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Towards Standardising SHPB Testing - A Round Robin Exercise

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Abstract. The Split Hopkinson Pressure Bar (SHPB) test, while widely utilised for high strain rate tests, has yet to be standardised. As an exploratory step towards developing a standard test method or protocol, a Round Robin test series has been conducted between four institutions: (i) Swinburne University of Technology, Australia (ii) University of São Paulo, Brazil, (iii) University of Cape Town, South African and (iv) Nanyang Technological University, Singapore. Each institution prepared specimens from a metallic material, and provided batches of specimens from their chosen material to the other institutions. The materials utilised in this round of testing were commercially pure copper and aluminium, magnesium alloy and stainless steel (316 grade). The intent of the first exercise is to establish the consistency of SHPB test results on nominally identical specimens at comparable elevated strain rates, conducted by different laboratories following notionally similar test procedures with some freedom in data processing. This paper presents and compares the results of the first batch of tests for copper, identifying variations between results from different laboratories. The variation between different laboratories' results for copper is sufficiently small that there is confidence in the potential to develop a draft standard in future.

1 Introduction

The Split Hopkinson Pressure Bar (SHPB) [1] or Kolsky Bar [2] test is a well established means of investigating mechanical response of a material to high strain rate ($\approx 10^2$ to 10^4 s^{-1}) loading. The fundamental principles and guidelines for setting up, conducting and analysing a SHPB experiment are well described by Gray III [3], and Chen and Song [4]. However, conducting a successful SHPB experiment requires decisions on a large range of parameters (e.g. bar materials, length, diameter, specimen dimensions etc) and post-processing methods (1,2 or 3 wave analysis, dispersive or non-dispersive wave propagation etc). No standard describes reasonable starting values for these parameters for typical engineering materials.

To the best of the authors' knowledge, no data has been published showing that SHPB testing conducted at different laboratories, on specimens of the same provenance, produce consistent stress-strain results to within an acceptable tolerance. This article documents a Round Robin test series, which sought to establish whether specimens of the same material, tested in compression at SHPB facilities at different institutions, would produce similar stress-strain results. The intent is to ascertain how much the raw experimental data varies, given different physical SHPB set ups, and how different data processing methods affect the stress-strain curves which are the ultimate output of the experiments. This would provide guidance for drafting a testing standard in future. Four institutions participated in the exercise, with each institution providing specimens of a nominated metallic material, prepared from a single source. Each institution performed SHPB tests on a batch of its own material, as well as three other batches of different materials, provided by the other institutions. The participating institutions, as well as the material provided, are detailed in Table 1.

2 Experimental Details

2.1 Specimen Details

Each laboratory manufactured 40 cylindrical compression specimens, of one of the materials specified in Table 1. The specimens were 6.0±0.1 *mm* in diameter and 4.0±0.1 *mm* in length. The end faces were machined parallel and polished using 600 grit SiC polishing paper. The diameter and length had tolerances of ±0.1 mm. Each laboratory retained 10 specimens for in-house testing, and shipped batches of 10 specimens to the three other institutions for testing.

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Table 1. Participants and materials.

Institution	Country	Material
Nanyang Technological University (NTU)	Singapore	Magnesium AZ31B
Swinburne University of Technology (SUT)	Australia	Stainless Steel 316
University of Cape Town (UCT)	South Africa	Aluminium 1100
University of São Paulo (USP)	Brazil	Copper (commercially pure)

2.2 Physical SHPB Details

All of the laboratories used conventional compression SHPB arrangements, as shown in Figure 1, with the striker being driven by a gas gun. The participating laboratories used SHPB of different dimensions and materials, detailed in Tables 2 & 3.

Each laboratory aligned and calibrated their SHPB according to their preferred procedures (not described for brevity). Alignment was not measured, though bar misalignment can introduce errors [5] and measurement thereof is being considered for a follow up study. The target for each laboratory was a plastic strain of approximately 20%, in a strain rate range of 1000 to 2000 s^{-1}. Each laboratory varied striker velocity to achieve this target. However, it was not specified as to whether the strain rate range, or the maximum plastic strain, was the more important target. To avoid increasing experimental complexity and cost, relatively simple pulse smoothing / shaping methods were used: 4 layers of paper (NTU), 4 layers paper masking tape (UCT), 3 layers of paper (SUT), while USP did not employ any pulse smoothing or shaping. Specimens were positioned by hand and lubricated with: common grease (NTU & SUT) petroleum jelly (UCT), while USP did not apply lubricant.

2.3 Instrumentation details

All the laboratories used a pair of diametrically opposed foil resistance strain gauges (nominal resistance 120 Ω) on each bar. The positions of the gauges on the input and output bar are noted in Table 2, while details of the amplification and data acquisition are provided in Table 4.

2.4 Data Processing

The data processing methodology was not prescribed as part of the exercise, to help ascertain how much variation in final results the different methods would induce. In this exercise, all laboratories employed input and output bars of equal diameter d, and therefore the area of the input and output bars A_B are equal. Obtaining specimen stress-strain from an SHPB experiment requires several decisions about how to process the captured incident ε_I, reflected ε_R and transmitted ε_T strain waves. Specimen strain may be calculated purely based on ε_R (1-Wave method), which assumes specimen equilibrium, or using all of ε_I, ε_R and ε_T (3-Wave method), which does not inherently assume

equilibrium [3]. Similarly specimen stress may be calculated from only ε_T (1-Wave), superimposing ε_I and ε_R (2-Wave), or averaging input and output face forces, which uses ε_I, ε_R and ε_T (3-Wave). All these methods require that the wave captured at the strain gauge be shifted to the relevant bar-specimen interface. This shift can either assume 1-dimensional wave propagation, and hence no shape change; or it can correct for dispersion of the wave in the frequency domain using a phase shift calculated from the Pochammer-Chree phase velocity-frequency relationship (originally proposed in [6, 7], current procedure described in [8]). The identification of the start of specimen loading may be either by inspection, or using techniques such as proposed by Zhao and Gary [9] or Li and Lambros [10]. While each laboratory used different methods for calibrating the bars' wave speed C_o and calibration factors for converting strain gauge voltage to actual strain, the details of these methods have been omitted from this publication for brevity. All laboratories confirmed dynamic equilibrium of the specimen for the test to be acceptable. The different processing methods employed by each laboratory are summarised in Table 5.

3 Results and Discussion

While four different materials have been tested in this exercise, only the data for copper are presented in this paper due to space constraints. Before data from any test was considered valid, the equilibrium of forces on the input and output faces of the specimen was checked. Some examples of this for each laboratory are shown in Figure 2. The valid data sets from each laboratory for copper are shown in Figure 3. The maximum plastic strain varies between laboratories, as is expected due to the different striker lengths and velocities. The strain rates stated in each figure are the average strain rate, taken from the peak rate to the point where the specimen begins to unload. As each laboratory could vary striker velocity, there is a variation in strain rates achieved between laboratories.

As is usual for SHPB data, there are oscillations on any given specimen's stress-strain curve as well as the usual specimen-to-specimen variation. Attempting to overlay all the data from the subfigures of Figure 3 on a single figure makes it very difficult to distinguish one batch of data from another. A reduced set of points from all of the flow stress curves from each laboratory are shown overlaid in Figure 4a. It is clear that there is significant overlap in the data from each laboratory. To help discern differences between the four laboratories' data sets, the entire flow stress data set from a single laboratory is fit to a power law, $A + B\varepsilon^n$.

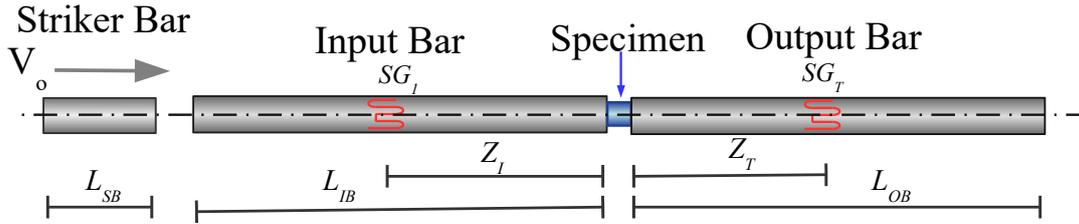[1]Gain is constant to 100 kHz, gain drop off and phase shift characterised up to 1 MHz and corrected in post processing

Fig. 1. Schematic of SHPB.

Table 2. SHPB Dimensions.

Parameter	NTU	SUT	UCT	USP
Bar Diameter D_B (*mm*)	12.7	14.5	12.7	24.99
Striker Length L_{SB} (*mm*)	300	300	350	253
Input Bar Length L_{IB} (*mm*)	1000	1200	1199	1990
Output Bar Length L_{OB} (*mm*)	1000	1200	700	1990
SG_I to specimen Z_I (*mm*)	500	500	599.5	1000
Specimen to SG_T Z_T (*mm*)	501	400	100	1000

Table 3. SHPB Mechanical Properties.

Parameter	NTU	SUT	UCT	USP
Bar Material	Stainless Steel 304	Maraging Steel 350	Stainless Steel 17-4 PH	Steel SAE 1055
Density ρ (*kg.m^{-3}*)	8000	8070	7735	7816
Wave Speed C_o (*m.s^{-1}*)	5138	4800	5025	5082
Elastic Modulus E (GPa)	200	186	195	194
Poisson Ratio ν	-	0.31	0.3	0.29

Table 4. Instrumentation details.

Parameter	NTU	SUT	UCT	USP
Amplifier Gain	1000	300	1000	n/a
Upper Frequency Limit (*kHz*)	3000	500	1000 [1]	500
Bridge Excitation V_{BR} (*V*)	2.46	2	2.27	5
DAQ Resolution (bits)	8	n/a	16	12
DAQ Full Scale (*V*)	0.5	0.5	±5	n/a
Sampling Rate (*MSa.s^{-1}*)	1.25	5	10	5
Sampling Duration (*ms*)	1.0	0.5	1.5	80

Table 5. Data processing methodologies.

	NTU	SUT	UCT	USP
Wave Shifting	1-D	1-D	Disp. Corr.	1-D
Specimen Strain Calc.	1-Wave	1-Wave	3-Wave	1-Wave
Specimen Stress Calc.	1-Wave	1-Wave	1-Wave	1-Wave
Start of loading	Insp.	Insp.	Insp.	Insp.

An example of the power law fit to all specimen plastic flow data for a single laboratory is shown in Figure 4b.

Figure 5 shows the power law flow curves fit to each laboratory's data set for copper, which makes some subtle differences more obvious. Based on the power laws, the average flow stress at $\varepsilon = 5\%$ is 335 MPa, with a standard deviation of 7 MPa. As the strain increases to 20%, the average flow stress increases to 377 MPa while the standard deviation also increases to 11 MPa. In the ASTM Standard Test Method for Quasi-Static compression of metals at room temperature [11], the 95% reproducibility limit for Al-2024 with a yield strength of

346 MPa was 19 MPa between laboratories. This gives good confidence in the reproducibility between laboratories conducting SHPB tests at high strain rates. The flow stress for the SUT data is higher than the other laboratories, though marginally so than that of USP. The flow stresses from the UCT and NTU data are practically indistinguishable. The SUT tests were conducted at the highest average strain rate $\dot{\varepsilon} \approx 2.55 \times 10^3 \pm 0.12 \times 10^3 \ s^{-1}$. The UCT tests were conducted at the lowest average strain rate $\dot{\varepsilon} \approx 1.05 \times 10^3 \pm 0.12 \times 10^3 \ s^{-1}$. The strain rate bands for NTU and USP overlap, at $\dot{\varepsilon} \approx 1.6 \times 10^3 \pm 0.3 \times 10^3 \ s^{-1}$ and $\dot{\varepsilon} \approx 1.5 \times 10^3 \pm 0.1 \times 10^3 \ s^{-1}$ respectively. If the variation
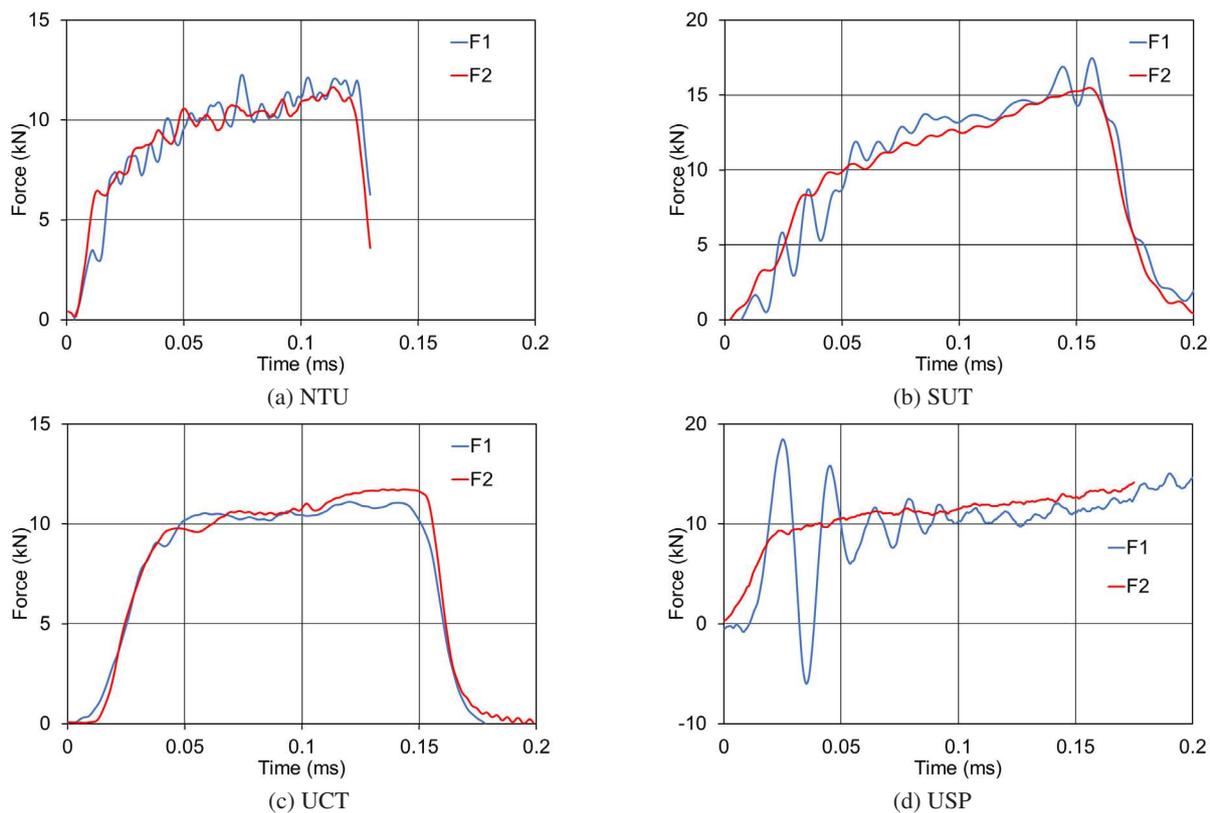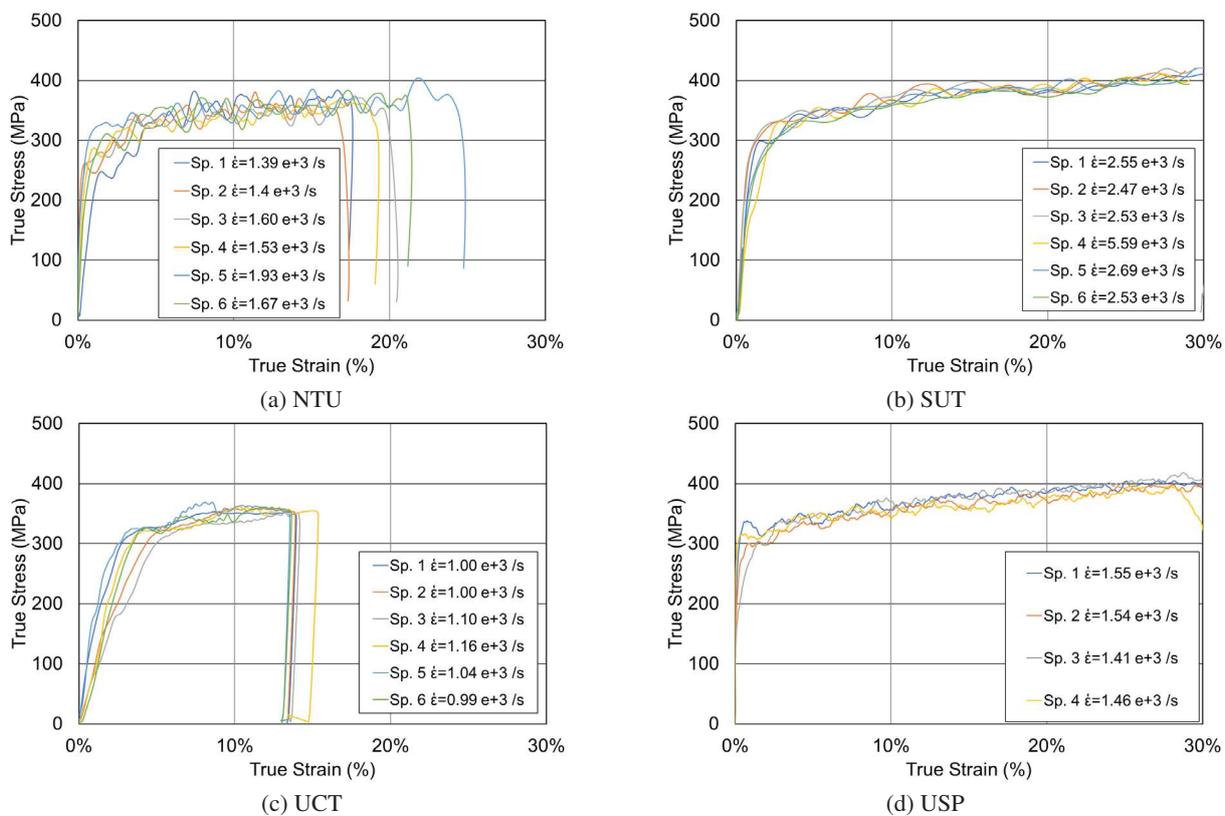
Fig. 2. Force equilibrium verification for copper.

Fig. 3. True stress-true strain data for valid copper tests from all laboratories.

(a) Flow stress point cloud for all valid copper tests from all laboratories.

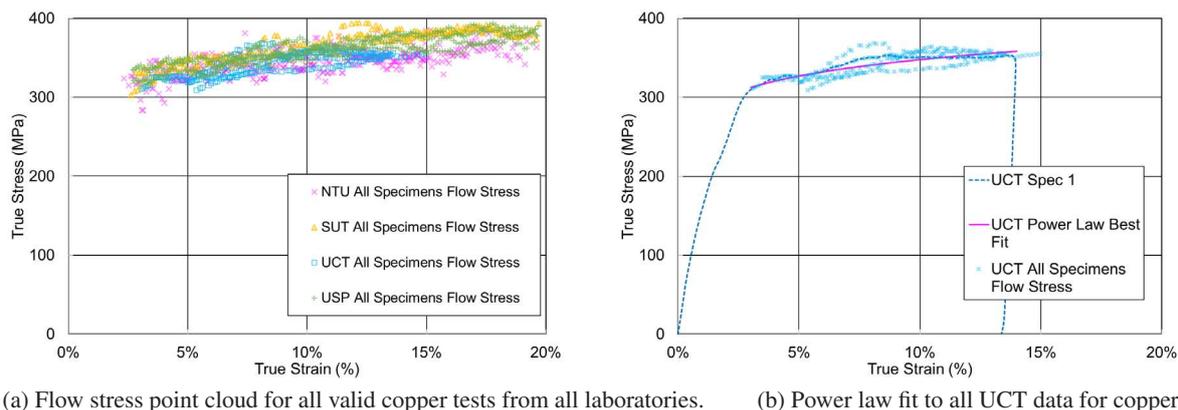(b) Power law fit to all UCT data for copper.

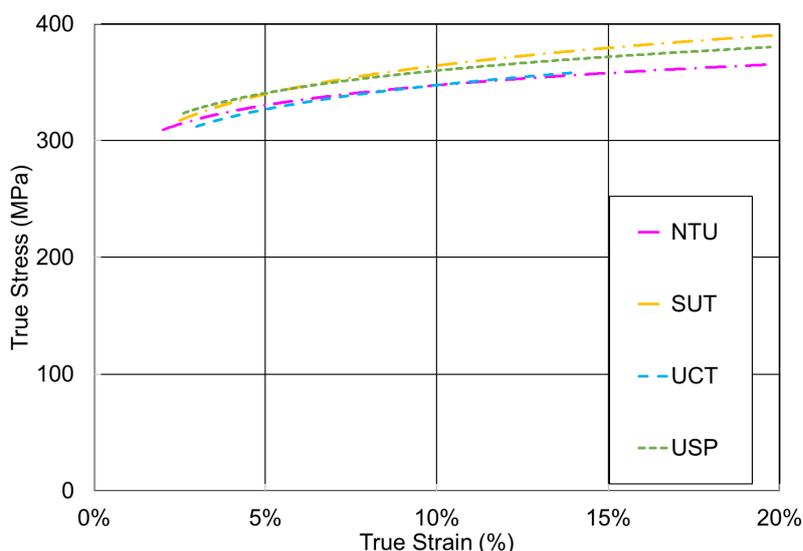**Fig. 4.** Flow stress data for copper and power law fitting.

Fig. 5. Best fit power law flow curves for all laboratories for copper specimens.

between the laboratories was purely due to strain rate, the data from NTU and USP should coincide, which is not the case. An analysis of the variations due to data processing methods and other experimental variables is not possible in this article due to space constraints. Nonetheless, the variation between laboratories' data sets is small enough that there is confidence moving forward.

4 Concluding Remarks

Four laboratories participated in a Round Robin exercise aimed at developing a standard test method for SHPB testing of metallic materials. The laboratories all used different physical SHPB arrangements, as well as instrumentation and data processing. The variation between flow stress curves shows that different laboratories can produce consistent data for the same specimens, even though a relatively broad range of instruments and data processing methods was employed. This suggests that a future standard test method for SHPB tests need not be onerously prescriptive in order to obtain consistent results. More detailed analysis of the variations between laboratories in experimental apparatus, test method and data analysis is

planned for future publications which are less space constrained. It is hoped that a further experimental Round Robin series can be conducted with more participants and a more refined prescribed method.

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