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Revisiting Kolsky bar data evaluation method

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ABSTRACT

Conventional Kolsky bar data evaluation method is based on the assumption of stress equilibrium within the specimen during testing. When the objective is to generate stress–strain diagrams up to failure, damage initiation and evolution within the specimen should be taken into account. In that case, stress wave attenuation would take place and the assumption of stress equilibrium would not be valid. In this study, the data evaluation method is revisited and analytical expressions considering possible damage are presented. The revisited method gives higher specimen strain rate and strain compared with the conventional method. Both methods give the same specimen stress.

1. Introduction

High strain rate characterization of materials is an important consideration for several structural and manufacturing applications. Considering the importance of this area, several material characterization techniques have been developed over the years. Among them, Kolsky bar technique [1] has been one of the widely used test methods to evaluate material behavior at high strain rates. Since its introduction, it has been the dominant technique for high strain rate characterization of materials in the strain rate range of 10^2 to 10^4 per sec [2,3]. The Kolsky bar, also known as compressive split Hopkinson pressure bar, was originally devised to determine the dynamic compressive stress–strain behavior of materials. Since then several advances have taken place with alternate schemes made available for tensile and torsional high strain rate testing of materials [3].

The design and development of Kolsky bar is based on the theory of one dimensional wave propagation in elastic bars. Analytical expressions for determining material properties under high strain rate loading have been developed [3,4]. Original high strain rate analysis by Kolsky [1] was based on the following basic assumptions:

- Wave motion in the bars can be described by one dimensional wave propagation theory.
- Stress and strain fields in the specimen are uniform in its axial direction.
- Specimen inertia effect is negligible.
- Friction effect in the compression test is negligible.

The first assumption is considered while selecting the length and diameter of the pressure bars. To ensure one dimensional wave propagation, a bar length in excess of 10 bar diameters is required [3]. However, based on other requirements like separation of incident and reflected waves, and maximum desirable strain rate and strain in specimen, much larger length to diameter ratios are employed. Considering specimen inertia effects, Davies and Hunter [5] suggested that the effects of radial and axial inertia cancel out when the specimen aspect ratio $l_S/d_S = (3\nu/4)^{1/2}$. For the effect of friction to be minimum, the aspect ratio should be in the interval $1.5 < l_S/d_S < 2$ [6].

Conventional equations assuming stress equilibrium within the specimen have been used for Kolsky bar analysis [7–15]. The assumption of specimen stress equilibrium during testing has been discussed by a few researchers [16–23]. However, to our knowledge, only nascent attempts have been made in literature to provide an alternate framework without considering specimen stress equilibrium. Equilibrium and axial uniformity of stress in a Kolsky bar specimen is assessed by comparing the stresses at the interfaces of incident bar–specimen and specimen–transmitter bar. For stress equilibrium to exist, stresses at both interfaces must be equal.

The assumption of stress equilibrium within the specimen would be valid for cases where damage initiation and evolution do not take place during testing. For the cases where the objective of Kolsky bar testing is to generate stress–strain diagrams up to failure for different materials, the specimen would experience damage initiation and evolution. In such cases, stress wave attenuation would take place within the specimen during testing and

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Nomenclature

A	cross-sectional area of the bar
A_B	cross-sectional area of incident/transmitter bar
A_S	cross-sectional area of the specimen
C	wave propagation velocity in the specimen
Co	wave propagation velocity in incident/transmitter bar
d_S	specimen diameter
D	diameter of incident/transmitter bar, diameter of specimen
E	Young's modulus of the bar material
I	incident pulse
l_S	specimen length
P_1	force on specimen–transmitter bar interface
P_2	force on specimen–incident bar interface
R	reflected pulse
t	time
T	transmitter pulse
x	distance from point of impact to element
u	particle displacement
u_1	particle displacement at interface 1
u_2	particle displacement at interface 2
v	particle velocity
v_1	particle velocity at interface 1
v_2	particle velocity at interface 2
v_I	particle velocity of incident wave
v_R	particle velocity of reflected wave
v_T	particle velocity of transmitted wave
ε	axial strain
$\dot{\varepsilon}$	strain rate
$\varepsilon_S(t)$	specimen strain
$\acute{\varepsilon}_S(t)$	specimen strain rate
ε_R	reflected strain
ε_I	incident strain
ε_T	transmitted strain
$\sigma_S(t)$	specimen stress
ρ	density, density of incident/transmitter bar
ν	specimen Poisson's ratio

the assumption of stress equilibrium would not be valid. This would have a bearing on reported results since the analytical expressions obtained by the conventional method have been simplified based on this assumption.

The objective of the present work is to revisit the data evaluation method in Kolsky bar testing. The focus is on validity of stress equilibrium assumption during damage initiation and evolution within the specimen. It is observed that the forces at both the specimen–bar interfaces are not equal during testing and the concept of stress wave attenuation is used to explain this observation.

2. Analytical expressions for material characterization during Kolsky bar testing

The conventional method to derive the analytical expressions used for data processing is presented in Appendix A. The final equations, namely Eqs. (A.17)–(A.19), are presented here as Eqs. (1)–(3) to facilitate discussion. The equations presented here are based on the assumption that specimen stress equilibrium exists during testing. The data evaluation method using these equations would be referred to as Case 1. The specimen strain rate, strain and stress are evaluated using the expressions given below:

$$\text{Strain rate, } \acute{\varepsilon}_S(t) = (2C_O/l_S)(\varepsilon_R) \quad (1)$$

$$\text{Strain, } \varepsilon_S(t) = (2C_O/l_S)\int_0^t (\varepsilon_R(t))\,dt \quad (2)$$

$$\text{Stress, } \sigma_S(t) = -E(A_B/A_S)[\varepsilon_T(t)] \quad (3)$$

Eqs. (1)–(3) are widely used by researchers to report Kolsky bar test results [7–15]. It should be noted that in the above expressions, compressive stress, compressive strain and compressive strain rate are taken to be positive. Also, the actual values (sign included) of incident, transmitted and reflected strains are considered.

3. Stress wave attenuation during Kolsky bar testing

The assumption of specimen stress equilibrium has been conventionally used in deriving the analytical expressions for evaluating specimen strain rate, strain and stress as given by Eqs. (1)–(3). Since damage initiation and evolution within the specimen are not considered in these equations, it is implied that same stress levels exist at interfaces 1 and 2. Here, the interface between incident bar and specimen is considered as interface 1 and the interface between the specimen and transmitter bar is considered as interface 2. Such an assumption may not be valid in case of damage initiation and evolution within the specimen. Therefore, the assumption of specimen stress equilibrium should be revisited. The difference in forces observed at interfaces 1 and 2 is explained on the basis of stress wave attenuation in the specimen during testing.

During Kolsky bar testing, damage initiation and evolution would take place prior to ultimate failure. Stress wave reflection and transmission would occur at the fracture surfaces, formed due to onset of damage within the specimen, leading to stress wave attenuation.

In case of metallic specimens, the concept of stress wave attenuation can also be explained on the basis of geometrical and metallurgical factors. During high strain rate tensile testing of metals, it is observed that specimen necking takes place before ultimate failure. In such a scenario, with a change in cross-sectional area along the gauge length, the specimen could be approximated as a stepped specimen. Due to necking, stress wave attenuation would take place as the stress wave propagates within the specimen since the stress wave would be partly transmitted and partly reflected due to geometrical variation in terms of cross-sectional area.

The metallurgical changes that occur within the specimen when it is tested at high strain rates is also a major contributing factor for stress wave attenuation. At high strain rate loading, as the strain increases, the dislocation density increases [24–26]. Hence, the incident stress wave would encounter more boundaries as the strain increases, leading to greater attenuation of the incident stress wave. This is valid for both tensile and compressive loading cases.

For the reasons presented above, the magnitude of force at interface 1 would be greater than the magnitude of force at interface 2. As a result, the conventional Kolsky bar expressions may not provide correct results. In other words, the assumption of stress equilibrium within the specimen during testing would not be valid. Therefore complete derivation of the analytical expressions needs to be revisited.

4. Revisiting Kolsky bar data evaluation method

The derivation of conventional analytical expressions used to characterize materials using Kolsky bar apparatus is explained in