NON-LINEAR CONTACT FINITE ELEMENT ANALYSIS OF SPLIT HOPKISNON TENSILE BAR

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidate for any degree.

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ABSTRAK

Untuk menguji sama ada reka bentuk komponen boleh menahan beban impak adalah penting. Ujian ini dikenali sebagai ujian kadar terikan tinggi. Bar Tekanan Split Hopkinson digunakan untuk mengkaji tingkah laku bahan pada kadar terikan yang tinggi. Walau bagaimanapun, tidak banyak garis panduan khusus untuk menentukan parameter reka bentuk SHPB Tegangan. Oleh itu, Tensile SHPB dimodelkan dalam Abaqus dan Ansys untuk mencirikan tegasan dalam bar insiden dan menggunakan keputusan simulasi untuk mencadangkan Tensile SHPB berskala kecil. Simulasi analisis dilakukan berdasarkan geometri dan bahan SHPB Tegangan yang dibangunkan di makmal Kejuruteraan Mekanikal. Analisis elemen terhingga dilakukan berdasarkan pendekatan mekanik kenalan. Dengan menggunakan tekanan maksimum dari tangki tekanan, tegasan maksimum yang dialami oleh bar kejadian di bawah keadaan tanpa geseran direkodkan sebagai 677MPa. Selepas itu, dengan mengambil kira kehilangan geseran dan tekanan dalam simulasi, tegasan maksimum 403.50MPa dialami oleh bar kejadian. Tensile SHPB berskala kecil dengan keupayaan yang sama ditetapkan untuk dimuatkan pada jadual biasa 1.8m x1.2m ditentukan oleh nisbah terikan tegasan σop / σy dan nisbah L/D. AISI 4340 yang dipadamkan dan bahan keluli terbaja digunakan untuk Tensile SHPB berskala kecil. SHPB tegangan berskala kecil boleh dibangunkan dengan teknik nisbah tegasan dan nisbah L/D yang digunakan dalam reka bentuk SHPB boleh diperolehi dengan bantuan FEA.

ABSTRACT

To test whether a component's design can resist impact loading is important. This test is known as high strain rate testing. Split Hopkinson Pressure Bar is used to study the material behaviour at high strain rates. However, there are not much specific guideline to determine the design parameters of a Tensile SHPB. Therefore, a Tensile SHPB is modelled in Abaqus and Ansys to characterize the stresses in the incident bar and using the simulation results to propose a small-scale Tensile SHPB. The analysis simulation is done based on the geometry and material of a Tensile SHPB developed in the Mechanical Engineering laboratory. The finite element analysis was done based on contact mechanic approach. By using the maximum pressure from the pressure tank, the maximum stress experienced by incident bar under frictionless condition is recorded as 677MPa. Subsequently, by taking inconsideration of friction and pressure losses in the simulation the maximum stress of 403.50MPa is experienced by incident bar. The small-scale Tensile SHPB with the same capability were set to fit on 1.8m x1.2m regular table determined by stress strain ratio σop / σy and the L/D ratio. The quenched AISI 4340 and tempered steel material is used for small-scale Tensile SHPB. A a small-scale tensile SHPB can be developed with stress ratio technique and L/D ratio used in SHPB design can obtained with the aid of FEA

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LIST OF SYMBOLS/ ABBREVIATIONS

A_b	Cross-sectional area of bar
A_o	Initial cross-sectional area of the material
A_{st}	Cross-sectional area of striker
C_b	Wave speed through the bar
C_d	Drag coefficient
D_b	Diameter of input bar
D_p	Inner diameter of pipe

d_i	Inner diameter of the striker
d_o	Outer diameter of the striker
E	Young's modulus
f	Friction factor
F	Force applied to the material
F_D	Drag Force
F_k	Kinematic friction force
F_y	Load at yielding
g	Gravitational force
H_f	Flange's height
k	Constant for virgin material
L	Current length of the material
L_f	Flange's length
L_p	Length of pipe
L_o	Initial length of the material
$L_{striker}$	Length of striker
L/D	Length-to-diameter ratio of the bar
m	Mass of object
N	Normal force
Re	Reynold number
S	Principal deviatoric stress
T_s	Thickness of striker
t_{total}	Total time of one test
V	Velocity of fluid
v	Kinematic viscosity
ε	Strain
$\acute{\varepsilon}$	Strain rate
ε_a	Absolute roughness
ε_i	Incident strain
ε_r	Reflected strain

ε_t	Transmission strain
ρ	Density
t_{bar}	Total time for the wave to travel through the striker bar one time
F_{st}	Maximum force applied to striker
P	Maximum pressure that can be exerted by the pressure tank
σ	Stress
ΔP	Pressure loss

CHAPTER 1 : INTRODUCTION

1.1 Overview of Project

According to Kolsky[1], engineers are interested in the mechanical behaviour of material at high strain rate because, they wish to use the material under behaviour where sudden impacts are exerted on it. Thus, the mechanical behaviour becomes important at high rates of loading. Impact is a phenomenon where high force is exerted onto an object by another object in a short period of time.[2] If a material is subjected to an impact, the loading time is reduced, and the material inertial effects becomes important, and the loading becomes dynamic. Therefore, the material needs to undergo high strain rate test. Unlike, quasi-stress strain rate which only test a material at low strain rate, high strain rate test provides us with an accurate and reliable material properties under high strain rate test while low strain rate test focuses more on fracture related problem at low strain rate.[3]

High strain rate is not only widely used in structural engineering application such as automotive, aerospace, and space vehicles but also in our daily life application material such as our handphone. Nowadays, smartphone is also design as crack prove when a sudden impact is exerted on it as the material used for the phone has high strain rate. There are a few methods to test material at high strain rate such as Dynamic Indentation and Split Hopkinson Pressure Bar. Split Hopkinson Pressure Bar initiated Bertram Hopkinson have been popular in engineering fields to study the dynamic mechanical properties of a material at high strain rate. The one-dimensional wave propagation working principle of SHPB is to make sure the impact load is directly transferred to the specimen of test material.

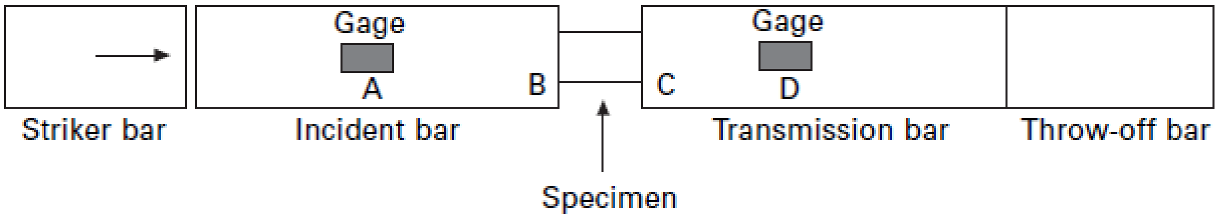

Figure 1. 1 Schematic of Split Hopkinson Pressure Bar.

Figure 1. 1[4] shows the schematic illustration of a traditional SHPB. The design guideline of SHPB machine is important to ensure the one-dimensional stress wave propagation.[4] SHPB design must be rigid so that it will not go through deformation while operating the machine. Therefore, the dimension and material of the parts and components of the machine are significant to get an accurate result while conducting high strain rate test. However, the current studies on this machine gave no specific design guideline of this machine. The general guideline from current studies only states that the ratio the $L/D \geq 20$. This enables the stress wave propagation.

Traditionally, the behaviour of structure under high strain rate is studied by a governing equation that can be solved via closed form solutions. However, it can be used only to study simple parts. Due to the evolution of software and technology, with the help of Finite Element Analysis (FEA) helps engineers to model and study complex engineering scenario. Therefore, numerical methods can be used to simulate and the impact behaviour Split Hopkinson Pressure Bar (SHPB). Nam Ho Kim[5] says that there is a contact surface where two bodies collide which prevents the overlapping of the object in space. Contact analysis helps us to study the stress in that contact surfaces. This study is important because it gives us the ability to determine whether the structure can withstand the load being applied on it. Therefore, contact analysis is very significant for the simulation of Split Hopkinson Pressure Bar to characterize the stresses experienced during the impact event and understand the limit of SHPB design for certain application.

1.2 Problem Statement

High strain rate testing is in need to test various load configurations in a unique SHPB set up and to test small specimens. High strain rate also is used to study crash and tensile impact such as in automotive, aerospace and etc.

To create a Split Hopkinson Pressure Bar (SHPB) that functions properly, it was required to abide by certain design specifications while deciding on important aspects like the SHPB's material and size. On the other hand, there were no suggestions for how to construct the Tensile SHPB in the literature review for this project. The advice made at the time solely utilised a qualitative approach to design, not a quantitative one. Additionally, there was no method for defining the stresses that the components in a traditional Split Hopkinson Pressure Bar faced as a design guideline. As a result, doing Finite Element Analysis for contact concerns to explain stresses of the components is necessary to design a SHPB machine.

1.3 Project Objectives

The objectives of my project research are:

1. To model Tensile SHPB in Abaqus software and to simulate the impact generated at the stopper due to incident bar.
2. To characterize stresses experienced by the components of a Tensile Split Hopkinson Pressure Bar (SHPB).
3. To include pressure and friction loss of Tensile Split Hopkinson Pressure Bar (SHPB).

1.4 Scope Of Work

For this project, the goal is to get a working model of Tensile Split Hopkinson Pressure Bar virtually which includes the bars, anvil and striker under impact load. This can be done by using the software called as Abaqus. The design is first made in Abaqus. Then the contact analysis is set by developing finite element mode. In this Abaqus software, 3 parts of tensile Spit Hopkinson Pressure Bar is design that is the striker, the incident bar, and the anvil. All of these parts are designed using actual dimensions and the material AISI 4140

Alloy Steel is assigned to the parts. Contact pairs are also assigned to the interacting parts according to the behaviour of the SHPB system. Constraints are also applied to ensure the SHPB machine in Abaqus exhibit only 1D stress wave.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction to Split Hopkinson Pressure Bar

Mechanical materials are increasingly being used in harsh settings, with forging and rolling being two examples of procedures that subject them to exceptionally high stresses and strain rates. To construct structures that will be used under severe loading conditions, we need to understand the mechanical deformation behaviours of the material under high strain rates. The process of gathering mechanical properties in a high strain rate loading scenario is not straightforward, though. Compressive and tensile tests should be performed at various strain rates in order to distinguish between high strain rate loading and low strain rate loading. The influence of inertia on the test is not negligible when there is high strain rate loading. Three main ways are where inertia manifests itself during a dynamic test.

2.1.1 Theory of Split Hopkinson Pressure Bar

Deformation of specimen is difficult to study because of plastic wave propagation and friction. The plastic wave propagation and friction will affect the elastic wave propagation in the pressure bars. Lubrication can help to reduce the frictional effects.

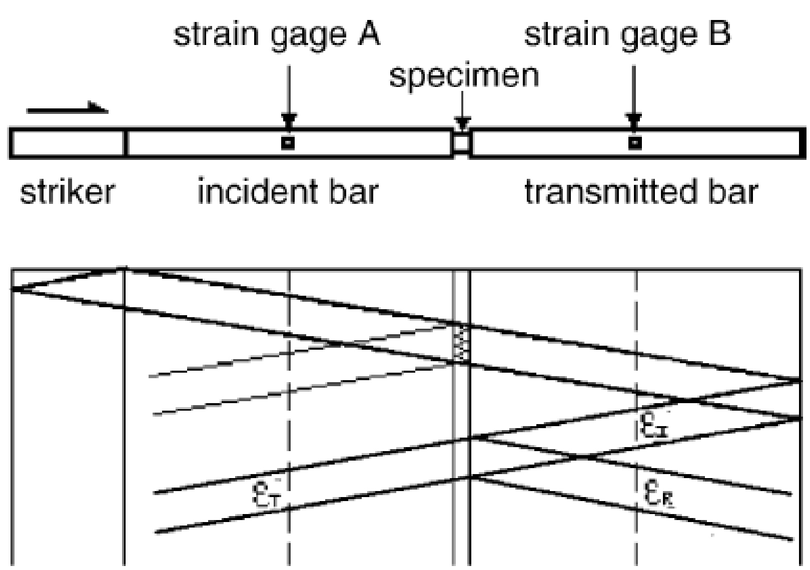

Figure 2. 1 A schematic diagram of specimen and elastic stress wave propagation for the tensile test[6].

Figure 2. 1shows the schematic diagram of specimen and elastic stress wave propagation in tensile test. In tensile test, the specimen will be sandwiched by the pressure bars. The striker bar's impact on the incident bar creates a compressive stress pulse that travels along the specimen and the split ring. The propagation of the compressive stress pulse continues until it reaches the transmitted bar's end. The tensile stress pulse's shape reflected the compressive stress pulse as it travelled to the end of the transmitted bar. At strain gauge B, the tensile stress pulse is monitored. Tensile stress pulse propagates to the incident bar in part and reflects to the transmitted bar in part after reaching the specimen. It's crucial to place the strain gauges where there won't be any interference between the spurious wave created at the bar/split ring interface and the incident tensile stress wave (ε_T). Because it elevates the specimen, the spurious wave has a negative impact on the outcomes.

2.2 Numerical Simulation of Split Hopkinson Pressure Bar

From the literature review, the numerical modelling of SHPB results was compared to an actual SHPB test and the specimen stresses on mechanical behaviour is characterised. From the article written by Fakhimi [6], a physical and numerical evaluation of rock strength was carried out to evaluate the strength characteristics of sandstone under uniaxial compressive loading.

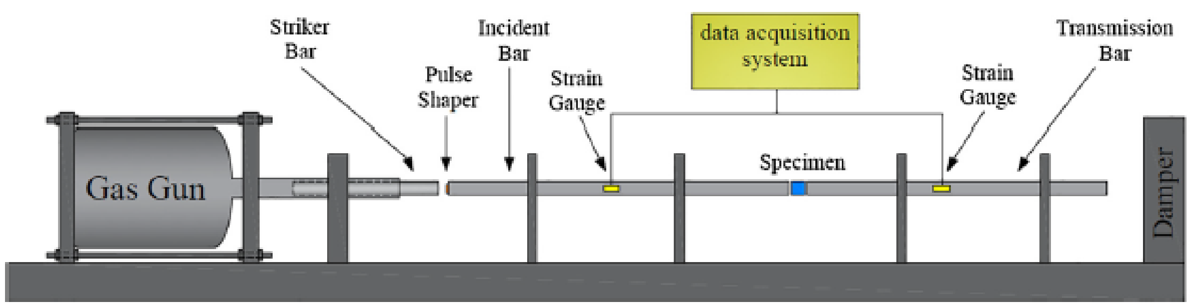

Figure 2. 2 Schematic view of the split Hopkinson pressure bar apparatus[6].

First the physical test was done with SHPB. Figure 2. 2**Error! Reference source not found.** shows the three-bar SHPB apparatus that was employed in our study: striker bars, incident bars, and transmission bars. Three distinct rounds of dynamic testing were performed on the sandstone samples. For each series of testing, the identical gas gun pressure and pulse shaping technique were used on two or more different specimens. Next the numerical simulation of SHPB was done on CA3 software. The inclusion of the elastic modulus, Poisson's ratio, and bar density in the CA3 programme allows the numerical analysis to replicate the whole SHPB construction, except for the striker bar. The boundary conditions of the model are shown Figure 2. 4 in as they were really put into practise. A stress wave is created when the striker bar and incident bar collide, and it moves along the incident bar before deforming the specimen and continuing along the transmission bar. The model is applied to the free end of the between the bars and the numerical sample.

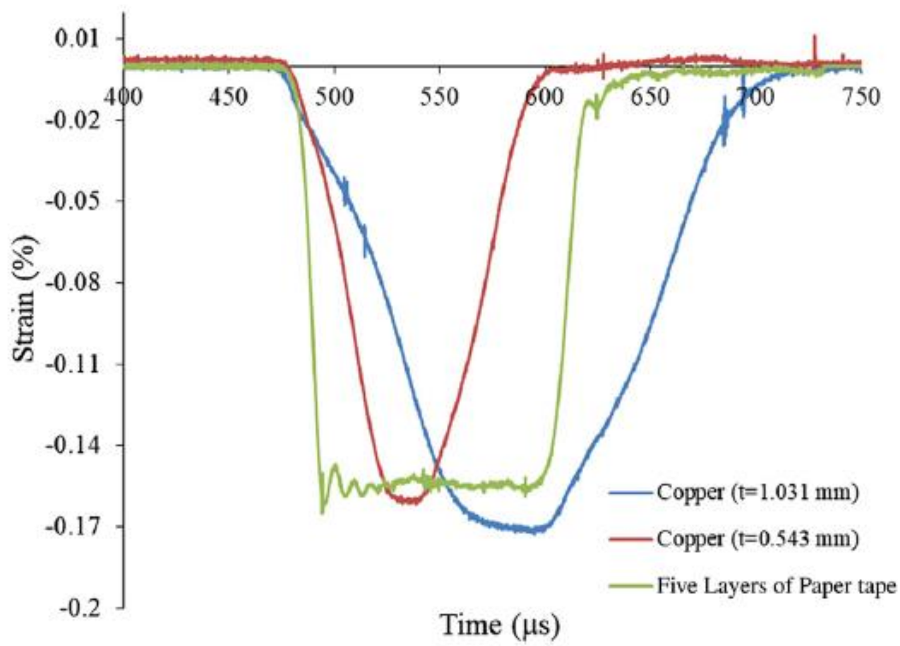

Figure 2. 3 Different incident waves which are the results of using different pulse shapers and gas gun pressures. The thickness of the copper pulse shaper is shown as t in the figure legend[6].

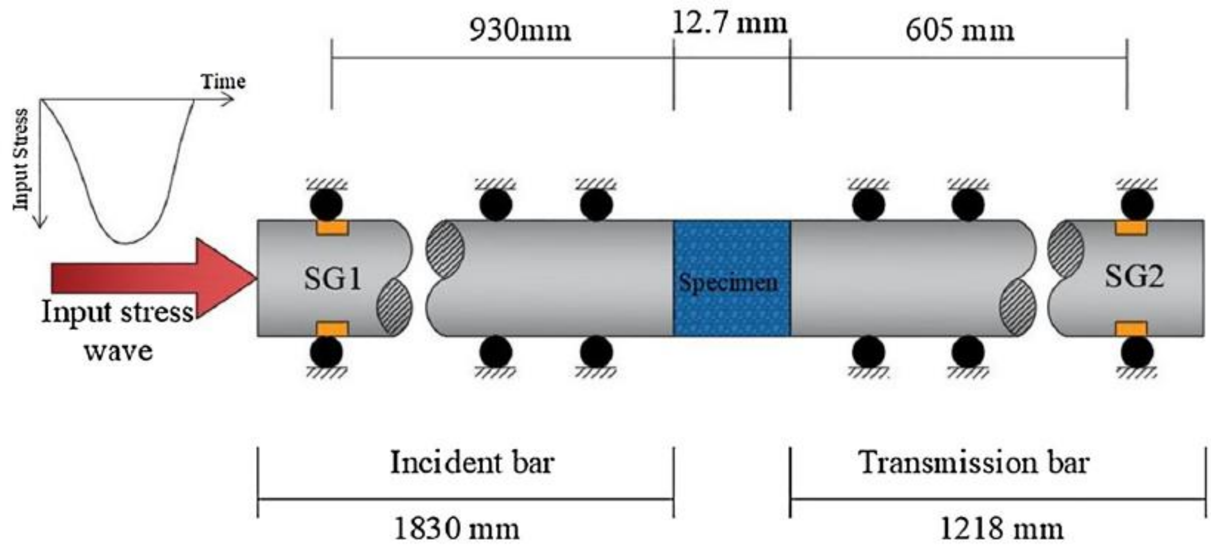

Figure 2. 4 The applied boundary conditions to the numerical model.[6]

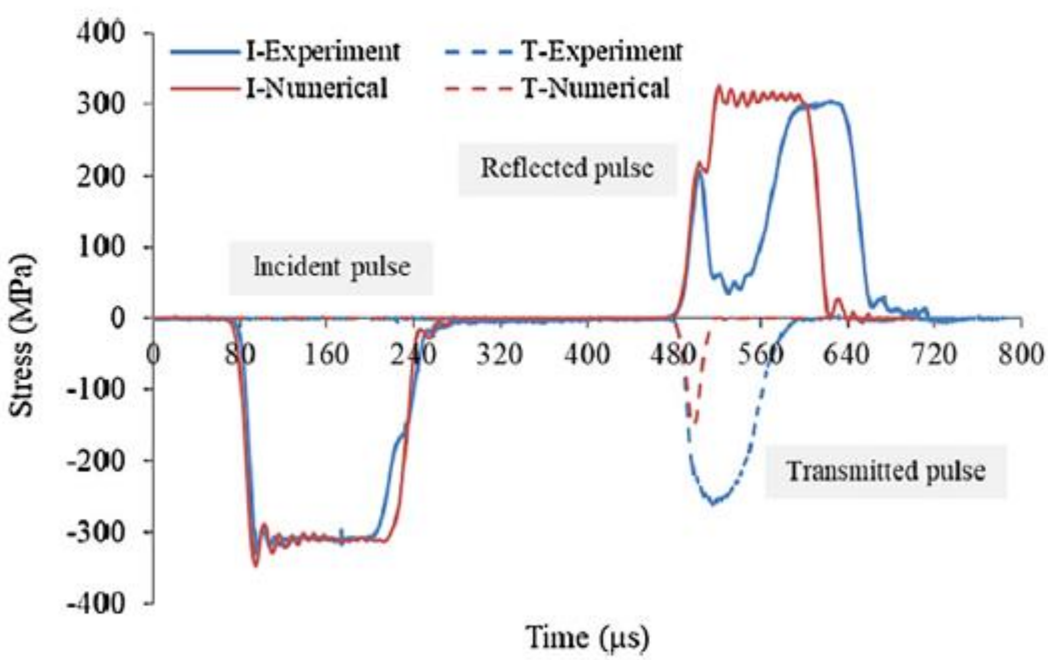

Figure 2. 5 Stress strain of the numerical model.[6]

From the comparison shown in the Figure 2. 5 above, we can see that the reflected and transmitted bar is different in the numerical simulation results and physical test results. We observe that the peak of reflected pulse is much higher for numerical simulation results compared to the physical experimental results. Fakhimi[6] says that the difference in results is because of axial and circumferential inertia of numerical specimen are not sufficient to give an accurate result. This suggest that some of the loading rate effects is not being considered in this simulation. Therefore, the model of rate dependency added in the simulation. This feature replaces the normal bod (n_b) and shear bond (S_b) of the contact point of two surfaces to normal and shear velocity components. Figure below Figure 2. 6 shows a more reliable numerical simulation results after this feature is considered.

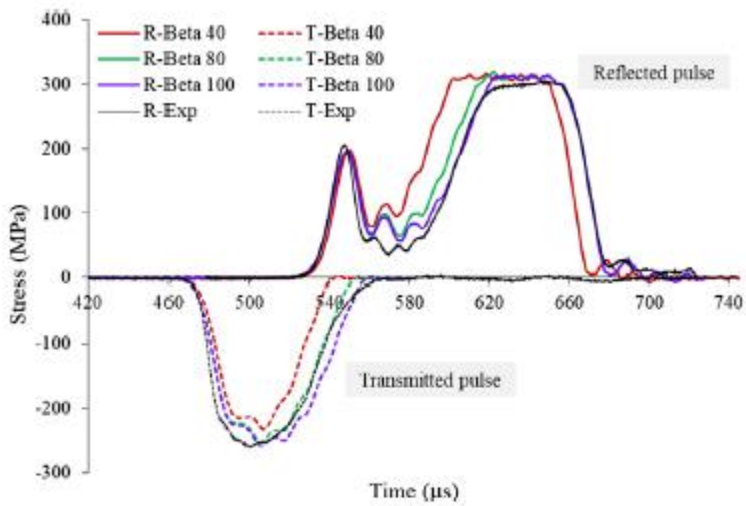

Figure 2. 6 Comparison between the numerical outputs with β =40–100 s/m and the experimental results for the third loading rate.

Another study was done by Gupta [7], whereby a numerical behaviour of AA7075 with different shapes and velocity exerted on the striker under dynamic loading performed in ABAQUS. The specimen length was kept constant, but the shape is varied from circular and square shapes. The impact velocity was varied from 20 to 50 m/s with circular. The numerical simulation was done to study the effects of striker velocity and shape of striker on stress strain behaviour of AA7075 and wave propagation in the SHPB. According to Gupta[7], as the striker velocity increases from 20m/s to 50m/s. The true yield strength increases from 38.85% to 67.5% respectively, while the ductility of AA7075 at 50m/s increased by 5 times compared to when the striker velocity at 20m/s. This shows the striker velocity affects both wave variation and flow curve of AA7075 under high strain rate.[7] The shapes of the striker also affect the yield strength, compressive stress, and ductility of the material. From Gupta discovery[7], yield strength increases by 2.2 times when the shaped of AA7075 changes from circular to square striker at 20m/s striker velocity for both. However, the compressive stress and ductility decreases. Table 2.2.1 below shows the results of the study under different condition

Table 2.2.1 Numerical results of compression tests under different conditions.

Parameters		True stress-strain curve		Total Compression (%)
		Yield stress (MPa)	Ultimate compressive stress (MPa)	
Striker velocity	20 m/s	278 ± 1	720 ± 1	6.52 ± 0.1
	30 m/s	338 ± 2	910 ± 2	14.21 ± 0.1
	40 m/s	353 ± 3	1020 ± 2	23.07 ± 0.2
	50 m/s	386 ± 1	1206 ± 1	31.62 ± 0.2
Striker shape	circular	278 ± 1	720 ± 1	6.52 ± 0.1
	square	615 ± 1	684 ± 2	4.75 ± 0.3
Specimen shape	circular	278 ± 1	720 ± 1	6.52 ± 0.1
	square	456 ± 1	719 ± 2	7.66 ± 0.1

Next, a study on coal and rock dynamic disaster was conducted using numerical simulation of SHPB for combined coal-rock by using Holmquist-Johnson-Cook model[8]. The numerical model of four types of combined coal and rock with different sandstone-coal-sandstone ratio including 1 :1: 1, 2 :1: 1, 1 :1 : 2, and 1 : 2 : 1, is conducted based on SHPB using LS-DYNA software. The studies cover the stress wave, oscillation phenomenon of stress wave and damage process of rock and coal. According to Beijing Xie [8], finding, the stress wave of simulated and measured have a good consistency and trends. Though the simulated and measured values are slightly different, Beijing Xie says that the numerical results can replace the experiments to study dynamic loading of combine coal-rock test. From the Figure 2. 7 [8], the simulated incident wave is slightly higher than measured incident wave due to the numerical simulation was done in ideal conditions.

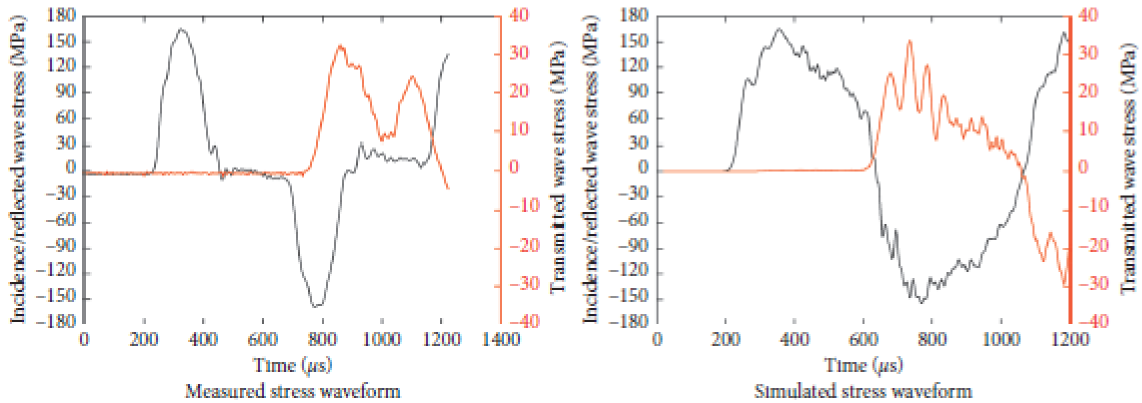

Figure 2. 7 Stress waves of the incident bar and transmission bar at bullet speeds of 7.671 m/s[8]

2.2.1 Numerical Modelling on Tensile SHPB

There numerical modelling on tensile SHPB was done by Acosta[9], using LS-Dyna. The model was generated in “dry” condition and full condition. Dry condition means only the incident bar, striker and transfer flange were modelled. According to J.F Acosta, there are two methods of loading techniques. We are more interested in direct loading technique assisted by transfer flange. In this loading techniques, Acosta says that the tensile loading pulse is generated after impacting the incident bar together with hollow striker on the transfer flange as shown in Figure 2. 8. The wave generated by the incident bar is partially transmitted to the specimen and to the transmitted bar as tensile wave and partially returns to incident bar as compressive wave.

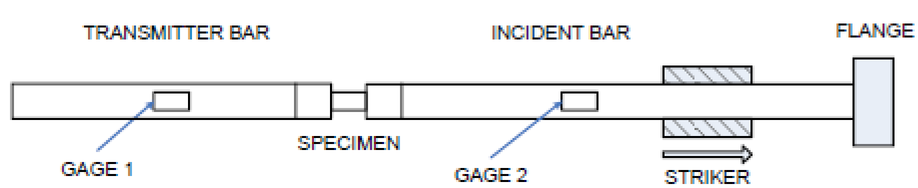

Figure 2. 8 Flange loading methodology.

However, for characterizing the incident pulse can be done in dry condition as Figure 2. 9 below. Models of the SHPB are put together under "dry conditions" to examine the mechanics of momentum transfer from striker to bar in a traditional compression SHPB or from striker to transfer flange and incident bar in a tensile SHPB (i.e., without test specimen and transmitter bar). A "dry" tensile SHPB has been developed in order to evaluate how the geometry of the transfer flange affects the generated load. The load generation examination thoroughly examines the mechanics of the momentum transfer from the striker bar to the transfer flange to the incident bar.

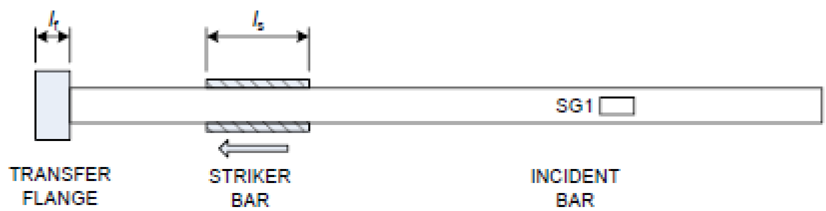

Figure 2. 9 Dry test on a tensile SHPB.

Furthermore, according to Acosta[9], friction between the components can be added in simulation to make the results as realistic as experimental results. A coulomb friction formulation will extrapolate the friction transition from static to dynamic condition. The dimensions and material properties are same as actual tensile SHPB. The analysis of incident bar and flange intersection is studied. The loading technique might need to be revised because of the joint's tendency for fatigue. The bar's maximum stresses outside of the joint are limited to 199 MPa. Standard 63 S-N curves for aluminium 7075-T6 estimate that the fatigue life will be around 5,000 cycles for a stress ratio of R = -1. This assumes a stress concentration factor of three. The Figure 2. 10 shows the stress analysis at the intersection of flange and incident bar.

Acosta found out that there is a minimum flange length for each striker based on the striker length. This is to avoid the secondary reflections overlapping the incident pulse. Numerical simulations and experimental shows that the reflected waves are significant as it could distort the primary incident pulse. Besides, for long flange have less oscillations of pulse. Supporting extra sections of incident bar has no benefits but give more distortion on the leading pulse.

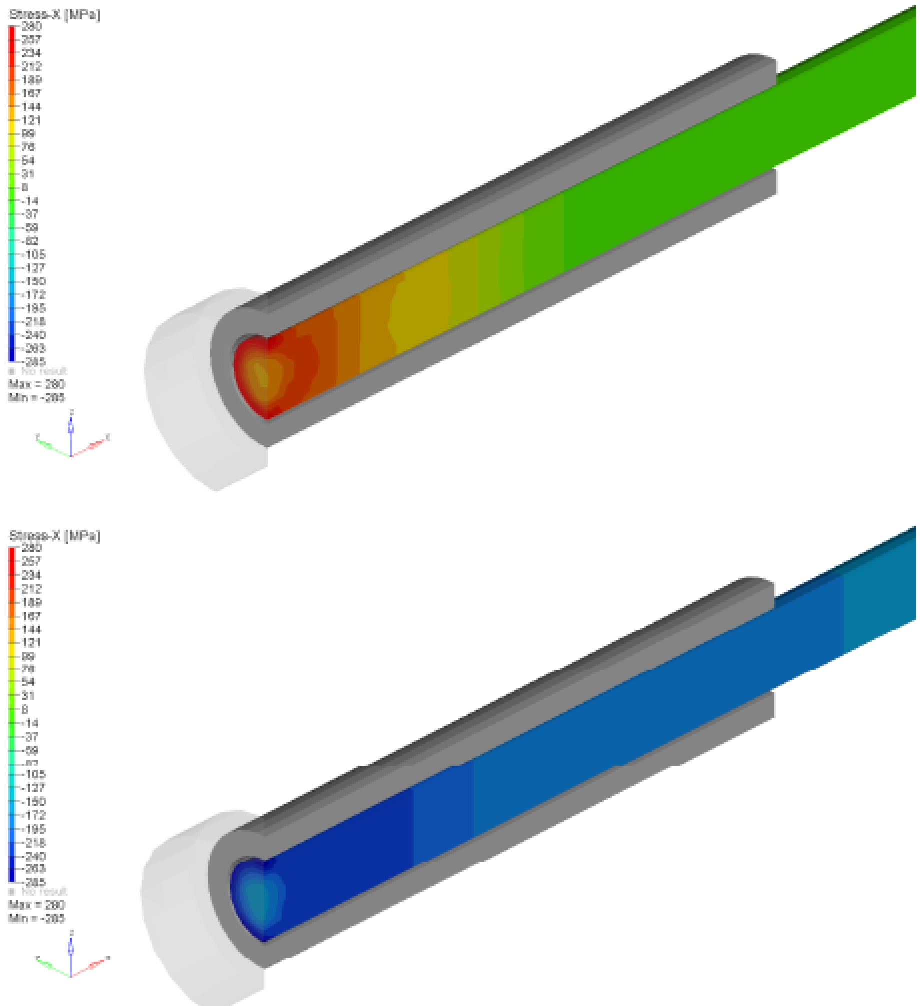

Figure 2. 10 Stress levels at incident bar and flange intersection.