Compressive behavior of Sulcata Tortoise’s carapace at high rate of deformation

Nadda Jongpairojcosit$^{1,2}$, Chinnawit Glunrawd$^1$ and Petch Jearanaisilawong$^{1,*}$

$^1$ Department of Mechanical and Aerospace Engineering, Faculty of Engineering
King Mongkut’s University of Technology North Bangkok,
1518 Pracharat 1 Rd, Wongsawang, Bangsue, Bangkok 10800, Thailand
$^2$ Defence Technology Institute (Public Organization), Ministry of Defence
Office of the Permanent Secretary of Defence (Chaengwattana)
4th Floor, 47/433 Moo 3, Ban Mai, Pak Kret, Nonthaburi 11120, Thailand

* Corresponding Author: petch.j@eng.kmutnb.ac.th

Abstract. This paper presents the dynamic compressive response of tortoise carapace at high rate of deformation. Disk specimens are cut from carapace and compressed using Split-Hopkinson Pressure Bar (SHPB) technique. The steel bar system together with a copper pulse shaper generate an incident wave that can achieve a constant rate of deformation within the specimens. The results show increasing compressive modulus and compressive strength compared to the quasi-static data of carapace. The strain waves on the incident and the transmission bars from finite element analysis based on the experimental setup agree with the test data.

1. Introduction
Sulcata tortoise or African spurred tortoise is a desert dwelling tortoise. It has a large shell, which the length from head to tail can reach 80 cm when fully grown. The shell is its natural shield to prevent its body from attack. The dome-shape of the shell known as carapace is the main part of the protection. The carapace structure has four distinctive layers, which are keratin scutes, dorsal cortex, cancellous interior and ventral cortex. The keratin scutes made of fibrous structural protein cover the outer shell surface. The other layers are bone-like materials; the dorsal and ventral cortices are dense solids, whereas the cancellous interior is a closed-cell structure. The mechanical responses under quasi-static loading and microscopic structures of turtle shells have been adapted in bio-inspired armor designs [1]-[2]. However, the discussion on the dynamic behavior of tortoise’s carapace is still limited.

Split-Hopkinson pressure bar (SHPB) technique is utilized to investigate mechanical behavior of materials under high strain rate. The test system consists of striker, incident and transmission bars of the same diameter and material. These bars are axially aligned with free movement in the longitudinal direction. The sample is placed between the incident and transmission bars. The striker launched by compressed gas hits the incident bar that generates the incident wave travelling along the incident bar. Some part of the incident wave passes through the sample and the transmission bar, while the other part reflects back along the incident bar. The strain waves on the incident and the transmission bars are recorded by oscilloscope for material behavior analysis. In the case of soft materials, pulse shaper technique is implemented to increase the rise time of incident wave to achieve dynamic equilibrium. Figure 1 presents a schematic of the SHPB system.
Figure 1. Split-Hopkinson pressure bar configuration in compression test.

With the assumption of one-dimensional wave propagation, the strain rate in the specimen \( \dot{\varepsilon}_s \) as a function of time, \( t \), can be calculated as \([3]\)

\[
\dot{\varepsilon}_s (t) = \frac{c_b}{l_s} (-\varepsilon_i (t) + \varepsilon_r (t) + \varepsilon_t (t)) \tag{1}
\]

where \( c_b \) is the elastic wave speed of the bars, \( l_s \) is the thickness of the specimen, \( \varepsilon \) is the strain wave and the subscript \( i, r \) and \( t \) stand for incident, reflected and transmitted wave, respectively.

The strain on specimen \( \varepsilon_s \) can be derived from the time integral of Equation (1) as shown in equation (2) and the stress on specimen \( \sigma_s \) is given by equation (3).

\[
\varepsilon_s (t) = \frac{c_b}{l_s} \int_0^t (-\varepsilon_i (t) + \varepsilon_r (t) + \varepsilon_t (t)) dt \tag{2}
\]

\[
\sigma_s (t) = \frac{A_b E_b}{2A_s} (\varepsilon_i (t) + \varepsilon_r (t) + \varepsilon_t (t)) \tag{3}
\]

where \( A_b \) and \( E_b \) are the cross-sectional area and elastic modulus of the bars, respectively. \( A_s \) is the cross-sectional area of the specimen.

The SHPB result is only valid when the specimen attains dynamic equilibrium. This condition is determined by force balance in equation (4). The forces are derived from equation (5) - (6).

\[
F_1 (t) = F_2 (t) \tag{4}
\]

\[
F_1 (t) = A_b E_b (\varepsilon_i (t) + \varepsilon_r (t)) \tag{5}
\]

\[
F_2 (t) = A_b E_b \varepsilon_t (t) \tag{6}
\]

where \( F_1 \) and \( F_2 \) the forces at the interfaces between the incident bar and the specimen and the transmission bar and the specimen, respectively.

The aim of this study is to examine the dynamic compression behavior of tortoise’s carapace using a compressive SHPB system with steel bars and a copper pulse shaper. The finite element analysis is carried out to explore the impact behavior of the carapace. The stress-strain result at high strain rate can be used to define dynamic plastic behavior of tortoise’s carapace that sheds light into the underlying energy absorption mechanism of the carapace layers.
2. Experiment and method

Circular disk samples are prepared from a dried carapace. The disk surfaces and edges are polished with sandpaper. The keratin scutes are totally removed because of its wavy surface. The dorsal and ventral cortices are slightly ground to obtain flat surfaces; the disk samples resemble bone-like sandwich structure with a porous core. The curvature and thickness of the carapace are major constraints of the sample size. Average diameter and thickness of specimens are 15.8 mm and 3.3 mm, respectively.

Our SHPB system consists of the striker, incident and transmission bars made of AISI 4340 alloy steel having the diameter of 20 mm and the length of 300 mm, 2000 mm and 1500 mm, respectively. The firing system is driven by compressed air and the velocity of the striker is controlled by the air pressure. The striker speed is measured by two infrared sensors attached at the end of the striker bar launching barrel. The strain gauges are attached on the incident and transmission bars for strain wave acquisition. The data is captured through a digital oscilloscope that has a sampling rate of 2.5x10^6 per second. Since the tortoise carapace is a biological and porous material that has a low wave speed, a pulse shaper is required to increase rise time to attain dynamic equilibrium. Vecchio and Jiang [4] proposed that the shape of the incident wave should be tailored to conform to the shape of the transmitted pulse to achieve a constant strain rate. C1100 copper disks with a diameter of 12 mm and a thickness ranging from 1.0, 1.5 to 2.0 mm were used as pulse shapers in this study. After preliminary measurements, the 2.0 mm pulse shaper with 4 bars firing pressure provide a striking velocity of 14 m/s and an incident wave that results in dynamic equilibrium at a constant strain rate. Figure 2 shows the positions of the pulse shaper and the specimen. The system is calibrated before the experiment to confirm the coaxial impact at the bar interfaces.

![Figure 2](image-url)

**Figure 2.** (a) copper pulse shaper (b) tortoise carapace specimen.

To gain an insight into the impact behavior of the carapace under compression, a numerical analysis of the specimen under SHPB system is performed. The finite element model is created in ANSYS using 3D hexahedral elements and frictionless conditions on the contact surfaces. To take advantage of the structural symmetry, only a quarter of the bars’ cross-section is modeled. Moreover, the specimen sandwich structure is simplified as a solid disk. The dimensions of bars, pulse shaper and specimen are replicates of the experimental values. The completed FE model consists of 45,942 elements. The AISI 4340 steel bar and copper pulse shaper are modeled as rate-dependent elastic-plastic materials with standard parameters from software’s library. The elastic behavior of the carapace is taken from [5]. Due to the limitations of rate dependent plastic data, the plastic behavior of the carapace is modeled after those of human skull [6]. Table 1 lists the material parameters in the finite element model. The strain wave signals on the incident and transmission bars from the analysis are compared with the experimental data.
Table 1. Material parameters in finite element model

|                   | Steel AISI 4340 | Johnson Cook Strength |
|-------------------|-----------------|-----------------------|
| Density           | 7830 kg/m³      |                       |
| Bulk modulus      | 159 GPa         |                       |
| Shear Modulus     | 81.8 GPa        |                       |
| Initial yield stress | 792 MPa     |                       |
| Hardening constant | 510 MPa       |                       |
| Hardening exponent | 0.26           |                       |
| Strain rate constant | 0.014         |                       |
| Thermal softening exponent | 1.03          |                       |
| Melting Temp.     | 1520 °C         |                       |

|                   | Copper          | Mie-Gruneisen equation of state |
|-------------------|-----------------|-------------------------------|
| Density           | 8900 kg/m³      |                               |
| Shear Modulus     | 46.4 GPa        |                               |
| Gruneisen coefficient | 2              |                               |
| C1                | 3958 m/s        |                               |
| S1                | 1.497           |                               |

|                   | Carapace        | Mie-Gruneisen equation of state [6] |
|-------------------|-----------------|-------------------------------------|
| Density           | 1470 kg/m³      |                                     |
| Shear Modulus     | 154 MPa         |                                     |
| Gruneisen coefficient | 1              |                                     |
| C1                | 1850 m/s        |                                     |
| S1                | 0.94            |                                     |

3. Results and discussion

Figure 3 presents the strain waves on incident and transmission bars. These data are derived from the voltage signal of the strain gauges using an in-house MATLAB code. The positive and negative values represent the characteristics of tension and compression in the specimen, respectively. When the striker bar hits the incident bar, it creates a compressive incident wave. Instead of a square wave, the steel bars together with the copper pulse shaper modify the incident wave and increase the rise time as shown in figure 3.

![Strain wave signals from SHPB testing.](image)

This pulse shaper induces a constant strain rate on SHPB testing of the carapace. It also matches with the report from Bekker et al. [6]. The incident wave travels along the bar to the interface between the incident bar and the specimen. At this point, the wave separates into reflected and transmitted waves. The reflected wave is in tension while the transmitted wave is in compression. The reflected wave is
measured from the strain gage on the incident bar, and the transmitted wave is measured from that on the transmission bar.

The dynamic equilibrium is investigated by comparing forces on both ends of the specimen. From equation (5) - (6), these forces are calculated from the strains of incident, reflected and transmitted waves. Figure 4 shows that the system attained dynamic equilibrium between 25-80 microseconds. The graph also illustrates that, after the force equilibrium, the $F_2$ calculated from the transmitted wave is lower than $F_1$. This characteristic supports the fact that the wave through the soft and porous material has a low transmitted pulse and difficult to attain the dynamic equilibrium.

![Figure 4](image_url)

**Figure 4.** Forces on front ($F_1$) and back ($F_2$) surfaces of the specimen.

![Figure 5](image_url)

**Figure 5.** Strain rate on the specimen.

Figure 5 presents the strain rate on the specimen over time. The average strain rate during dynamic equilibrium (between 25-80 microseconds) is $1500 \text{ s}^{-1}$, which is classified as high strain rate deformation ($10^2$-$10^4 \text{ s}^{-1}$).
The stress-strain data of quasi-static compression test was taken from the literature [5]. The cube samples of tortoise carapace were compressed along the through-thickness direction at a strain rate of 0.0025 s\(^{-1}\). The engineering stress-strain data on the specimen at 1500 s\(^{-1}\) is compared with the quasi-static data in figure 6. The graph shows the strain rate hardening characteristic of the material where compressive strength increases from 126 MPa to 215 MPa at high strain rate. In quasi-static compression, the curve shows a characteristic of sandwich structure with a porous core where the linear elastic behaviour is followed by a softening response due to the collapse of porous cells. At a strain of 0.5, the collapsed porous cells densify and the structure exhibits a hardening response. In comparison, the response of carapace in the SHPB test exhibits the characteristic of a brittle material with a small strain-to-failure. This is because at high rate of deformation, the rapid increase of stress in the structure lead to fracture of solid layers prior to the collapse and densification of the porous cores.

![Figure 6. Dynamic and quasi-static stress-strain curve of tortoise carapace.](image)

![Figure 7. Comparing strain wave signals.](image)
The normal strain in the longitudinal direction of the bar at the same position as the strain gauges are plotted in figure 7. The graph shows that the simulation result has the same trend as the test data with slightly lower magnitude of the strain. This demonstrates that the defined materials can capture the phenomenon of the experiment. With good agreements between numerical and experimental results, this simulation model demonstrates an insight into the dynamic behavior of the carapace under high strain rate regime. In particular, the mechanical response at high strain rate that cannot be observed in the experiments can be investigated in the simulation. In addition, the experimental parameters such as dimension of pulse shaper, impact velocity and thickness of specimen can be validated in this model to achieve the desired strain rate for future experiments.

4. Conclusions
This paper presents the SHPB testing of the tortoise carapace. The stress-strain data of this bone-like sandwich structure at strain rate 1500s\(^{-1}\) shows an increasing compressive strength compared to the quasi-static data of the same material. The simulation results using compatible material properties and simplified model of the tortoise carapace can capture the same response as the experiment.

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