Ahmedabad University

Learning Factory Project

Project Design File SHPB

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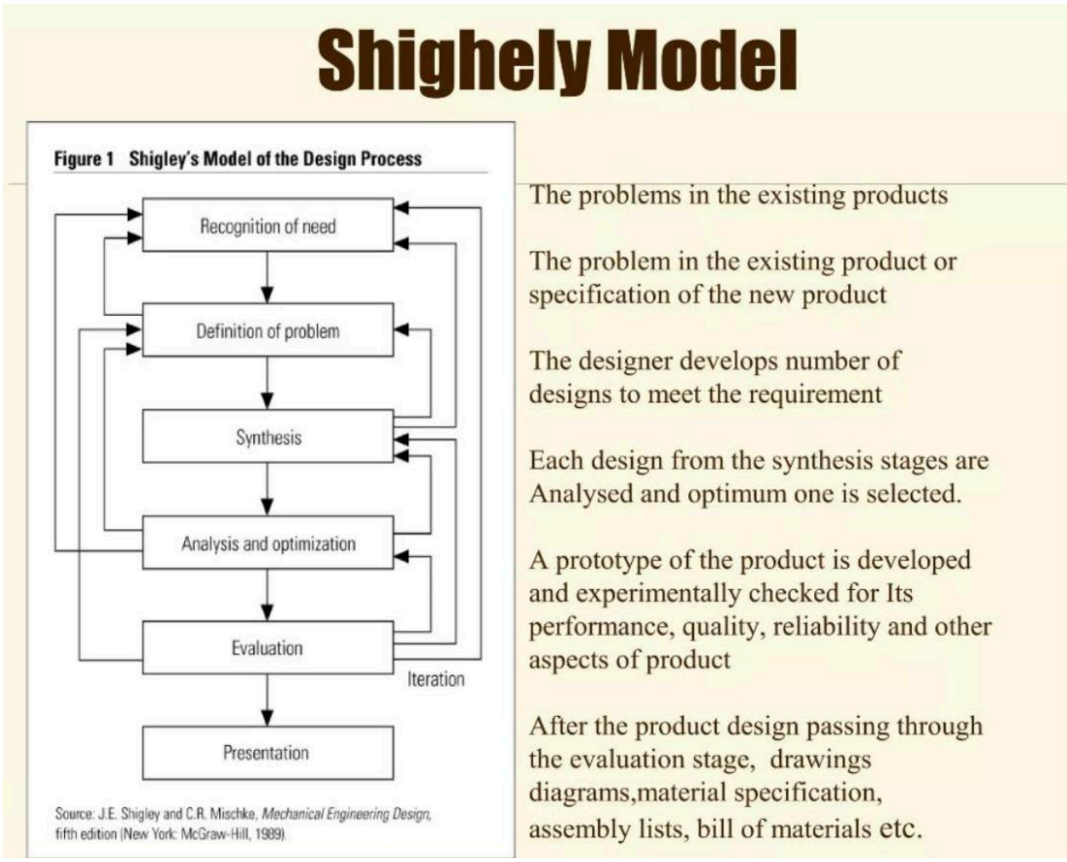
Shigley's design steps:



1. Recognition of Need

The need for a Split Hopkinson Pressure Bar (SHPB) arises from the challenge of characterizing the behavior of materials under dynamic loads, such as impact events, high-speed crashes, or explosive scenarios. These situations are critical for the development of high-strength, lightweight armor materials, especially those incorporating polymers and shear thickening fluids (STFs). In military applications, understanding the behavior of such materials under high strain rates is essential to ensure their performance during ballistic impacts.

The SHPB setup is developed specifically to address the need for a high strain rate testing apparatus that can simulate these extreme conditions. The SHPB is a crucial tool in materials engineering, allowing researchers to investigate material properties such as strength, deformation characteristics, energy absorption, and stress-strain responses at high strain rates.

The SHPB is used extensively in research laboratories for dynamic material testing, and the data obtained from these tests are critical for developing materials capable of withstanding extreme conditions. This data is also vital for optimizing material properties for aerospace, defense, and automotive applications, improving both safety and performance. The recognition of this need serves as the basis for the entire design process, setting forth the technical requirements and specifications of the SHPB.

2. Definition of Problem

The primary problem is to design an SHPB capable of accurately testing materials at strain rates ranging from 1000 to 5000 s^{-1}, which is suitable for soft materials such as polymers and FRPs that are commonly used in lightweight armor systems. The design considerations include factors such as the length, diameter, material choice for the bars, and precise alignment to minimize wave dispersion and reflection, ensuring consistent results during dynamic testing. It is also important to achieve an L/D ratio greater than 75 for the SHPB to function effectively without buckling between supports. To further improve accuracy, the SHPB uses a pair of supports for each bar, ensuring that any potential bending or misalignment is minimized.

The SHPB also needs to be designed to accommodate different material specimen sizes while ensuring precise data collection. The material selection for pressure bars should focus on properties such as high yield strength, high elastic deformation capability, and reasonable acoustic impedance matching with soft specimens. However, an ideal material that is more resistant to damage and suitable for long-term durability should be identified and used if possible. Additionally, a sophisticated data acquisition (DAQ) system, including strain gauges and velocity measurement using infra-red sensors, has been integrated to ensure precise recording of stress-strain data. The overall challenge is to create a cost-effective, modular, and easy-to-maintain SHPB apparatus that meets all requirements for high accuracy, repeatability, and adaptability for various materials under different testing conditions.

3. Synthesis (2 proposed designs)

Design 1:

This Split-Hopkinson Pressure Bar (SHPB) design utilizes EN36 steel rods (16 mm diameter, 1.6 m length) for the incident and transmission bars, supported by four evenly spaced low-friction supports per rod to ensure precise alignment and minimize energy loss. The base is made of heavy aluminum extrusion, providing structural integrity and vibration damping, secured with six mounting points for stable ground anchoring. This modular setup allows for easy assembly and adjustments while ensuring efficient stress wave propagation and high repeatability. The design is ideal for high-strain-rate testing of materials, balancing robustness with flexibility for precise and reliable performance.

1. **Details of the design**

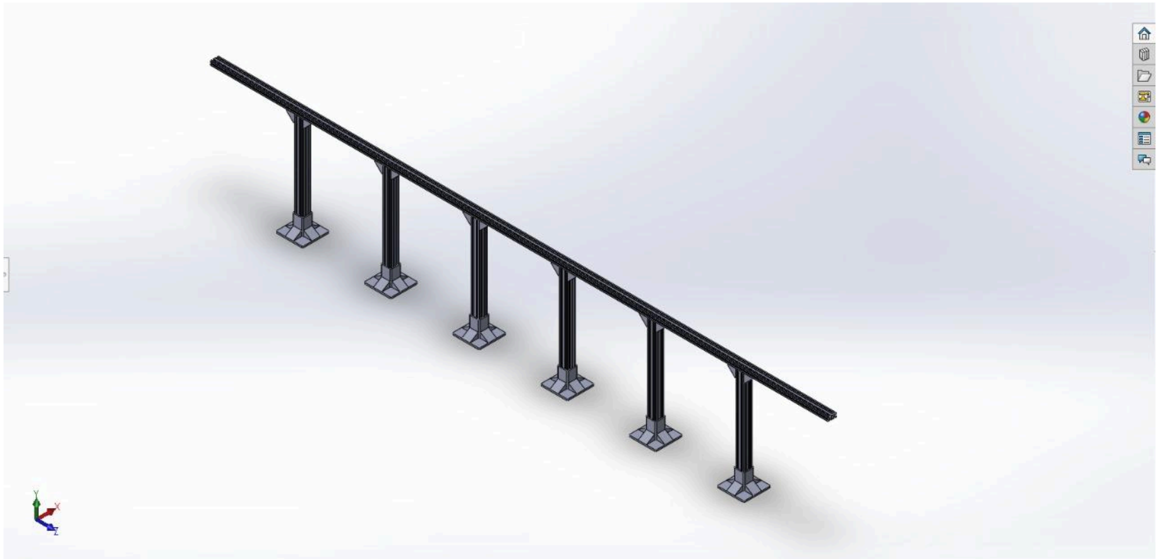
   Components:

   a. **Incident Bar:** Transfers stress wave to the specimen.
   b. **Transmitter Bar:** Receives stress wave after passing through the specimen.
   c. **Specimen:** Material being tested.
   d. **Strain Gauges:** Attached to the bars to measure strain induced by the stress wave.
   e. **Pressure Gun/Strike Mechanism:** Generates the initial stress wave by propelling a striker.
   f. **Data Acquisition System:** Records strain gauge output.

   Design Parameters:

   g. **Material:** High-strength materials (e.g., maraging steel, titanium) for bars to ensure elasticity during wave propagation.
   h. **Geometry:** Bars should have a uniform diameter to minimize wave dispersion and maintain accuracy.
   i. **Alignment:** Precision alignment of bars to avoid bending or off-axis loading.
   j. **Specimen Preparation:** Uniform dimensions to ensure homogeneous stress distribution.

2. **CAD:**



CAD design of the base

Software Used: Solidworks

The SHPB design is developed using CAD software to:

- Create precise 3D models for each component.
- Simulate assembly to verify alignment and tolerances.
- Evaluate interactions between parts to ensure reliability under dynamic loads.

The use of materials like 8040H and 8080M extrusions, suggests modularity and ease of assembly in the design.

3. **Cost:**

The total cost for the materials and components required for the Split-Hopkinson Pressure Bar (SHPB) system, based on vendor quotes, amounts to ₹1,03,834. Key items include EN36 bars for the pressure system, aluminum extrusion profiles for the base and support structure, machined blocks for precise bar alignment, and additional components like Delrin stocks and copper sheets.

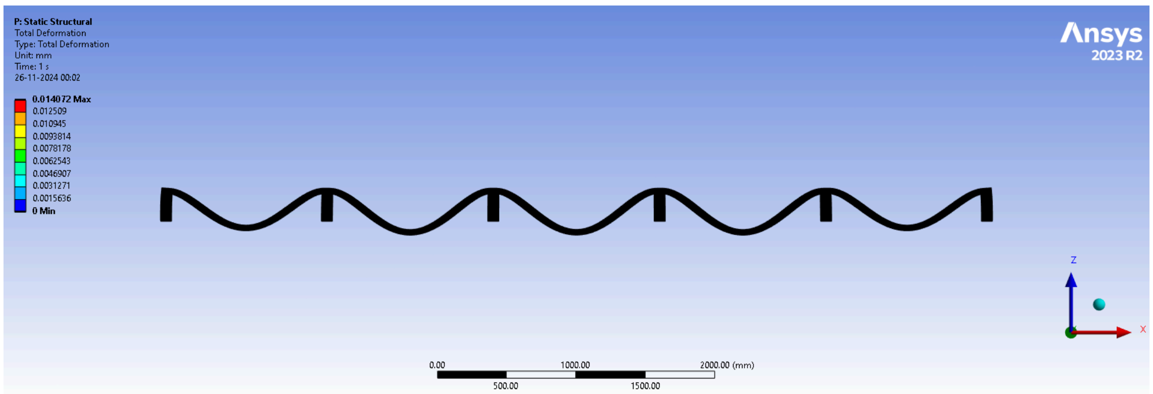
Sr No.	Name	Quantity	Size	Quote Price	Total
1	8040H 6m Length	6	6m	2260	13560
2	8080M 0.5m Length	8	8m	3060	24480
3	8080 Die Cast Foot	8	8080	2400	19200
4	PG40 8080 L Bracket	44	8080	575	25300
5	PG 4080 End CAP	2	4080	300	600
6	Machined 40 mm Thick MS Block Support for Pressure Bars	12	-	1000	12000
7	40mm Dia Delrin Stock	1	0.5m	944	944
8	Unannealed Copper Sheet - 1mm thickness	1	0.5m * 0.5m	1000	1000
9	CNG en36 Bars 16mm Dia	2	-	700	1400
10	CNG en36 Striker Bar	5	160mm, 200mm, 240mm, 280mm & 320mm	700	3500
11	CNG en36 Damper Bar	2	300mm, 400mm	700	1400
12	SS 304 Barrel	1	OD - 26, ID - 20.5	450	450
					Rs 1,03,834

4. **Benefits:**
    a. **High Strain Rate Testing:** Allows material testing in regimes (10^3–10^4 s^{-1}) where traditional methods fail.
    b. **Material Characterization:** Provides insights into yield strength, ultimate strength, and failure modes under dynamic conditions.

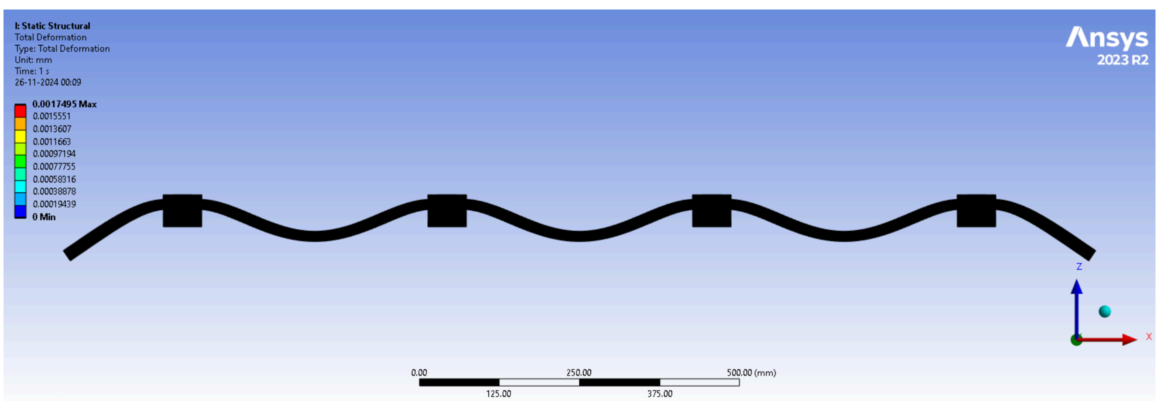
c. **Non-destructive Measurement:** Wave propagation through bars ensures the specimen's stress-strain state can be recorded without destructive methods.

d. **Wide Applicability:** Useful in aerospace, automotive, defense, and materials research industries.

5. Ansys Analysis:



Simulation of the 6 meter long base with 6 Supports Max Deformation under gravity 0.014mm



Simulation of Dia 16mm 1.6 m long EN36 Rods with 4 Supports, Max Deformation under gravity 0.0017mm

Objective: Simulate the load and natural deformation of the setup.

Analysis Types:

- **Structural Analysis:** Validate bar strength and rigidity under dynamic loads.

Steps:

1. **Model Import:** Import CAD geometry of the SHPB.
2. **Material Definition:** Define properties (e.g., elastic modulus, density) for bars and specimens.
3. **Boundary Conditions:** Apply striker velocity, bar constraints, and contact interactions.
4. **Meshing:** Ensure fine mesh at impact zones for accuracy.
5. **Simulation Run:** Analyze strain, stress distribution, and waveform behavior.
6. **Post-Processing:** Visualize stress wave profiles, deformation patterns, and energy dissipation.

Results:

- Stress and strain data for bars and specimens.
- Validation of uniform wave propagation through bars.
- Identification of potential design improvements.
- Maximum deformation of 0.014mm was calculated and the ideal support distance was validated.

Design 2: Mini SHPB

1. **Overview:**

This Split-Hopkinson Pressure Bar (SHPB) design utilizes SS304 stainless steel rods, each 600 mm in length, supported by two precision-aligned supports per rod. The base is constructed from a robust mild steel slab for maximum stability and durability, ensuring accuracy and reliability in high-strain-rate material testing.

2. **Design Features:**

Materials and Dimensions:

- Incident and Transmission Bars: SS304 stainless steel rods, 600 mm in length, selected for their high corrosion resistance, strength, and ability to withstand dynamic loading.

- Support System: Each rod is supported by two strategically positioned supports to ensure accurate alignment and minimize deflection during testing.
- Base: A solid mild steel slab forms the foundation of the system, providing excellent rigidity and vibration resistance.

Support Design:

- Supports are made of machined blocks, ensuring precise alignment and minimal friction during stress wave propagation.
- Low-friction inserts or rollers are used to reduce energy loss and preserve the wave integrity.

Base Mounting:

- The mild steel slab is securely anchored to the ground, ensuring stability under dynamic testing conditions.
- It is designed with sufficient thickness to dampen vibrations and maintain the structural integrity of the setup.

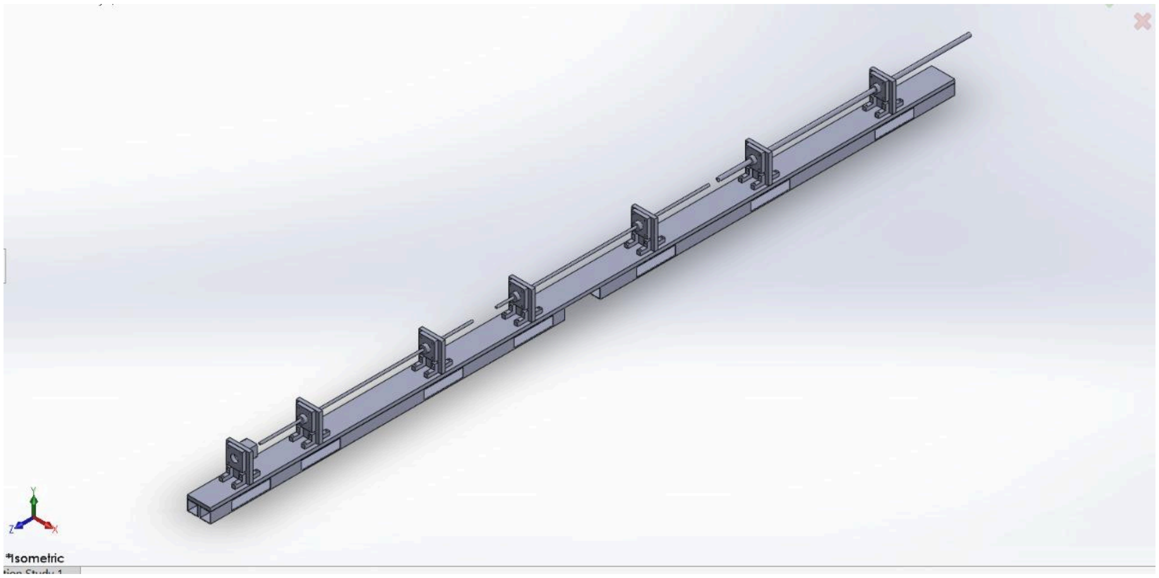
Wave Propagation Accuracy:

- The shorter SS304 rods enhance portability while maintaining sufficient length for reliable wave generation and propagation.
- The design minimizes energy loss and wave distortion, ensuring high precision in test results.

Modularity:

- The system is designed to allow for easy disassembly and adjustments, making it adaptable for a range of testing scenarios.
- Compact dimensions enhance portability and ease of use in laboratory settings.

3. CAD

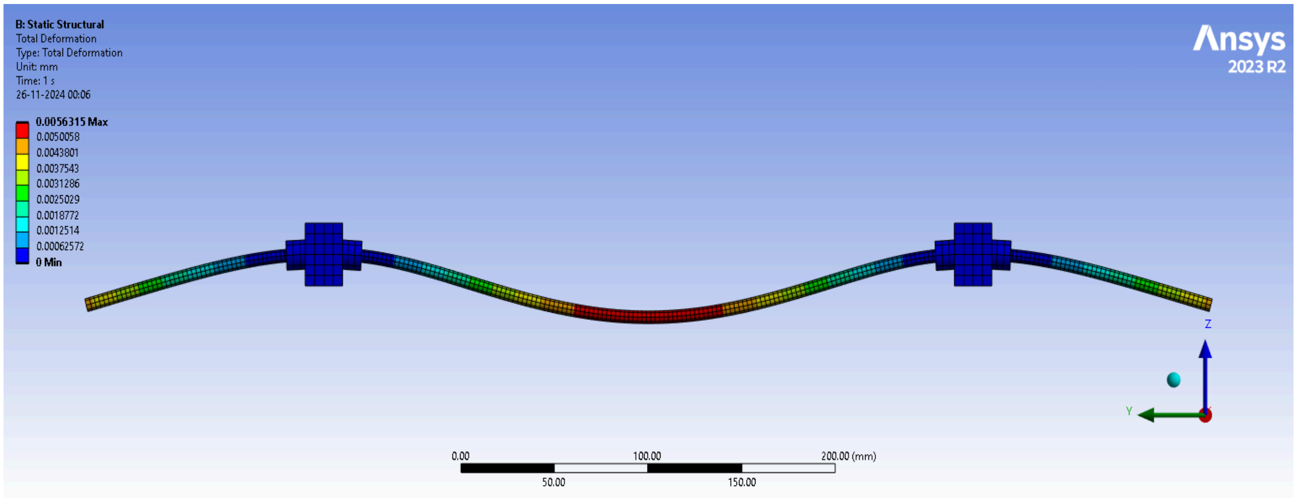


CAD Assembly of the Mini-SHPB

Changes to CAD design for Mini SHPB:

- Square metal tubes are used as a base to reduce height and impart structural integrity.
- The design accommodates easy disassembly and transport, making it ideal for laboratory use.
- We have reduced the overall size to decrease the cost.

4. Ansys Simulation



Simulation of Dia 6mm, 600mm long SS304 rod, with 2 support, Max Deformation under gravity is 0.0056 mm

4. Analysis and Optimization

Analysis

The decision to adopt the second SHPB design with 600 mm SS304 rods and a mild steel slab base was driven by practical considerations of space efficiency and cost optimization. The shorter rod length significantly reduces the overall footprint of the setup, making it suitable for laboratories with limited space. Additionally, the use of two supports per rod strikes a balance between structural alignment and material savings, ensuring precision without unnecessary complexity.

The choice of SS304 stainless steel for the rods is both economical and practical, offering excellent strength, corrosion resistance, and wave propagation characteristics at a competitive cost. The mild steel slab base provides robust support and vibration damping at a lower cost than heavy aluminum extrusions used in the first design. Moreover, the simplified support system and reduced material requirements result in lower fabrication and assembly costs.

Optimization

1. **Space Efficiency:** By reducing the rod length from 1.6 m to 600 mm, the overall setup becomes compact and portable, addressing space constraints without compromising testing accuracy.
2. **Cost Reduction:**
    - Using SS304 instead of EN36 steel rods provides adequate performance at a lower price point.
    - The mild steel slab base is more economical than aluminum extrusion while maintaining the necessary structural integrity.
    - Fewer support points reduce machining and installation costs without sacrificing stability.
3. **Simplified Assembly:** The compact design requires fewer components and machining steps, reducing assembly time and associated labor costs.

5. Evaluation

Feature	Design 1: Full-Scale SHPB	Design 2: Mini-SHPB
Material (Bars)	EN36 Steel (16 mm, 1.6 m)	SS304 Stainless Steel (6 mm, 600 mm)
Base Material	Aluminum Extrusion	Mild Steel Slab
Supports	Four per bar	Two per bar
Max Deformation (Gravity)	0.0017 mm (Bars), 0.014 mm (Base)	0.0056 mm (Bars)
Footprint	Larger, requires more space	Compact, space-efficient

Modularity	Highly modular for various applications	Simple, portable design
Cost	₹1,03,834	Significantly lower about 10% of the Design 1 Cost
Use Case	Precision testing with large samples	Budget-sensitive, small-scale testing

Benefits and Limitations

- **Design 1:**
    - **Advantages:** High precision, superior vibration damping, and adaptability for different sample sizes and applications.
    - **Disadvantages:** Higher cost and larger physical footprint.
- **Design 2:**
    - **Advantages:** Compact, cost-efficient, and easier to assemble. Suitable for laboratories with space or budget constraints.
    - **Disadvantages:** Limited wave propagation length due to shorter bars, reducing suitability for certain material tests.

Preferred Design

- For laboratories with **budget constraints and space limitations**, **Design 2** is the better choice due to its portability, affordability, and adequate testing accuracy for most materials.
- For applications requiring **high precision, repeatability, and larger sample testing**, **Design 1** is more suitable despite the higher cost.

6. Detailed Manufacturing Steps for SHPB Components

The manufacturing steps for the various components of the Split-Hopkinson Pressure Bar (SHPB) system have been broken down into material specifications, machining processes, and quality control measures to ensure precision and functionality. Here are the detailed steps:

1. Base Slab

- **Material:** Mild Steel (MS) slab for its rigidity and ease of machining.
- **Dimensions:** Original: 6 m × 65 mm × 10 mm. Final: 2.1 m in length with 36 holes (Ø7 mm).

Manufacturing Process:

1. **Cutting to Length:**
    - The 6 m slab was cleaned to remove surface contaminants.
    - Marked and cut to 2.1 m using a power saw, ensuring perpendicular edges.
    - Deburred edges for safe handling.
2. **Drilling Ø7 mm Holes:**
    - CNC drilling was performed in two stages due to the slab's length.
    - First set of holes drilled on one side, slab rotated for the second set.
    - Coolant used to maintain dimensional accuracy; holes deburred after machining.
3. **Surface Preparation:**
    - Slab cleaned of oils and debris after machining.
    - Anti-corrosion spray applied to enhance durability.

2. Barrel, Striker, and Rods

- **Material:** SS304 (Stainless Steel) for its high strength and corrosion resistance.

Manufacturing Process:

1. **Barrel:**
    - SS304 pipe selected with inner diameter matching striker (6 mm) and threaded for pneumatic connectors using a lathe.
    - Threads verified with a thread gauge.
2. **Rods:**
    - SS304 rods machined to 700 mm × 6 mm dimensions.
    - Centerless grinding applied for smooth surface finishing, ensuring minimal energy loss during wave propagation.
3. **Strikers:**
    - Three strikers fabricated (100 mm, 150 mm, and 200 mm lengths; Ø6 mm).
    - Precision ground for uniformity and surface smoothness.

3. Bushing

- **Material:** Delrin (PolyOxyMethane) chosen for low friction, dimensional stability, and moderate strength.

Manufacturing Process:

1. **Material Preparation:**
   - Delrin rod selected and rough-cut to manageable sizes using a band saw.
2. **CNC Machining:**
   - Outer diameter turned to specifications with CNC lathe for tight tolerances.
   - Inner diameter drilled and bored, ensuring concentricity with the outer diameter.

4. Support Bracket

- **Material:** Laser-cut 10 mm thick mild steel sheet for strength and cost-effectiveness.

Manufacturing Process:

1. **Laser Cutting:**
   - CAD files programmed into a CNC laser cutter for precise cutting of parts.
   - Parts included dimensions for Ø4 mm and Ø20 mm holes, with smooth laser edges.
2. **Deburring:**
   - All edges manually deburred for safe handling.
3. **Drilling Additional Holes (Part 2):**
   - CNC milling used to drill Ø5 mm holes with tight tolerances.
   - Coolant applied to prevent tool wear and maintain accuracy.

5. Square Pipe Legs

- **Material:** Mild Steel (MS) square pipes (32 mm × 32 mm cross-section).

Manufacturing Process:

1. **Cutting to Length:**
   - Pipes are cut into 1 m sections using a power saw, with deburred edges for safety.
2. **Drilling Holes for Bolts:**
   - Bench drills are used to create precise holes, with coolant applied during machining.
3. **Cutting Access Windows:**
   - Rotary cutter used to create access windows for nut tightening.
   - Window edges are smoothed with a rotary grinding tool.
4. **Surface Grinding:**
   - All sharp edges are ground for safety and improved finish.

7. Assembly Steps

The **assembly process**, starting from the base and progressing upward, is detailed with proper alignment and securing methods:

1. **Base Slab and Legs:**
   - Attach square pipe legs to the slab using M4 bolts, nuts, and washers.
   - Ensure vertical alignment and stability.
2. **Support Brackets:**
   - Fix support brackets onto the slab with M4 bolts and washers.
   - Verify alignment with a leveling tool.
3. **Pressure Bars:**
   - Mount the incident and transmission bars onto the brackets.
   - Secure with M4 bolts, ensuring parallel alignment.
4. **Bushings:**
   - Slide Delrin bushings onto the bars at specified points and secure them in place using the circlips.
5. **Barrel:**
   - Mount the barrel between the bars and fix it with M4 bolts.
   - Ensure proper alignment with the striker.
6. **Striker:**
   - Insert the striker into the barrel and verify free movement.

8. Measurement and Analysis

Dimensional Verification:

- All sub-components were measured post-manufacturing using precision tools such as **micrometers** and **calipers**.
- Measurements were compared against the CAD specifications, and any deviations were documented for further analysis.

GD&T Compliance:

- Key GD&T checks were conducted to ensure the functionality of the SHPB setup:
  1. **Flatness**: Ensured the flat surfaces of the base slab and support brackets were free of warping.
  2. **Straightness**: Verified the alignment and straightness of the pressure bars and support brackets.

3. **Concentricity**: Checked the alignment between the inner and outer diameters of bushings and the threaded barrel to prevent misalignment during operation.

Observations and Deviations

1. **Support Bracket (Part 2 - Elbow):**
    - **Observation:** Laser cutting did not leave a perfectly straight edge on Part 2 of the support brackets.
    - **Impact:** The uneven edge caused slight misalignment during assembly, requiring manual deburring and adjustment.
    - **Mitigation:** Additional machining and finishing were applied to restore straightness.
2. **Base Slab:**
    - **Observation:** Machining on the slab was not performed uniformly, resulting in dimensional discrepancies. In some areas, the width measured **63 mm instead of 65 mm** as specified.
    - **Impact:** This variation introduced challenges in aligning the square pipe legs and support brackets, potentially affecting overall alignment.
    - **Mitigation:** Adjustments were made during assembly by repositioning the brackets and ensuring alignment with the pressure bars.

Post-Measurement Actions:

- **Corrective Steps Taken:**
    - For **Part 2**, the uneven edges were corrected by additional deburring and edge finishing.
    - For the **slab**, shimming techniques were applied in affected areas to restore uniformity in alignment.
- **Re-Verification:**
    - All corrected parts were re-measured, and alignment was verified during assembly to ensure no functional impact on the final setup.

9. Variation Analysis

Observed Variations

1. **Drilling Holes for Square Pipe Feet:**
    - **Observation:** The holes drilled for the square pipe feet were not perfectly aligned due to center punch marks being made manually.
    - **Reason for Variation:**
        - Manual punching lacks precision compared to CNC or automated marking processes.
        - Operator skill and slight deviations during marking contributed to the misalignment.
    - **Impact on SHPB:**
        - Misaligned holes resulted in uneven attachment of square pipe legs to the slab, affecting the overall structural stability.
        - Alignment corrections were necessary during assembly, consuming additional time and effort.
2. **Windows on Square Pipes:**
    - **Observation:** The windows cut into the square pipes for nut access were uneven and lacked uniformity, as they were manually created using a rotary cutting tool.
    - **Reason for Variation:**
        - Manual cutting tools inherently lack the precision of laser or CNC cutting.
        - Variations arose due to operator handling and the difficulty of achieving consistent cuts with handheld tools.
    - **Impact on SHPB:**
        - Uneven windows created challenges during nut tightening and assembly, increasing the time required for proper fitment.
        - Aesthetic inconsistencies also affected the overall finish of the SHPB structure.
3. **Base Width Inconsistency:**
    - **Observation:** Variations in the base slab width (63 mm in some areas instead of the specified 65 mm) caused misalignment of holes for square pipe feet.
    - **Reason for Variation:**
        - Machining errors during slab preparation led to inconsistent width dimensions.
        - Manufacturing tolerance limits were exceeded due to improper quality control during slab machining.
    - **Impact on SHPB:**

        - Hole misalignment required smaller nut bolts to compensate for the discrepancy, reducing the intended clamping force and potentially affecting the system's long-term rigidity.
        - Misaligned feet and brackets introduced slight angular deviations, impacting the precise alignment of the pressure bars and wave propagation accuracy.

Root Causes of Variations

1. **Manufacturing Tolerance:**
    - The processes for slab machining, drilling, and cutting lacked strict adherence to tolerance limits.
    - Manual operations such as center punching and rotary cutting introduced operator-dependent errors.
2. **Equipment Limitations:**
    - Use of handheld or less precise tools (e.g., rotary cutter, manual punch) resulted in variations compared to CNC or automated machining.
3. **Quality Control:**
    - Insufficient inspection during intermediate stages of manufacturing allowed deviations to accumulate, particularly in slab width and hole alignment.

Impacts of Variations on SHPB Performance

1. **Structural Stability:**
    - Misaligned square pipe feet and smaller nut bolts reduced the overall rigidity of the base structure, making the system more susceptible to vibrations during operation.
    - Improper fitment of feet may lead to uneven load distribution, increasing wear and tear over time.
2. **Wave Propagation Accuracy:**
    - Misalignment of the pressure bars due to angular deviations could distort stress wave propagation, affecting the accuracy of material testing results.
    - Reduced stability might introduce noise or inconsistencies in data acquisition.
3. **Assembly Time and Effort:**
    - Variations caused significant delays and additional labor during assembly, as components required adjustments to fit properly.

Process Sheet

The table below outlines the manufacturing processes used for the fabrication of the SHPB components, along with details of materials, tools, and purpose:

Component	Material	Process	Tool/Equipment Used	Purpose
Base Slab	Mild Steel (MS)	Cutting	Power Saw	Cut a 6-meter slab to 2.1-meter length.
		CNC Drilling	CNC Drilling Machine	Drill 36 Ø7 mm holes for assembly.
		Deburring	Countersink Tool	Remove sharp edges from drilled holes.
		Surface Treatment	Anti-Corrosion Spray	Prevent rust and ensure durability.
Bars	SS304 Stainless Steel	Cutting	Power Saw	Cut rods to 700 mm length.
		Centerless Grinding	Centerless Grinding Machine	Achieve smooth surface and uniformity.
Barrel	SS304 Stainless Steel	Threading	Lathe Machine	Add external threads for pneumatic connectors.
		Cleaning	Cleaning Agents	Ensure smooth internal surface for striker.
Strikers	SS304 Stainless Steel	Cutting	Lathe Machine	Cut to lengths of 100 mm, 150 mm, and 200 mm.
		Centerless Grinding	Centerless Grinding Machine	Ensure precision and smoothness.
Support Brackets	Mild Steel	Laser Cutting	CNC Laser Cutter	Cut brackets (Parts 1, 2, 3, 4) to precise dimensions.
		Deburring	Mechanical Deburring Tool	Smooth edges for safe handling.
		Drilling	CNC Milling Machine	Create additional Ø5 mm holes on Part 2 for alignment.
Bushings	Delrin (POM)	Rough Cutting	Band Saw	Roughly size the raw material for CNC machining.
		Turning	CNC Lathe	Machine outer diameter (OD) to specifications.

		Drilling and Boring	CNC Lathe	Create precise inner diameter (ID) for concentricity.
Square Pipe Legs	Mild Steel	Cutting	Power Saw	Cut 6-meter pipes into 1-meter sections.
		Drilling	Bench Drill	Drill holes for bolts to attach to the base slab.
		Rotary Cutting	Rotary Cutter	Create access windows for nut tightening.
		Grinding	Rotary Grinding Tool	Smooth edges of cut pipes and windows.