Potential Applications of the Natural Design of Internal Explosion Chambers in the Bombardier Beetle (Carabidae, Brachinus)

by

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ABSTRACT

The Bombardier Beetle (*Carabidae, Brachinus*) has a unique form of defense mechanism which involves the explosive mixing of hydroquinones and hydrogen peroxide in its internal explosion chambers and using the resultant high pressure to spray out a heated corrosive fluid containing p-benzoquinones in a controlled direction [1][2]. Three salient features of the internal explosion chambers were found to be instrumental in withstanding the high pressures generated from the explosive mixing and protecting the Bombardier Beetle’s internal organs [3]. Using simulations performed with finite element analysis, it was discovered that such design features employed by the Bombardier Beetle are suitable for incorporation into helmet designs. An in-depth analysis of the market potential of such a design with respect to the motorcycle helmet market is presented along with implementation strategies and proposed business plans.

Thesis supervisor: Christine Ortiz
Title: Professor of Materials Science and Engineering
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It is my sincerest belief that no man can accomplish anything alone and this thesis is no exception. It does not exist as a result of a lone man’s effort but is a culmination of both direct and indirect work from many others.

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1. Introduction

Insects in nature has often served as valuable inspirations for engineered processes, substances, devices and systems but none has fascinated researchers and engineers more than the Bombardier beetle (*Carabidae, Brachinus*) or ground beetle (Fig. 1) in recent years. It is a unique insect that biologically produces hydroquinones and hydrogen peroxide and stores them in a large reservoir (~2mm) housed within its abdomen [1]. When it feels threatened, the hydroquinones and hydrogen peroxide are instinctively channeled into twin internal explosion chambers lined with cells that secrete oxidative enzymes such as peroxidases and catalases [1]. The hydrogen peroxide is then rapidly broken down as the hydroquinones are converted into p-benzoquinones (a known chemical irritant) [4], often with loud audible detonations [5][6][7]. Using the heat and pressure generated from the release of oxygen gas in the chemical reaction, the beetle then propels the boiling corrosive spray (~100ºC) [1] at a rate of 500 pulses per second [8] towards its target [2] in an attempt to mitigate the threat.

![Bombardier Beetle defending itself with a controlled spray of corrosive fluid](image)

Despite a clear understanding of how the defensive spray of the Bombardier Beetle is generated, consideration of the protective design principles of the explosion chamber has been lacking until recent (unpublished) work by Ortiz et al revealed three salient features of the Bombardier Beetle’s internal explosion chambers that enable them to contain the internal explosive reaction without damaging its surrounding internal organs -- a unique kidney-shaped microscopic geometry (Fig. 2a) of the chambers, a multi-layered, undulating wall structure (Fig. 2b) and a “forest” of internal tapered fibers integrated with the wall inside of the explosion chamber (Fig.
2b) [3]. BSEM and EDX experiments suggest that the chamber is un-mineralized and completely organic (biomacromolecules). Preliminary computation simulations (finite element analysis) gave positive indications that the observed microstructural features are advantageous for resisting blast, thereby protecting the vital organs of the Bombardier beetle. A provisional patent has been filed on the use of these designs for resisting mechanical loads [9].

![Figure 2: Scanning electron microscopy images showing (a) the kidney-shaped internal explosion chambers and (b) the forest of internal tapered fibers on the inside of the undulating chamber walls of the Bombardier beetle [3].](image)

The objectives of this thesis are to consider possible real world applications of the Bombardier Beetle’s explosion resistant design and to evaluate the market potential of suitable applications. Due to the immaturity of the technology, however, an emphasis was also placed on simulations to advance the research so as to understand the technical capabilities of the design features and better match it to a potential market application. Implementation strategy and a business model were proposed also.
2. Background of Impact Mechanics

The field of impact mechanics, characterized by high loading rates over extremely short periods of time, is a special subset in the study of the mechanics of materials to which collisions and shockwaves belong. It has important applications in the failure designs in aerospace [10], civil [11] and military sectors [12] and therein lies its fundamental difference in usage from the usual study of quasi-static material mechanics – while structures that can succeed in withstanding loads for extended periods of time are built with traditional quasi-static mechanics of materials, the main aim of understanding impact mechanics is to build structures that will fail predictably in the event of an unforeseen collision.

2.1. Rigid Body Impact Theory

A rigid body can be defined as one in which all points within that body are set in motion instantaneously upon the application of a force and the distance between any two points of the body never changes [13]. During the actual collision of two solid bodies, however, a large contact force that transforms the velocities into deformation of both bodies at the point of contact is created. To reconcile this deformation with the theoretical definition of a rigid body, a real body is often modelled with an infinitesimal particle acting as a spring at the point of contact [14].

![Figure 3: Schematics showing the modelling of rigid body impact. (a) Before collision. (b) During collision. (c) Modelling of collision with an interconnecting spring.](image)

In most cases, this spring has a small compliance and large forces will only deform the bodies to a small extent. This implies that the stress at the contact point (which may become a contact patch after the deformation) is very large, although it decays rapidly ($\propto \frac{1}{r^2}$ where r is the radius from the contact point) away from the contact point/patch [14]. After being compressed, the
spring subsequently releases the stored strain energy back to the bodies in the form of kinetic energy.

When conservative forces act on the bodies during the period of contact (i.e. reversible process), the collision is termed elastic. When the forces are not conservative (e.g. friction, elastic-plastic deformation etc.), there is an overall loss of kinetic energy from the bodies and the collision is termed inelastic. This loss of energy can be represented by the coefficient of restitution, $e$, given by:

$$ e = \frac{v_2 - v_1}{u_2 - u_1} \quad [13] $$

Rigid body impact theory can only be applied when the following conditions are satisfied:-

(i) Contact area during collision is small when compared to the dimensions of interacting bodies
(ii) Contact period is brief enough that any displacements during collision are negligible and there are no changes to the system configuration.

Unlike structures subjected to sustained loads, impact forces leave little time for the atoms and molecules of a material to rearrange itself, resulting in the relatively brittle behaviour of such target materials [14]. It also brings about the reasonable estimation that all velocity changes of bodies are instantaneous due to the very short period of contact. With that in mind, the velocity change of a body in a collision can be described by the impulse-momentum law [14]:

$$ m (v - u) = \int_0^T f(t) dt $$

The Third Law of Newton states that for every action force on Body A, an interacting Body B will experience an equal and opposite reaction force. When this is taken into account, the two colliding bodies can be described in a single equation:

$$(m_1 m_2)(v_1 - v_2) = (m_1 m_2) (u_1 - u_2) + (m_1 + m_2) \int_0^T f(t) dt$$
2. 2. Stress Wave Propagation in Perfectly Elastic Media

Stress waves that carry strain energy away from the point of contact are generated upon impact. When these vibrations constitute a substantial portion of the total energy of the system as in the case of axial and transverse impact on flexible bodies [13][14], rigid-body impact theory fails and a transient model based on wave propagation becomes more suited to explain the impact process [13]. For the example of a rod subjected to impulsive loads, the displacement of the rod at various points along its length is given by

\[
u = -\left(\frac{\sigma_0 t^2}{2\rho L} + \frac{2\sigma_0}{\pi^2 E} \sum \frac{(-1)^i}{i^2} \cos \left(\frac{i\pi t}{L}\right) \left[1 - \cos \frac{i\pi c_0 t}{L}\right]\right)
\]

\[i = 1, 2, 3 ...\]

Initial condition:

\[
\frac{\partial u}{\partial t} = 0, \quad t = 0, \quad 0 \leq x \leq L
\]

Boundary conditions:

\[
\frac{\partial u}{\partial x} = 0, \quad x = 0, \quad t \geq 0 \quad \text{and} \quad \frac{\partial u}{\partial x} = -\frac{\sigma_0}{E}, \quad x = L, \quad t \geq 0 
\]

The major flaw of this transient model lies in its inability to describe local deformation. Consequently, the Hertz contact formula,

\[
F = K_c \alpha^{3/2}
\]

where \(K_c = E_{33} \approx E_{22}\) for unidirectional composites [16], has to be used in conjunction with the equation of motion of target to obtain contact force history and duration [13][17].
2.3. Stress Wave Propagation in Imperfectly Elastic Media

In the event that mild plastic deformation occurs from an impact, the elastic contact impact model can be modified to account for it, often by adding a spring-damper model at the contact, similar to the infinitesimal spring model for rigid body impact [13].

\[ F = F_c(\alpha) + F_v(\alpha, \dot{\alpha}) + F_p(\alpha, \dot{\alpha}) \]

- \( F_c \) – elastic/conservative contact force
- \( F_v \) – viscous damping force
- \( F_p \) – dissipation force due to plastic deformation
- \( \alpha \) – deformation
- \( \dot{\alpha} \) – deformation rate

If the plastic deformation is significant, however, the elastic contact impact model becomes obsolete and the Hugoniot equations and plastic wave propagation theory is used instead.

2.3.1. Shockwaves: Rankine-Hugoniot Equations

Shockwaves are abrupt, nearly discontinuous changes in the mechanical or thermodynamic properties of the medium and can propagate through solid, liquid and gas [18]. It can be produced by a sudden, rapid expansion of the medium as in an explosion or by a projectile impact after which it is possible for the shockwave to move ahead of the projectile itself [19][20]. The existence and utilization of shockwaves permeates through to explosions [21][22], traffic conditions [23], manufacturing [24], medical treatments [25][26], geography [19] etc. and is a phenomenon more common than most would realize.

Figure 4: A Schlieren photograph showing shockwave produced by a micro-explosion [27].
Figure 5: Schematic illustration of stress/shock waves produced by the impact of a meteorite. It shows the decoupling of the shock wave from the excavation flow and the two graphs on the right indicate that particles within the target material continue to carry a residual velocity despite the pressure of the shock wave having decayed to zero. This residual velocity is responsible for the excavation of the resulting crater [19].

The Rankine-Hugoniot Equations [18][21] can be derived by considering a “black-body” system, the “black-body” being the shock wave front. Although the state of the medium at the wave front is unknown, its equilibrium state before and after the wave front is known and is sufficient for analysis. Consider the following model:

By the conservation of mass,
\[ \frac{\rho_1}{\rho_0} = \frac{D - v_0}{D - v_1} \]

By the conservation of momentum,
\[ P_1 - P_2 = \rho_0(D - v_0)(v_1 - v_0) \]
By the conservation of energy,

\[ E_1 - E_0 = \frac{1}{2} (v_1 - v_0)^2 \]

The above analysis, to be sure, is of a very simplified and ideal nature. Nevertheless, the Rankine-Hugoniot equations do provide some basis for understanding the phenomenon of shockwaves and laid the groundwork for more complicated theories. Shockwaves in real life are very complex and as a result, there has been continual research seeking to understand and simulate shockwaves and explosions [28][29][30]. To achieve a more realistic rendering of shockwaves generated from detonated explosives, for instance, some researchers prefer to utilize the Jones-Wilkins-Lee equations of state which are as follow:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + (\mathbf{u} \cdot \nabla) \rho &= -\rho \mathbf{u} \\
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} &= -\frac{1}{\rho} \nabla \rho \\
\frac{\partial e}{\partial t} + (\mathbf{u} \cdot \nabla) e &= -\frac{p}{\rho} \nabla \mathbf{u} \\
\frac{\partial \alpha}{\partial t} + (\mathbf{u} \cdot \nabla) \alpha &= 0
\end{align*}
\]

where the ideal gas equation is taken as \( P_{air} = (\gamma - 1) \rho e \) and the ratio of specific heats for the gas, \( \gamma = 1.4 \) [30].

### 2.3.2. Plastic Wave Propagation Theory

The theory of plastic waves assumes that the material is incompressible in the plastic domain. To form this theory, a temperature independent constitutive equation that relates stresses, strains and strain rates is used together with equations of motion.
Three phases of plastic wave propagation have generally been identified [31]. In the first phase which occurs immediately after impact, the plastic wave front moves in a non-linear manner and is overshadowed by shockwaves. After approximately 10μs into the impact, the second phase, which is characterized by the steady motion of the plastic wave front, initiates. This carries on until the third phase in which deceleration of the plastic wave brings deformation to a halt. It is worth noting that the excavation flow described in Fig. 5 is caused by this plastic wave and the piston velocity considered in the Rankine-Hugoniot equations is synonymous with the plastic wave velocity presented in the following.

Figure 8: Analysis of Taylor impact test [31].
By considering an axial impulse on a cylindrical rod fixed at one end against a wall, Jones et al were able to derive a one-dimensional plastic wave propagation theory that matches with data from the Taylor impact test [31].

For Phase I:

\[
\sigma = (1 + e) \left[ \sigma_0 + \frac{\rho}{e} (v_0 - u)^2 \right]
\]

\[
u = u_0 + u_1 \left( \frac{t}{\bar{t}} - \frac{t^2}{2 \bar{t}^2} \right)
\]

\[
h = \frac{u_0 - (1 + e) v_0}{e} t + \frac{u_1}{e} \left( \frac{t^2}{2 \bar{t}} - \frac{t^3}{6 \bar{t}^2} \right)
\]

For Phase II and III:

\[
\dot{h} = -\left( 1 + \frac{1 - \beta}{e} \right) v
\]

\[
h_f = \bar{h} = -\left( 1 + \frac{1 - \beta}{e} \right) (s_f - \bar{s})
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma)</td>
<td>engineering stress on plastic front</td>
</tr>
<tr>
<td>(\nu)</td>
<td>velocity of undeformed section</td>
</tr>
<tr>
<td>(u)</td>
<td>particle velocity of plastic material at wavefront</td>
</tr>
<tr>
<td>(e)</td>
<td>engineering strain at front</td>
</tr>
<tr>
<td>(s_f)</td>
<td>final position of plastic wavefront at back end of specimen</td>
</tr>
<tr>
<td>(\bar{s})</td>
<td>position of plastic wavefront at the back end at the end of phase</td>
</tr>
<tr>
<td>(h)</td>
<td>time dependent position of plastic wavefront</td>
</tr>
<tr>
<td>(h_f)</td>
<td>final position of plastic wavefront at front end of specimen</td>
</tr>
<tr>
<td>(\bar{h})</td>
<td>position of plastic wavefront at the front end at the end of phase</td>
</tr>
<tr>
<td>(\dot{h})</td>
<td>plastic wave velocity</td>
</tr>
<tr>
<td>(\beta)</td>
<td>empirical dimensionless constant</td>
</tr>
<tr>
<td>(t)</td>
<td>time</td>
</tr>
</tbody>
</table>

2.3.3. Absorption, Transmission and Reflection of Impact Waves: An Original Analogy with Electromagnetic Waves

Before delving into the topic, the author wishes to make the appropriate disclaimer that the originality of this analogy extends only as far as the literature review on impact waves conducted
by the author in the course of this research is concerned which, though extensive, is far from being exhaustive. The purpose of this analogy is to better illustrate the science of the behaviour of impact waves in response to encounters with materials by drawing a suitable comparison with electromagnetic waves.

![Diagram](image)

**Figure 9: Absorption, transmission and reflection of waves upon encountering a material.**

Consider the case of an electromagnetic radiation striking a material. In the most general case, three processes can result from this encounter between material and wave – reflection, transmission and absorption. The magnitude of each phenomenon largely depends on the dielectric constant of the material and the frequency (and therefore, energy) of the incident electromagnetic wave. For instance, the skin depth, a measure of penetration into the material by the wave, of a non-magnetic material is inversely proportional to the square root of the wave frequency i.e. \( \delta \propto \frac{1}{\sqrt{\omega}} \) [32]. Excluding the consideration of plasma frequencies, this relation therefore shows that with increasing frequency and energy of the incident electromagnetic wave, the skin depth and therefore, transmission of the wave, decreases while the reflection and/or absorption of the wave energy by the material increases.

Extending this illustration to the mechanical domain, it can be seen how impact waves, which can be elastic waves or shock waves, interact with a body. Essentially, the strength of reflection, transmission and absorption of impact waves, like in the case for electromagnetic waves, depends largely on the interplay between material properties and energy of the impact wave. In this case, the material properties involved are the Young’s Modulus, E, and yield stress, \( \sigma_y \).

When an impact wave (e.g. shock wave) arrives at a body, reflection of the waves can take place by means of elastic collisions between the molecules of the two different medium. This elastic
collision may not necessarily limit its effect to the reflection of waves as forward elastic collision (where all the molecules from the wave and material medium end up moving forward) can take place too, leading to transmission of impact energy. Inelastic collisions between molecules as the impact waves propagate through the body are not uncommon also, causing plastic deformation of the material in the body. In this case, some of the impact energy is converted into electrostatic potential energy when the equilibrium distance between atoms is permanently altered. This plastic deformation can be considered as the absorption of impact energy by the material.

Now, whether a body will transmit and reflect the energy of an impact or absorb it depends on whether the impact energy is larger than the strain energy \( \frac{\sigma_y^2}{2E} \) required by the particular material for the onset of plastic deformation. In the case of steel, for instance, an impact energy of 0.1 MJ/m\(^3\) is required before the material starts to absorb the impact energy through plastic deformation (assuming E = 200GPa and \( \sigma_y = 200\)MPa). This is analogous to the transmission, reflection and absorption tendencies of the electromagnetic waves which depend on the wave energy and material properties. The difference, however, is that high energy impact waves (with respect to the material properties) tend to be absorbed and low energy impact waves, transmitted. The converse is true for electromagnetic waves.

![Figure 10: A stress-strain curve illustrating the elastic and plastic strain energy regions [33].](image)

With this in mind, designers of structures made to take impact loads have to perform careful material selection to ensure that the yield stress, fracture stress and Young’s modulus of the chosen material will allow for plastic deformation but not fracture for absorption of the anticipated impact energy. At the same time, they must balance this consideration with the
amount of material required to take the impact load. Neither too much (material wastage, high production cost etc.) nor too little material (lack of room for deformation and/or deceleration) will do for any design.

2.4. Mechanical Response of Materials to Highly Intense Dynamic Loading

Of interest to this thesis would be the overall response of a mechanical structure to an explosive impact. To this end, it is necessary to integrate the principles discussed in the previous sections to form a coherent understanding of the material reaction. In this case, we can separate the entire process into four stages, using a honeycomb core (sandwich) structure as an example.

Stage I: Detonation of an explosive

Upon detonation of an explosive charge, the gaseous products produced from the reaction expand rapidly and compress the surrounding air, forcing it outwards at an initial velocity close to the detonation velocity of the explosive (~7200 m/s). Shockwaves as described by the Rankine-Hugoniot equations ensue [22].

As can be observed from Fig. 9, the pressure of the air/gas mixture introduced by the shockwave spikes up instantaneously after detonation, resulting in a blast overpressure. It then decays exponentially with time such that by \((t_a + t_d)\), the pressure drops below the initial atmospheric pressure.

Figure 11: Air blast pressure response [22].
level, causing a suction phase. Using a Friedlander relation, the free-field pressure-time response can be predicted as

$$P(t) = (P_s - P_a) \left[1 - \frac{t - t_a}{t_d}\right] e^{-(t - t_a)/\theta}$$

and the peak pressure approximated by

$$P = K \frac{m}{r^3}$$

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Meanings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_a$</td>
<td>time taken for overpressure to be reached</td>
</tr>
<tr>
<td>$t_d$</td>
<td>time taken for suction phase to initiate</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
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<tr>
<td>$P$</td>
<td>Pressure</td>
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<tr>
<td>$\theta$</td>
<td>time decay constant</td>
</tr>
<tr>
<td>$K$</td>
<td>explosive material parameter</td>
</tr>
<tr>
<td>$m$</td>
<td>mass of explosive</td>
</tr>
<tr>
<td>$r$</td>
<td>radial distance from explosive</td>
</tr>
</tbody>
</table>

Stage II: Contact between shockwaves and material

When the shockwaves arrive at the material surface, reflections of the waves occur, thus amplifying the overpressure. The impulse load on the structure is therefore,

$$I = \int_{t_a}^{t_a+t_d} B.P \, dt$$

where $B$ is the reflection coefficient which is dependent on the angle of incidence of waves and the incident shock strength. $B$ can vary from a value of 2 for weak shocks to a destructive value of 20 when dissociation and ionization of non-ideal air take place [21].

Figure 12: Reflection of shockwave from surface of honeycomb core structure [22].
Stage III: Plastic wave propagation through structure

By the end of stage II, the shockwave would have penetrated the target material. Assuming a lack of reflection from the back surface of the material, the shockwave will cause a mass of $m_f$ to move from the front face of the structure towards the back face with a velocity of $V_1$. This results in a plastic wave speed, $V_p$, given by

$$V_p = \sqrt{\frac{E_t}{\bar{\rho}}}$$

where $E_t$ is the tangent modulus of the material and $\bar{\rho}$, in this case, is the relative density of the core material to the face panel material in a sandwich structure [22]. This is the stage where plastic deformation of materials and thus, dissipation of shockwave energy, starts to take place.

Stage IV: Deformation of more rigid structures

In Stage III, the plastic wave propagation begins to compress materials within the structure that is of lower yield strength. Should the explosive impulse be sufficiently large, however, materials with higher yield strength will start to deform as well, adding to the energy dissipation of the shockwaves initiated in Stage III. Stages III and IV, by consuming the energy of the shockwaves through the deformation of sacrificial materials, are critical in ensuring that the back face of the sandwich structure does not receive intense loading [22]. The full mechanism of the dissipation of shockwave energy by a sandwich structure is given as
$$M \ddot{w}(t) = -P$$

where $P = \begin{cases} 
K_h \delta^{3/2} & \text{Elastic loading, } 0 \leq \delta \leq \delta_y \\
Py & \text{Elastic plastic loading, } \delta_y \leq \delta \leq \delta_d \\
K_u(\delta - \delta_r) & \text{Unloading/Reloading, } \delta_t \leq \delta \leq \delta_m \\
Py + K_D(\delta - \delta_r) & \text{Densification, } \delta_d \leq \delta \leq \delta_m
\end{cases}$

M – mass of projectile  
w – displacement of projectile  
Py – yielding load  
Kh – contact stiffness at loading stage  
Ku – contact stiffness at unloading stage  
K_D – contact stiffness at densification

[36]
3. Background of Crash Designs

When designing crash structures, two important criteria must be fulfilled:-
(i) The structure must absorb as much energy as possible from the high velocity impact and/or shockwaves so that a minimal level of stress will reach the protected region.
(ii) The structure must spread out and direct the residual energy away from the region it is supposed to protect as much as possible.
Of course, these criteria must be balanced against other design requirements of the structure, depending on its application.

3.1. Military Helmets

Modern military helmets are mostly built from composite materials such as Kevlar, which provides very good specific strength, allowing them to be stiff while at the same time, lightweight. Ballistic protection is provided to the wearer via delamination of the composite sheets and fiber cracking during impact, both of which help to decelerate any projectile rapidly to prevent penetration.

The basic components of the military helmet include the helmet shell, retention system (chinstrap/ napestrap) and in the case of the Advanced Combat Helmet (ACH) shown below, a pad suspension system, helmet cover and eye strap [37]. A 1.3cm gap is maintained between the head and helmet as part of the suspension system [38]. This ballistic standard gap allows the suspension system to absorb some of the projectile energy and provides space for the deceleration of an impacted round and helmet. Assuming that the round sticks in the helmet after impact, a quick calculation shows that if a 5.56mm round hits the ACH head-on the suspension system, with a 1.3cm gap from the helmet shell, will only be subjected to a force of 254N, which it is certainly more than capable of handling (Appendix A). Another plausible reason for this gap is that it provides ventilation to a soldier’s head, ensuring that he/she does not suffer from heatstroke or related illnesses.
Other important considerations for the design of a military helmet include [37]:-

(i) Weight (e.g. ACH is 1.59kg (3.5lbs) lighter than its precedent, the Personnel Armor System Ground Troops (PASGT) helmet).

(ii) Comfort (e.g. ACH utilizes foam pads on the inside of the helmets for cushion [39]).

(iii) Compatibility with the mounting of night vision devices, communications packages, nuclear, biological and chemical defense equipment, body armor etc.

(iv) The field of vision and ambient hearing abilities conferred on wearer. Situation awareness is extremely important to soldiers as it contributes to active safety i.e. It gives soldiers the opportunity to escape compromising situations. The impact resistance of the helmet contributes to passive safety.

(v) Balance, stability and fit. The helmet must minimize hampering the wearer especially during bouts of intense physical activities.

(vi) Ventilation.

3.2 Limitations of Present Military Helmet Design

While the design of the military helmet has evolved over the years to achieve a certain degree of success in preventing projectile penetration, recent studies, concerned with the significant rate of Traumatic Brain Injury (TBI) sustained amongst military personnel, revealed potent weaknesses when the design was tested against shockwave blasts [39][40].

In a study which involves the simulation of a skull protected by an ACH or PASGT and subjected to blast waves, it was discovered that the shockwave from a grenade or Improvised
Explosive Device (IED) actually washes into the 1.3cm gap between the helmet and head in a PASGT. This geometric focusing of shockwaves causes pressure under the helmet to exceed the levels outside the helmet, resulting in skull deformation and subsequent pressure gradients on the brain. While the foam pads of the ACH largely prevents this entry of shockwaves into the gap, its tight fit causes another problem entirely – helmet deformations and accelerations are transferred to the skull more effectively due to the tight coupling.

![Figure 16: Blast pressure amplification under the helmet without foam pads as a result of geometric focusing [39].](image)

In a separate study conducted by the Naval Research Lab, the result obtained was exactly the same as the preceding study with one difference – the geometric focusing of the shockwaves leads to the highest pressure on the side of the skull facing away from the blast, instead of at the top of the head, as indicated in Fig. 14 [40]. These findings concur with the experimental results obtained when crash dummies, with pressure sensors mounted on their heads, were exposed to explosions [40]. There is therefore, and urgent need to redesign the geometry of the military to withstand explosive blasts and reduce the incidence rate of TBI amongst service personnel.

![Figure 17: Time-resolved images showing the pressure contours from a frontal blast generated by the detonation of 1.5kg of C4 at a distance of 3m. Black indicates 1 atmospheric pressure while red indicates >3.5 atmospheric pressure. The total time taken for blast to propagate through the model was 0.65ms [40].](image)
3.3. Motorcycle Helmets

Despite the numerous types (shorty, full face, modular etc.) and models of motorcycle helmets on the present market, the structure of a motorcycle helmet follows a template format. Design variations seek to improve aerodynamics, ventilation or performance in other areas but hardly ever to improve safety. That is not to say, however, that helmet designers neglect safety aspects in their design. Rather, most designers had relied on better materials (e.g. composites) instead of better designs to minimize head injuries sustained in traffic accidents.

Fig. 16 succinctly presents the various components of a motorcycle helmet namely the helmet shell, liner, comfort padding, retention system (such as chin straps) and face shield in the case of a full face helmet. The most critical components involved in protecting the rider’s head from an impact in a traffic accident are the rigid helmet shell and impact-absorbent liner.

The relatively thin and stiff outer shell typically made out of polycarbonate, Acrylonitrile Butadiene Styrene (ABS) or fiber-reinforced plastic composites, acts to prevent abrasion and localised penetration of sharp objects into the helmet [43][33]. Without the outer shell, penetration of objects into the helmet can cause skull fractures. However, most researchers believe that the same force required by a sharp object to penetrate the helmet would cause a TBI so severe that any skull fractures will be comparatively negligible in damage [43].
the outer shell serves to spread out the impact energy over as large an area as possible before transferring the bulk of that energy to the liner [43][33]. It might absorb some of this energy if it fractures, but since it does yield very much before fracturing, it cannot substantially lower the impact energy. Lastly, the helmet shell has the secondary function of providing a smooth surface for cosmetic decorations of the helmet which does not serve any purpose in impact aversion but is crucial to sales.

Because of its rigidity, the helmet shell does not deform easily to absorb any impact (i.e. elastic rigid body collision) but rather, allows the resultant elastic, plastic and shock waves to pass easily through to the liner. The much thicker helmet liner, almost universally made out of Expanded Polystyrene (EPS), is therefore the component that deforms substantially to mitigate any impact energy and decelerate the rider’s head to as gentle a stop as possible. The thickness of this liner must be carefully designed depending on the level of impact energy the helmet is designed to take, the maximum deceleration on the head allowed and the material used [33]. It must not pass the designed deflection limit or “bottom out” while bringing the head to a stop using the maximum allowable deceleration. Fig. 17 presents this concept clearly in a graphical manner.

![Figure 19: Force-deflection curve showing the impact energy to be absorbed by the liner without crossing the limit of maximum deceleration on the rider's head and foam deflection limit [33].](image)

Although it can be observed from Fig. 17 that a larger liner thickness and corresponding deflection limit will always allow for a lower force on the head in the event of an impact, other
design constraints will not allow liner thicknesses to be excessively large. Amongst the considerations would be the stability and weight of the helmet, which contributes to active safety. Making the helmet excessively large and difficult to balance on the head may increase the risk of accidents due to the greater fatigue load on riders and lead to greater number of casualties instead.

![The striker force versus foam deflection](image)

Figure 20: Force-deflection curves for various foams [33].

Fig. 18 clearly shows the reason EPS is the choice of liner material. It absorbs the greatest amount of energy for the same level of deflection and does not add much weight to the helmet despite its significant thickness as a result of its very low density (54 - 68 kg/m³) [33]. Its low yield stress of 0.7-1.08 MPa [33] means that it will deform plastically even at low impact conditions, ensuring that it will not spring back into its original shape and thus, jolting the head in the other direction after decelerating it. The energy absorbed by a material can also be presented as the area under the stress-strain curve (Fig. 19). In this particular case, the polypropylene liner has a yield stress of 0.5 MPa.
Motorcycle helmets have to be certified safe before they are allowed to be marketed. For helmets to be marketed in the United States, they must first meet the Federal Motor Vehicle Safety Standard (FMVSS) known as FMVSS 218 (49CFR571.218) or more commonly termed the Department of Transport (DOT) standard [44]. Likewise, helmets meant for the Europe market must meet the Economic Commission of Europe ECE 22.05 standard [45]. The toughest standard for motorcycle helmet safety belongs, however, to the one set by Snell Memorial Foundation, commonly termed the Snell standard [46]. Unlike the DOT or ECE standards which are legal requirements, the Snell standard is a voluntary standard but because of its strictness, helmets that pass the Snell standard often brings lucrative returns to their manufacturers due to the premium consumers are willing to pay for the improvements in safety (Fig. 20) [47].
Impact tests on motorcycle helmets are generally conducted with a “drop” test i.e. a weight is dropped from a certain height and thus have a certain amount of energy. The helmet must absorb this impact energy without compromising the maximum deceleration and foam deflection levels allowed by the particular standard as described with Fig. 17. The relation for this energy transfer is simply given by

\[ \frac{mgh}{at} = \int_0^{\varepsilon_{\text{max}}} \sigma \, d\varepsilon \]

For instance, the toughest portion of the Snell standard impact test requires helmets to withstand 2 impacts made by a flat anvil dropped from a certain height. The first impact will be 150J and the second, on the exact same site, will be 110J. To pass the test, the helmet must transmit less than or equal to 290g of deceleration (or acceleration in the context of the test) to the headform. For the penetration test, it employs a flat cone with an included angle of 60° ±0.5° and a height of 38 ±0.38 mm as the anvil. The striking tip of the cone, of radius 0.5 ±0.01 mm, has a hardness of 60 Rockwell (scale C ±3 points) will fall through an altitude of 3 m ±15 mm (~90J of impact energy) before striking the helmet. To be Snell certified, the cone must not pierce the helmet at all.

Other design considerations [48]:-
(i) Comfort and fit
(ii) Weight
   A lower weight reduces a rider’s fatigue and allows him/her to be more alert.
(iii) Ventilation system
   The helmet being enclosed from all sides by thermal insulating EPS does not allow for effective heat removal from the rider’s head. Channels like the ones shown in Fig. 16(b)
have to be designed to let air in and out. The ventilation system also affects the noise level within the helmet too.

(iv) Compatibility with other components such as visors, retention systems and cosmetic designs.

3.4. Limitations of Present Motorcycle Helmet Design

Motorcycle helmets nowadays have evolved to become very effective in taking impact loads [47]. However, some have expressed doubt over the ability of motorcycle helmets to truly protect the head of a rider during an actual crash, giving the reason that standards today, especially the Snell standard, do not accurately reflect most crash scenarios [47]. Tests like those conducted by Snell have encouraged helmet manufacturers to build helmets with a harder and/or thicker outer shell when studies have shown that a more compliant outer shell would be more beneficial [43]. However, by using softer materials for the helmet shells, it is unlikely for these helmets to pass the penetration test. It appears therefore that only a switch to a more compliant design of the helmet shell can mitigate these demands for penetration resistance and impact mitigation.

A concern has also been raised with regards to the design of side of the motorcycle helmet. Through a compilation of research data, Shuaeb et al showed that side impacts occur fairly frequently during traffic accidents but most helmets have lower shell and liner thicknesses on their side, in part due to reduced test requirements on the sides of helmets [43]. To compound the problem, the skull of a human being also possesses reduced thickness at its sides, increasing the vulnerability of the brain in this direction [43]. Lastly, the side of a helmet also suffers from edge flexibility associated with a larger shell curvature in that region [43].

3.5. Crumple zones

Crash mitigation is an integral part of any automobile design these days. The responsibility of protecting passengers in the automobile falls onto its crumple zone, the automobile’s answer to a motorcyclist’s helmet. Prior to 1952, it was believed that a safe car is one which does not yield in
a collision [49]. As observed in our previous sections, this would result in rigid body impact and elastic collision with the result that the energy of the collision passes undiminished to the passengers causing severe injuries. With the patent DBP 854-157, Béla Barényi built the first automobiles (Mercedes-Benz 220, 220 S and 220 SE models) that were designed to take crashes in 1959 [49]. A revolution in the design of cars soon followed, and the crumple zone became a staple in automobiles touting today.

A crumple zone is simply the softer outer section of an automobile (including the boot, bonnet and even tyres) which deforms to absorb the impact energy in a collision. The crumple zone surrounds a rigid, protective passenger cell designed to prevent passengers from being crushed. The axles direct the impact energy away from the passenger cell and re-distribute it, as much as possible, throughout the entire vehicle [50]. Calculated notches, for instance, can be made on the axles and other parts of the crumple zone to enable them to deform in a predictable manner during actual collision. Sensitive regions like engine compartments cannot be deformed and designers have to ensure that during a collision, the frame surrounding an engine would deform in a manner that will push the engine out of the way so that it does not collapse and cause an explosion or toxic fume leakage [50]. Designers have also gotten around this problem by stopping fuel supply to the engine of novel vehicles in an event of a crash [51].

![Figure 23: Simulated crash of a Mercedes-Benz SLS AMG. The transmission and rear axle took part of the impact load too, via the transaxle [52].](image)

Specific crumple zone designs of individual car manufacturers are generally closely guarded proprietary secrets [50] and the materials employed in the crumple zones may differ from car to
car. For instance, 96% of the Mercedes-Benz SLS AMG was built out of aluminium [52] whereas the Volvo XC-60 uses different grades of steel in its crumple zone, with the softer grade on the outside and the harder grade on the inside [53]. Crumple zones do not exist solely in cars. Locomotives and aircraft designers have seen the benefits of such a contingency design and have separately included them in their products too [10][54].

Unlike helmets which are not subjected to loads until the event of a crash, crumple zone components have, in a sense, dual functions. They are required to be stiff enough to perform everyday duties, carrying a designated load without significant deformation but at the same time, soft enough to deform substantially during a crash to absorb impact energy since they are a constant part of the vehicle [50][54]. If entire portions of an automobile had been set away as a crumple zone, it wuld not have been very fuel efficient. High performance cars usually employ a honeycomb design, which is stiff enough to take daily loads and can crumple during a crash [50]. In addition, crumple zones tend to have an optimum range of impact energies they can take, as designers have to compromise between designs that are too stiff (which will not allow for efficient energy absorption) and designs that are too soft (which may be too completely crushed in the event of a severe crash) [50].
4. Proposed Designs

Constructing impact absorbent designs always presents a big challenge as various phenomenons (wave propagation, dynamic cracks, delamination, dislocation generation, growth and motion) act at the same time and interact with each other [13]. Indeed, the response of a structure to an impact load or shockwave is so complex that researchers have increasingly turned towards computer simulations to solve large numbers of complex equations to accurately evaluate the effectiveness of an impact-resistant design [13][16] [22]. Amongst the computational methods currently in use are Finite Element Analysis (FEA), Finite Difference Modelling (FDM) and Mesh-Free Methods (MFM), each with their advantages and disadvantages [13]. For instance, Lagrange codes used in FEA face difficulty when dealing with large distortions and Eulerian codes in FDM cannot deal with motion of materials and surfaces as effectively. MFM, on the other hand, can be computationally demanding [13]. There has been no consensus on which method is the best, although FEA usage via commercial software LS-DYNA and ABAQUS is relatively ubiquitous [13][43][54].

To analyse the potential of the design of the Bombardier Beetle’s internal explosion chambers, one of the design features, the undulating wall, was computationally incorporated into existing helmet designs and cantilevers meant to simulate axles in crumple zones via finite element modelling using Solidworks 2009 and 2010. The modified helmets and cantilevers were then subjected to a series of static and dynamic loads and their results, based on the Von Mises stress criterion, were compared with those obtained using existing designs. Parameters of the FEA employed are given in Table 1.
<table>
<thead>
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<th>Solid Mesh</th>
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<td>Jacobian points</td>
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<td>Element size</td>
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<tr>
<td>Tolerance</td>
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<td>Mesh quality</td>
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<tr>
<td>Maximum Aspect Ratio</td>
<td>8 (undulating helmet) – 15 (smooth helmet)</td>
</tr>
<tr>
<td>Material</td>
<td>Medium-high impact acrylic</td>
</tr>
</tbody>
</table>

Table 1: Parameters of FEA on designed helmets and cantilevers.

4.1. Static Loading

As a preliminary analysis, the modified structures were subjected to a static load of 5000N in each of the 3 orthogonal directions in separate scenarios. 5000N is the average force a 65kg person will experience in a collision if he/she retained a velocity of 10km/h before hitting an immovable wall and decelerating to a complete halt using 5cm of EPS deformation in the helmet (Appendix B1). It is also the approximately the average force that four 5.56mm rounds exert on a military helmet that uses the full 1.3cm gap to fully decelerate (Appendix B2).

Although the stress and displacement distribution on the helmets and cantilevers were given in each set of tests, attention should be given to the last row of diagrams which indicate the regions that will yield under the given load. A larger yield region (in red), implies that a particular design is more compliant and will likely absorb more impact energy during a crash. Since the parts, modelled with medium-high impact acrylic, do not fail at a load of 5000N, the factor of safety (FOS) was raised in most cases so that the yield regions can become visible. Assuming the relation between the load and stresses is linear, the diagrams actually represent the scenario when the models are loaded with a force of (5000 x FOS) N or when a material of yield strength 1/FOS that of the acrylic is used.
4.1.1. Helmet

Both the undulating helmet and the smooth helmet were designed with an inner hemispherical cavity of diameter 300mm, large enough to fit a human head. This inner cavity was completely constrained in the tests, presenting the boundary condition. Because the outer contours of both helmets are different, the view from the insides of the helmets (which are of the same dimensions) is presented in most cases for an unbiased view. Both helmets are of the same mass and the 5000N load is in the form of a flat anvil, pushing against the helmet in the required direction of the test. The smooth helmet is modelled as a half-face helmet which is currently in use on the roads.

Figure 25: (a) Undulating helmet and (b) smooth helmet exhibiting the finite element meshwork that make up their structures.
Top Load

Figure 26: Plots of von Mises stress distribution for each helmet design due to top load.
Figure 27: Plots of displacement distribution for each helmet design due to top load.
Figure 28: Diagrams showing the yielded regions of each helmet design subjected to a load from top. FOS = $10^5$. 
The displacement distribution plots shown in Fig. 25 display the various distances travelled by individual finite elements from their original position on the model. Note that a large displacement does not indicate high strain as a finite element may move large distances due to the compression of adjacent elements without experiencing any compressive or tensile strain itself. The plot is therefore useful only for measuring the absolute deformation of a helmet.

As can be intuitively deduced, the flat anvil contacts and stresses the undulating helmet at two points while doing the same at only one point on the smooth helmet. The difference between the regions that will yield in the undulating helmet and in the smooth helmet is not significant and both appear to spread out the stresses over approximately the same area.
Side Load

Figure 29: Plots of von Mises stress distribution for each helmet design due to side load.
Figure 30: Plots of displacement distribution for each helmet design due to side load.
Figure 31: Diagrams showing the yielded regions of each helmet design subjected to a load from side. FOS = $10^5$. 
A rather dramatic difference is observed when both helmets are loaded from the side. The stresses on the smooth helmet appear much more localized, with materials from the outer surface of the helmet displacing all the way through to the helmet thickness. This is undesirable if it happens during a crash as the rider’s head will be deformed. The undulating helmet, in contrast, spreads the stress over a larger region, allowing more material of the helmet to absorb impact energy and reduce localized damage. As observed from the displacement distribution diagrams, the deformation of the helmet does not penetrate from the outer surface through the thickness into the inner surface, keeping the rider’s head safe.
Front Load

Figure 32: Plots of von Mises stress distribution for each helmet design due to front load.
Figure 33: Plots of displacement distribution for each helmet design due to front load.
Figure 34: Diagrams showing the yielded regions of each helmet design subjected to a load from front. FOS = 10^5.
The results observed in this set of experiments involving a front load is similar to that involving a side load, except that the improvements offered by the undulating helmet in terms of stress distribution and thus, energy absorption is less dramatic, although still significant. Once again, it was noted that the outer surface of the smooth helmet had penetrated all the way through the helmet thickness whereas the deformed outer surface of the undulating helmet remains some distance from the inner surface.

4.1.2. Cantilever

A series of tests were also conducted on a smooth cantilever, reflecting axles used in crumple zones and cantilevers modified with an undulating structure inspired by the Bombardier Beetle. The 5000N load was evenly distributed perpendicular to the direction of testing on the surfaces of the cantilevers which were completely constrained at one end. Therefore, the dimensions of the undulating and smooth cantilevers (100mm x 25mm x 25mm) were kept constant instead of their mass. For increased clarity, the direction of the load (purple arrows) and constraints (green arrows) are shown on the smooth cantilevers.
Axial Loading

Figure 35: Plots of von Mises stress distribution for each cantilever design due to axial load.
Figure 36: Plots of displacement distribution for each cantilever design due to axial load.
Figure 37: Diagrams showing the yielded regions of each cantilever design when subjected to an axial load. FOS = 25.
The results of the tests showed that the undulating cantilever can absorb much more impact energy than the smooth cantilever can. For the smooth cantilever, only the four corner points at its constrained end yielded in contrast to the undulating cantilever where nearly the entire structure yielded. This is fairly intuitive, since the undulating cantilever resembles a spring. However, with this level of yielding occurring in the undulating cantilever, there might be problems of it “bottoming out” (crossing the deflection limit) at low impact loads.
Transverse Loading along y-axis (FOS =1)

Figure 38: Plots of von Mises stress distribution for each cantilever design subjected to a top load.
Figure 39: Plots of displacement distribution for each cantilever design subjected to a top load.
Figure 40: Diagrams showing yielded regions of each cantilever design subjected to a load from top. FOS = 1.
Once again, the undulating cantilever shows a significantly higher impact absorption capability than the smooth cantilever, but also a lower stiffness at the same time. The end of the undulating cantilever was deflected two orders of magnitude more than that of a smooth cantilever.

**Transverse Loading along x–axis**

![Stress distribution plots](image)

*Figure 41: Plots of stress distribution for each cantilever design due to side load.*
Figure 42: Plots of displacement distribution for each cantilever design due to side load.
Figure 43: Diagrams showing yielded regions of each cantilever design subjected to a side load. FOS = 2.
When the undulating cantilever is loaded from the side, it exhibits a lower impact absorption capability as compared to the previous 2 load directions. This is expected as the undulating cantilever resembles less of a spring from the side direction (x-direction). It does, however, still perform slightly better than the smooth cantilever in impact mitigation but tend to fail at its constrained end under static side loading.

4.2. Aerodynamics Simulation

In addition to static load tests, simulations were also conducted to find out the aerodynamic properties of the undulating helmet and how its performance measures up to that of the smooth helmet. The results of this preliminary analysis have implications on the aerodynamics of a motorcycle helmet (an important aspect of the helmet design) and the motion of shockwaves past the outer surface of the helmet. The fluid used in this simulation is air at 293K and the flow rate from inlet to outlet was set at 10m$^3$/s.

Figure 44: Diagrams showing the positions of streamlines flowing past each helmet from the side view (first row) and the top view (second row).
The results of the flow analysis indicate that there is a smaller wake region for the flow around the undulating helmet. This appears to suggest that the undulating helmet is relatively more aerodynamic and suffers from a lower drag when moving through air [55]. In addition, it could also indicate that shockwaves can pass through the undulating helmet more easily and a lesser amount of energy will be lost to the helmet. Consequently, the wearer will sustain less impact from a shockwave moving past the outer surface of the undulating helmet. The velocities along the streamlines in both cases are similar.

4.3. Impact Loading

Static loading tests might have been a useful preliminary analysis of the impact absorbent capabilities of a design but there are differences between a static load and dynamic load that cannot be ignored. For instance, as mentioned previously, under an impact load, a material tends to act in a more brittle manner and the presence of stress waves cannot be ignored [13][14]. This therefore calls for a dynamic loading test, to accurately reflect the impact resistance of the proposed designs.

4.3.1. Helmet

The helmet models, each having a mass of 4.2kg, were subjected to a drop test in which the velocity before impact was 3 m/s (the highest value that was accepted by the programme). Once again, the test was conducted in each of the three orthogonal directions. The wall against which they were dropped was immovable. Cut-away sections are presented for each helmet to clearly show the stress and strain distribution through the helmet thickness. The stress-time graph of a particular node (Node 1) is also presented for each helmet and although it would be tempting to compare the graphs of each helmet quantitatively, it should not be done as the node would be in a different location on the helmet due to the different meshwork of the undulating and smooth helmet. Thus, the stress-time graphs can only be used as a general indication for the presence of stress waves and flexibility of the design.
To effectively interpret the results, first consider a single finite element. Under a particular stress, it will exhibit a particular strain for a given material (if the deformation is within the elastic region, stress = Young’s modulus x strain) and the strain energy absorbed by this finite element is the area under the stress-strain curve [33]. Therefore, since the materials in both helmet models are the same, the greater the region of helmet that is above a given stress level, the greater will be the amount of strain energy stored in the helmet and the better it is at protecting the wearer’s head by turning the impact energy into strain energy. With this in mind, the diagrams showing the regions of the helmet above an arbitrary low stress level of 5 MPa are presented so that by simply judging the spatial extent of damage to the helmet, the impact absorption capability of the helmet can be deduced. Although it can certainly be argued that a higher level of strain energy could very well be stored within a smaller region (e.g. a large percentage of the small region is subjected to very large stress and strain values), it is not the case in the results presented in the following. Stress and strain values are comparable in all the results of both helmets. In addition, if a very large level of strain energy is stored within a small area of the helmet, it also demonstrates the inability of the design to distribute the load over as large a region as possible. In truth, the diagrams describing the regions of the helmet above a threshold stress level are simply a slight variation of the FOS diagrams presented in the results of the static loading tests.
Top Impact

Figure 46: Plots of stress distribution of each helmet design when subjected to top impact load.
Figure 47: Plots of strain distribution of each helmet design when subjected to top impact load.
Figure 48: Diagrams showing regions on each helmet design exceeding a stress of 5MPa when subjected to a top impact load.
Figure 49: Stress-time profiles of node 1 in the FEA of undulating helmet design (top) and conventional helmet design (bottom) subjected to a top impact.
There are no significant differences in the impact energy absorbed by the undulating helmet in comparison with the smooth helmet although the stress-time graph does show improved damping capabilities of the undulating helmet design with regards to stress waves.

Side Impact

Figure 50: Plots of stress distribution of each helmet design when subjected to side impact load.
Figure 51: Plots of strain distribution of each helmet design when subjected to side impact load.
Figure 52: Diagrams showing regions on each helmet design exceeding a stress of 5MPa when subjected to a side impact load.
Figure 53: Stress-time profiles of node 1 in the FEA of undulating helmet design (top) and conventional helmet design (bottom) subjected to a side impact.
Since both helmets contact the immovable wall at the same impact velocity, they must be subjected to the same impact energy. In the absence of other bodies, this necessarily implies that both helmets absorbed all of the impact energy. With reference to Fig. 50, Fig. 51 and Fig. 52, it can be seen that the plastically deformed regions of the undulating helmet design (assuming a yield stress of 5MPa) are both more widespread and of higher stress and strain values. The impact energy permanently absorbed by the undulating helmet design in the form of plastic strain is therefore likely to be greater. With the traditional helmet design, there are two possibilities that can cause it to have a smaller region of deformation of lower average stress and strain:

(i) Most of the strain energy is stored in other parts of the helmet elastically.
(ii) There is a small region of very high stress and strain.

Neither of the two possibilities is desirable for a helmet subjected to a dynamic load. In the first instance, the strain energy will eventually be released by the helmet to the detriment of the user’s head and in the latter case, there exists a very real danger of penetration through the helmet via the small region of high stress.

By considering the volume of deformed regions only, an improvement of about 80% to 100% in impact absorption by the undulating helmet can be expected. The undulating helmet also appears to have a lower resistance to elastic stress wave propagation which might be instrumental in the distribution of stress throughout the helmet.
Front Impact

Figure 54: Plots of stress distribution for undulating helmet design (top) and conventional helmet design (bottom) when subjected to front impact load.
Figure 55: Plots of strain distribution for undulating helmet design (top) and conventional helmet design (bottom) when subjected to front impact load.
Figure 56: Diagrams showing regions with stress levels greater than or equal to 5MPa on each helmet design when subjected to a front impact load.
Figure 57: Stress-time profiles of node 1 in the FEA of undulating helmet design (top) and conventional helmet design (bottom) subjected to a front impact.
Like the results presented for the helmets subjected to a top impact, there are no significant differences between the impact absorption capabilities of the undulating helmet and smooth helmet. The stress-time curves for both helmets are similar too. However, from another view (Fig. 35), we can see that the contour in the undulating helmet directs the impact energy away from the immediate region and spreads it over a larger area, protecting the part of the head that is directly in the line of impact.

Figure 58: Bottom view of the stress distribution diagrams of the helmets subjected to a front impact load.
4.4. Proposed Design to Mitigate Shockwave Concentration

With regards to the shockwave “underwash” that assails a soldier’s head during an explosion, shockwave guides on the inside of a helmet are proposed (Fig. 36 and 37). The geometry of these waveguides is designed to channel shockwaves out of the helmet by forming a path that discourages the shockwaves from converging at the side of the helmet facing away from the blast. These waveguides are proposed to be made of fine bristles (another design feature inspired by the Bombardier Beetle’s internal explosion chamber design) so that they can deflect and deform to absorb shockwave energy. Of course, the bristles must not be so stiff that the wearer will be subjected to the danger of head injuries caused by penetration from a thousand pins, but not be too soft as to be too easily deflected, for in that case, they will not serve their functions well.

![Figure 59: Bottom view of a helmet showing the design of waveguides and a blowup that shows the tiny hairs that make up the waveguides.](image)

![Figure 60: Cut-away of a helmet showing the design of the waveguides from the front view.](image)
An aerodynamic test was conducted on the proposed helmet with the waveguide design to evaluate its effectiveness in channelling the shockwaves. Air of temperature 500K and 3 atmospheric pressures (simulating conditions of air in a blast) [40] was made to flow from the bottom of the box towards the reader, to a region of 1 atmospheric pressure (Fig. 38). This may not be the most accurate representation of the air in an actual blast though, as the simulation was done with streamlines instead of shockwaves of air. Nevertheless, it does provide useful preliminary indications on the actual behaviour of air through the helmet during a blast.

It was discovered that only two out of the fifty streamlines simulated flowed through the gap between a helmet and the head (partly due to the small gap between the head and helmet), suggesting that the shockwaves prefer to travel along the outer surface of the helmet. The two dark blue streamlines that flowed through the helmet were effectively guided along the channels out of the helmet. It can also be observed that velocity remains low along the streamlines passing through the waveguides. Assuming that the air flow in the simulation is incompressible, we can see that according to Bernoulli’s equation, \( \frac{v^2}{2} + gz + \frac{P}{\rho} = \text{constant} \), the blue lines, which represent streamlines of low velocity, experience higher pressure than streamlines which move freely outside of the helmet. This is consistent with the results obtained in other studies [39][40].

**Figure 61: Streamlines of air flowing from the bottom surface towards the reader. Note the two dark blue lines that flowed through the helmet and were guided by the waveguides.**
4.5. Improvements over Current Designs

In terms of collisions with another rigid body such as a wall or projectiles, the undulating helmet appears to give significant advantage over the smooth helmet when the impact is to the side of the helmet. Not only was the impact energy directed away, it was spread to a larger area so that yielding occurs over a larger region, absorbing more of the impact energy. Although no quantitative conclusions can be made without an energy dissipation curve which is unavailable in the Solidworks programme, the undulating helmet appears to increase impact absorption by approximately 100%.

When the impact is to the front of the helmet, there were no observable improvements in terms of energy absorption in comparison to a smooth helmet but the contours assisted in the redirection of impact away from the area of the head directly adjacent to the impact. As for dynamic loading from the top of the helmets, both performed equally well.

In terms of aerodynamics, the undulating helmet offers a lower drag when moving through air and this feature is advantageous in motorcycle helmets. At the same time, it appears that shockwaves will transmit less energy to the undulating helmet when passing it by, a feature that would be invaluable in a military helmet.

The results for an undulating cantilever are not so favourable, however, as it deforms excessively under static loads. As mentioned before, crumple zone components in cars are also required to perform load-bearing activities before any crashes, assuming any will occur. This is as important a function as energy absorption in a crash. Because the undulating axle was unable to perform better than or as well as the smooth axle in any of the directions in this aspect, the design should be reconsidered.

Lastly, the proposed waveguides on the inner surface of helmets appear to be successful in discouraging the convergence of shockwaves, assuming the streamline results obtained can be extrapolated to results of actual shockwave simulations. Further tests, which may be computationally demanding, need to be carried out by modelling the waveguides with bristles to
see if the bristles are effective in mitigating the shockwave energy. If the bristles do not give significant energy absorption, perhaps the waveguides can simply be made out of foam pads.

In conclusion, the undulating helmet design provides an advantage over the smooth helmet in terms of aerodynamics and impact mitigation. When applied to a motorcycle helmet, the design essentially allows a very hard shell (for penetration resistance) to be made more deformable (to absorb impact energy by plastic yielding and densification) while reducing the drag on the helmet to improve motorcycle performance. In addition, the waveguides within the helmet are effective in re-directing shockwave flows and this design, together with the undulating shell design, can potentially reduce the impact transmitted to a soldier’s head during a blast when incorporated into a military helmet.

4.6. Challenges to the Incorporation of Proposed Design

Although the undulating helmet design has given favourable results in the series of simulation tests conducted in this thesis, the simulation tests required to certify a design’s viability as a military helmet or motorcycle helmet is far from being complete. The main weaknesses of the simulation tests that have been carried out so far is the lack of information on energy dissipation and the fact that the designs were not subjected to an actual simulated blast unlike other studies [22][39][40]. Such critical information were mostly inferred from the simulation tests carried out instead of being directly read off and thus, any misunderstanding or other errors introduced in the inference could lead to mismatches between expected and actual results. As it is, there is insufficient understanding in the mechanics of a helmet response to a real blast and experiments and data gathering are still carried out actively by researchers [39][40].

As for the incorporation of the design into motorcycle helmets, each motorcycle helmet manufacturer will have its own simulation tests that the design will be required to pass before it is even willing to produce a prototype [56][57]. To overcome any unforeseen problem associated with the draft designs presented in this thesis, repeated optimization has to be conducted in correspondence to results obtained from simulation tests conducted by motorcycle helmet companies. Unlike simulations of military helmets subjected to explosions, simulations involving
motorcycle helmets in crashes are fairly mature. Even in the event that the designs, after many fine, calculated adjustments, have fully satisfied the simulation requirements, prototypes will still need to be produced to verify computer simulation results.

Lastly, there is also a need to take into account the compatibility of the proposed helmet shape with other design requirements. For the military helmet, the major challenge that the undulating helmet design faces is the mounting of equipment like night vision goggles on the helmet. These equipments were designed with smooth surfaces and not undulating surfaces in mind. Accessories may have to be designed to enable equipment mounting compatibility with the undulating helmet. As for the incorporation of design into motorcycle helmets, the undulations do not interfere with any other design concerns except for cosmetic ones (painting and decoration with water decals may prove to be difficult on an undulating surface), which manufacturers pay great attention to. Painters and helmet workers may need to pick up new tricks to compensate for the difficulty based on their experience.

## 4.7. Complementary Research

Accurate simulations of the mechanical response of a helmet to a blast can assist in the optimization of the undulating helmet design greatly by precisely pointing out its advantages and flaws. This can significantly shorten the time required to design the most effective helmet structure and by accurately reflecting how a design will react in a real blast, it also closes the gap between simulations and actual scenarios, thus reduces the time and effort required to produce a working prototype too. To do so, researchers need as much real data as can be gathered from helmets exposed to actual blasts so that the modelling can be as realistic as possible. This complementary research field was opened up recently when The United States Department of Defense recognized this necessity of data gathering and commissioned various institutes and companies to outfit sensor chips in the helmets of 101st Airborne and 4th Infantry division during their deployments to Afghanistan and Iraq respectively [58][59].

As for the incorporation of the undulating design into motorcycle helmets, assuming that all the simulation tests have been passed and a working prototype is available, more research pointing
to the benefits of a more compliant outer shell [43][47] will likely pressure manufacturers into adopting the undulating helmet design with less objections. Of course, such research must first convince the standard setters (e.g. ECE 22.05, DOT and Snell) that the helmet requirements need to be revised in light of the new data.

4.8. Competitive Research

As of the writing of this thesis, there is no research directed at modifying present helmet designs to become more compliant to impact loadings or shockwaves. Neither has there been any shockwave guides nor the likes proposed. That is not to say, however, that there are no alternatives to the proposed design. A similar design, known as the honeycomb core sandwich design, has already found success with crumple zones and bridges [11][50]. It has also been proven in research papers that honeycomb core sandwich panels are effective in taking explosive blasts [22]. A slight variation of this honeycomb design gives the sinusoidal core sandwich design (Fig. 40) which bears only subtle differences to the proposed undulating design [60]. The research on honeycomb/ sinusoidal core sandwich panels has not extended to helmet designs yet, probably because of the difficulty in fabrication and modelling of such structures in the form of helmets and therein lie the advantage of the proposed design over sandwich structures.

Figure 62: Sandwich panels with sinusoidal core configuration [60].
5. Market Outlook

5.1. Helmet Users

5.1.1. Traumatic brain injury

Traumatic brain injury (TBI) refers to injuries sustained by the brain due to external forces that may or may not involve intracranial injury and can be broadly classified into three categories using the Barell Matrix based on the severity of the injury [61]. Table 2 summarizes the characteristics of each category.

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (most severe)</td>
<td>Intracranial injury or moderate or prolonged loss of consciousness, shaken infant syndrome or injuries to the optic nerve pathway</td>
</tr>
<tr>
<td>II</td>
<td>No intracranial injury, loss of consciousness of less than an hour or loss of consciousness of unknown duration or unspecified level of consciousness</td>
</tr>
<tr>
<td>III (least severe)</td>
<td>No intracranial injury and no loss of consciousness</td>
</tr>
</tbody>
</table>

Table 2: Characteristics of each type of TBI [61].

TBI occurrence in the military

Soldiers being deployed to frontlines are most susceptible TBI caused by explosions from Improvised Explosive Devices (IEDs) and grenades (Table 3) [40][62]. Statistics presented in Table 4 show that for every 1000 deployed soldiers, 2.82 will be hospitalized for TBI during deployment. Soldiers in Iraq face an even higher risk -- 3.1 soldiers out of every 1000 will be subjected to hospitalization for TBI. This level of TBI occurrence can be partly attributed to one major reason and that is the failure of the present military helmet to protect a soldier’s head from the shockwaves of the blast. Studies suggest that the helmet not only fails to protect the wearer’s head; it might even aggravate the TBI by focusing the shockwaves with the geometry of its construct [39][40].
Table 3: Contribution of various causes to TBI hospitalizations during deployment [62].

<table>
<thead>
<tr>
<th>Location/direct mechanism</th>
<th>TBI prognosis</th>
<th>n (%)</th>
<th>n (%)</th>
<th>n (%)</th>
<th>n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afghanistan</td>
<td>Type 1</td>
<td>23 (65.7)</td>
<td>19 (34.5)</td>
<td>1 (25.0)</td>
<td>42 (46.7)</td>
</tr>
<tr>
<td></td>
<td>Type 2</td>
<td>1 (5.1)</td>
<td>21 (38.2)</td>
<td>1 (25.0)</td>
<td>24 (26.7)</td>
</tr>
<tr>
<td></td>
<td>Type 3</td>
<td>4 (11.4)</td>
<td>5 (9.1)</td>
<td>1 (25.0)</td>
<td>10 (11.0)</td>
</tr>
<tr>
<td></td>
<td>Any</td>
<td>4 (11.4)</td>
<td>10 (18.2)</td>
<td>1 (25.0)</td>
<td>14 (15.6)</td>
</tr>
</tbody>
</table>

| Iraq                      | Type 1       | 478 (67.8) | 334 (58.1) | 56 (64.4) | 829 (63.9) |
|                          | Type 2       | 94 (13.3) | 154 (28.8) | 21 (24.1) | 248 (19.1) |
|                          | Type 3       | 116 (16.5) | 22 (3.8) | 9 (10.3) | 143 (11.0) |
|                          | Any          | 1 (0.1) | 1 (0.2) | 0 (0.0) | 1 (0.1) |
|                          | Other        | 705 (100.0) | 575 (100.0) | 87 (100.0) | 1298 (100.0) |

Table 4: Occurrence of TBI amongst military personnel deployed to Afghanistan and Iraq [62].

<table>
<thead>
<tr>
<th></th>
<th>Afghanistan Population (n=145,505)</th>
<th>Any TBI (n=207)</th>
<th>Iraq Population (n=722,474)</th>
<th>Any TBI (n=2,241)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n (%)</td>
<td>n (%)</td>
<td>n (%)</td>
<td>n (%)</td>
</tr>
<tr>
<td>Female</td>
<td>12,465 (8.6)</td>
<td>6 (2.9)</td>
<td>80,666 (11.2)</td>
<td>56 (2.5)</td>
</tr>
<tr>
<td>Male</td>
<td>132,882 (91.3)</td>
<td>201 (97.1)</td>
<td>641,699 (88.8)</td>
<td>2,185 (97.5)</td>
</tr>
</tbody>
</table>

In recent years, TBI amongst deployed military personnel has faced a nearly unabated rise in occurrence (Fig.40) [62]. There is therefore, mounting pressure to design a helmet that is effective in mitigating shockwave damage to a soldier’s brain without losing its present efficiency in arresting projectile penetration. The need for this new helmet design then translates to the market potential for the proposed helmet design that was inspired by the Bombardier Beetle’s internal explosion chambers.

However, because of the military’s ability to act like a monopoly, it can carry a product through an entire innovation cycle of 15-20 years even if it is the sole consumer as long as the product works. This translates to an almost unlimited market potential for any military related product.
and thus, the market and implementation research for military helmets will not be evaluated beyond this point.

![Figure 63: TBI hospitalization episode rates as a percentage of total injury rate [62].](image)

### TBI occurrence amongst civilians

In the United States alone, an estimated 1.4 million cases of TBIs occur each year amongst civilians, causing 1.1 million emergency department visits, 235,000 hospitalizations and 50,000 deaths [63]. 80,000 to 90,000 of these TBI patients will be permanently disabled and 5.3 million of them currently have a long term requirement for daily assistance [64]. Direct healthcare costs have been estimated at USD$48.3 billion per year [65]. Indeed, TBI is so widespread that the Centers for Disease Control and Prevention (CDC) has viewed it as an important public health problem and made references to it as the “silent epidemic” [63].

The leading causes of TBI are falls (28%) and motor-vehicle traffic accidents (20%) (Fig.41), with the majority of the TBI cases caused by falls involving children between the ages of 0-14 and all the TBI cases caused by motor-vehicle accidents involving adults between ages 15-54. While the solutions for reducing TBI occurrence due to falls are not very forthcoming (perhaps by closer supervision of children), TBI reduction amongst adults involved in motor-vehicle accidents can be easily and effectively achieved by passing and enforcing a mandatory motorcycle helmet law.
5.2. **Mandatory Helmet Laws**

Despite protests on the basis of personal freedom, most governments in the world today upholds the mandatory helmet laws as research has shown time and time again the effectiveness of such laws in reducing fatalities, head injuries (mostly TBI) and healthcare costs [66][67][68][69][70]. Table 5 summarizes some of these findings.

<table>
<thead>
<tr>
<th>Country/ State</th>
<th>Mandatory Helmet Law</th>
<th>Change in helmet usage</th>
<th>Change in injury rate</th>
<th>Change in motorcyclist fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>Enacted</td>
<td>+198%</td>
<td>-</td>
<td>-38%</td>
</tr>
<tr>
<td>Nebraska</td>
<td>Enacted</td>
<td>-</td>
<td>-22%</td>
<td>-</td>
</tr>
<tr>
<td>Texas</td>
<td>Repealed</td>
<td>-</td>
<td>-</td>
<td>+35%</td>
</tr>
<tr>
<td></td>
<td>Enacted</td>
<td>+239%</td>
<td>-11%</td>
<td>-</td>
</tr>
<tr>
<td>Taiwan</td>
<td>Enacted</td>
<td>+457%</td>
<td>-33%</td>
<td>-33.2%</td>
</tr>
<tr>
<td>Thailand</td>
<td>Enacted</td>
<td>+500%</td>
<td>-41.4%</td>
<td>-20.8%</td>
</tr>
</tbody>
</table>

Table 5: Correlation between mandatory helmet laws and helmet usage, injury rate and fatalities amongst motorcyclists [66][67][68][71].

In another study conducted in Illinois, one of the three remaining states in the US that has not yet imposed a mandatory helmet law, it was shown that non-helmeted motorcycle riders are 5.85 times as likely to be hospitalised as a helmeted rider, with 1.7 times the severity of injuries [72]. They are 25 times as likely to die and increase healthcare costs by approximately 23% [72]. In a
separate study, researchers estimated that the state of Nebraska saved USD$ 1.1 million in healthcare costs two years after the enactment of the mandatory helmet law [71].

With such research results, it is not difficult to fathom the reason behind the determination with which governments have upheld the mandatory helmet law against personal freedom, best summarized in a statement by a federal court of Massachusetts in 1972 [66]:

“The public has an interest in minimizing the resources directly involved. From the moment of injury, society picks the person up off the highway; delivers him to a municipal hospital and municipal doctors; provides him with unemployment compensation if, after recovery, he cannot replace his lost job; and, if the injury causes permanent disability, may assume responsibility for his and his family’s subsistence. We do not understand a state of mind that permits plaintiff to think that only he himself is concerned.”

This decision was affirmed by the US Supreme Court. Today, most doubts and protests have already been quelled, allowing for a near universal enactment of the mandatory helmet law [73].

5.3. Market Statistics

Because of the mandatory motorcycle helmet law passed in most countries, a big market opportunity is presented for the undulating helmet design. Since the governments are generally steadfast in upholding this law, the market for motorcycle helmets is relatively stable as well.

There are no statistics that have compiled the market size of motorcycle helmets either worldwide or for a particular country. As such, the market size for individual countries has to be inferred from the number of motorcycles utilized as transportation tool. Asia is generally a hotspot for motorcycles. In Malaysia, for instance, motorcycle travel constitutes approximately 50% of the traffic and in Vietnam, 8000 motorcycles are registered daily [74]. 1 in 1.9 people in Taiwan owns a motorcycle [75] so that the total motorcycle population in Taiwan was already 9 million in 1997 [76].
There are, however, concrete statistics representing the global market for premium motorcycle helmets, a subset of the generic motorcycle helmet market. Premium helmets can be defined as helmets that are fashionable and confer greater safety to its wearer [77]. Each helmet is generally priced at USD$375-800 [77].

According to Shoei and a recent report by Global Industry Analyst Inc, the global trade of premium helmets currently stands at USD$542 million [78] and is expected to expand to USD$851 million by 2015 [77]. Europe is the single largest contributor to the premium helmet demand, accounting for half of the global market [77]. Substantial growth of the premium helmet market, attributed to a rise in motorcycle registrations and enactment and enforcement of mandatory helmet laws, was also observed in India, Vietnam and US [77]. As a result of rising income levels and implementation of the mandatory helmet law, Asia-Pacific will likely become the fastest growing regional market for premium motorcycle helmets [77].

5.4. Helmet Manufacturers

The end market for motorcycle helmets is an extremely competitive business, with more than twenty separate companies vying for a piece of market share [79]. Helmet manufacturers aggressively differentiate their products in an attempt to win over more customers by improving or tweaking any of the following attributes of their helmets: quietness, ventilation/air flow, defogging, face shield ability to keep wind out, face shield ability to resist scratching, ease of replacing face shield, scratch resistance of shell, color/graphic design, weight, ease of fastening the strap and comfort/fit [79]. Based on the evaluation of these qualities in a helmet, it was found that Arai leads all the motorcycle helmet companies in consumer satisfaction with Shoei coming in a close second (Fig. 42) [79].
The two key areas that matter most to a consumer, however, lie in the prestige of a helmet’s branding (possibly based on endorsements from a popular racer and/or history of the brand) and the level of safety the helmet confers on its wearer. The latter also serves to bolster the prestige of a helmet brand as such helmets are often marketed as a high-end, high-technology good. That is the reason consumers are willing to pay a significantly higher price for premium helmets. It is also the reason why Shoei continues to own more than 50% of the premium helmet market share based on its strong brand name [78] despite Arai making helmets of the best quality.

5.5. Competitive Market Technology

In 2009, Belgium based motorcycle helmet company, Lazer, introduced the Superskin® helmet which incorporated a novel design that can reduce rotational acceleration and related injuries
during an oblique impact. It started with a British doctor, Ken Philips, who first conceptualized the design fifteen years ago [80].

![Figure 66: Anti-rotational membrane on Superskin® helmet [81].](image)

The Superskin® helmet is essentially the same as an average helmet with one major difference – the outermost layer of the helmet consists of a membrane placed on a lubricating gel mattress laid on top of the helmet shell [81]. The membrane can stretch up to eight times its original length and is extremely tough. The structure of this layer, based on the Philips Head Protection System (PHPS™), is designed to imitate the human scalp which limits rotation of the head during an oblique impact by sliding on the skull [82]. In this way, the Superskin® reduces rotational acceleration of the head and brain which, if left unchecked as with a traditional helmet, may be large enough to cause severe intracranial shearing of blood vessels and nerve fibres [83][84]. In addition to such neurological lesions, skull fracture and subdural haematoma can occur also [84].

Simulations and experiments have found that the Superskin® helmet can reduce the mechanical impact load of an oblique collision by 50%, resulting in a corresponding fall in risk of lesion formation by 67.5% [85]. These results were corroborated by the Louis Pasteur University of Strasbourg in association with the CNRS, the French National Scientific Research Centre [86]. For its work on Superskin®, Lazer was awarded the Best Patented Innovation of the year 2009 in a contest organized by Belgian magazine "Industry, Technique and Management" in collaboration with Roularta, the leading business weekly [87].
Figure 67: Intracerebral shearing found in brain of a person wearing a (a) standard helmet and a (b) Superskin® helmet 17ms after simulated impact (Von Mises stress [85]).

Figure 68: Superimposed graphs showing the stresses sustained by a brain employing the classic helmet and the Superskin® helmet [85].

Since the Superskin® design only acts to reduce rotational forces in oblique impacts, it is not a direct competitor to the undulating helmet shell design in terms of technology. This is especially true when one considers the fact that the designs of the undulating shell and Superskin® are not mutually exclusive, assuming a way can be found to drape the membrane and lubricating gel mattress over the contours of an undulating helmet shell. Nevertheless, it may choose to present itself as an alternative instead of complementary method for helmet makers to differentiate their
products and thus, draw away a portion of the target market for the undulating helmet shell design.

It is also worth noting that the Superskin® technology took the average 15 years to be implemented and commercialized, demonstrating that innovation in motorcycle helmets is not all that different from other industries. In addition, like the undulating shell design, Superskin® was inspired by a design from nature.
6. Implementation

In the considerations of the implementation of a particular design or prototype, the process flow for fabrication of existing products must be clearly understood so as to foresee any difficulty and accurately predict the costs of modifying the process.

6.1. Process Flow

6.1.1. Shell Fabrication

Motorcycle helmet shells are commonly made from either thermoplastics (e.g. ABS, polycarbonate etc.) or glass/carbon fiber reinforced polymeric (GFRP/CFRP) composites, each with their own set of pros and cons. The main advantage of a thermoplastic helmet shell is the relatively lower weight of the finished helmet, an important factor affecting performance [88]. For most polymers like ABS, the ease of processing and good surface finish quality also add to their popularity as the material choice for motorcycle helmets [88]. However, some polymers, such as polycarbonate, are not as easy to process and are vulnerable to organic solvents and lacquer, complicating the manufacturing process [88]. In addition, thermoplastics tend to become brittle due to photo-oxidation [89] and other degradation mechanisms when they experience prolonged exposure to the environment, thus limiting the lifetime of the final product. FRP helmet shells, on the other hand, confer better corrosion resistance and shock absorbing capacity to the helmet, albeit at a relatively higher cost [88]. For this reason, FRP shells are usually found in premium motorcycle helmets and thermoplastic shells are offered as cheaper alternatives.

The method of manufacturing a thermoplastic helmet shell is relatively simple. It consists of a single step involving injection molding of the polymer of choice [90]. The molten thermoplastic is injected into a die at a particular temperature and pressure, after which it is allowed to cure. Next, the die, which is made up of two separate halves, parts to release the finished helmet shell.

The manufacturing process for composite shells, however, is comparatively more complex. The details of each step are given in the following and a summary can be found in Fig. 49.
**Step I**

A releasing agent and a cover layer of thermosetting resin which will determine the basic colour of the finished helmet is sprayed onto a negative helmet mold that looks like a headform [90]. Small strips of glass or carbon fiber mats pre-impregnated with highly viscous polyester or epoxy resin and hardener are then manually applied onto the moist cover layer [90]. Using special tools and a positive helmet mold, pressure is applied onto the FRP mats to make them conform to the contours of the mold [90]. This step is repeated until the shell is built out of the required number of FRP layers (usually less than nine) [90]. Shoei, for instance, uses only four to five layers to produce its Advanced Integrated Matrix (AIM) and AIM+ helmet shells (Fig. 46) [91]. Care must be taken to remove any air bubbles trapped between layers in this step, as they will likely compromise the mechanical properties of the final helmet.

![Figure 69: AIM and AIM+ layers of a SHOEI helmet shell [91].](image)

**Step II**

The composite helmet shells are sent into an oven for baking. The thermosetting polyester/epoxy resin within which the fibers are suspended in hardens and sets the shape of the helmet. This process is crucial as the optimum baking temperature and time gives the resin the right levels of strength and elasticity required of a motorcycle helmet for impact absorption and penetration resistance [91].

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**Step III**
After the separation of the helmet shell from the mold with the help of the releasing agent between them, the helmet shell is given its final shape by a laser that removes any unwanted protrusions and cut out openings for the face shield and ventilations ducts according to a particular model’s design [91].

### 6. 1. 2. Shell Finishing

**Step I**
After the thermoplastic/ composite shells have been given their final shapes, they are given their first coat of primer before being sanded and manually polished (more for composite shells than thermoplastic shells as injection molding usually gives very good dimensional tolerances) [92].

**Step II**
A uniform coat of paint is manually applied to the outer surface of the helmet shell with a spray can. The quality of helmets today generally do not allow for drips, inclusions or even unevenness of colour, and thus, only qualified employees in the company will be allowed to perform this step [92].

**Step III**
Customized graphics involving water decals applied by hand are transferred onto the helmets [92].

**Step IV**
A layer of protective varnish is given to the helmet to protect the decorations and increase the light reflectivity of the helmet [92].

**Step V**
Ventilation sliders, shield seals, EPS foam liners and comfort padding are assembled together with the helmet shell [92].
6.1.3. Foam Fabrication

The process of producing the EPS liner of a helmet is very similar to the process of producing thermoplastic helmet shells. It essentially consists of an injection molding step, but because the material is EPS, it has to undergo a pre-expansion procedure [88].

Polystyrene beads are first fed into a large, pre-heated cylindrical tank pressurized with hot air. The beads are allowed to soften uniformly before a vacuum is applied to the tank, causing the polystyrene to expand [88]. The density of the EPS required can be controlled with this expansion [88]. The pressure within the tank is then returned to normal atmospheric levels and the polystyrene is discharged to the holding bin. This completes the pre-expansion step.

The pre-expanded polystyrene is then injected with a blowing agent (usually hot air or superheated steam) while being guided into the mold where additional expansion of the beads caused by venting of the mold forces the polystyrene beads to fuse to one another and conform to the shape of the mold [88].

After the cooling of the mold and stabilization of the EPS, the mold is separated and the EPS liner is released with a blast of air or ejection pin [88]. As with the fabrication process of the composite shell, the mold is usually coated with a release agent such as Teflon to increase the
ease of liner removal. It is imperative that the liner is not damaged in any way during this ejection process as its effectiveness in shock absorption decreases with increasing defects.

Figure 71: Schematic diagram showing the machines involved in the pre-expansion phase of EPS liner fabrication [93].
Figure 72: Summary of process flow for fabrication of motorcycle helmet.

- Thermoplastic shell
- Composite shell
- Foam Liner

1. Injection molding
2. Layer by layer build-up of shell using composite mats
3. Baking
4. Laser machining
5. Application of primer
6. Sanding and manual polishing
7. Painting
8. Decorations
9. Varnish
10. Pre-expansion
11. Injection molding
12. Assembly
6.2. Modifications and Costs

To incorporate the undulating helmet design into motorcycle helmets, the shell and the foam liner must be molded with the undulations. The inner surface of the foam liner will return to the traditional shape with a spherical curvature so that the designs for the other components need not be changed. To transfer the undulating pattern to the foam liner and helmet shell, all that is required of an existing helmet manufacturer is two new molds; one for the foam liner and the other for the helmet shell. A mold with the undulating helmet design made of say, aluminium, will implement the design directly onto the foam liner and thermoplastic helmet shell during the injection molding process. As for the composite helmet shells, a starting mold with the undulating design will transfer the pattern to the composite mats applied onto it. After baking, the composite helmet shell will retain the undulating design. The downstream processes after these stages are assumed to be compatible with the new design and remain unchanged.

Figure 73: A finite element model showing how a motorcycle helmet with an undulating shell might look like.

Based on this modification in the original process flow for helmets, a cost model was developed. Since the final optimized design is not known, the cost model was extended to cover the possibility that the final design could be highly complex. The existing helmet design is taken to be a design of low complexity and the undulating shell design is taken to be of medium or high complexity. A list of assumptions made and parameters involved in the cost model is given below.
**Assumptions** [94]

(i) The foam is made of EPS with 95% air and the helmet shell is made of polycarbonate.

(ii) The helmet shell with foam liner is approximately a sphere with an outer radius of 160mm and an inner radius of 100mm. The thickness of the helmet shell is 10mm.

(iii) Specific gravity of molten polymer = 1.00

(iv) Number of gates in injection molding machine = 1

(v) Number of cavities per mold = 2

| Parameters of injection molding of EPS foam liner affected by assumptions [94] |
|-----------------------------------------------|----------------|----------------|
| Fill, Pack and Cool Time                      | Low Complexity | Medium Complexity | High Complexity |
| Ejection Time                                 | 55.12          | 55.12           | 55.12           |
| Injection Pressure                            | 4.14           | 4.14            | 4.14            |
| Injection Pressure                            | 11.8MPa        | 11.8MPa         | 11.8MPa         |
| Clamp Tonnage                                 | 28.7 tons      | 28.7 tons       | 28.7 tons       |
| Parts/hour                                    | 121            | 110             | 97              |
| Tool Cost                                     | USD$41,087     | USD$42,895      | USD$45,607      |
| Machine Cost                                  | USD$51.91/hr   | USD$51.91/hr    | USD$51.91/hr    |
| Material Cost                                 | USD$1.98/kg    | USD$1.98/kg     | USD$1.98/kg     |

**Table 6: Table showing the various parameters in the cost model for EPS liner fabrication.**

| Parameters of injection molding of Polycarbonate helmet shell affected by assumptions [94] |
|-----------------------------------------------|----------------|----------------|
| Fill, Pack and Cool Time                      | Low Complexity | Medium Complexity | High Complexity |
| Ejection Time                                 | 78.74s         | 78.74s          | 78.74s          |
| Injection Pressure                            | 4.49s          | 4.49s           | 4.49s           |
| Injection Pressure                            | 15.9 MPa       | 15.9 MPa        | 15.9 MPa        |
| Clamp Tonnage                                 | 98.7 tons      | 98.7 tons       | 98.7 tons       |
| Parts/hour                                    | 72             | 66              | 58              |
| Tool Cost                                     | USD$66,603     | USD$90,063      | USD$101,259     |
| Machine Cost                                  | USD$56.58/hr   | USD$56.58/hr    | USD$56.58/hr    |
| Material Cost                                 | USD$4.4/kg     | USD$4.4/kg      | USD$4.4/kg      |

**Table 7: Table showing the various parameters in the cost model for helmet shell fabrication.**
Results of Cost Model

It should be noted that the costs presented in the following represents only the fabrication costs of a helmet shell and foam liner with an undulating shell or traditional design. They are not reflective of the costs involved in producing a full helmet, which include labour costs, marketing costs and fabrication costs of other parts of the helmet. However, they serve as a useful guide in estimating the capital cost that an existing helmet manufacturer needs to invest to produce undulating helmets by indicating the differential cost between producing a helmet with the traditional design and undulating shell design.

Since the additional cost and therefore, capital, that a manufacturer needs is the fixed cost of two new molds (USD$40,000/mold - USD$100,000/mold) for the foam liner and helmet shell, the additional cost required to produce each helmet with the undulating helmet design is inversely proportional to the production run i.e. as the overhead tooling cost spreads out over a greater number of helmets, the average cost of each helmet decreases (Fig. 51 shows the typical shapes of curves for various costs). The amount of material required and fabrication time in the machine
is the same for every helmet and hence, material and processing costs remain constant regardless of production size.

![Production Cost of Helmets](image)

*Figure 75: Diagram showing the average cost of producing an undulating helmet of different complexity with respect to production run.*

Because of the spreading out of overhead tooling costs, the total cost of fabrication of both the helmet shell and foam liner decreases significantly under higher production runs. As can be observed in Fig. 52, a production run of approximately 25,000 - 30,000 will lower the cost per helmet shell with liner significantly to USD$22, USD$10 less than if the production run stops at 5000 helmets. Beyond this threshold run however, the cost per helmet decreases slowly as material and processing costs become dominant.

As expected, a highly complex helmet design requires the highest cost of production at all levels of production size due to a more expensive starting mold and longer processing time. It is worth noting, however, that the difference in cost between producing a highly complex helmet with undulating design and a simple, traditional helmet is approximately only USD$1/helmet,
representing a variation of cost less than or equal to 3%. The cost of production, therefore, is not strongly dependent on the design of the helmet.

The estimated capital cost that a manufacturer needs to raise for the molds to start producing undulating shell helmets is USD$133,000 if the final optimized undulating shell design is of medium complexity and USD$147,000 if the design is of high complexity.
7. Business Plan

Due to the competitive nature of the end market for motorcycle helmets, it is not advisable to form a start-up company to market the undulating helmet. Firstly, start-ups do not have the brand power of other companies, a major selling point in the market. Secondly, there is not enough marketing power in an undulating helmet design alone to compete with the finely tuned technology of existing companies in other areas of the helmet, including aerodynamics, paintwork, ventilation etc. Lastly, a significantly large amount of funds will be required to form a motorcycle start-up company.

With these considerations in mind, the proposed business plan is to shift the market focus from end-users of the helmets to the helmet manufacturers instead. A list of the mutual benefits that can be reaped by both the research group and helmet manufacturer is given in the following table.

<table>
<thead>
<tr>
<th>Research Group</th>
<th>Helmet Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduced cost of research by using manufacturer's test facilities</td>
<td>• Opportunity to differentiate goods in highly competitive market</td>
</tr>
<tr>
<td>• Consistent research funding from manufacturer</td>
<td>• Improve brand name with better safety features so other helmet models sell better too</td>
</tr>
<tr>
<td>• Lower barrier of market entry for design since manufacturer already has most of the required infrastructure</td>
<td>• Lower cost in adoption of cutting edge technology as it will be co-developed by company</td>
</tr>
<tr>
<td>• No other way to sell into supply chain since most companies do in-house production for all the processes</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Mutual benefits from research collaboration.
7.1. Partners

Since the target market is now the helmet manufacturers, to maximize future earnings, the collaboration should be made with the company with the largest share in the current motorcycle helmet market. In addition, it must be interested in research and should be capable of the eventual investment required to incorporate the undulating design into motorcycle helmets.

The company that fits these criteria best is Shoei, the leading manufacturer for premium helmets. It owns 53.9% of the global market, has a strong brand name and caters to the demand of 50 countries worldwide [78], with Europe contributing to 50% of its sales and North America, 20% [95]. In addition, it puts a strong emphasis on the safety features of helmets, using them as to market and differentiate its helmets. It has a strong interest in research too, destroying more than 3000 helmets per year for safety tests [92] and owns a wind tunnel within which aerodynamic tests on the helmets are conducted [57]. Shoei also performs all of the manufacturing processes in-house, from shell molding to painting and assembly, using a Toyota production system [78]. This further bolsters the need for a partnership since there is no way to sell an optimized undulating shell design into the global supply chain as it does not exist outside of individual helmet companies. Lastly, Shoei will be more than capable of investing the estimated USD$133,000 - USD$147,000 for the production of helmets with undulating shell design after it has been fully developed (Table 9). Although its sales have been decreasing for the past year, it still makes a significant profit and the decrease in sales could have been a result of the recent global economic downturn [95].

Another company that is also suitable for collaboration would be the aforementioned Lazer. Its success with the Superskin® technology proves their emphasis on safety research in motorcycle
helmets and it is no stranger to collaborations with universities and research centers worldwide [56].

### 7.2. Intellectual Property

As with any endeavours in innovation, a background check on intellectual properties is necessary to ensure that there will be no infringements on any existing patents still in effect. This background check also serves the purpose of keeping the research abreast with the newest developments in the field. A summary of patents related to this thesis is shown below.

<table>
<thead>
<tr>
<th>Related Field</th>
<th>Patent Number and Title</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helmets</td>
<td>US 6604246: Protective Helmet [99]</td>
<td>Novel design of helmet shell of variable impact resistance to complement weaker and stronger regions of the head.</td>
</tr>
<tr>
<td>Sandwich structures</td>
<td>US 6644535: Truss Core Sandwich Panels and Methods for Making Same [100]</td>
<td>Novel design of triangular cells in core and method of fabrication.</td>
</tr>
<tr>
<td></td>
<td>US 7208063: Double walled structural reinforcement [101]</td>
<td>Novel design of having each cell of a honeycomb core surrounded by another honeycomb cell rotated by 30° to improve mechanical strength of structure and method of producing the structures.</td>
</tr>
</tbody>
</table>

Table 10: Table showing patents related to designs for improved impact resistance or mechanical properties.
7.3. Patent Strategy

Since there are currently no patents pertaining to an improved impact absorption design based on the designs of the internal explosion chambers of the Bombardier Beetle, there is no copyright infringements involved in the development of the undulating design of the helmet. In addition, since a patent has been applied by Yao et al on the features of the internal explosion chamber of the Bombardier Beetle [9], the intellectual property of any modified designs of the undulating shell design should belong to the research group unless the patent is bought over by the company. This agreement of intellectual property should be made before official collaboration with any helmet manufacturer. It is also recommended that rapid prototyping be used as a technique to produce the undulating helmet design or modified versions of it during the research phase so that the designs can be reduced to practice and additional patents can be applied for them. In the event that a new process for production is developed, the patent can be shared between the research group and company if it was jointly developed.

7.4. Pricing Strategy

The above graph gives an indication of how much improvements in safety mean to a typical consumer. It can be observed that the differential gain to a consumer at very high or very low absolute safety levels is relatively low as compared to the approximately linear mid-region. This
is to be expected, as consumers are unlikely to pay very much more for a helmet that can only withstand a collision with a beetle as compared to one that can withstand only the impact of a fly. Similarly, they will probably not pay more to own a helmet that can withstand the shockwaves of two atomic bombs when a helmet that can only withstand one atomic bomb is on the market, as the safety conferred is already beyond the desired limit. These two extreme examples serve to explain the shape of the curve on the graph.

Based on the example of the Superskin® technology, a reasonable pricing for the undulating helmet can be deduced. Since Lazer intends to price the Superskin® helmet about 150 euros (USD$190) higher [102] and the Superskin® reduces rotational load by 50% in all directions, therefore

$$\frac{\partial (utility)}{\partial (safety)} = \frac{USD \ 190}{3} = USD \ 63.3$$

for 50% reduction of rotational stress per orthogonal direction. Since the simulations for the undulating helmet show that stresses on the head will be reduced by 40% during an impact on the side and assuming that rotational loads and linear loads are of the same utility to consumers, the helmets with an undulating shell design should be priced at an estimated USD$50 above an average DOT/ECE approved helmet.

7.5. Expected Profits

<table>
<thead>
<tr>
<th>Production cost of helmet shell and foam liner (USD/helmet)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Production size</td>
<td>Traditional Design</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>30.75</td>
</tr>
<tr>
<td>20000</td>
<td>23.05</td>
</tr>
<tr>
<td>50000</td>
<td>21.48</td>
</tr>
<tr>
<td>100000</td>
<td>20.96</td>
</tr>
<tr>
<td>200000</td>
<td>20.68</td>
</tr>
</tbody>
</table>

Table 11: Total cost of producing helmet shell with foam liner for each kind of design.

Consider then, the profits a helmet manufacturer can make with the assistance of the production cost of the undulating helmet in the above table. Assuming that the average price of a Shoei
helmet is the same as the median of the price range for premium helmets (~USD$590), Shoei produces 200000 helmets annually at a price of USD$20.68 per helmet shell with foam liner. The incorporation of the undulating shell design of medium complexity into 5000 helmets will cost Shoei USD$31.39 per helmet, USD$10.71 more than the usual cost. However, it is able to price the helmet at USD$50 more, giving it a net profit of USD$39.29 per helmet. A more detailed calculation following this logic is presented below.

![Profits](image.png)

*Figure 77: Profits that can potentially be reaped with respect to production size.*

<table>
<thead>
<tr>
<th>Production size</th>
<th>Profits (million USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Medium Complexity</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5000</td>
<td>0.196</td>
</tr>
<tr>
<td>20000</td>
<td>0.947</td>
</tr>
<tr>
<td>50000</td>
<td>2.451</td>
</tr>
<tr>
<td>100000</td>
<td>4.957</td>
</tr>
<tr>
<td>200000</td>
<td>9.972</td>
</tr>
</tbody>
</table>

*Table 12: Profits that can potentially be reaped from the undulating helmet design.*
As can be readily observed from the graph, the eventual complexity of the final design of the undulating helmet shell does not significantly influence the profit margin. In addition, the overall profit is a linear function of the production size and if Shoei, for instance, adopts the design for all the helmets it produces for a year, it can reap about USD$ 10 million worth of additional profits, improving its financial income by about 25%. Approximately 3% - 5% of this additional profit will go to the research team, depending on the collaboration agreement. This scenario, of course, hinges on the unrealistic optimism that Shoei will be able to continue selling the same number of helmets despite a USD$50 price hike. In truth, the high elasticity of demand for motorcycle helmets will prevent Shoei from reaping the full USD$ 10 million of profits by driving away some of the consumers to other readily available substitutes. Nevertheless, this sort of calculation is instrumental in tabulating the range of expected profits.

Despite the rewards of a large production size, it is recommended that a low production run of about 10,000-20,000 helmets should be tried out first to find out the receptivity of the market before approaching full-scale mass production.
8. Conclusion

The natural design of the internal explosion chambers of the Bombardier Beetle presents an invaluable opportunity to improve the efficiency of current impact and shockwave absorbing engineering designs. Three applications for the design -- the military helmet, motorcycle helmet and crumple zone in automobiles and locomotives were considered.

Preliminary results from simulations based on finite element analysis showed that when the undulating membrane design of the internal explosion chambers of the Bombardier Beetle was applied to helmets, impacts on the helmet are directed away from the inner surface and head and a substantial amount of impact absorption took place when the dynamic loading was to the side of the helmet. Improvements were also made to the aerodynamics of the helmet and suggest a lower impartation of energy from shockwaves of an explosion to the helmet. The same analysis done on the cantilevers in a crumple zone gave similar results but the corresponding reduction in stiffness rendered them unsuitable for its other function of sustaining non-dynamic loads.

The market potential of the helmets was evaluated next and although there is a strong demand for a helmet design that could mitigate shockwaves better than the current military helmet, the details of the market were not examined as the military was recognized to have an unrestrained power to produce market demand and fund research and innovation. An in-depth analysis of the motorcycle helmet market found that the growing demand for motorcycle helmets is stable and presents a lucrative opportunity for the undulating shell design.

Implementation issues were considered and it was found that an investment of USD$133,000 – USD$147,000 in molds is required of an existing manufacturer to produce the motorcycle helmets with the undulating shell design.

Lastly, a business plan which encouraged collaboration with existing helmet manufacturers, specifically Shoei and/or Lazer, was formulated. A background check on existing intellectual properties turns up no dangers of infringement. In addition, because a patent on the features of the internal explosion chambers of the Bombardier Beetle had been applied by the research
group, pre-collaboration agreements should state the ceding of all intellectual properties of any
product produced based on the designs by the company to the research group. The price of the
helmet was recommended to be USD$50 above average and a maximum profit of about USD$10
million can be expected from a production run of 200,000, out of which 3% - 5% should be
allotted to the researchers. The profits increase linearly with production size and were found to
be independent of design complexity. A more pragmatic approach was suggested though, and it
was recommended that the manufacturer adopt a lower production size for the initial phase to
examine the receptivity of the market to the new design.
References


Smart USA, “Hard Shell with a Soft Exterior,” smart.


J. Passmore, N.T.H. Tu, M.A. Luong, N.D. Chinh, and N.P. Nam, “Impact of Mandatory


[82] Lazer, “the greatest advance in head protection since the invention of the full-face helmet,” 2010.


[84] Lazer, “The cost 327 European study - Rigorous scientific studies open the way to innovative industrial application,” 2010.


Appendix A

Mass of a round without shell, $m_r \approx 0.001$ kg
Mass of helmet, $m_h = 1.36$ kg [40]
Velocity of round, $v_r \approx 1000$ m/s

By conservation of momentum,

Velocity of helmet and round $= v_h = \frac{m_r v_r}{m_h + m_r}$

$= 2.2$ m/s

Average deceleration (assuming all the 1.3cm gap is used), $a = \frac{v_h^2}{2 \times 0.013}$

$= 186.2$ m/s$^2$

Average force on the suspension system $= (m_h + m_r) a$

$= 254$ N
Appendix B1

Average deceleration of motorcycle helmet, \( d = \frac{v^2}{(2 \times s)} \)
\[
= \frac{(10 \text{ km/h})^2}{(2 \times 0.05)}
= \frac{(2.78 \text{ m/s})^2}{0.1}
= 77.3 \text{ m/s}^2
\]

Average force on rider = \( d \times m_{\text{person}} \)
\[
= 77.3 \times 65
= 5025 \text{ N}
\]

Appendix B2

Following the analysis in Appendix A,
Velocity of helmet and round = \( v_h = \frac{5m_r v_r}{(m_h+5m_r)} \)
\[
= 8.75 \text{ m/s}
\]

Average deceleration (assuming all the 1.3cm gap is used), \( a = \frac{v_h^2}{(2 \times 0.013)} \)
\[
= 2943 \text{ m/s}^2
\]

Average force on the suspension system = \( (m_h+m_r) \times a \)
\[
= 4038 \text{ N}
\]