



## DEVELOPMENT OF A NUMERICAL MODEL FOR SIMULATIONS OF SPLIT HOPKINSON PRESSURE BAR

Afdhal<sup>1</sup>, Annisa Jusuf<sup>1</sup>, Muhammad Agus Kariem<sup>2</sup> and Leonardo Gunawan<sup>1</sup>

<sup>1</sup>Lightweight Structures Research Group, Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Indonesia

<sup>2</sup>Mechanical Design Research Group, Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Indonesia

E-Mail: [gun@ae.itb.ac.id](mailto:gun@ae.itb.ac.id)

### ABSTRACT

To measure the dynamic behavior of material at high strain rates, ranging from 500/s to 10000/s, a Split Hopkinson Pressure Bar was developed. Numerical simulations had been used to verify the performance of the design using 2D axisymmetric model before the SHPB system was manufactured. The numerical model was validated by using measurement parameters of experiments using existing SHPB, which had been carried out to measure the dynamic behavior of St 37 and Al 6063 specimens at strain rates of 3500/s and 4000/s respectively. The results of the numerical simulations fitted the experimental results with difference of less than 10%, which validated the use of the numerical modeling in the design process of the SHPB.

**Keywords:** split hopkinson pressure bar, numerical model, experiment, high strain rate.

### INTRODUCTION

Split Hopkinson Pressure Bar (SHPB) has been widely used as a tool to measure mechanical properties of a material at high strain rates, ranging from 500/s to 1000/s [1]. The stress-strain data at high strain rate is needed in the analysis of structure response loaded at very short time as impact loads, blast loads, etc.

In the development of a new SHPB system, numerical simulations were used in to verify its performance. The numerical model was validated by comparing the simulations with the parameters of tests carried out in CSMD KAIST [2]. The measurements were carried out to measure the stress-strain relationship for St 37 and Al 6063 material at strain rates of 3500/s and 4000/s, respectively. This paper presents the development of the numerical model of the SHPB and its validation using experimental data.

### SPLIT HOPKINSON PRESSURE BAR

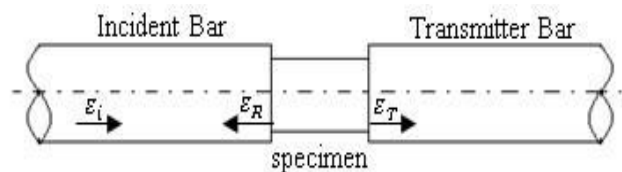
A Split Hopkinson Pressure Bar consists of an incident bar, a transmitter bar, a striker bar, a loading system, and a data acquisition system. The specimen is positioned between the incident and the transmitter bars. The striker bar, which is launched by the loading system, is used to impact the incident bar and thus generates strain wave ( $\epsilon_i$ ) in the incident bar traveling to the specimen. When the wave reaches the incident bar-specimen interface, it will partially be reflected to the incident bar as reflected strain wave ( $\epsilon_R$ ) while the other part will travel to the specimen and then to the transmitter bar as transmitted strain wave ( $\epsilon_T$ ). Figure-1 schematically describes the propagation of strain waves in SHPB. Strain gauges as parts of data acquisition system measure the incident, the reflected, and the transmitted strain waves. These signals are then used to calculate strain rate, strain, and stress of test specimen as follow [1]:

$$\dot{\epsilon}_s = 2 \frac{C}{L_s} \epsilon_R(t) \quad (1)$$

$$\epsilon_s(t) = \int_0^t \dot{\epsilon}_s(\tau) d\tau \quad (2)$$

$$\sigma_s(t) = E \frac{A_0}{A} \epsilon_T(t) \quad (3)$$

where  $A$  and  $A_0$  are the area of the bars and the specimen initial area respectively, and subscripts  $s$  indicate specimen. Eq. (1) shows that the strain rate of the specimen is proportional to reflected strain wave, Eq. (2) shows that the strain of the specimen is obtained by integrating the strain rates in time domain, and Eq. (3) shows that the stress of the specimen is proportional to the transmitted strain wave. This analysis is called one dimensional – wave analysis.



**Figure-1.** Strain waves propagation in SHPB.

To calculate the strain rate, the strain and the stress of the specimen from the measured strain waves, a starting point of each pulse was defined. Procedure to determine the starting point is shown in Figure-2. [3].

Time window of period  $T$  for incident wave is defined as 1.6 of pulse duration  $T_p$ , in other word  $T_p$  will be around 60% of  $T$  and positioned in the middle of time window [3]. The start point for reflected wave is  $(\Delta x_1 + \Delta x_2)/c_0 + \tau_s$ , where  $\Delta x_1$  and  $\Delta x_2$  are the position of strain gauge on incident and transmitter bar (50% of bar length),



$c_0$  is the elastic wave speed, and  $\tau_s$  is the characteristic time of specimen ( $\tau_s = L_s/c_s$ ).

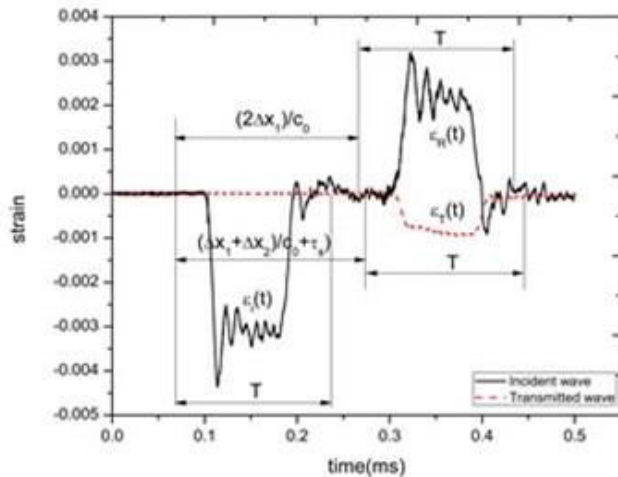


Figure-2. Determination of a start point for each pulse.

Before conducting the experiment with SHPB, bar components must be calibrated with two calibration procedures, i.e. bar apart testing and bar together testing [4]. The bar apart testing was performed by using the striker and incident bar only to obtain a correction factor of strain, i.e. the magnitude of theoretical strain ( $V/2c_0$ ) divided by measured strain. The bar together testing was performed by using the striker, the incident, and the transmitter bars. This procedure was carried out to obtain correction factor of the stress, i.e. the ratio between the transmitter and incident wave. Results of these two calibration tests are used to indicate the alignment of the bars.

Three (3) main properties of the bars, i.e. the Young's Modulus ( $E$ ), the density ( $\rho$ ), and the speed of elastic wave ( $c$ ) have to be known since they are directly related to the calculation of the strain rate, the strain and the stress of the specimen. These main properties were obtained by correcting their nominal values by following procedure described in [3].

The data calculation that has been carried out in this work is shown schematically in Fig.3.

## NUMERICAL MODEL

Finite Element Method was used to model and simulate the measurement using SHPB. The data of the bar system of the SHPB used in the experiment is shown in Table-1. In this numerical model, the three moving parts of SHPB were modeled: the striker, the incident, and the transmitter bars, and the specimen.

In the beginning, solid model was used in this SHPB numerical model, i.e. eight nodes hexahedron with element size of 0.7 mm x 0.7 mm x 1 mm [3].

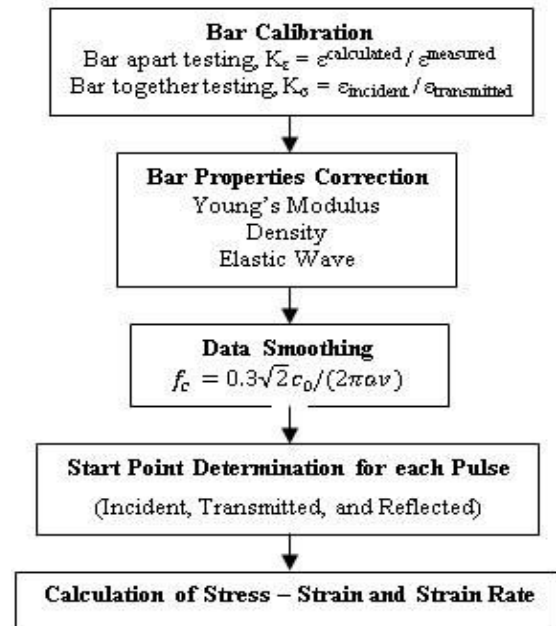


Figure-3. SHPB data calculation procedure.

The bars were meshed using Cylinder-solid meshing in LS-DYNA prepost. Solid element was chosen as the property for SHPB solid model as a representation of the physical condition of SHPB. Basically solid model is good to model the SHPB, however, it needs a lot of data storage and a long computational time. These problems eventually suggested the use of axisymmetric SHPB numerical model. In axisymmetric model, each bar was meshed using 4N-shell meshing in LS-DYNA Prepost. Axisymmetric shell element with type 15 – volume weighted was employed in this model to reduce cost and computational time. The size of the element was 1.0 x 1.0 mm [3]. Figure-4 shows a model of the SHPB bar which was constructed with 4N-shell meshing for axisymmetric model.

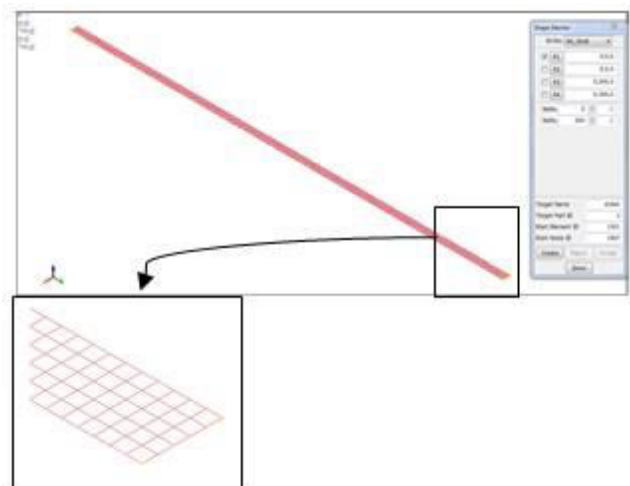


Figure-4. 4N-shell meshing for 2D axisymmetric model.



During the operation of the SHPB, the striker, the incident, and the transmitter bars are kept in elastic condition while the specimen experiences elastic-plastic deformation. Thus, the elastic material model was selected to model the bars. Since the specimens of the experiments being used for validation were kept in constant room temperature, the Simplified Johnson-Cook Mat#98 was selected as the material model of the specimen. Eq. (4) shows the flow stress equation for the Simplified Johnson-Cook [5].

$$\sigma = [A + \varepsilon^n][1 + C \ln \dot{\varepsilon}] \quad (4)$$

where A, B, n, C are material constants,  $\varepsilon$  is strain and  $\dot{\varepsilon}$  is strain rate. This model neglects the temperature parameter in the Johnson Cook model. The use of this model can give 50% faster computational time than that of full Johnson-Cook model does [5]. The coefficients of the Simplified Johnson Cook for St 37 [6] and Al 6063 [7] materials are shown in Table-2.

The simulations were performed by introducing initial velocity of 20 m/s to the striker bar, which is the same as the velocity of the striker bar during tests. Time history of strains at the middle position of incident and transmitter bars were recorded and then analyzed to obtain the strain rates, strain and stress of the specimen according to Eq. (1) to (3).

**Table-1.** SHPB parts model dimension.

| Part Name       | Length (mm) | Diameter (mm) |
|-----------------|-------------|---------------|
| Striker Bar     | 200         | 20            |
| Incident Bar    | 1500        | 20            |
| Transmitter Bar | 1500        | 20            |

**Table-2.** St 37 and Al 6063 simplified Johnson-Cook material model coefficient.

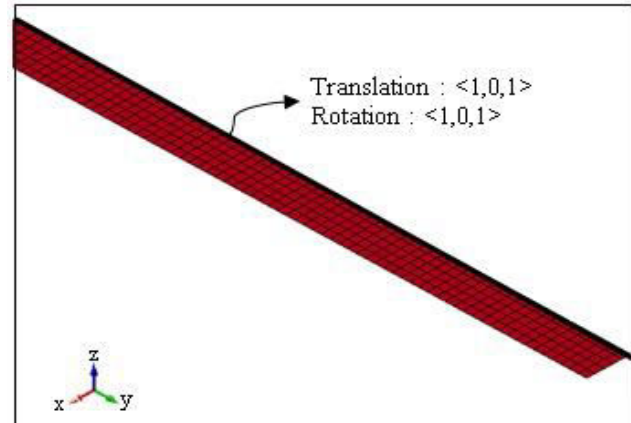
| Material | A (GPa) | B (GPa) | C     | N     |
|----------|---------|---------|-------|-------|
| ST 37    | 0.307   | 0.800   | 0.022 | 1.067 |
| Al 6063  | 0.337   | 0.343   | 0.01  | 0.41  |

Physically, there are three contacts surfaces in the SHPB system, i.e. the striker to the incident bar, the incident bar to the specimen, and the specimen to the transmitter bar. Automatic Surface to surface contact model was selected to represent the physical condition in SHPB.

The 2D axisymmetric model of SHPB was established in y-symmetric axis. The translation and rotation about y-axis were allowed but restricted in other two axes. Figure-5 shows the boundary condition that applied to the SHPB numerical model.

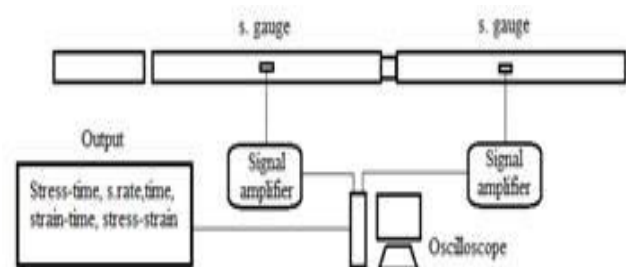
Two simulation parameters were defined to control the numerical simulations. First, the time step which was set to 1e-3 ms. This parameter was set in

ELOUT, RBDOUT, RCFORCE, and D3PLOT as the database of simulation result. Second, the termination time which was set to 0.5 ms. This parameter which determines the length of simulation time was set in ENDTIME. To activate the database, extent binary has to be defined in order to obtain the strain wave data.



**Figure-5.** Boundary condition in SHPB numerical model.

Experimental works using SHPB to obtain stress-strain relationship curves of St 37 and Al 6063 material had been carried out in CSMD Lab., Korean Advanced Institute of Science and Technology (KAIST), Rep. of Korea. The bars of the SHPB are made from Maraging steel. The diameter of the bars are the same, i.e. 20 mm. The lengths of the incident and transmitter bars are 1500 mm and the length of the striker bar is 200 mm [2]. The specimens, St 37 and Al 6063, have the same dimension, i.e. 5 mm thick and 10 mm in diameter [8]. Two strain gages were used as sensors in the data acquisition system to record the strain waves during the test. One strain gauge was mounted in incident bar and the other in transmitter bar. Each strain gauge was then connected to a bridge box, a signal amplifier, and an oscilloscope. Figure-6 shows the data acquisition scheme in experimental work.



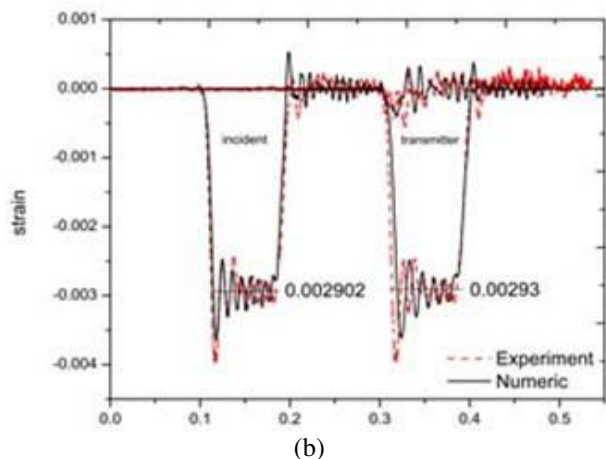
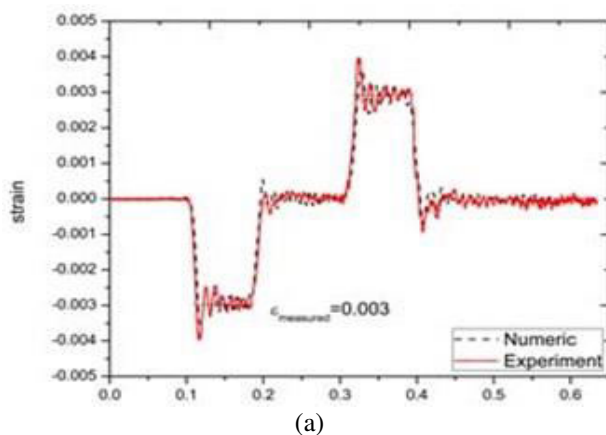
**Figure-6.** Data acquisition scheme.

Measurements were carried out in several pressure levels as the initial condition to launch the striker bar. This paper only presents the result of measurements with pressure levels of 20 psi for both St 37 and Al 6063, which equivalent to a striker speed of 20 m/s.



### SIMULATIONS OF BARS CALIBRATION

The strains of the incident bar measured in bar apart testing is shown in Figure-7(a). and those of the incident and transmitter bars in the bar together testing is shown in Figure-7(b). From this data, the strain correction factor, i.e. the magnitude of theoretical strain ( $V/2c_0$ ) divided by measured strain (0.003), was 0.98 and the stress correction factor, i.e. the ratio between the transmitter and incident wave, was 0.99. Results of these two calibration tests indicated that the bars were well aligned. Simulations carried out using ideal bar geometries and alignments with the same experimental parameters produced strains which fitted the measured strains of both calibration procedures.

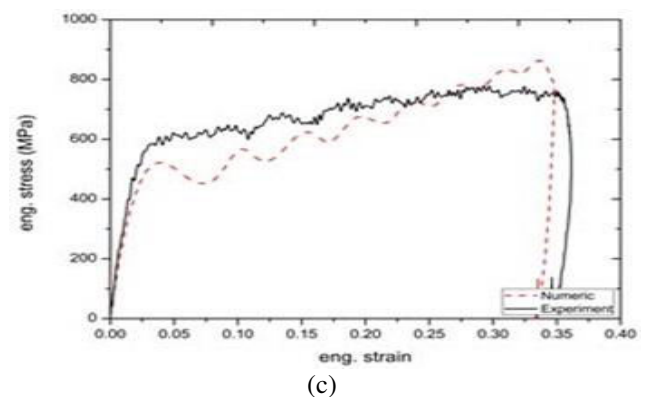
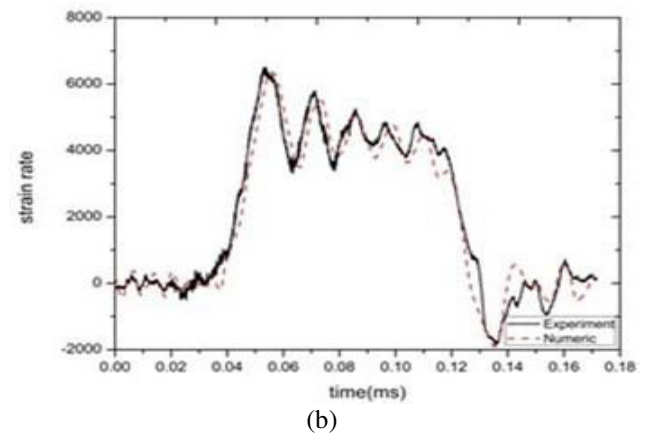
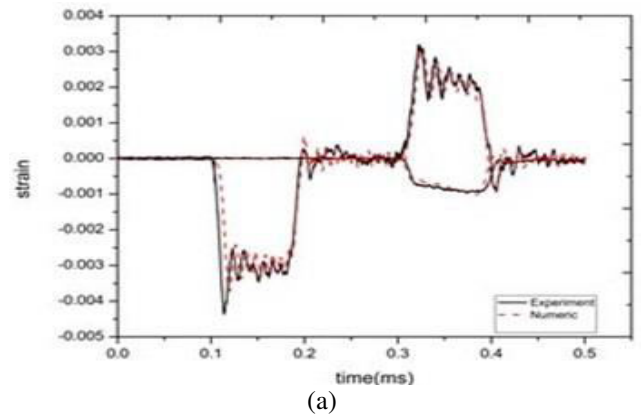


**Figure-7.(a)** The measured and simulated strains of incident bar in bar apart test and (b) those of incident and transmitter bars in bar together test.

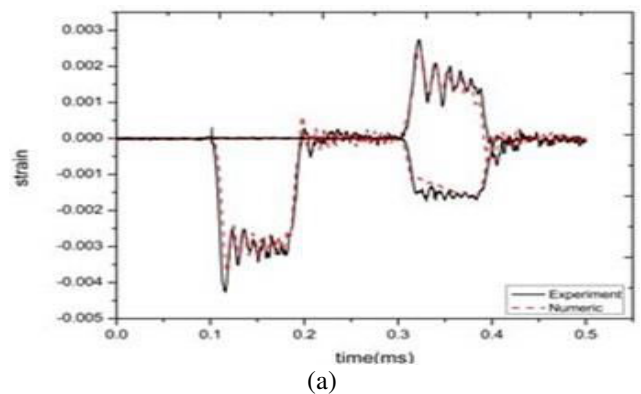
### SIMULATIONS OF EXPERIMENTS

#### Al 6063 material

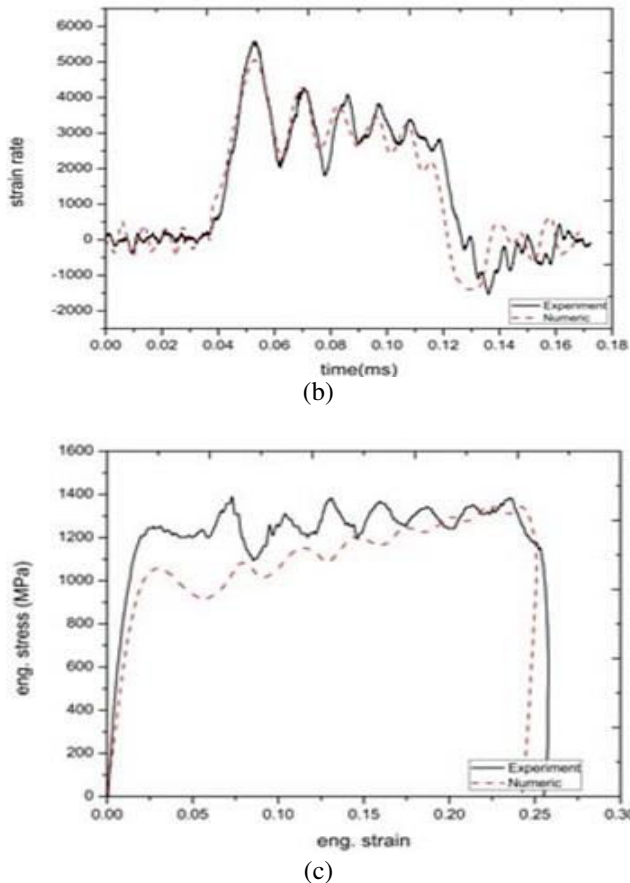
Figure-8(a) shows the strain waves of the incident and transmitter bars for Al 6063 obtained from experiments (solid line) and from numerical simulations (dashed line).



**Figure-8.** Experimental and numerical results for Al 6063 material, (a) Strain waves, (b) Strain rate, (c) Stress-strain curve.







**Figure-9.** Experimental and numerical results for St 37 Material, (a) Strain Waves, (b) Strain Rate, (c) Stress-Strain Curve.

It can be seen that the numerical model can produce strain time history that fits those obtained in the experiments. The typical incident wave has the loading duration around 0.1 ms. By using Eq. (1), (2), and (3) the strain rate and stress-strain curve of Al 6063 material were determined as shown in Figure-8(b) and Figure-8(c). The value of strain rate obtained from results of experiments and from numerical simulations are about the same, around 4000/s. The stress-strain curve for Al 6063 obtained from simulation at this strain rate fits those from experiment. The difference of maximum strain level is 5.1% and difference between stress level is below 7.3%.

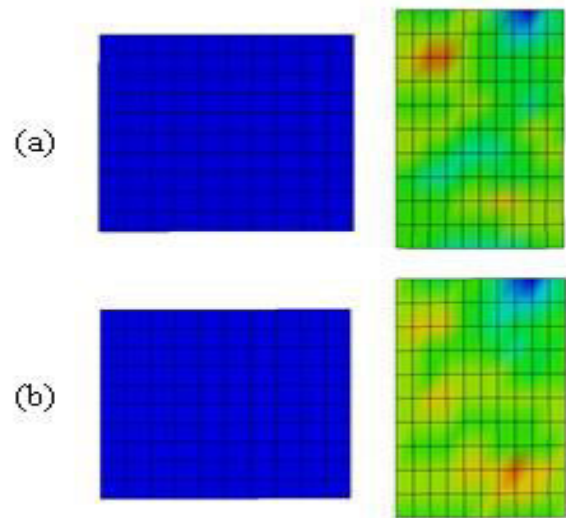
#### St 37 material

Figure-9(a) shows the strain waves obtained from experiments and numerical simulation for St 37 material. From this data, the strain rates were calculated by using Eq.(1), and the results are shown in Figure-9(b) for experiments and numerical simulation. The results show that the strain rate of this material in this test is around 3400/s. The strain and stress of the material at this strain rate were then calculated by using Eq.(2) and (3), and are shown in Figure-9(c). The numerical simulation

fits the experimental result with acceptable differences of 8.3% for stress and 3.3% for strain.

#### Deformation of specimens

Figure-10a and b show the comparison of specimen axial deformation before and after the test for Al6063 and St37, respectively. It can be seen that both Al 6063 and St37 specimens the stresses were practically uniform.



**Figure-10.** Specimen deformation before and after numerical simulations for (a) Al6063, (b) St37.

The detailed numerical and experimental results of the deformation of both specimens are shown in Table-3. The difference of the strain obtained in the numerical and experimental study are 7.2% and 7.5%, respectively, which can be accepted.

**Table-3.** Deformation of specimens.

|             | Specimen | $t_i$ | $t_f$ | Strain |
|-------------|----------|-------|-------|--------|
| Experiments | St37     | 5.21  | 3.75  | 0.28   |
|             | Al 6063  | 5.05  | 3.5   | 0.30   |
| Simulations | St37     | 5     | 3.7   | 0.26   |
|             | Al 6063  | 5     | 3.34  | 0.33   |

#### CONCLUSIONS

Numerical simulation of SHPB has been performed and validated with experimental results. Stress – strain curves and strain rates obtained from the results of the numerical simulation and experiment are successfully constructed. Numerical simulation results fits experimental results with acceptable error (<10%). The numerical model are validated to be used as a tool design in developing anew SHPB.

#### ACKNOWLEDGEMENTS

This research is funded by The Directorate of Research and Community Service – Ministry of Research,



Technology and Higher Education, Republic of Indonesia, under the scheme of Decentralization Grant Fiscal Year 2015. The support from Prof. Hoon Huh from CSMD Laboratory of Korea Advanced Institute of Science and Technology, South Korea in this research is gratefully acknowledged. Thanks also to LS-DYNA for supporting Finite Element Software that is used in this research.

## REFERENCES

- [1] W. Chen, B. Song (2011), Split Hopkinson (Kolsky) Bar Design, Testing, and Applications, Springer.
- [2] Afdhal, L. Gunawan, S. P. Santosa, I. S. Putra, H. Huh (2014), Measurement of Mechanical Properties of St 37 Material at High Strain Rates Using a Split Hopkinson Pressure Bar, Applied Mechanics and Material.
- [3] M. A. Kariem (2012), Reliable Materials Performance Data From Impact Testing, PhD Dissertation, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology.
- [4] Muhammad A. Kariem, John H. Beynon, Dong Ruan (2012), Misalignment Effect in The Split Hopkinson Pressure Bar Technique, International Journal of Impact Engineering
- [5] LSTC (2007), LS-DYNA Keyword User's Manual, Vol. II, Material Models.
- [6] L. Gunawan, S.A. Sitompul, T. Dirgantara, I.S. Putra, H. Huh (2014): Material Characterization and Axial Crushing Tests of Single and Double-Walled Columns at Intermediate Strain Rates, Journal of Mechanical Engineering, Vol. 10, No. 2.
- [7] A. Jusuf (2013), Crashworthiness Analysis of Multi Cells and Double-Walled Foam Filled Prismatic Structures, PhD Dissertation, Aeronautics and Astronautics, Faculty of Mechanical and Aerospace Eng. ITB.
- [8] [Chunghhee Park, Hoon Huh, Jungsu Park (2014), Rate-Dependent Hardening Model for Polymer-Bonded Explosives with an HTPB Polymer Matrix Considering a Wide Range of Strain Rates, J. Composite Materials.
- [9] K. F. Graff (1991), Wave Motion in Elastic Solids, Dover Publications, New York.