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Rebuild The Niu Split-Hopkinson Pressure Bar Apparatus For High Strain Rate Tensile Test

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ABSTRACT

REBUILD THE NIU SPLIT-HOPKINSON PRESSURE BAR APPARATUS FOR HIGH STRAIN RATE TENSILE TEST

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A split-Hopkinson apparatus is a device used to dynamically test material properties for constructing constitutive model and can be used for high strain rate deformation research and experiments. NIU currently has a split-Hopkinson apparatus that can conduct compressive tests only. The goal of this thesis is to redesign and rebuild the existing apparatus, so the high strain rate tensile tests can be conducted.

Multi-improvements were applied to the split-Hopkinson apparatus in order to improve its working performance. For conducting high strain rate tensile test, the split-Hopkinson system has been rebuilt with a load-inversion device. The load-inversion device was designed for converting compressive loading pulse to tensile pulse such that an output bar connected to the device can apply the tensile loading pulse to the specimen. The rebuilt system has been used to conduct high strain rate tensile test on stainless steel 304 foils with thickness of 100µm. The signals from the two strain gauges on the output bars can be used to calculate the flow stress curves of the specimens. A high-speed camera was also used to take pictures of the deformation history of the specimen that can be used to obtain the relation of strain and time for computing strains and strain rates.

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REBUILD THE NIU SPLIT-HOPKINSON PRESSURE BAR APPARATUS FOR HIGH STRAIN RATE TENSILE TEST

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Finally, I wish to thank my family members and friends for their support and encouragement throughout my study.

DEDICATION

To my family

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CHAPTER 1. INTRODUCTION

1.1 History of the split-Hopkinson pressure bar

The split-Hopkinson pressure bar (SHPB) is a widely used system to observe material properties at high strain rate loading conditions from $10^2 s^{-1}$ to $10^4 s^{-1}$. In 1872, John Hopkinson conducted rupture testing of an iron wire by the impact of a drop weight, he found that the break location of iron wire changes from the impact end to the fixed end while the impact speed changes. However, it was difficult to build the data measurement system due to the limitation of the electronic equipment at that time. In 1938, Davis made a critical improvement of the technique, he measured the pressure-time curves and movements of a bar produced by detonation. The first version of SHPB that could measure the stress-strain response was refined in 1949 by Herbery Kolsky. He measured and calculated dynamic stress-strain behaviors of many materials by put the testing samples between two bars in compression tests.

The original SHPB was designed only for compression testing, the split-Hopkinson tensile bar was developed in the 1960s to look into the high strain rate material properties under tensile stress. Many improvements have been applied to the SHPB system, resulting in wider application. The SHPB and split-Hopkinson tensile bar work with similar principles. However, the gauge-section in the strain rate calculations are more complicated since specimens should be attached to the end of the bar in the tension experiments. The high strain rate tensile test has been conducted with multiple materials in different situations over the last few decades.

1.2 Backgrounds of SHPB

The general setup of the SHPB experiment shown in Figure 1-1, normally consists of three parts. They are the launching system, bar system, and data acquisition and recording system.

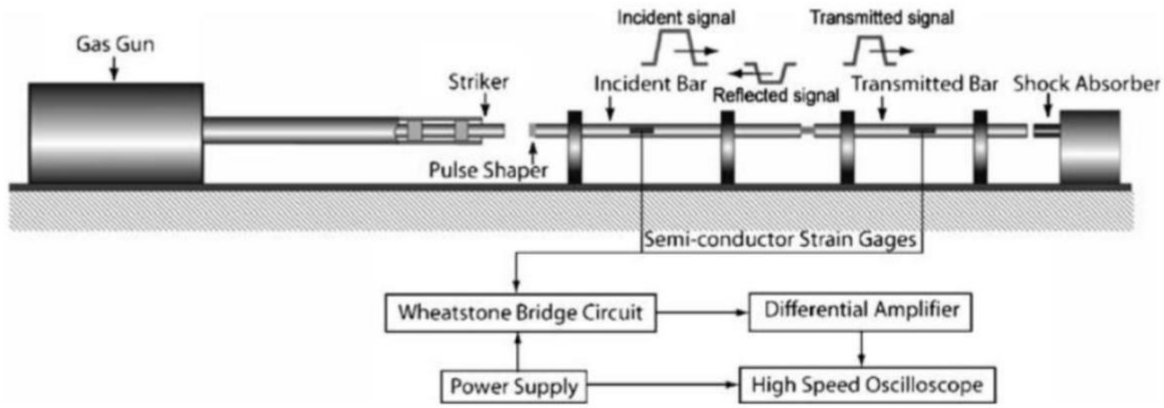


Figure 1- 1: General split-Hopkinson compression bar apparatus [1].

The launching system includes an electronic launching system and a gas tank that connects to a gun barrel. With the electronic launching system, the gas tank is safe to store or release at different pressures. Once the launching system is started, the compressed gas releases through the gun barrel creating high pressure to shoot the striker bar from inside of the gun barrel. The bar system consists of a striker bar, incident bar, transmitted bar, and a stopper placed at the end, each bar is made of the same material and with the same diameter. The striker bar is located in the gun barrel, from which the remaining bars have to be aligned along a common straight axis. In the data acquisition and recording system, two strain gauges will attach to the surface of the incident and transmitted bars. After striker bar impact, a stress wave is generated and propagates through the incident and transmitted bars. The strain gauges detect the stress wave inside of the bars whose resistance will change as the wave propagates. A Wheatstone Bridge circuit connects to the strain gauges so that the output from the gauge transfers to a voltage signal. That signal will be amplified through the amplifier and then be recorded by the oscilloscope. The simplified working mechanism is shown in Figure 1-2.

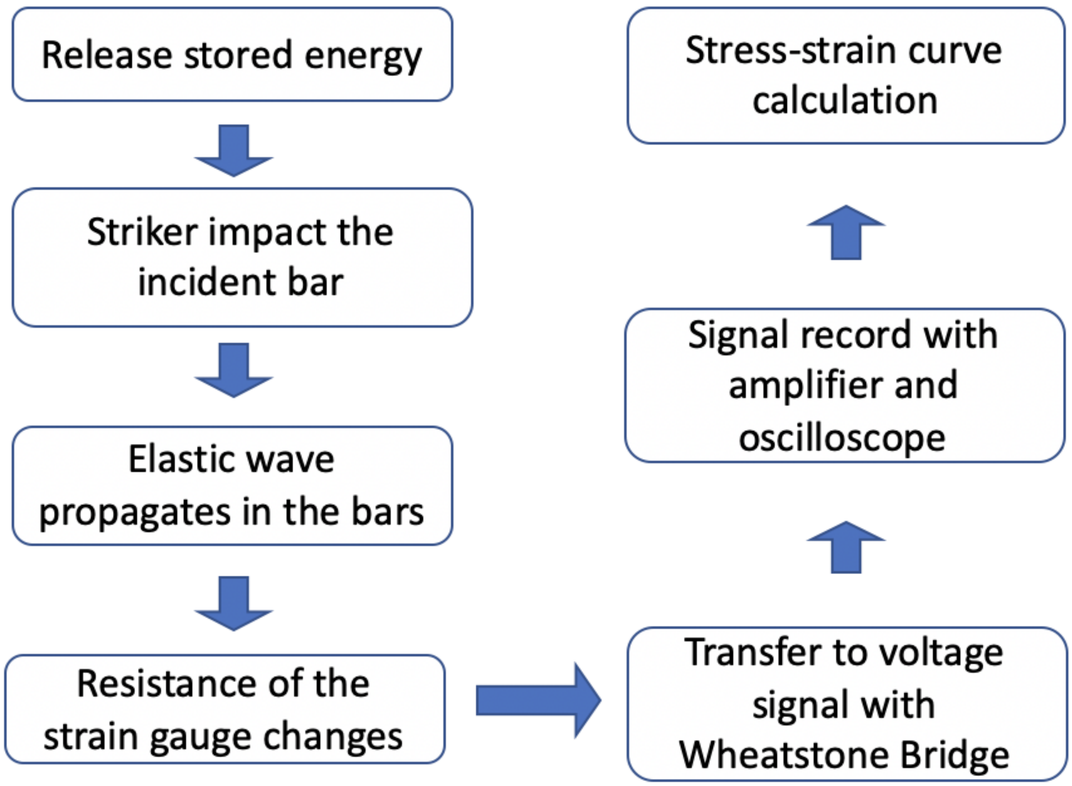


Figure 1- 2 : Flow chart of SHPB system signal.

In the SHPB compression test, the first step is to insert the striker bar into the gun barrel which connects to the gas tank. Then the specimen will be placed between the incident bar and transmitted bar. After launching the gas tank, the striker will be shot out at a high speed and hit the incident bar. At that time, a stress wave, also called incident wave is generated in the incident bar and will be transmitted to the transmission bar through the sandwiched specimen. The specimen is under compression in that process. The wave is split into two parts when it passes to the specimen due to the mismatch of the surface area and materials of the bars and specimen. Some of the elastic wave travels through the specimen and propagates to the transmission bar; this is called the transmitted wave. The rest of the wave is reflected off the specimen and propagates back to the incident bar; this is named the reflected wave. Figure 1-3 shows the typical wave measurements from compression testing using a SHPB apparatus.

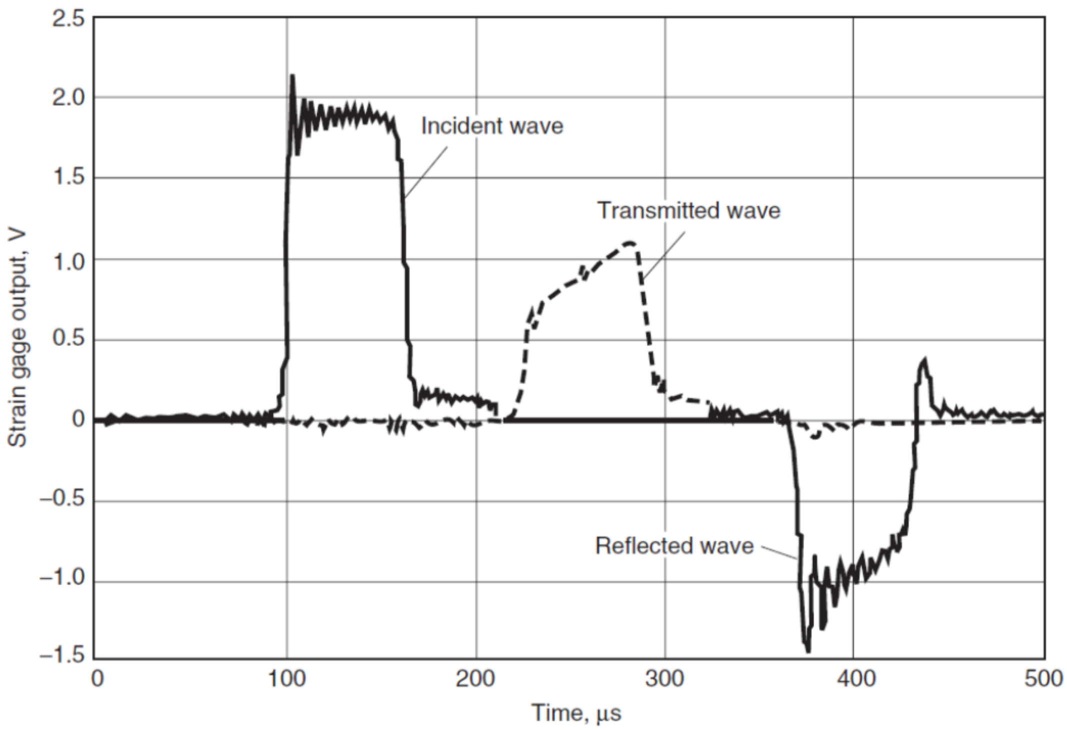


Figure 1- 3: Typically measured signal from a SHPB compressive test [2].

The length of the incident and transmitted bars need to be at least twice as long as the striker bar so that the stress wave will not overlap on the strain gauge and affect its recording of the signal. A good system allows the bars to move freely in an axial direction and provides accurate uniaxial alignment.

1.3 High strain rate material response

Under dynamic loading, the mechanical behavior of most materials depends on the strain rate [3]. The concept of strain rate was first proposed by Jade LeCoq in 1867, it is the derivation of the strain with respect to time and is demonstrated in the Equation (1.1). The strain is a geometric measure of the deformation representing the relative change to its original length [4]. In that equation, L_0 is its original length of the sample, and $L(t)$ is the length of the sample at a specific time t.

$$\dot{\varepsilon}(t) = \frac{d\varepsilon}{dt} = \frac{d}{dt}\left(\frac{L(t) - L_0}{L_0}\right) = \frac{1}{L_0}\frac{dL}{dt}(t) = \frac{v(t)}{L_0} \tag{1.1}$$

It has been found that the influence of internal forces and the effects of wave propagations will increase with high strain rate. Figure 1-4 shows the stress-strain curve of stainless steel under different strain rates. It can be observed the strength of the material increases while the strain rate increases.

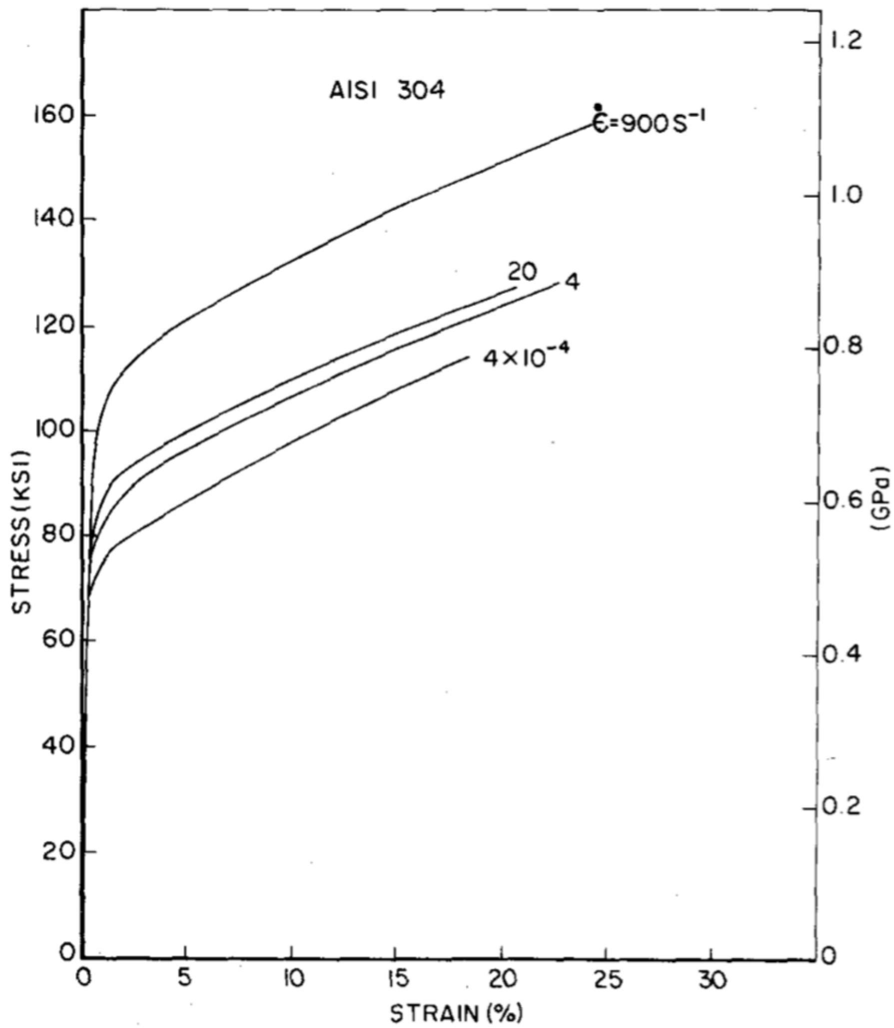


Figure 1- 4: Stress-strain curve of stainless steel under tension [5].

High strain rate characterizations have become an important aspect of material research to observe basic microstructural mechanisms and properties such as failure criteria and energy absorption. By observing the material response under a high strain rate condition, the data and results obtained can be applied to different fields, such as high-speed forming, automotive industry, mathematical modeling and numerical simulations.

1.4 Split-Hopkinson tension bar setup

1.4.1 Split-Hopkinson tensile test setup

Some materials present very different properties in tension and compression. Specifically, there are some materials, such as fibers, that can only sustain tension. So it is essential to develop a tensile version of the split-Hopkinson technique to explore the high-rate response of these materials. Different versions of tensile SHPB apparatus have been developed over the years. Figure1-5 shows some typical ways to set up the split-Hopkinson tensile test system. Type (a) is designed for conducting tensile tests with a hat-shaped specimen; in type (b) the specimen needs to be threaded into the end of the bars and a rigid collar is placed over the specimen between the bars so that the compressive stress wave can propagate from the incident bar to transmitted bar and the specimen would be subjected to tension; as for type (c), the specimen is placed into a hollow tube, which will move rightwards after being hit by the striker bar; type (d) shows a way to use direct tension as a loading method, which is the most commonly used method.

There are multiple methods to build a split-Hopkinson tension bar, however, it would be most efficient to have a SHPB system that can conduct both compressive and tensile tests with some interchangeable components.

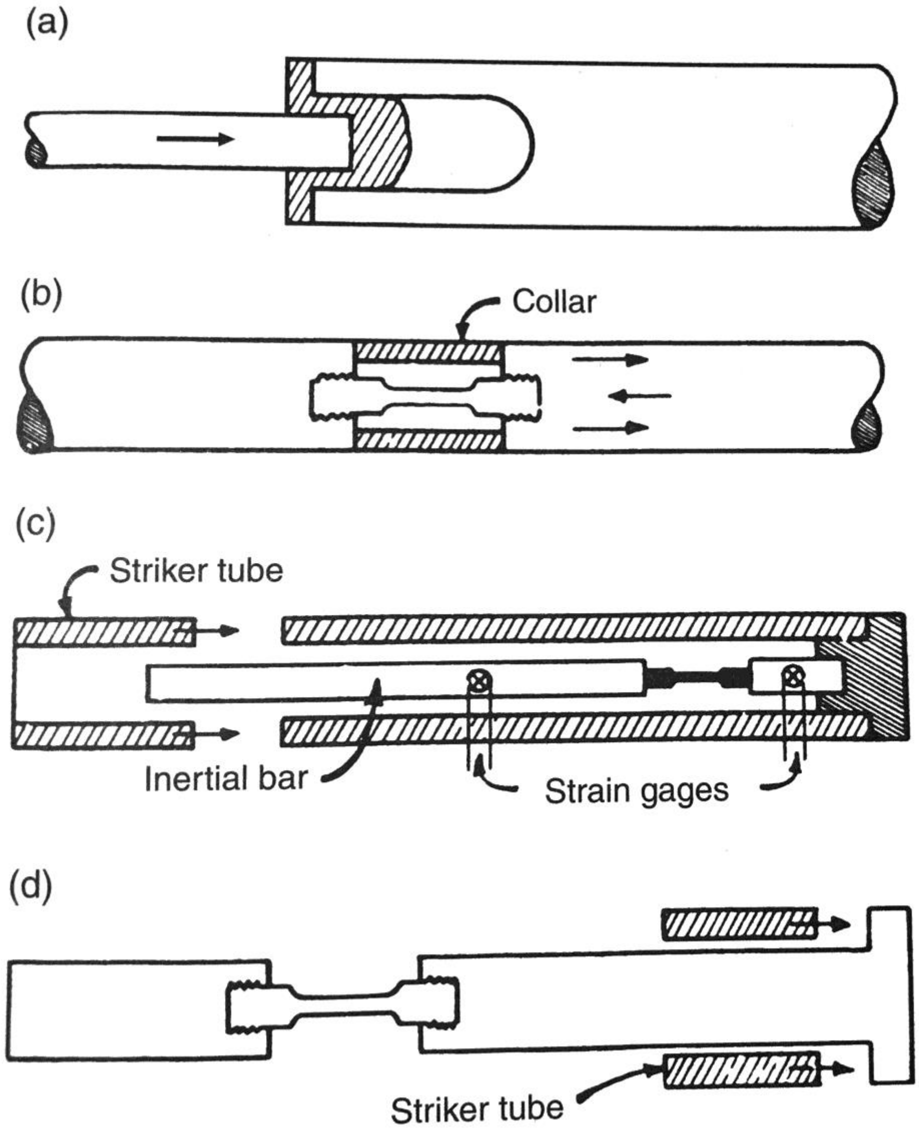


Figure 1- 5: Split-Hokpinson tension bar variants [3].

1.4.2 Digital image correlation

Digital image correlation(DIC) is an imaging technique that is used to calculate the strain and deformation of a test material through a series of images and is widely used in high strain rate tensile tests. Due to the varied cross-section nature of tension specimens, the determination of the initial specimen length is hardly unique [6]. With the use of a high-speed camera for capturing images in testing, the strain data of the tested specimen is then able to be computed using DIC. Figure 1-6 shows the working theory for calculating the displacement and strain of a specimen with the use of a high-speed camera and DIC.

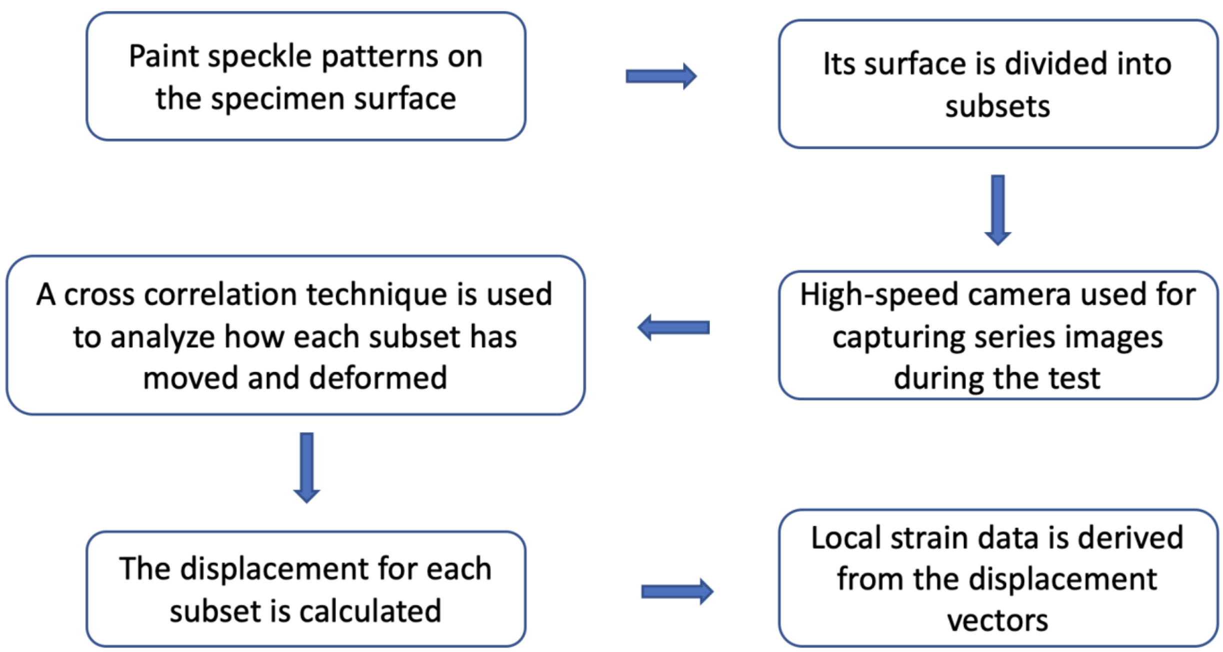


Figure 1- 6: DIC working theory flow chart.

1.5 Objective

The SHPB system in the NIU Materials Analysis Lab was only developed to perform the compressive test under high strain rate and suffers from unstable performance. The main objective of this thesis is to redesign and rebuild the SHPB system used in the NIU lab to make it more flexible and stable, and modify it to conduct tensile tests on dog-bone shape sheet material.

CHAPTER 2. REBUILDING THE SHPB SYSTEM

2.1 The original NIU SHPB system

The original setup of the split-Hopkinson compression bar in the NIU Materials Analysis Lab is shown in Figure 2-1. This system consists of a gas tank, gun barrel, incident bar, transmission bar, stopper, electric launching device, signal conditioning amplifier, and one oscilloscope.

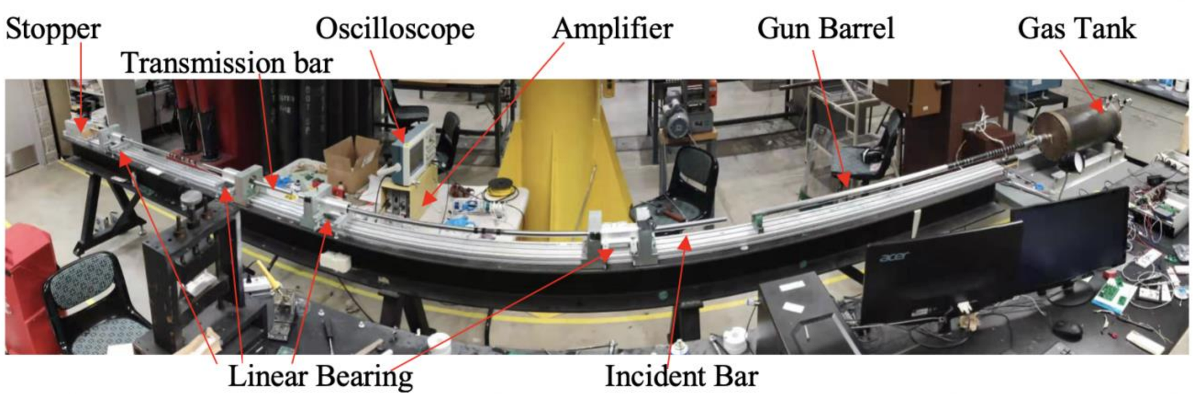


Figure 2- 1: Original compression setup of NIU SHPB system [7].

In this SHPB system, a long T-slot rail is placed on the H-beam base to provide a stage for the bar system. Linear bearings are used to support the 1-inch diameter incident and transmission bars. Figure 2-2 shows the linear bearing support device, which is made up of four bolts and nuts. These function as its feet, which support it and allow its height to be adjusted for bar alignment. The linear bearing is not fixed to the base part, which causes the incident and transmission bars to vibrate, affecting the testing signal. The unstable support device also increases the difficulty in positioning the linear bearing during the alignment checking process.

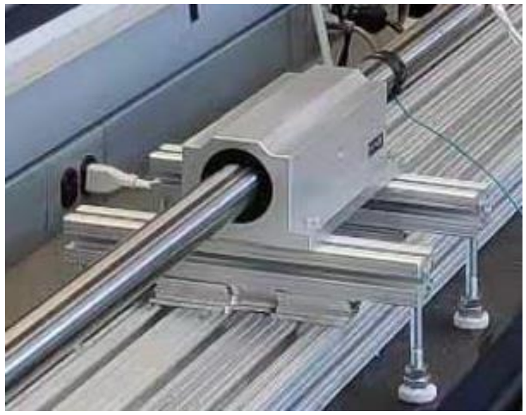


Figure 2- 2: Linear bearing support device [7].

The gas tank in the system is placed on a separate table to one side of the H-beam base. The gas tank is placed on the table without any constraint, and the table's height is not adjustable. The gun barrel is connected to the tank, and therefore it is not stable or adjustable. Once the height of the H-beam is changed, it is difficult to adjust the height of gas tank to make the gun barrel match the position of the bars.

In order to improve the system, the friction between the bars and their supports needs to be minimized and the accuracy of the alignment bars needs to be improved. To accomplish this, the bar support device needs to be fixed to the H-beam base.

2.2 Improvements

2.2.1 Increasing striker bar velocity

The original 1-inch diameter bars with 80-inch length have a substantial weight; its weight decreases the acceleration of the bars while testing. To increase the bars' velocity at current releasing conditions and reduce energy loss, 0.5-inch diameter bars are used to replace the 1-inch diameter bars. The length of the striker bar is 12-inches and the length of the incident and transmission bars are 78-inches.

2.2.2 Reducing friction

The four metal linear bearings that are used to support the bars in this system can reduce much of the friction when the bars are moving at a high velocity. However, it is hard to reach zero-friction status by using metal linear bearings. With the size change of the bars, air bearings become a better choice to support the bars. Continuous air from the connected compressed air system will cause the bars to float, thereby minimizing the friction.

The air bearings involve no contact between themselves and the bars, which provides better performance and minimizes the friction compared to the metal linear bearings. For air bearing functionality, it needs to be connected to a built-in compressed air system. Figure 2-3 shows the air bearing used for 0.5-inch diameter bars in the SHPB system and the compressed air system.

(a)

(b)

Figure 2- 3: Air bearing and compressed air system.

(a) Air bearing for 0.5-inch diameter bars. (b) Compressed air system.

A filter regulator is used to connect the air bearings to the compressed air system so that continuous air can be provided. It has a gauge that shows the real-time pressure and it will filter the water in the compressed air before it moves to the air bearing. 6-mm tubes and push-into connectors are used to connect six air bearings to the filter regulator. When the pressure of the compressed air reaches around 40-psi, the bars are able to move freely with zero friction in the air bearings.

2.2.3 Increasing alignment precision

To obtain an easily adjustable system, the 2-axis manual linear sliding platform in Figure 2-4 was selected as a part of the support apparatus for the air bearings. This platform can provide enough moving range in the X and Z axes, has good stability, and also has a micrometer drive mode for extra accuracy. By using this kind of platform, it will be easier to check the alignment for the bars, which makes the system much more flexible.

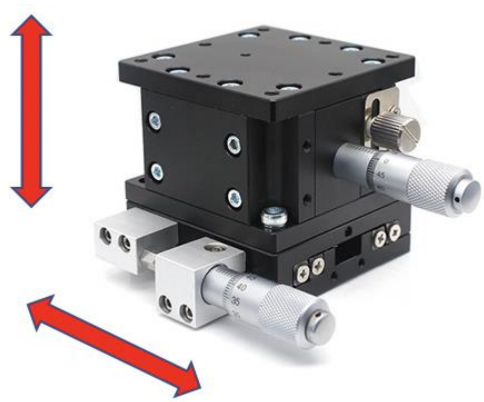
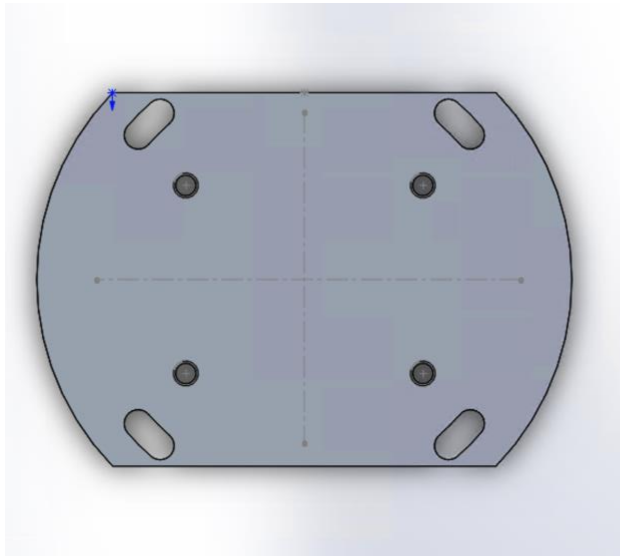


Figure 2- 4: 2-axis manual linear sliding platform.

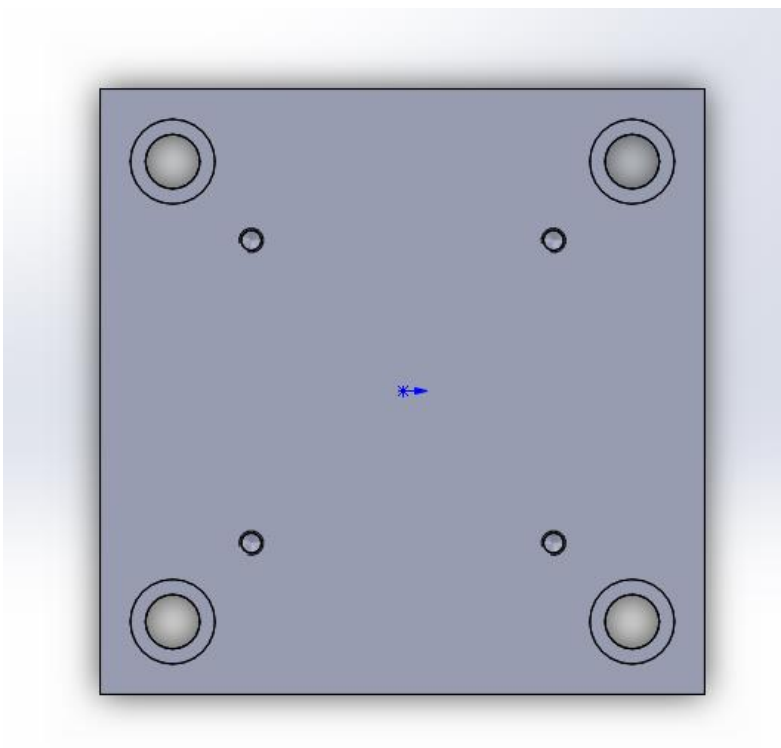
To improve the system's stability and make it adjustable, there are two parts that need to be altered: the gas tank support table and the bar support apparatus. The first step to change the gas tank alignment is to measure out the centerline of the support table, which helps define the exact position to place the gas tank. Once aligned, bolts are used to fix the gas tank to the support table. Additionally, four leveling mounts were welded to the four feet of the support table, making the height of the table changeable by rotating the nut of the leveling mounts.

Next, the bar support apparatus needs to be fixed to the T-slot rail, which is placed on the H-beam. With the change to bearing selection, the support apparatus that connects the bearings and the T-slot rail would need to be re-designed. Each new support apparatus consists of a sliding platform and two metal plates. In total six new apparatuses were created, in each support apparatus, a metal top plate was used to fix the air bearing to the sliding platform and a metal bottom plate was used to fix the platform to the T-slot rail, both 3D models are shown in Figure 2-5, with the design drawings shows in Figure 2-6. Each metal top plate has four short, curved slots that allow the air bearing to rotate for better alignment.

The new support apparatus for bars is assembled with the machined metal steels and shown in Figure 2-7. This apparatus can provide three degrees of freedom for adjusting the alignment in the SHPB system which also makes the process of the alignment checking easier and more efficient.

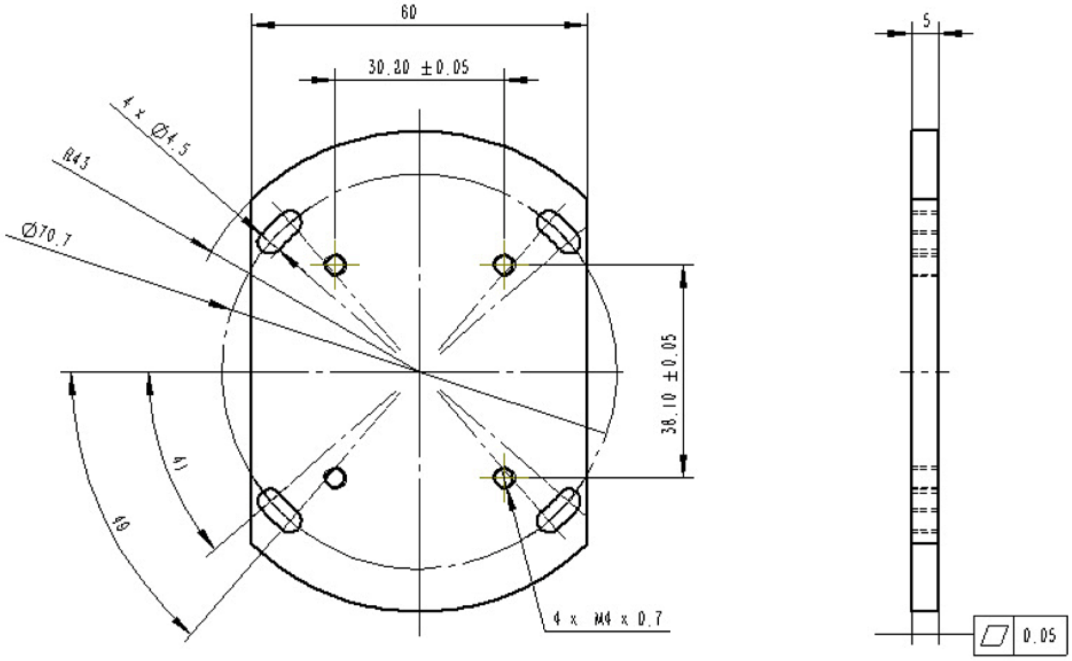


(a) Metal top plate.

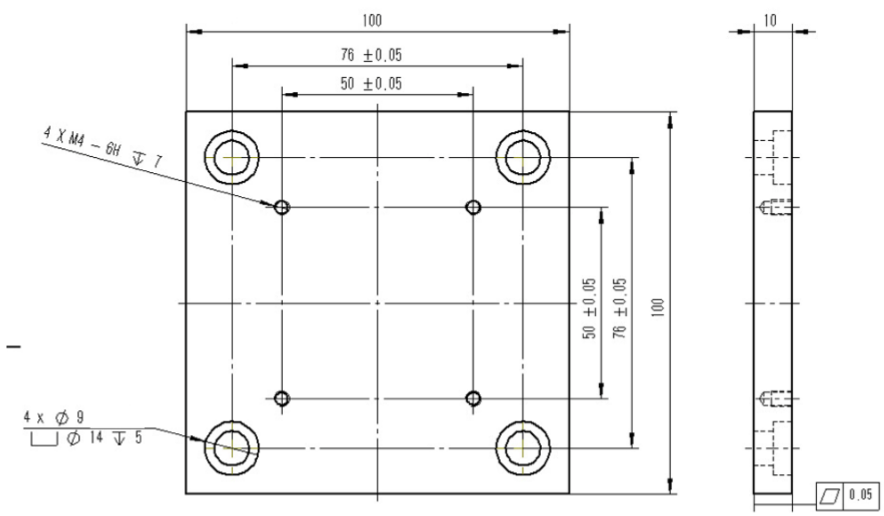


(b) Metal bottom plate.

Figure 2- 5: Metal plate designs for bar support apparatus.



(a) Metal top plate.



(b) Metal bottom plate.

Figure 2- 6: Design drawings for metal plates.

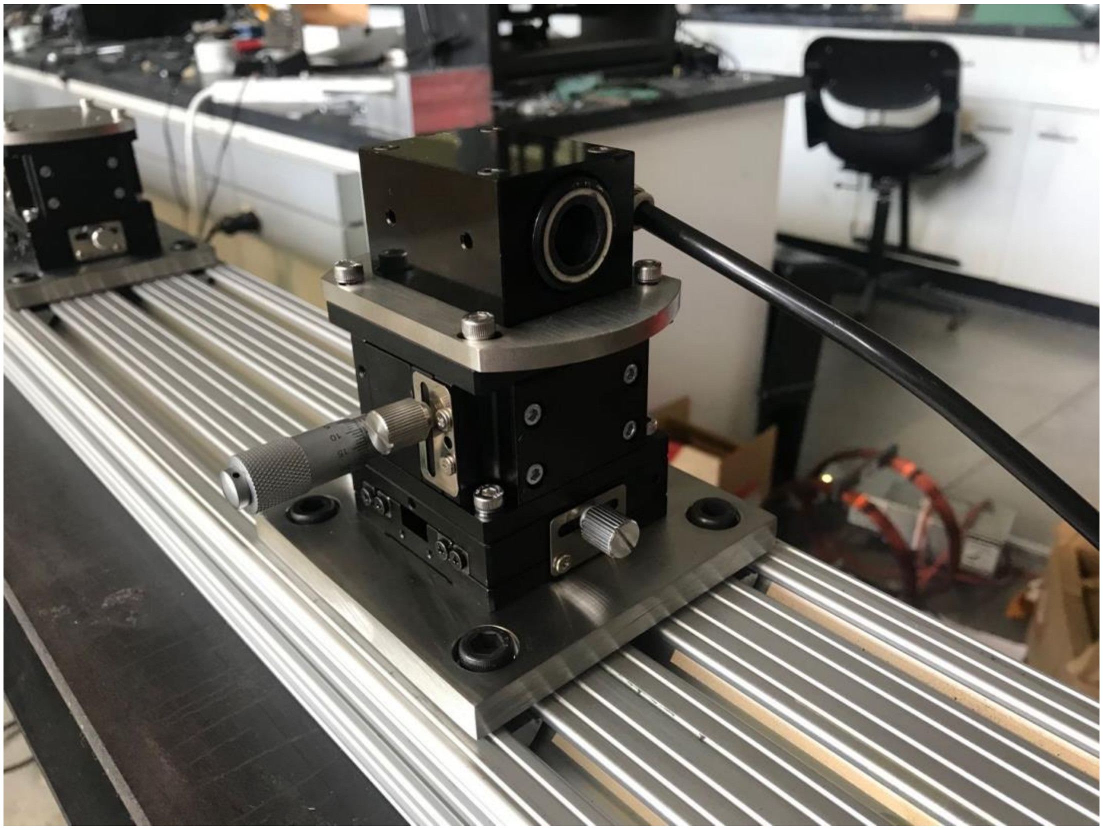


Figure 2- 7: Assembled new support apparatus for bar mounting.

2.2.4 Verifying the improvements with compression test

Figure 2-8 shows the current setup of the SHPB compression system after rebuild. The strain gauge employed in the system for signal measuring has a width of 6-mm, a resistance of 350-ohm, and a gauge factor of 2.12. To identify the performance of the rebuilt SHPB compression system, non-sample compression tests were conducted on it. The test results of the stress wave signal recorded by the oscilloscope is shown in Figure 2-9(a), it shows a standard square pulse signal with no reflected wave. Figure 2-9(b) is the stress wave signal obtained by using the original SHPB system before rebuild, the signal dispersion problem is solved in the rebuilt system. It can be concluded that the system performed well after improvements were made, is repeatable for conducting compression tests, and reaches excellent performance.

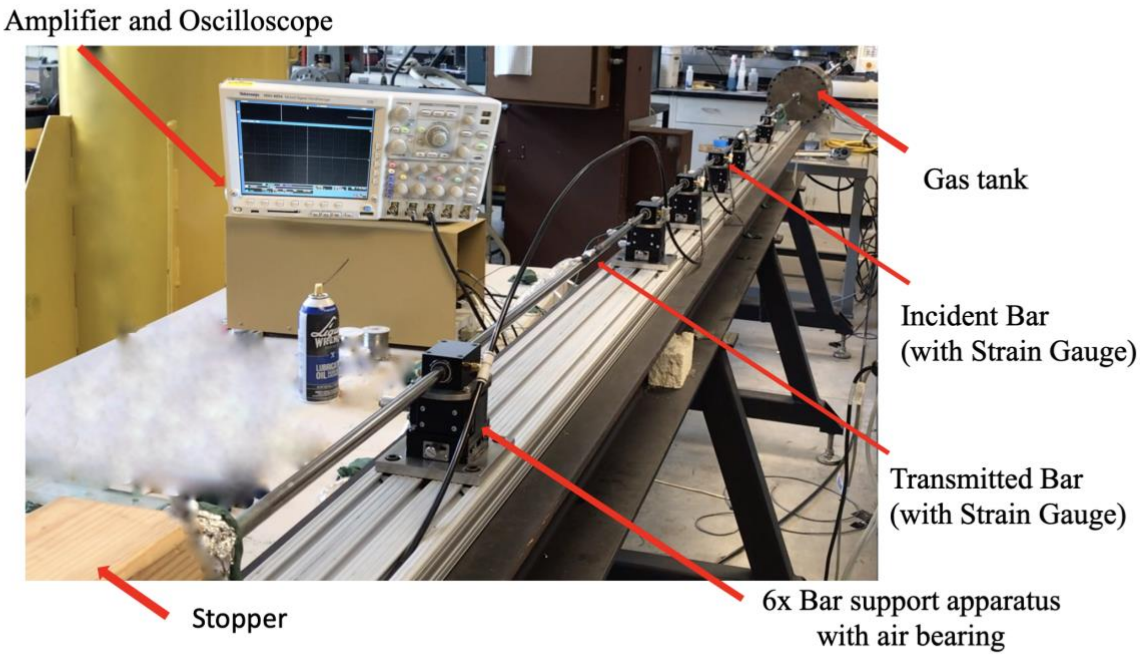
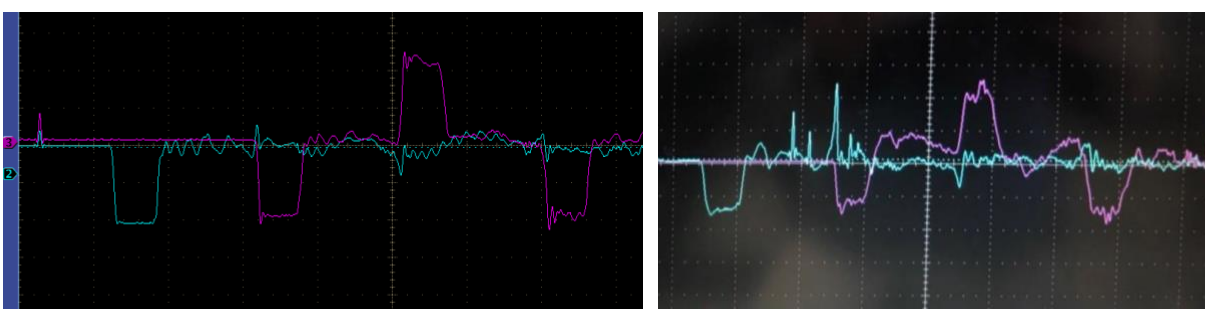


Figure 2- 8: Rebuilt NIU SHPB compression system.



(a) (b)

Figure 2- 9: Test results of compression test.

(a) After system rebuild. (b) Before system rebuild.

CHAPTER 3. TENSILE TEST WITH SPLIT-HOPKINSON COMPRESSION BAR

3.1 Converting from compression to tensile system

Building a SHPB tension system is helpful to explore tensile properties of materials at high strain rates for further research at NIU. A new device has to be designed if the main test rig of the NIU SHPB compression system has to be maintained for building a tension system with minor changes. Some methods were created to conduct tensile tests with a split-Hopkinson compression bar. They were built by adding a collar or placing an external device between the incident bar and transmitted bar. Due to the limitation of the bar diameter used in the NIU SHPB compression system, it is unreal to conduct the tensile tests by using those typical methods. Therefore, it is necessary to design a special device to convert the compression system into a tension system based on the current setup.

3.1.1 Design of testing specimen

A tension test with a dog-bone shaped specimen provides well-defined boundary conditions and a gauge part that is convenient for the determination of the uniaxial response of the material [8]. The specimen designed for conducting tensile tests with the NIU SHPB system is shown in Figure 3-1. The specimen is in the shape of a dog bone, and features three holes on each side allowing it to be secured with bolts. 304 stainless steel foils with 0.1-mm thickness were selected as the specimen material. The thickness of the specimen is very thin, so accurate machining was required. During machining the stainless steel foils must be sandwiched between two aluminum plates and fixed so that the water jet can cut out the shape and holes of the specimen without curling.

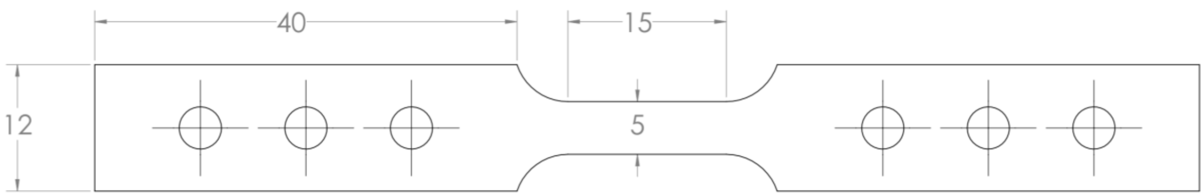
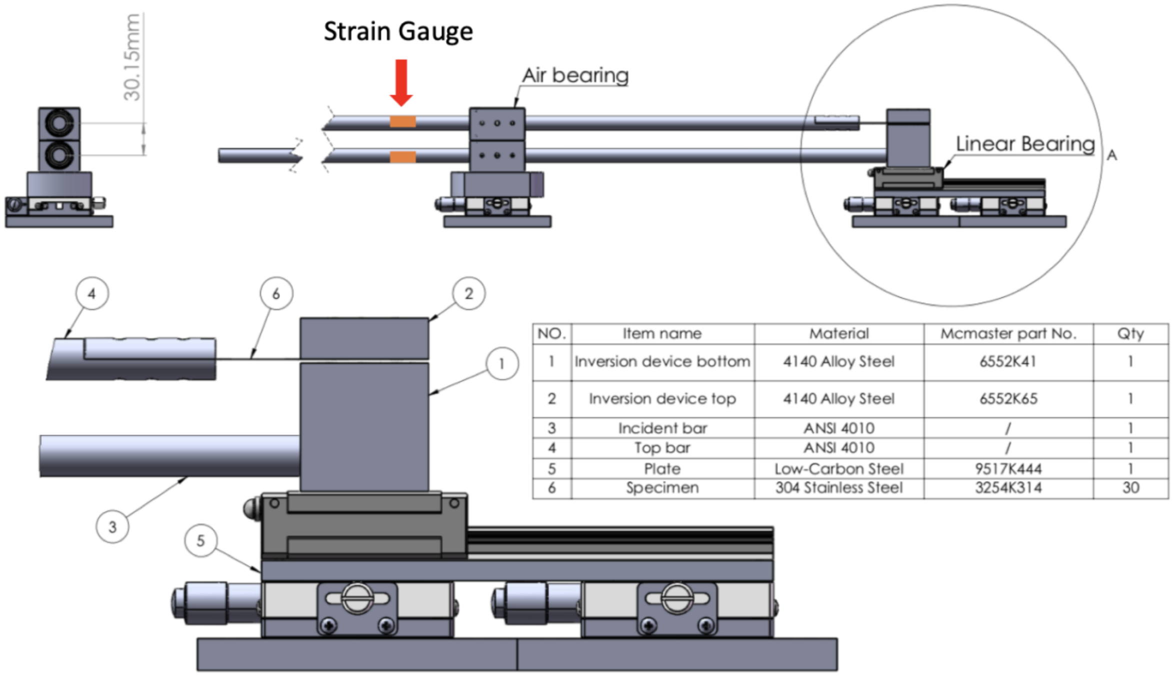


Figure 3- 1: Design drawing for dog-bone specimen (Unit:mm).

3.1.2 Design of load-inversion device

A load-inversion device(LID) is designed to work with the current devices from the SHPB compression system and converts the compression pulse generated to a tensile pulse. The incident bar is connected to the LID and the LID connects to one side of the specimen. The other side of the specimen is fixed to the output bar. When performing a tensile test in this system, a compression wave is created in the incident bar when the striker bar hits it. The compression wave transfers to the LID and is converted into a tension wave which is applied to the specimen. Figure 3-1 shows the first designed version of the LID mechanism. This version was updated based on troubleshooting, which resulted in the final version, the details of these improvements are described in section 3.3.

With the use of the LID, most of the original setup from the SHPB compression system can be preserved. To convert the SHPB compression system to SHPB tension system, one more air bearing was mounted to each bearing holding the incident bar in the bar support apparatus to support the stacked output bar. The support design for the LID used two sliding platforms for adjusting its alignment. A linear bearing supports the LID which decreases its moving friction in testing. The guide rail of the linear bearing is placed on the sliding platform with a metal connection plate, Figure 3-3 is the design drawing of the connection plate. Two strain gauges are attached to the incident bar and output bar, respectively, to measure the generated compression wave and converted tension wave.



NO.	Item name	Material	Mcmaster part No.	Qty
1	Inversion device bottom	4140 Alloy Steel	6552K41	1
2	Inversion device top	4140 Alloy Steel	6552K65	1
3	Incident bar	ANSI 4010	/	1
4	Top bar	ANSI 4010	/	1
5	Plate	Low-Carbon Steel	9517K444	1
6	Specimen	304 Stainless Steel	3254K314	30

Figure 3- 2: Mechanism drawing of the first version LID.

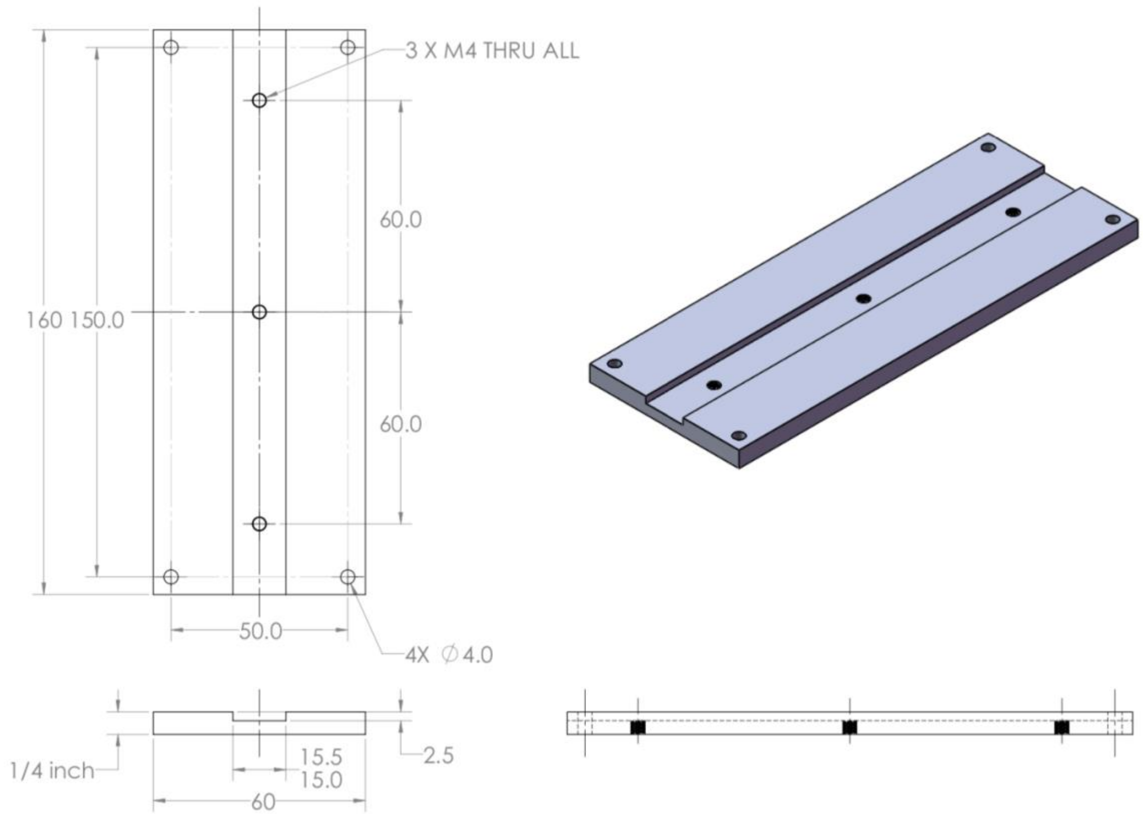


Figure 3- 3: Design drawing of the metal connection plate.

3.2 Testing the tension system with the LID – shortcomings and troubleshooting

A change was made before the start of machining the first version of the LID, the updated design drawing is shown in Figure 3-4, which can have the specimen placed on the side instead of the top. This provides direct observation of the high-speed camera, allowing for focusing on the specimen's gauge section. Figure 3-5(a) is the setup of the first version LID with specimen installed, and 3-5(b) is a tested specimen. This proves that the SHPB system can handle tensile tests with the LID.

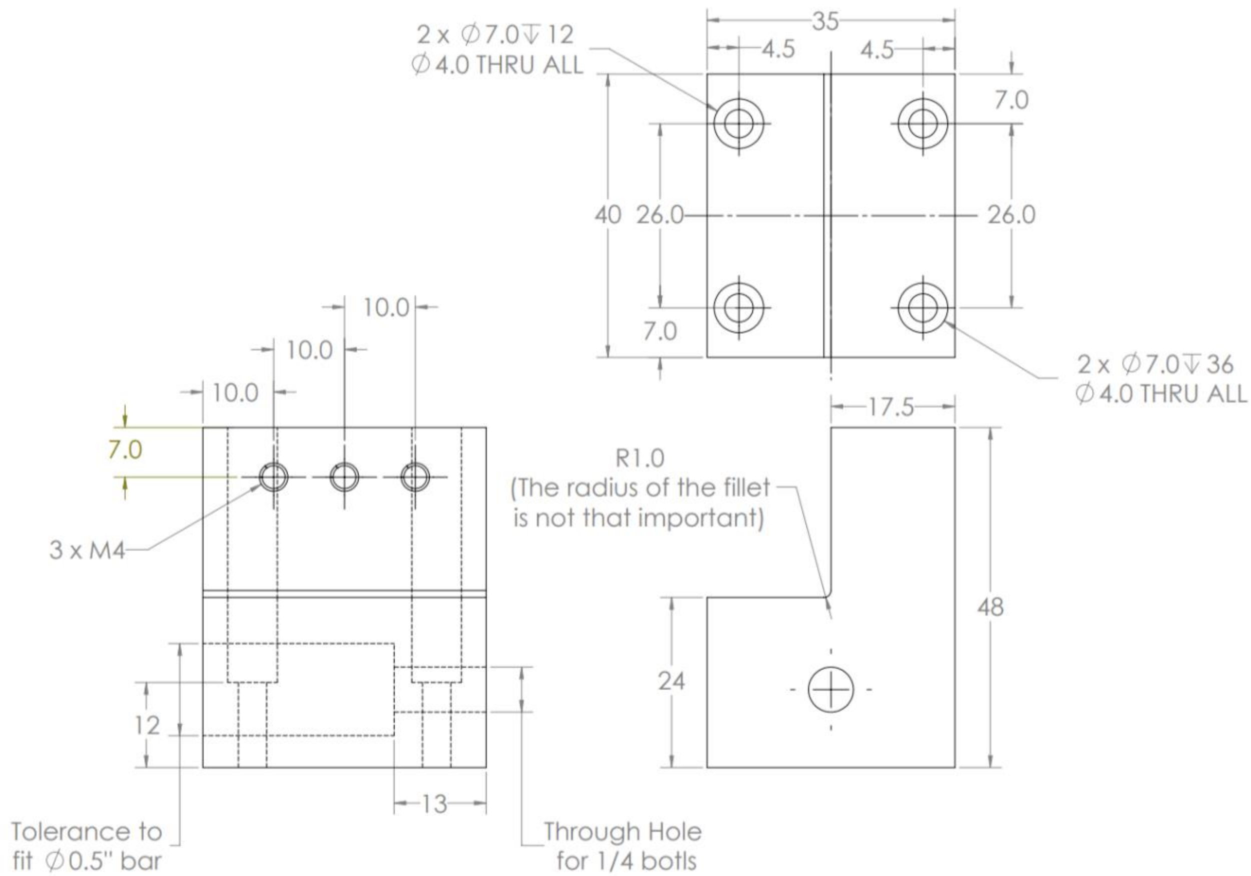
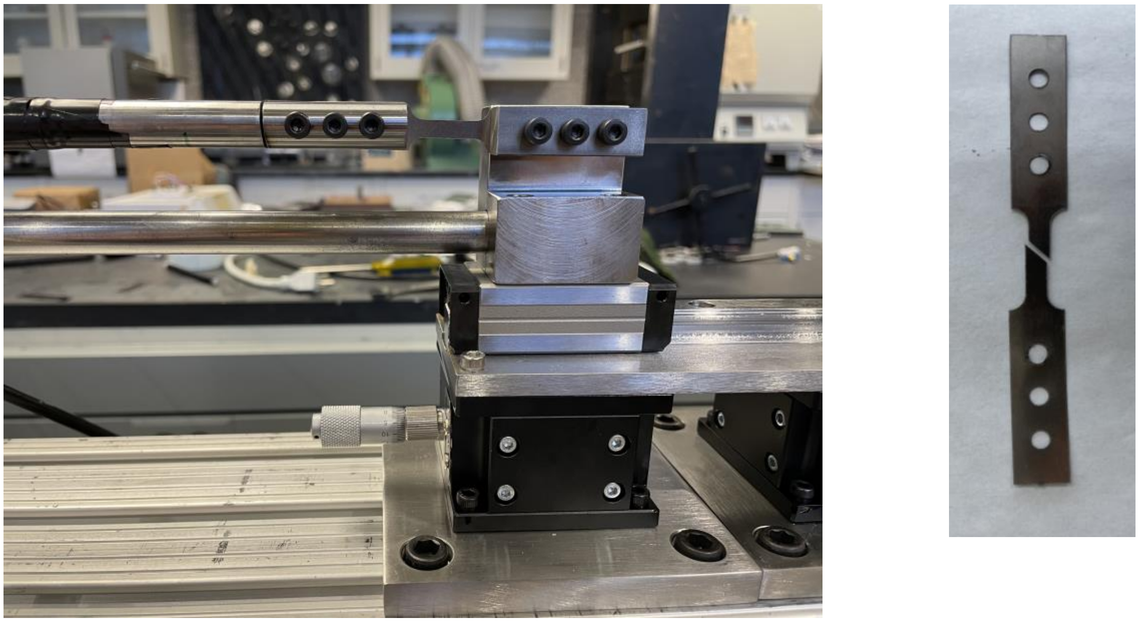


Figure 3- 4: Updated design drawing of the LID.



(a) (b)

Figure 3- 5: First version of LID.

(a) LID setup with specimen. (b) Tested specimen.

Although the system can complete the tensile test using the LID, it has some shortcomings that cannot be neglected. Four bolts were used to attach the LID to the linear bearing, in testing, these bolts failed to withstand the shear forces generated in the LID and part of them were left behind in the screw holes, is shown is Figure 3-6. Meanwhile, the recorded testing signal was bad and could not be used for further signal processing.

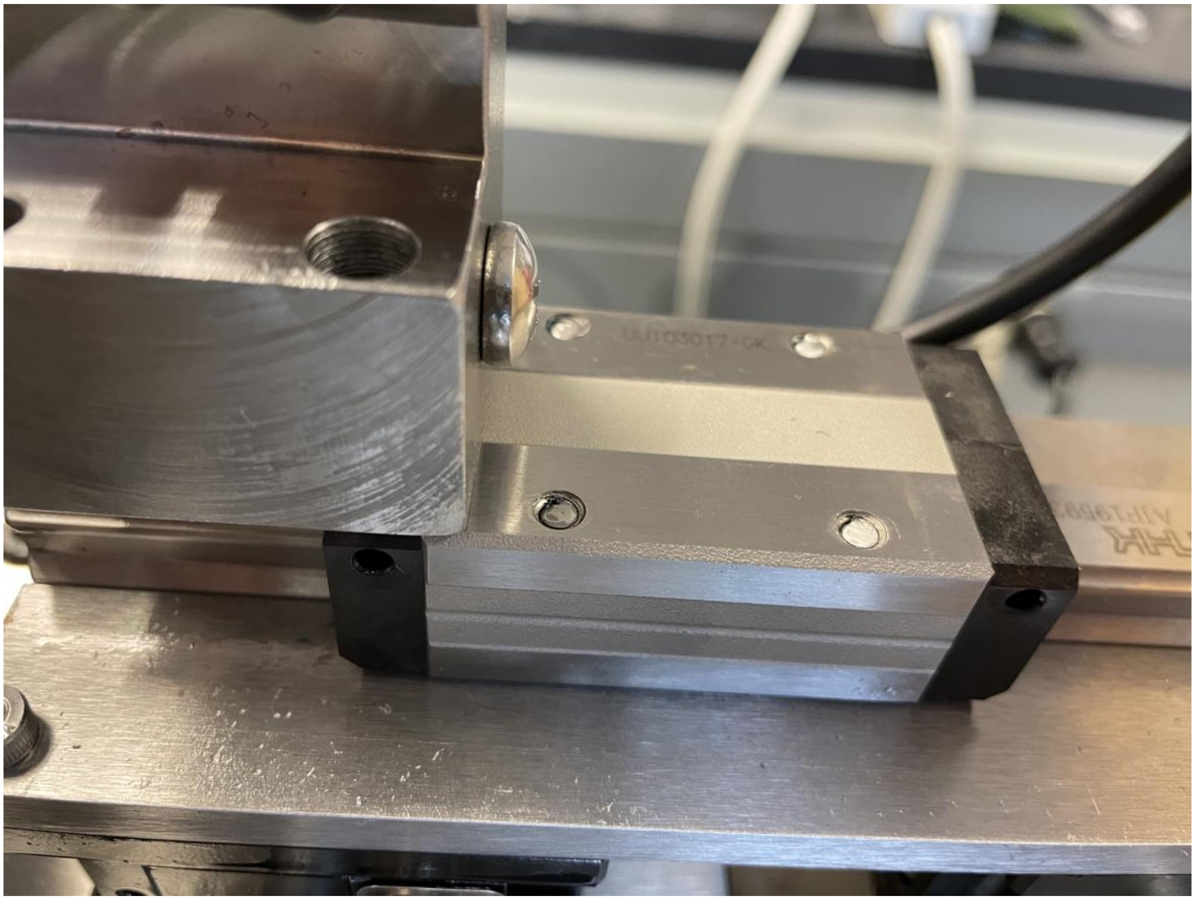


Figure 3- 6: Failed screws in linearing bearing.

3.3 Improving the tension system

Signal measurement is critical for tensile testing, therefore, a new method to set up the SHPB tension system was defined as shown in Figure 3-7. Two input bars and two output bars are applied to the new version of SHPB tension system. One input bar and one output bar is connected to the LID, and the LID provides as a function to convert the compression pulse from the input bar to a tensile pulse and transfer it to the output bar. Both output bars have strain gauges installed, and by fixing the specimen between two output bars, the stress on the specimen can be calculated with the measured wave propagation signals. A high-speed camera is set up to focus on the surface of specimen, pictures will be taken to record specimen deformation history. The strain history of the specimen is calculated by using DIC with the captured pictures.

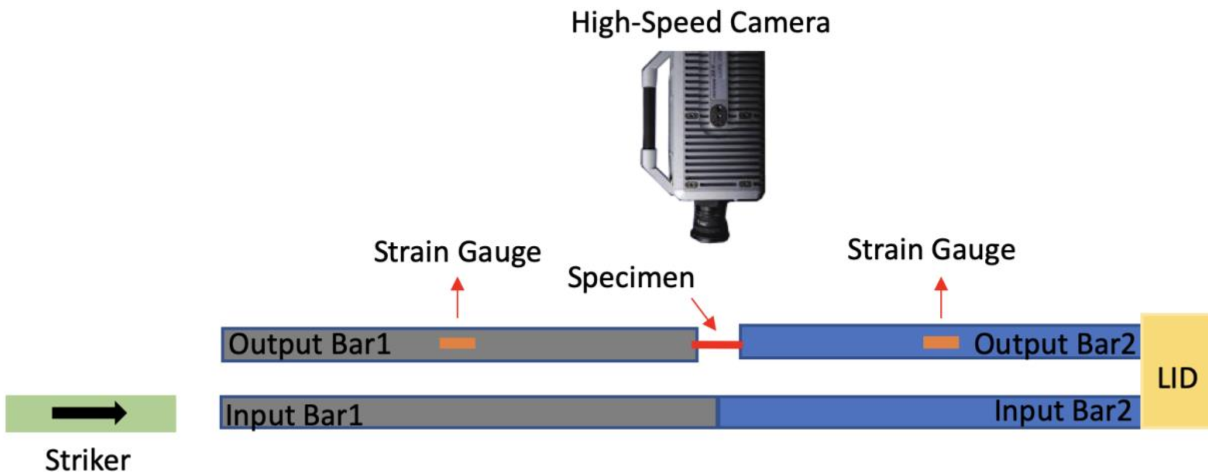


Figure 3- 7: Improved design concept of tension system.

Compared to the previous version of the tensile test, an additional output bar was added in the new designed tension system. The first used connection between the previously designed LID and the output bar is shown in Figure 3-8. At the right end of the output bar, its cross-section was cut in half and three holes were drilled, therefore, three bolts were able to secure that bar to the LID. The other side of this output bar was attached to one side of the specimen so the tension wave passes through it. However, the bolts connecting the output bar to the LID broke due to the shearing force, this is presented in Figure 3-9. With the newly defined design concept of the tension system, more improvements would need to apply in the system and the mechanism of the LID need to be updated, and most important thing is to avoid the generation of shearing force in the LID.

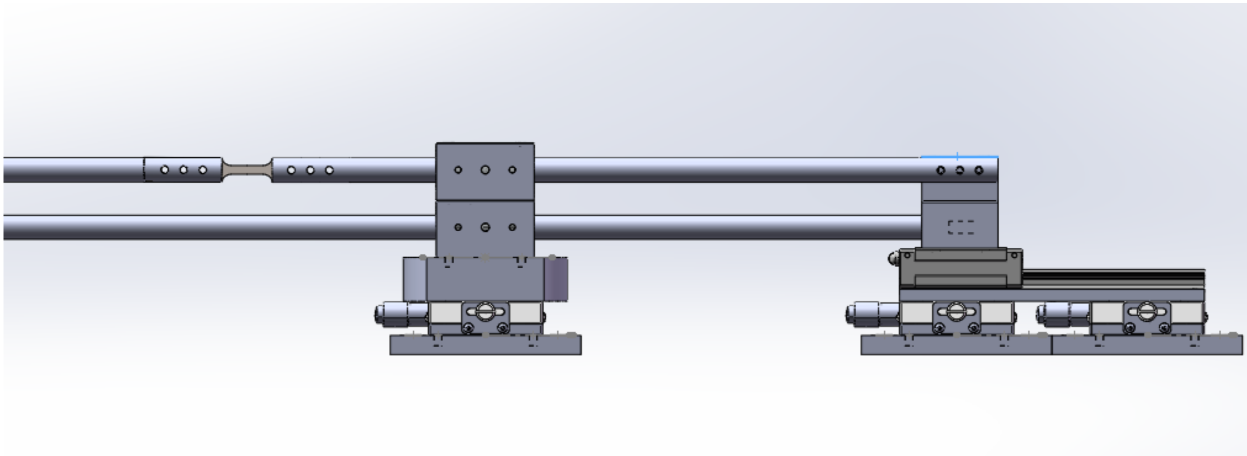


Figure 3- 8: First used connection between LID and output bar

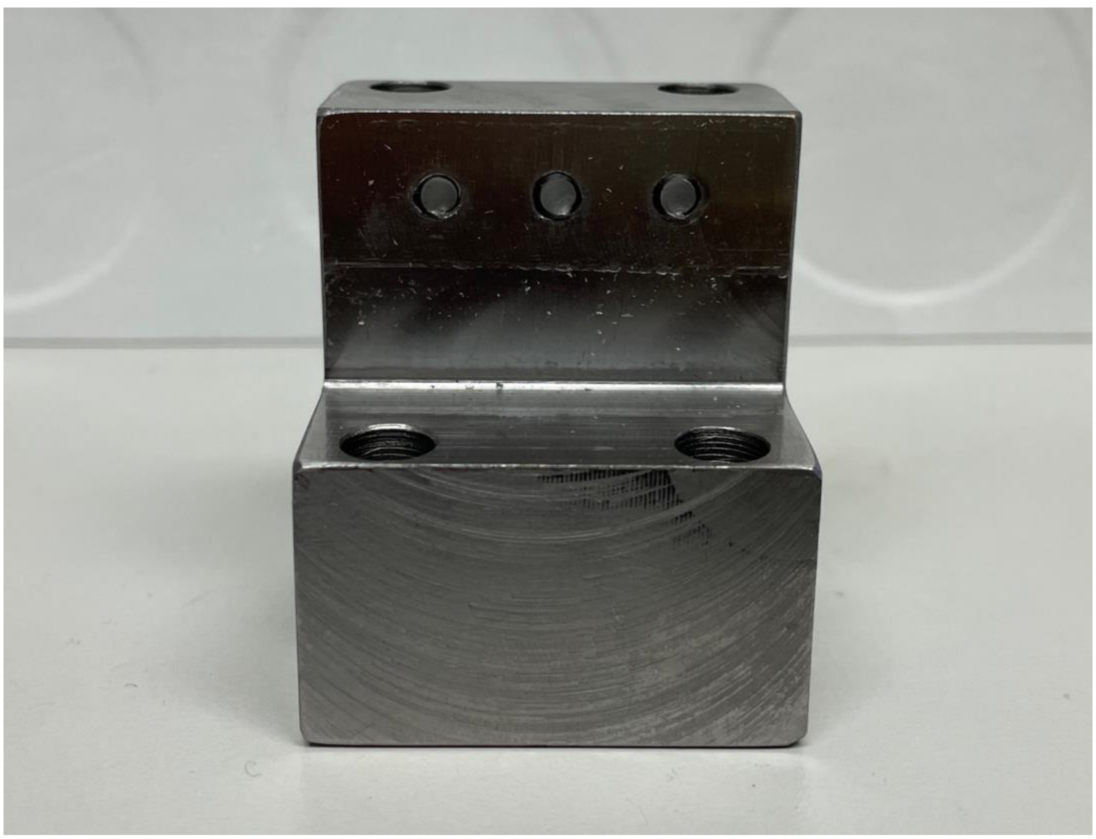


Figure 3- 9: Failed screws in the LID.

After analyzing and summarizing all the problems in the SHPB tension system and the LID, the solution to improve the system was able to be determined. In the SHPB system, a stopper is usually placed at the end of the bar component system to absorb additional testing energy. Clay was used as part of the stopper to absorb the extra energy in the NIU lab, however, the clay was not absorbing the energy from the LID but reflected the energy back created a counter impact force, which generated the shear force and resulted the bolts failed. Instead, a shock absorber with the 5-inch stroke length was chosen and placed at the end side of the system as a stopper to decelerate the load applied to the LID. Meanwhile, the guide rail of the linear bearing was replaced by one with a longer length to provide more moving distance for the LID.

The connection between the output bar and the LID has been improved to an indirect connection, so the tension wave can be transmitted without effect by the shearing force. This improved indirect connection requires the mechanism of LID to be redesigned, on which a through-hole was drilled to allow the output bar to move freely through it. An component was machined to attach to the right end of the output bar, which would be hit by the moving LID, and applies direct tension on the specimen. Moreover, in order to obtain a better signal, all bars used in the system are updated to longer length to avoid signal overlap. Figure 3-10 shows the layout of the updated NIU SHPB tension system.

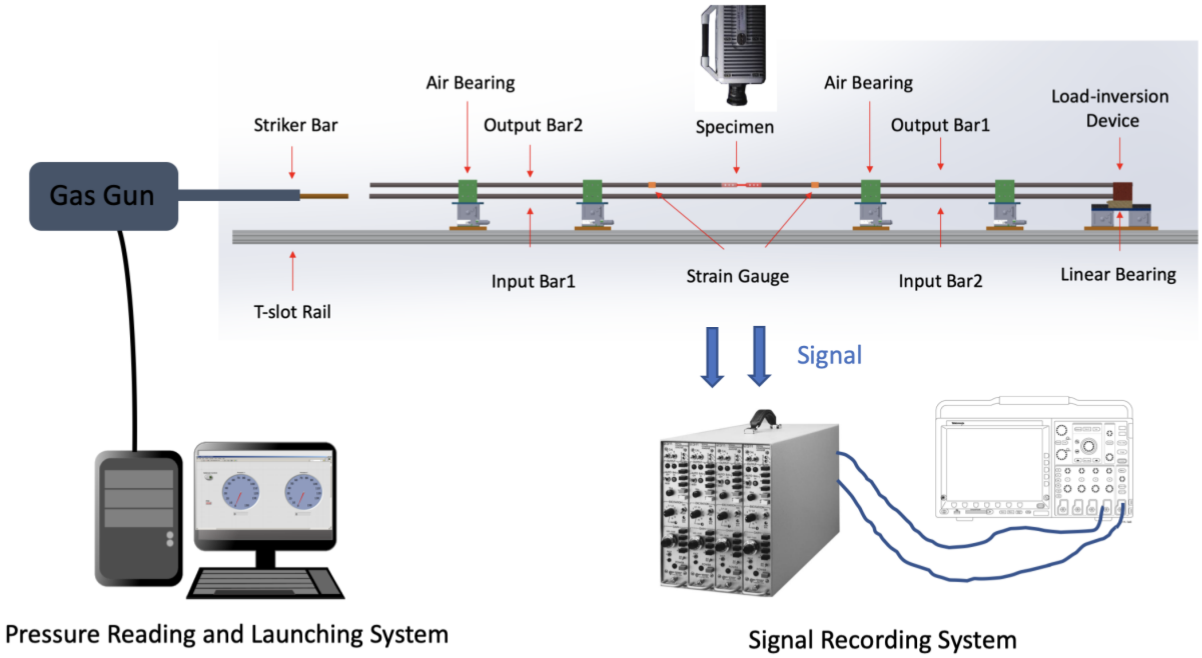


Figure 3- 10: Layout of NIU SHPB tension system.

3.4 Tension system installation and specimen setup

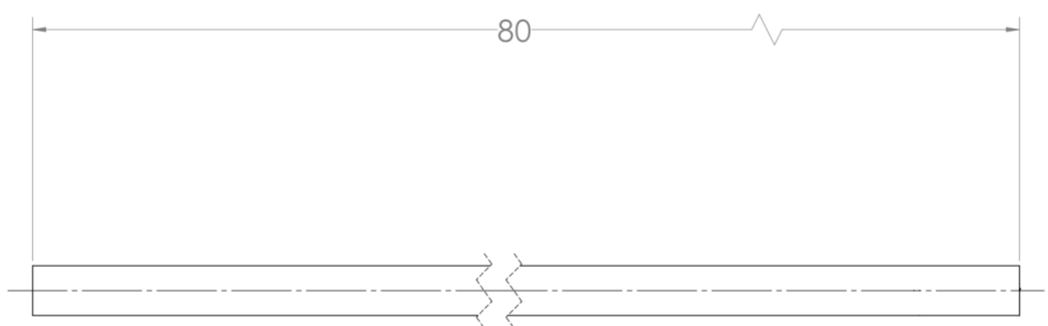
The updated SHPB tension system is set up in the lab as shown in Figure 3-11. In this system, improved LID and output bar connection is used. In the process of converting the rebuild compression system to a tension system, the following devices were added: two output bars, four air bearings, the LID, and its support device.

Figure 3- 11: NIU SHPB tension system in the lab.

The bar components of the tension system consists of one striker bar, two input bars, and two output bars. The striker, the incident, and transmissison bars used in the compression system were kept as striker bar, input bar 1 and input bar 2 in the tension system, respectively. Two output bars were added and placed above the input bars. The following Table 3.1 shows the details of the bars used in the tension system. All bars were case hardened for high hardness to prevent deformation in testing. The detailed information of the design mechanism of all the bars is shown in Figure 3-12, they were machined according to these drawings, as specimen fixtures and connectors connected to the LID.

Table 3.1: Geometry and Material Properties of the Bars

Part	Length	Diameter	Material	Young's Modulus	Density
Striker	12''	0.5''	ANSI 4010	205 GPa	7850 Kg/m^3
Input Bar1	78''	0.5''	ANSI 4010	205 GPa	7850 Kg/m^3
Input Bar 2	78''	0.5''	ANSI 4010	205 GPa	7850 Kg/m^3
Output Bar 1	80''	0.5''	1566 Carbon Steel	200 GPa	7800 Kg/m^3
Output Bar 2	80''	0.5''	1566 Carbon Steel	200 GPa	7800 Kg/m^3



(a) Input bar 1.

Figure 3- 12: Design drawing of the bars(Unit is mm if not specified).
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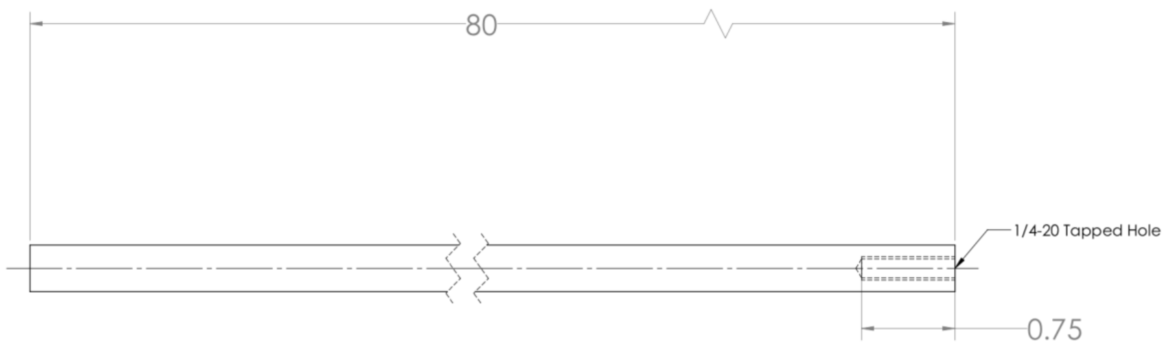
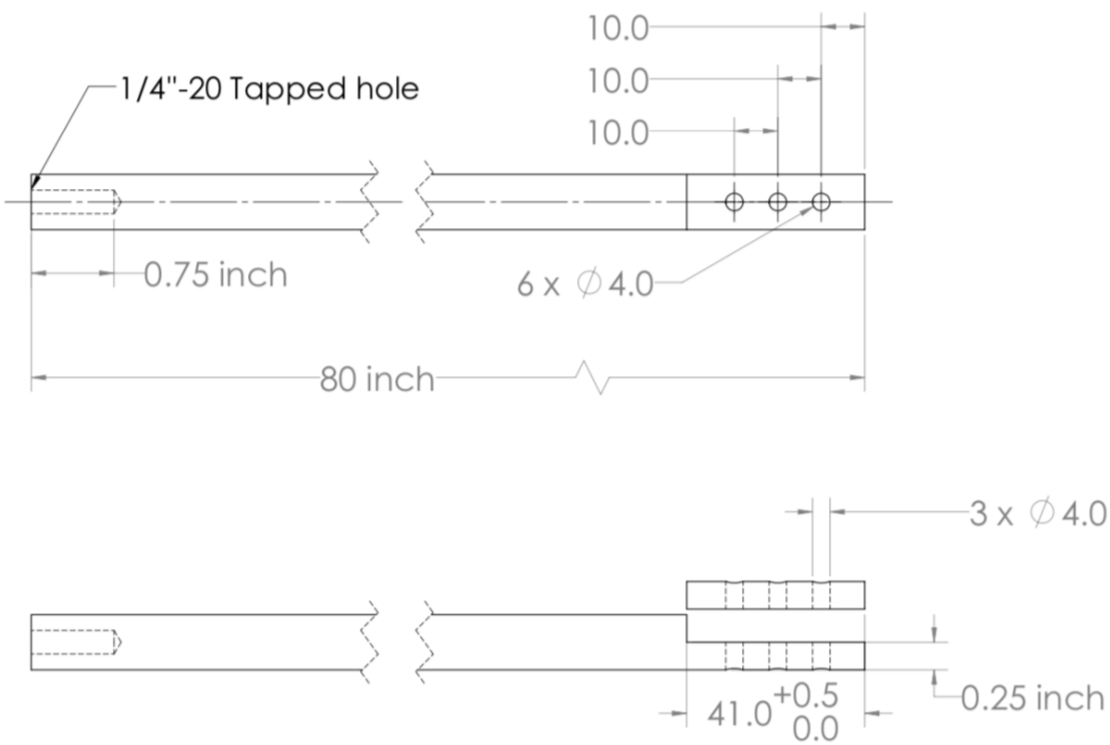
Figure 3 -12 continued.



(b) Intput bar 2.



(c) Output bar 1.

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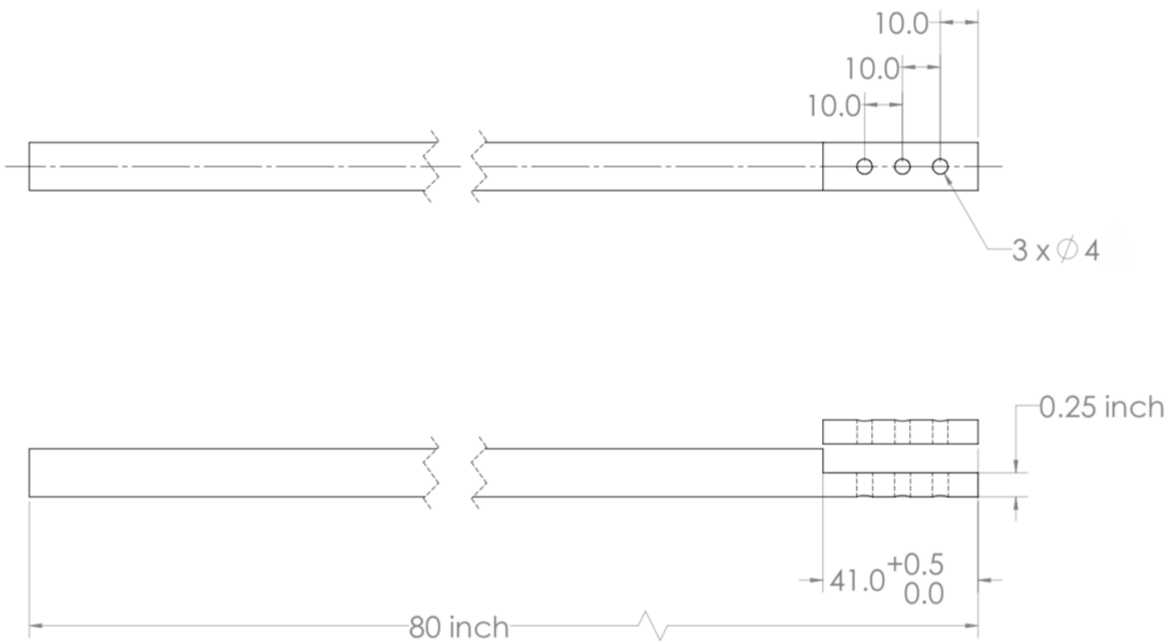
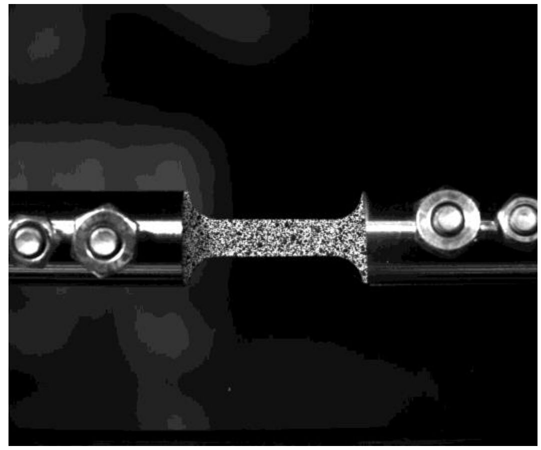
Figure 3 -12 continued.



(d) Output bar 2.

Before the specimen is installed to the output bars, random speckle partterns was applied to the surface using black and white acrylic paints. After the paint dried, the specimen could be installed for testing. In Figure 3-13(a), the specimen was fixed to the output bars, and the high-speed camera was placed near the specimen for taking pictures. The camera was connected to the computer so that the pictures could be imported for analysis. Two work lights were used with the high-speed camera to provide a brighter view when taking photos. The camera was set to focus on the gauge section of specimen. Figure 3-13(b) is a captured picture from the camera.



(a) (b)

Figure 3- 13: High-speed camera setup.

(a) High-speed camera and lights focused on the specimen. (b) Picture of the specimen from the high-speed camera.

3.5 Conduct tensile test

With the specimen installed in the SHPB tension system, tensile tests are able to be conducted using the following procedures:

1. Check the alignment of the gas tank and bar system to ensure that all the bars are parallel and centered. It is necessary to place the two input bars as abutted as possible without mismatch.
2. Run the air compression system to provide compressed air for the air bearings. Check whether there is gas leakage at the connection joints. The pressure value should be set from 40 to 50 psi.
3. Insert the striker bar into the gun barrel with a stick.

4. Check the capturing view of the high-speed camera and adjust its focus and brightness as necessary. Make sure the painted patterns on specimen are clearly visible in the view.
5. Flip the AUTO BAL switch down on the amplifier, the Wheatstone bridge circuit will adjust its balance automatically. If the panel still shows the circuit is unbalanced, a TRIM bottom should be used to adjust the circuit manually.
6. Fill the gas tank to the target pressure.
7. Confirm the recording scale on the oscilloscope and set it to automatic trigger mode, which allows it to record the signal automatically once the system is launched.
8. Make sure that no one is near the test area, then launch the system.

CHAPTER 4. RESULTS AND ANALYSIS OF TENSILE TEST

4.1 Experimental output

The high strain rate tensile test was conducted using the NIU SHPB tension system and Figure 4-1 shows the tested specimen. During the test, the specimen cracked at a 45 degrees angle in the middle of its gauge section. The voltage history signal recorded by the oscilloscope showed a square-shaped incident wave, transmitted wave and reflected wave, which is clear to read and analyze. Figure 4-2 shows the fisrt waveform of the measured incident wave, reflected wave and transmitted wave in the test, respectively. The obtained voltage signal measurement and images taken by the high-speed camera were later used for further analysis.

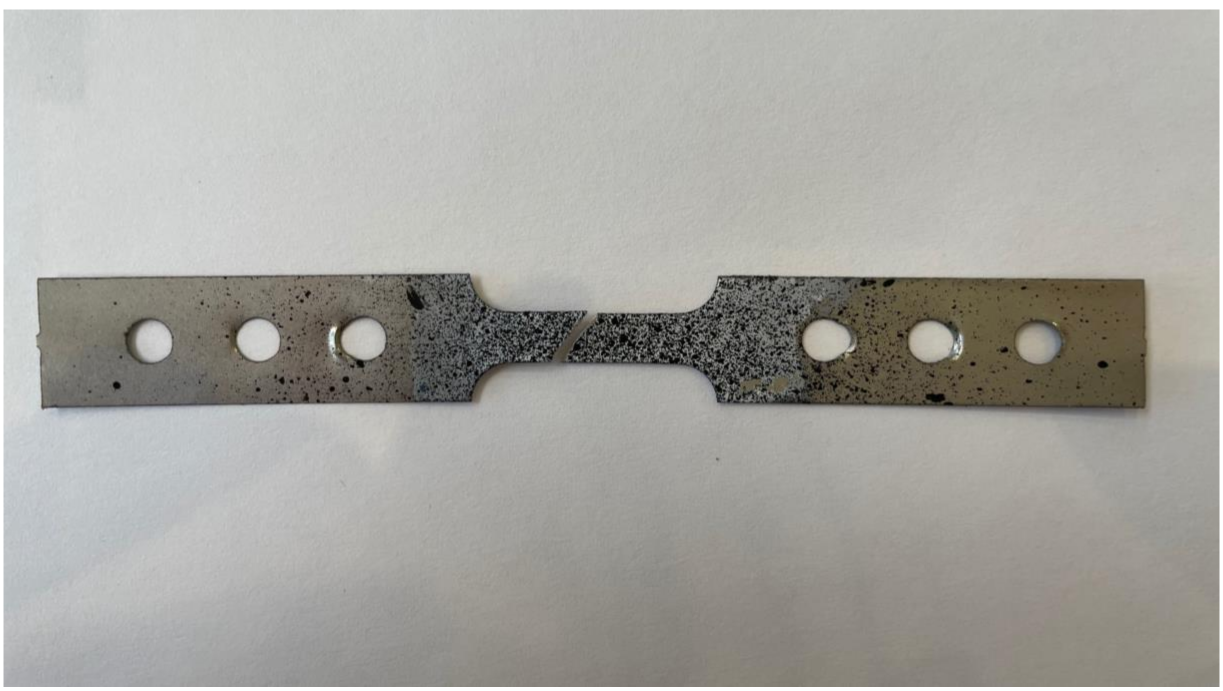


Figure 4- 1: Tested sample of tensile test.

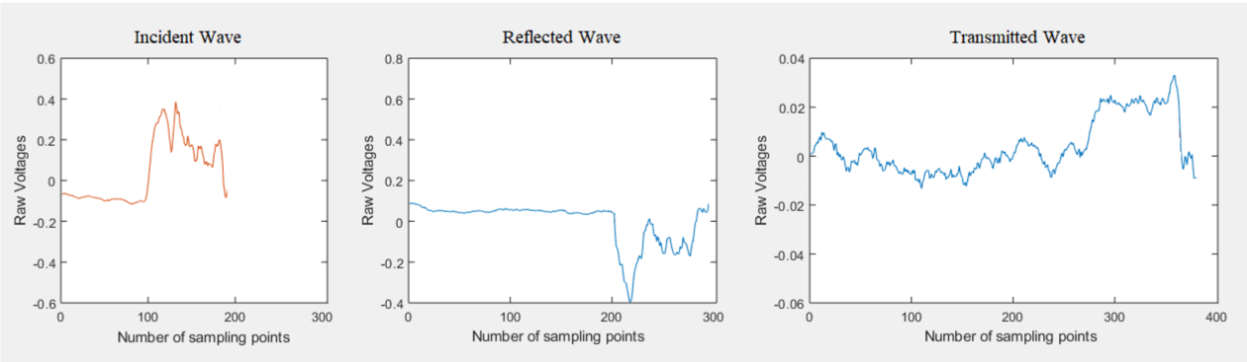
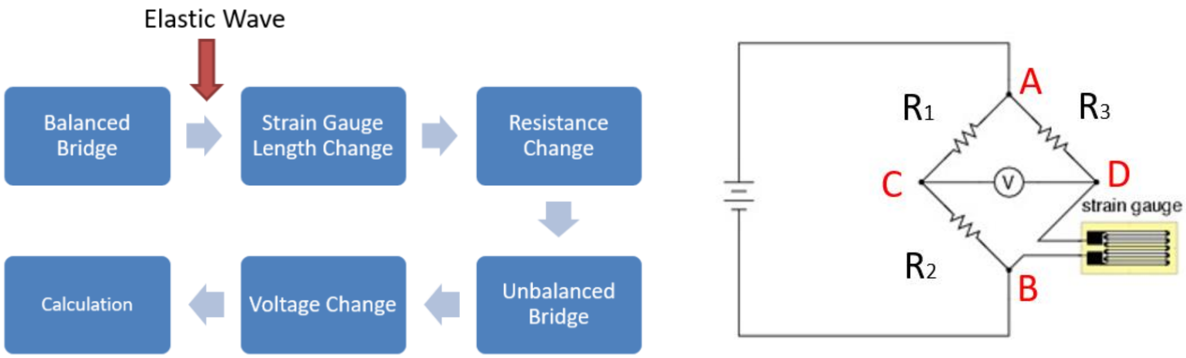


Figure 4- 2: First wave of voltage history recorded during the test.

4.2 Stress curve calculation

There are multiple ways to measure the stress and strain value on a specimen during testing. To monitor and acquire the strain history in tensile tests that conducting on the NIU SHPB tension system where two strain gauges were installed to the outputs bars. The working theory about the strain gauge measurement shows in Figure 4-3. The strain gauge normally has a defined value of resistance which changes in a small range when it suffers elongation, it connects to a Wheatstone bridge which can convert its resistance change to voltage change.

The amplifier with a built-in Wheatstone bridge is worked with the strain gauge in the system, which can amplify the voltage signals as output and conveying them to the oscilloscope. Equation (4.1) and equation (4.2) are used to calculate the strain change with the recorded voltage signal history by using the oscilloscope.



(a) (b)

Figure 4- 3: Working theory of strain gauge measurement [4].

(a) Strain gauge measurement. (b) Wheatstone bridge circuit.

$$V_{out} = V_{in}[\frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2}] \tag{4.1}$$

$$\text{GF} = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} \tag{4.2}$$

In equation (4.1), R_1, R_2 and R_3 present the resistance value of the resistors in the Wheatstone bridge circuit, R_g is the resistance value of the strain gauge. V_{in} and V_{out} are the input and output voltage in the Wheatstone circuit, respectively. As for equation (4.2), GF is the gauge factor that comes with the strain gauge, ε represents the value of strain.

With one set of voltage signal data from a real tensile test conducted on the current system, the voltage history recorded by strain gauge which shows in Figure 4-2 is able to be analyzed by using the split-Hopkinson Pressure Bar Graphical Analysis Tool [9]. This tool includes the needed equations for SHPB system to process graphical analysis with the imported data. The calculated history of incident strain, reflected strain and transmitted strain are shown in Figure 4-4.

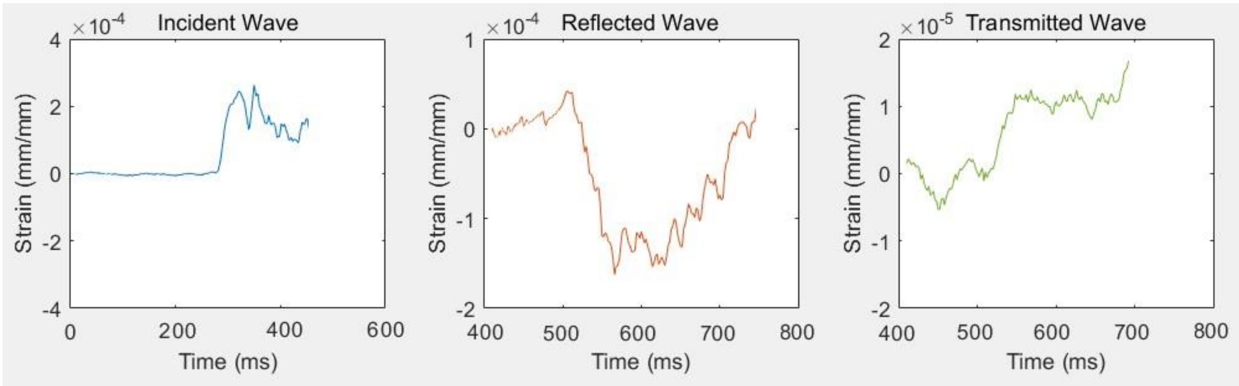


Figure 4- 4: Calculated strain history.

The two-wave calculation method is widely used for SHPB system to obtain the engineering strain rate, engineering strain, and engineering stress with equation (4.3), (4.4) and (4.5). In these three equations, c is the wave propagation velocity, which relates to the material of the bars, ε_r and ε_t are the reflected strain and transmitted strain calculated from the strain gauge outputs, the results of the calculated history of these strains are shown in Figure 4-4, E is Young's modulus of the bar material, A_B is the cross-section area of the bar and A_S is the cross-section area of the specimen.

$$\dot{\varepsilon}(t) = \frac{2c}{L_0}\varepsilon_r(t) \tag{4.3}$$

$$\varepsilon(t) = \frac{2c}{L_0}\int_0^t \varepsilon_r(t)\,dt \tag{4.4}$$

$$\sigma(\mathrm{t}) = \frac{A_B}{A_S}E\varepsilon_t(t) \tag{4.5}$$

The specimen stress in the tensile test is calculated with the equation (4.5), with the previous calculated transmitted strain history, the engineering stress history on the specimen is able to obtained and is shown in Figure 4-5.

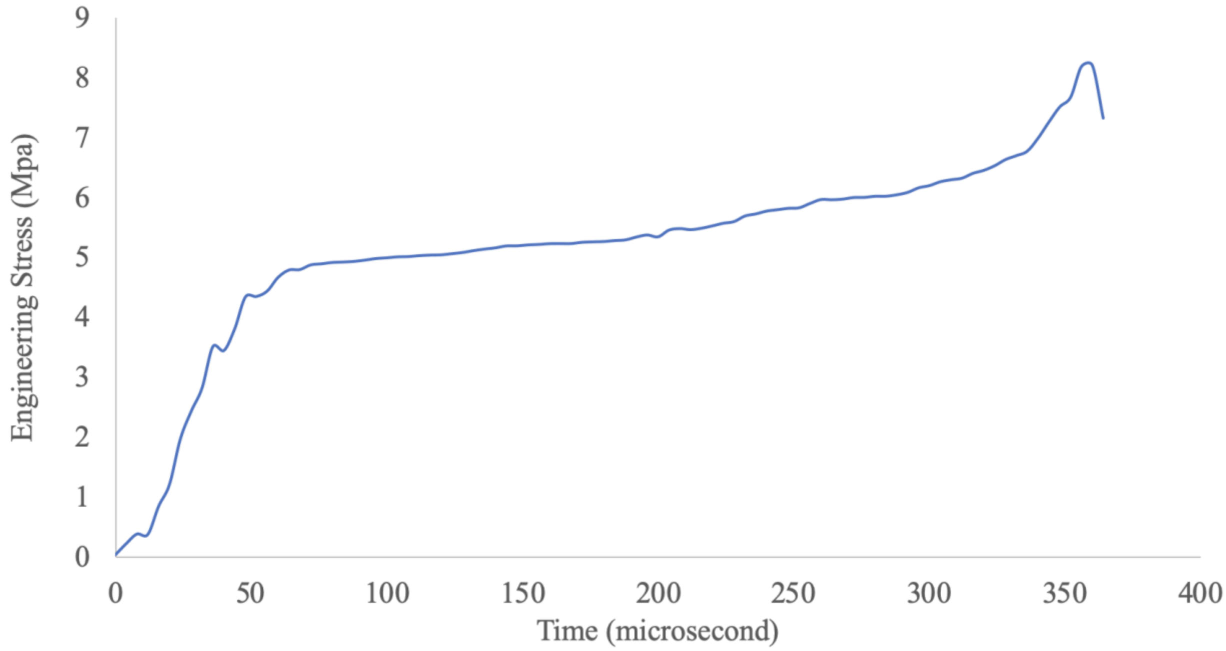


Figure 4- 5: Engineering stress history on the specimen.

4.3 Strain and displacement

As mentioned earlier, a DIC technique is employed in the tension system for processing strain history on the specimen gauge section. Ncorr [10] is a 2D digital image correlation MATLAB program which is used to deal with the pictures taken by the high-speed camera in the test and output the analysis results of displacement and strain. Its overall workflow shows in Figure 4-6. The preferred observation area in the images could be set in the set ROI step to calculate the displacements and strains on Nacorr.

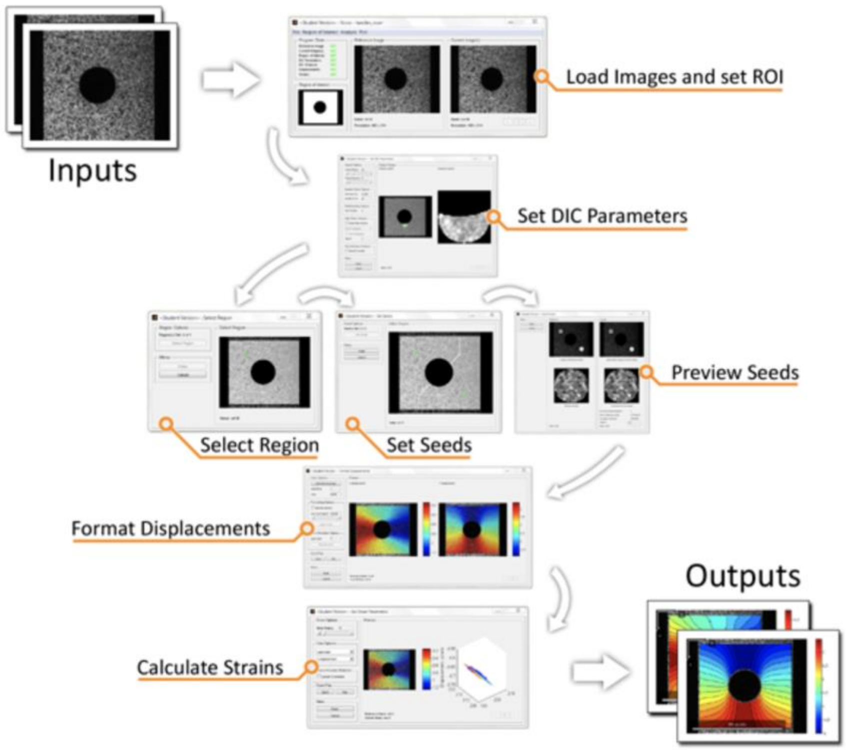
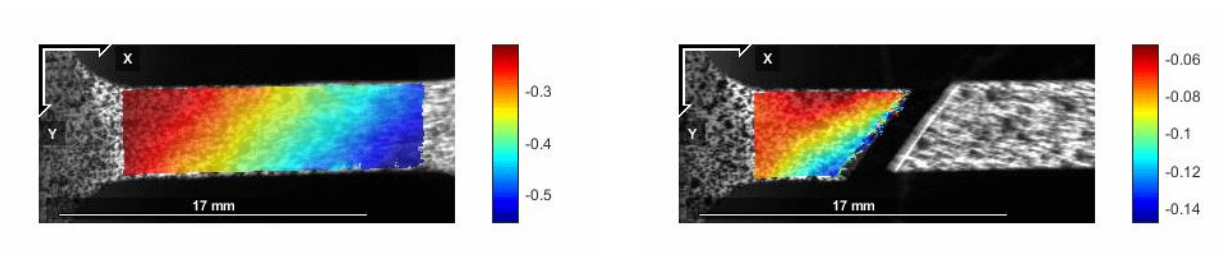


Figure 4- 6: Workflow of Ncorr.

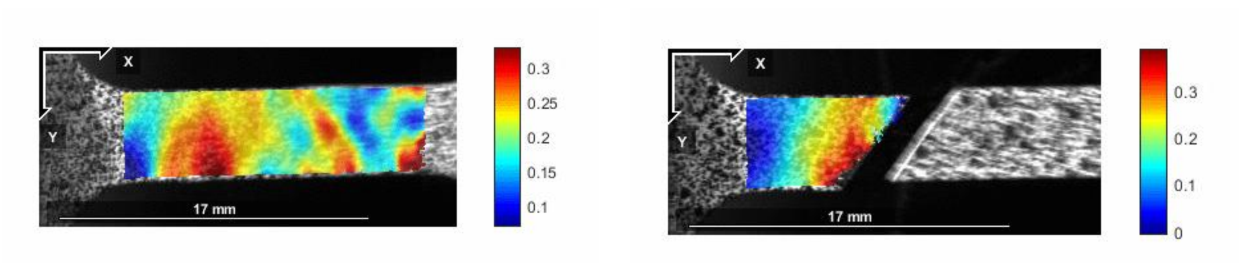
The high-speed camera used in the NIU SHPB system provides a 2000 frames per second sampling rate, which means a total of around 5000 pictures can be captured in each test. However, the high strain rate tensile test happens in micro-seconds, only 10 pictures of them were valuable for the DIC program to process. By processing the taken pictures of the tested specimen through Ncorr, the analyzed outputs as the field of displacement and strain before and after the tested specimen is broken are shown in Figures 4-7 and 4-8, respectively.



(a) (b)

Figure 4- 7: Displacement output on specimen.

Right before broken. (b) Right after broken.



(a) (b)

Figure 4- 8: Strain output on specimen.

(a) Right before broken. (b) Right after broken.

4.4 Discussion and conclusion

The experimental outputs were analyzed to observe the stress and strain history on the testing specimen. The output of the voltage history measured by strain gauges was used to calculate the engineering stress and its history curve was plotted. The output of captured pictures from the high-speed camera was processed by using the DIC technique and the displacement has been formatted and the strain has been calculated. However, due to the limited number of images obtained by the high-speed camera, a reliable strain history curve could not be plotted for now.

This study shows that the method of combining a high-speed camera and the DIC technique for strain history calculation is feasible for the SHPB tension system. By increasing the sampling rate of the high-speed camera in the future, the reliable strain history would be calculated and used for plotting the stress-strain curve of the testing material.

CHAPTER 5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

The current SHPB system at NIU was redesigned and improved so that it can conduct both compression and tension tests.

The first step I performed was redesigning the original NIU SHPB compression system. Once the problems in the compression system were addressed, I redesigned the support apparatus of the bars, which is critical to avoid vibration during the tests. This improved the stability and flexibility of the system. Air bearings can provide best performance to minimize the friction in the SHPB system. Air bearings were used to mount with the bars with zero friction. Alignment precision is the most important factor because it affects the accuracy of the signal. The sliding platform used in the bar support apparatus increased the flexibility in adjusting alignment, allowing for better accuracy. The performance of the compression system was confirmed by conducting testing and obtaining accurate data.

After setting up and testing the rebuilt SHPB compression system, a LID was designed to convert the installed compression system to a tension system for conducting tensile tests. Through troubleshooting, the tension system was improved and the mechanism of the LID and its connection to the output bar was refined. The main goal in this study was achieved in that the NIU SHPB compression system can now be converted to a tension system with minor changes.

The NIU SHPB tension system was used to conduct high strain rate tensile testing on a dog-bone shaped specimen with a material of 304 stainless steel. The obtained data of signals and images were imported into the analysis program, which were used to calculate history outputs of the stress and strain. After the improvements made in this research, future studies using the SHPB system at NIU will be able to conduct more tests of different materials to observe their properties. This rebuilt system allows researchers to collect data more efficiently and reliably.

5.2 Future work

1. Further study can be done on adding or designing bar support apparatuses to improve the stability of the system and avoid the signal being affected by vibration.
2. Further study can be done to solve the un-balance problem of the bar, caused by the weight of the shield cable, which connects to the strain gauge.
3. Further study can be done to connects the oscilloscope and computer so that the recorded data would automatically be saved in the computer, which is convenient for signal processing.
4. A high-speed camera with an improved sampling rate can be used for taking more pictures to improve the accuracy of strain history analysis.

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