventional SHPB, the strain rate is calculated at the interface of the incident bar and specimen and found it is not linear from the Figures 4.10 and 4.11. Also the stiffness value of the spring in the striker bar varies from 1000 lb/in to 100,000 lb/in using different velocities that varies from 3 m/s to 50 m/s.

The ideal incident pulse for achieving a constant strain rate would be one where the leading part would be of short duration up to an amplitude which just allows the specimen to yield, after which the amplitude should increase at a lower rate more appropriate to the reduced modulus. To achieve the required incident pulse and constant strain rate in the specimen few parametric study has been done on the computational model of conventional SHPB. Based on Ellwood [23] theory, a modified version of SHPB system was built at National Institute for Aviation Research (NIAR) and the same is used in the present research work, where the computational analysis of modified SHPB has carried out using the finite element code LS-DYNA.
CHAPTER 5

NUMERICAL SIMULATION OF MODIFIED SHPB

For dynamic characterization of materials advance SHPB technique is used. This research deals with the numerical simulation of SHPB to make further improvements of this technique, i.e. by shaping the Incident wave [23]. This model is truly based on the one dimensional wave propagation theory which assumes that wavelengths are much longer than the transverse dimensions of the pressure bars. The SHPB modification is shown in the Figure 5.1.

Figure 5.1: Modified split Hopkinson Pressure Bar

The following photographs are of the modified split Hopkinson pressure bar apparatus used at NIAR’s facility.
Figure 5.2: Apparatus at NIAR as viewed from the Transmitted bar end

End view of the transmitter bar which shows the length of the pressure bars.

Figure 5.3: Apparatus as viewed from the striker bar end.
Figure 5.4: Striker bar impacting the preloaded bar

Figure 5.5: Apparatus as viewed from the end of the preloaded bar.

In the Figure 5.5, a gap exists between the preloaded bar and the incident bar and also it shows the length of the preloaded bar. A wave shaper is placed in the gap that exists between the preloaded bar and the incident bar.
Figure 5.6: Specimen is sandwiched between the incident bar and the transmitter bar with the help of the specimen holder.

To simulate the specimen with the loading pulse of duration 1000 µs the above model is used. Due to symmetry in the loading/unloading sine pulse has been targeted. The length of the Incident bar should be chosen long enough to achieve the incident and reflected waves separated in time, which will improve the measurement accuracy. The Incident pulse resembles a sine pulse but has slightly different slopes during loading and unloading. This is because of the fact that the Incident pressure bar has finite impedance.

The strain rate of the material is calculated by the stress waves produced in the specimen. By using the formulas mentioned in chapter 3 the strain rate is calculated from the stress waves. The effect of the wave travel transit time of the wave shaper can be seen in the stepwise behavior of especially the loading part of the strain curve. The reflected wave caused by a small impedance difference between specimen and Incident bar will
have small amplitude. The transmitted wave will be similar to the incident wave but with little small amplitude.

The stress, strain and strain rate in the specimen used can be calculated from the incident, reflected and transmitted waves. In this research the main focus is on reducing the uncertainty in the stress and hence making strain rate constant in the specimen. If the slope of the incident wave is linear then the strain rate in the specimen will be constant, which will satisfy the Hooke’s law of elasticity property.

The calculated results have been achieved by a proper choice of material properties for the simulated system, which are shown in the Table 2.

Table 2: Geometry and material parameters of the modified SHPB

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Striker bar</th>
<th>Preloaded bar</th>
<th>Wave shaper</th>
<th>Incident bar</th>
<th>Specimen bar</th>
<th>Transmitter bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [in]</td>
<td>2</td>
<td>12</td>
<td>0.75</td>
<td>48</td>
<td>0.5</td>
<td>36</td>
</tr>
<tr>
<td>Diameter [in]</td>
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<td>1</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Material</td>
<td>Steel</td>
<td>Steel</td>
<td>Aluminium</td>
<td>Steel</td>
<td>Aluminium</td>
<td>Steel</td>
</tr>
<tr>
<td>Modulus(E) [Pa]</td>
<td>2e11</td>
<td>2e11</td>
<td>7e10</td>
<td>2e11</td>
<td>7e10</td>
<td>2e11</td>
</tr>
<tr>
<td>Density(ρ) [kg/ m³]</td>
<td>7700</td>
<td>7700</td>
<td>2800</td>
<td>7700</td>
<td>2800</td>
<td>7700</td>
</tr>
<tr>
<td>Poisson’s Ratio(υ)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
By using the data in Table 2, the geometry of SHPB is done using the software PATRAN on a Windows operating system. The main part of the Incident pulse is transmitted through the specimen, which is modeled as a homogeneous Aluminium (Al) cylinder in this simulation. The modified version of SHPB has a preloaded bar together with a wave shaper of different material as that of specimen. Using the transmitted pulse through the wave shaper as a tailored incident pulse for the loading the test specimen enables testing to be carried out at constant strain rates from about 100 µs to 3000 µs. In normal SHPB there will be considerable variation in strain rate throughout the test with a consequent uncertainty in the interpretation of the results.

Using the computational model of the conventional SHPB many variations in the parameters were done such as varying the modulus ratio of specimen to that of incident bar, modifying the shapes of the striker bar by using the spring in between the striker as well as modifying the shape of the striker face, using the compliant material in between the striker bar and the incident bar. But none of these methods could lead to a better result for a change in the wave shape in the incident bar. In this research the main focus is on reducing the uncertainty in the stress and hence making strain rate constant in the specimen.

Then the idea of the preloaded bar and wave shaper came into existence [23]. By using the preloaded bar and wave shaper the pulse in the incident bar is refined and thus obtaining the constant strain rates in the specimen.

When the striker impacts the preloaded bar, a pulse is generated in the preloaded bar of trapezoidal shape. Different velocities are used as a parametric study ranging
between 100 in/s to 1000 in/s. The strain pulse which is generated in the preloaded bar is shown in the Figure 5.7.

![Strain in the Preloaded bar](image)

**Figure 5.7:** Trapezoidal strain pulse generated in the preloaded bar when the striker hits the incident bar with a velocity of 100 in/s in the modified SHPB.

In the Figure 5.8, we can see that the incident and reflected pulses are refined well to form a sinusoidal shape from the previous trapezoidal shape with the help of the preloaded bar and wave shaper. This refined incident pulse will lead to the constant strain rate in the specimen as shown in the Figure 5.8.
Figure 5.8: Strain pulse generated in the incident bar when the striker hits the preloaded bar with a velocity of 100 in/s.

Figure 5.9: Strain rate in the specimen using modified SHPB at a speed of 100 in/s.

Likewise, the transmitted pulse generated in the transmitter bar is also plotted using the strain values and is shown in the Figure 5.10.
Initially the length of the preloaded bar is taken as 40 inches and the wave shaper is designed having the parameters same as that of the specimen. Later the length of the preloaded bar is decreased to 12 inches for a matter of cost reduction and computational analysis is done on the modified SHPB using the specifications mentioned in Table 2. Strain rate in the specimen using modified SHPB is compared with the strain rate in the specimen using conventional SHPB, plotted together as shown in the Figure 5.11.
Figure 5.11: Comparison of strain rate in the specimen using conventional SHPB and modified SHPB

Since we achieved constant strain rate in the specimen with the use of modified SHPB, we further proceed to perform dynamic tensile tests using split Hopkinson pressure bar.
CHAPTER 6

DYNAMIC TENSILE TEST: SPLIT HOPKINSON TENSION BAR (SHTB)

6.1 Introduction

Although the development of a method to test materials in tension under high strain rate (later called Split Hopkinson Tension Bar, SHTB) was introduced a decade later after the SHPB, the progress in using SHTB was very slow due to difficulties inherent in sample design, load application, and data interpretation. There are many arrangements which have been used to apply a tensile pulse to the specimen. The differences between them inherent in the load application, sample design, and bars arrangement. The historical prospective and the development of SHPB can be found elsewhere Al Mousawi [29], Nicholas and Bless [30] and Mostafa Shazly [31]. To perform tension tests in metallic specimens the experimental set up was reconfigured and its procedure and instrumentation are also presented. The test set up for tension are described and discussed by providing with the advantages and limitations. In addition to preliminary results obtained in metallic test specimens the stress wave propagation in slender bars are also shown.

Using classical tensile tests, the major mechanical properties of the specimen at very slow rate of deformation are obtained. For accurate design optimization complete material properties under realistic test conditions are required. Moreover, the same material behaves slightly different at higher strain rates. To get the compressive material properties at strain rates near to $10^4 \text{ s}^{-1}$, split Hopkinson pressure bar apparatus is used widely for this purpose. Devices such as SHTB have been developed in order to get
tensile properties at higher strain rates. However, these setups provide less success to dynamically characterize the composites.

The problems while setting up the SHTB for tension test are, aligning and positioning the specimen without generating reflective waves while generating traction pulses. The use of grips without impedance match generates many reflections in wave propagation. Using a solid input bar and a hollow tube output bar, it is possible to perform tension tests using compressive pulse, Lindholm & Yeakley [8].

### 6.2 Set-up to Perform Tension Test

A longer bolt head input bar is used to drive a hollow tube impactor, with the same inner diameter and area. This tension test set-up is to direct generate a traction pulse in the input bar, Ferreira [27]. In this processes it is necessary to fix the specimen on both bars, usually threads are used for metals. The Figure 6.1 shows the tension test set-up to generate a tensile pulse in the incident bar of SHPB.

![Figure 6.1: Set up for split Hopkinson tension bar (SHTB)](image)

Using finite element code LS-DYNA, the above SHTB set up is modeled in a similar way as that of conventional SHPB as it is very similar to it. Only the shape and
length of the incident bar has changed. Also an impactor is used instead of striker bar to generate a traction pulse in the incident bar. The parameters of the components of SHTB are given in the Table 3.

Table 3: Geometry and material parameters of the SHTB

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Impactor</th>
<th>Bolt Head</th>
<th>Incident bar</th>
<th>Specimen</th>
<th>Transmitter bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [in]</td>
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<td>3</td>
<td>96</td>
<td>0.5</td>
<td>36</td>
</tr>
<tr>
<td>Diameter [in]</td>
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<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Material</td>
<td>Steel</td>
<td>Steel</td>
<td>Steel</td>
<td>Aluminium</td>
<td>Steel</td>
</tr>
<tr>
<td>Modulus(E) [Pa]</td>
<td>2e11</td>
<td>2e11</td>
<td>2e11</td>
<td>7e10</td>
<td>2e11</td>
</tr>
<tr>
<td>Density((\rho)) [kg/ m3]</td>
<td>7700</td>
<td>7700</td>
<td>7700</td>
<td>2800</td>
<td>7700</td>
</tr>
<tr>
<td>Poisson’s Ratio((\nu))</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

By using the parameters of split Hopkinson tension bar (SHTB), finite element modeling in this research is done by using the similar methods as that of conventional split Hopkinson pressure bar. Here the impactor moves with an initial velocity and impacts the bolt head incident bar. When the wave front reaches the end of the cross-section with the difference in area value, at this point some of the waves begin to reflect and continuous to reflect until the wave passes through it. If in case two different areas
are located near to each other part of the wave traps between them with forward and backward propagation.

Based on this, the compressive pulse generated in the bolt head gets converted into tensile while propagating in the incident bar. This tensile pulse propagates through incident bar and reaches the specimen. At the incident bar-specimen interface, partial tensile incident pulse gets reflected as a compressive pulse and the remaining transmits into the transmitter bar through specimen in the form of a tensile pulse. Using the equations 3.3 stress, strain and strain rate in the specimen are calculated.
CHAPTER 7

RESULTS AND DISCUSSION

7.1 Computational Analysis of Conventional SHPB

In the following, the simulation results for the conventional SHPB as well as for the modified SHPB are evaluated. Apart from that, the influence of various FEA parameters affecting the results on the simulation processes is also discussed. Different parameters are changed in the process of simulation to show the influence of each parameter considered, so that at the end abundance of different results are present which makes the computational analysis less predictive.

SHPB contains numerous nodes and shell elements with one material model described as the MAT_ELASTIC. The simulations were carried out with the same speeds of 30m/s and boundary conditions, which prevailed during the experiment. In order to get the complete behavior of the specimen tested, the simulations were carried out without any failing strain.

The behavior of the stress waves in the incident bar, transmitter bar as well as specimen in a conventional SHPB is shown in the Figure 7.1.

![Figure 7.1: Stress waves in the incident bar using conventional SHPB](image)

By using the stress waves in the specimen, strain and strain rate is calculated and the behavior of the strain rate is observed. In the conventional SHPB, the strain rate is
calculated at the interface of the incident bar and specimen and found it is not linear as shown in the Figure 7.2.

![Figure 7.2: Strain rate in the specimen using conventional SHPB](image)

After observing that the strain rate is not linear, modifications are done using various modulus ratios for the incident bar and specimen. In this research, modulus ratios of specimen to that of incident bar are chosen to be 0.1, 0.35, 0.5, 1.0 and 2.0 and are shown in the Figure 7.3.

![Figure 7.3: Strain rates in the specimen for various modulus ratios using conventional SHPB](image)
Modifying the modulus ratios in the conventional SHPB did not lead to the better result of obtaining the constant strain rates in the specimen.

### 7.2 Computational Analysis of Modified SHPB

Here we come with the idea of introducing the preloaded bar and wave shaper in the conventional SHPB design. The preloaded bar and wave shaper is set just before the incident bar and the computational analysis is done.

![Figure 7.4: Computational model of modified SHPB](image)

Initially the length of the preloaded bar is taken as 40 inches and the wave shaper is designed having the parameters same as that of the specimen. Later the length of the preloaded bar is decreased to 12 inches for a matter of cost reduction and computational analysis is done on the modified SHPB. Initially when the length of the preloaded bar is taken as 40 inches then the strain rate in the specimen is as shown in the Figure 7.5. The strain rate in the specimen is linear in the latter case (i.e. modified SHPB) whereas it is not linear in the conventional SHPB as shown clearly in the Figure 7.5.
Looking into this and proceeding further by varying the parameters of the wave shaper and specimen, such as taking same young’s modulus for both wave shaper and specimen and also taking half of the young’s modulus for the wave shaper to that of the specimen as shown in the Figure 7.6.

Figure 7.5: Comparison of strain rate in the specimen using conventional SHPB and modified SHPB

Figure 7.6: Comparison of strain rate in specimen between the conventional SHPB and modified SHPB for different modulus ratios
In both the cases of modified SHPB shown in the Figures 7.6 and 7.7, the strain rate in the specimen is constant. This shows that the preloaded bar and wave shaper refines the pulse generated in the incident bar. The transmitted pulse generated in the incident bar is used as the incident pulse before reaching the specimen interface.

Using different initial velocities of the striker bar, strain rates in the specimen were observed as shown in the Figures 7.8, 7.9 and 7.10.
Figure 7.8: Comparison of strain rate in specimen between conventional SHPB and modified SHPB for an initial velocity of 3m/s

Figure 7.9: Comparison of strain rate in specimen between conventional SHPB and modified SHPB for an initial velocity of 30m/s
Figure 7.10: Comparison of strain rate in specimen between conventional SHPB and modified SHPB for an initial velocity of 50m/s

Also many modifications are done in the computational model of the modified SHPB concerning with the length of the preloaded bar, materials used for the preloaded bar and wave shaper. Here in this research many parameters of the modified SHPB were studied and compared with the computational results of the conventional SHPB. The materials used for the wave shaper and specimen were same and as well studied for the different materials.
Figure 7.11: Comparison of strain rate in specimen for different modulus ratios using the same material properties for both wave shaper and specimen

Figure 7.12: Comparison of strain rate in specimen for different modulus ratios and different initial velocities using the same material properties for both wave shaper and specimen
When the striker impacts the preloaded bar, a pulse is generated in the preloaded bar of trapezoidal shape. Different velocities are used as a parametric study such as 250in/s, 500in/s and 1000 in/s.

Figure 7.13: Strain pulse generated in the incident bar when the striker hits the preloaded bar with a velocity of 250 in/s

Figure 7.14: Transmitted pulse for a speed of 250 in/s using different materials for both wave shaper and specimen
Figure 7.15: Strain rate in the specimen using modified SHPB at a speed of 250 in/s.

Figure 7.16: Strain pulse generated in the incident bar when the striker hits the preloaded bar with a velocity of 500 in/s.
Figure 7.17: Strain rate in the specimen using modified SHPB at a speed of 500 in/s.

Figure 7.18: Strain pulse generated in the incident bar when the striker hits the preloaded bar with a velocity of 1000 in/s.
Figure 7.19: Strain rate in the specimen using modified SHPB at a speed of 1000 in/s

Figure 7.20: Transmitted strain pulse shape using different materials for wave shaper and specimen in the modified SHPB
Strain rate in the specimen using striker velocity as 1000 in/s

<table>
<thead>
<tr>
<th>time (sec)</th>
<th>strain rate (per sec)</th>
</tr>
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<td>3.71E-04</td>
<td>3.71E-04</td>
</tr>
<tr>
<td>3.76E-04</td>
<td>3.76E-04</td>
</tr>
<tr>
<td>3.81E-04</td>
<td>3.81E-04</td>
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<tr>
<td>3.86E-04</td>
<td>3.86E-04</td>
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<tr>
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<tr>
<td>4.06E-04</td>
<td>4.06E-04</td>
</tr>
</tbody>
</table>

Figure 7.21: Comparison of strain rates in the specimen between conventional SHPB and modified SHPB (using same & different materials) for a speed of 1000 in/s

7.3 **Split Hopkinson Tension Bar (SHTB)**

Since the SHTB is a symmetrical model, an axis-symmetrical finite element model as shown in the Figure 7.22 is constructed and meshed following the same procedures as in conventional SHPB.

![Figure 7.22: FEA model of SHTB](image)
The SHTB results are as shown in the following figures:

Figure 7.23: Tensile incident wave in the incident bar of SHTB and the compressive reflected wave

When the impactor moves with an initial velocity and strikes the bolt head incident bar, a tensile incident wave is generated in the incident bar which propagates along the bar and reaches the specimen. At the incident bar-specimen interface, a compressive reflected wave is generated due to the mismatch of incident bar and specimen. This phenomenon is shown in the Figure 7.23.
Figure 7.24: Tensile stress wave in the specimen of SHTB

Figure 7.25: Tensile stress wave and reflected wave in the transmitter bar of SHTB
Figure 7.26: Strain rate in the specimen using SHTB
CHAPTER 8
CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

The purpose of this research was to study the wave shaping techniques of split Hopkinson pressure bar (SHPB) and also to study the tensile test set up of the Hopkinson bar.

• At higher strain rates SHPB proved to be a successful method to obtain the stress strain curves of the materials.

• One disadvantage of the conventional SHPB method is that it does not produce a constant strain rate during a test, particularly so in the early stages of loading where strain rate sensitivity effects are most important to study the mechanical properties of materials.

• The modified SHPB at National Institute for Aviation Research (NIAR) has demonstrated that constant strain rate testing is possible at high rates of strain. This will enable tests on the strain rate sensitivity of materials to be carried out far more precisely and with much more confidence than has been possible hitherto.

• Modified SHPB gave better results using different materials of wave shaper and specimen.

• The various lengths of the preloaded bar that has considered during wave shaping techniques in this research, does not have much effect on the impact pulse generated in the incident bar.

• Even by changing the shapes of the striker bar, by introducing spring with different stiffness in the middle of the striker bar does not have any significant impact in the strain rates of specimen.
• Using different modulus ratios for both wave shaper and specimen has given more satisfactory results when compared to the same modulus ratios.

• Test set up which involves (bolt head, impactor, incident bar, specimen and transmitter bar) is successful in generating a tensile pulse in the incident bar, as the impactor impacts the bolt head incident bar.

• When generated by a tubular impactor during the tensile test of SHTB, the incident wave generated is not a smooth rectangular pulse shape as that of the conventional SHPB.

• The main problems in set-ups for tension are how to fix the specimen without generating reflections in wave propagation and how to generate traction pulses.

• It is more evident to evaluate material properties at high strain rates using the impactor tensile test set up of split Hopkinson tension bar (SHTB).

8.2 Future Recommendations

• Further study can be done on the materials used for the preloaded bar and the wave shaper in the modified SHPB.

• Further techniques can be developed to produce tensile pulse in the incident bar of SHTB.
REFERENCES


